

Urban water and sanitation in Siem Reap, Cambodia: a transdisciplinary case study informing the inclusive and systemic planning of heterogeneous service provision configurations

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A thesis submitted in fulfillment of the requirements for the
degree of Doctor of Philosophy under the supervision of
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May 2025

Certificate of original authorship

I, Simon Ross declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Institute for Sustainable Futures at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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I did not embark on this PhD journey expecting the ordinary to persist. However, completing the thesis and following through with the intention to change a situation has undoubtedly been coupled with *transformations* of my own. During this time, I twice committed to my partner and re-integrated with her into life as a now small, third-culture Australian family after a decade together in Cambodia. Notwithstanding the significance of these watersheds, the most profound has been coming to self-awareness and acceptance of my *autism*.

Defining the depth to which this has shaped my identity is elusive. Still, I choose to acknowledge differences in how I communicate, where my focus is drawn, and how I perceive situations as strengths that have shaped my research.

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Format of thesis and included publications

This thesis is submitted as a *thesis by compilation* as outlined in the University of Technology Sydney's Graduate Research Candidature Management, Thesis Preparation and Submission Procedures 2023 (*Section 10.1.2*), comprising a combination of chapters, and published or publishable works, supported by a conference poster and conference abstract used to progress concepts in this work, as included in the *Appendix*. These included works are:

1. Ross, S., Fane, S. & Foster, T. 2023, 'Defining socio-technical diversity in urban WASH systems' *Water and WASH Futures*, Brisbane, Australia. washfutures.com/resources (Appendix A)
2. Ross, S., Fane, S. & Foster, T. 2023, 'Least-cost economic evaluation of citywide inclusive sanitation interventions in low- and middle-income countries', *IWA Water and Development Congress and Exhibition*. Kigali, Rwanda. waterdevelopmentcongress.org/wp-content/uploads/2023/12/IWA-WDCE-2023-Technical-Session-Programme.pdf (Appendix B)
3. Ross, S., Fane, S. & Foster, T. 2024, 'Evaluative criteria for least-cost economic analysis of citywide inclusive sanitation: A scoping review', *Journal of Water, Sanitation and Hygiene for Development*. DOI: [10.2166/washdev.2024.209](https://doi.org/10.2166/washdev.2024.209)
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Declarations of co-authorship

Conference Poster: Defining socio-technical diversity in urban WASH systems

In the case of the conference poster *Defining socio-technical diversity in urban WASH systems*, presented at the *Water and WASH Futures conference*, in Brisbane, Australia in February 2023, and compiled in the Appendix of this thesis, we, the undersigned, agree that the nature and extent of the contributions to the work was as follows:

Co-author	Nature of contribution	Extent of contribution (%)	Signature	Date
Simon Ross	Led the conceptualisation, research, data analysis and visualisation, and design and of the poster in response to feedback. Presented the poster at the conference	90	Production Note: Signature removed prior to publication.	29/4/2025
Simon Fane	Provided critical feedback on drafts of the poster during supervision meetings	5	Production Note: Signature removed prior to publication.	30/4/2025
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Co-author	Nature of contribution	Extent of contribution (%)	Signature	Date
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Sunday Yim	Provided critical feedback on final draft. Validated the approach in the Cambodian context	5	Production Note: Signature removed prior to publication.	30/04/2025

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Abstract

Within cities of low- and middle-income countries (LMICs), the heterogeneity of demand for water and sanitation services contributes to persistent inequalities in how the benefits and costs of managing urban water resources are distributed. A need for planning approaches that accommodate the bottom-up, demand-driven provision of mixes of service provision models has long been evident. A more holistic understanding of the complexity of existing *heterogeneous infrastructure configurations* and the diverse perspectives from which they are understood is essential for planning a transition to citywide inclusive services.

Conceptual frameworks supporting endogenous urban water and sanitation planning have been established and refined over several decades. This thesis aims to validate a practical methodology that frames urban water and sanitation planning as a flexible action-oriented learning process that may be adapted to be culturally feasible and context specific.

The thesis is structured as three transdisciplinary cycles of action-oriented learning. The first focuses on the problematical situation of applying comparative economic analysis methodologies to prioritise interventions in heterogeneous urban water and sanitation configurations. This research has scoped and synthesised fragmented least-cost economic principles from the related literature to devise evaluative criteria for appraising and enhancing least-cost methodologies, thereby addressing limitations experienced by water and sanitation professionals. The second learning cycle organised for the problematical situation of heterogeneous water and sanitation configurations to be observed from diverse issue-owner perspectives in a real-world case study. Knowledge was generated through a heterogeneous residential end-use water demand analysis, and various soft system models as learning devices, to explore their potential in shifting how societal actors and water and

sanitation professionals think about service provision in Siem Reap, Cambodia, and prompt actions to improve it.

The third learning cycle sought to think through how the use of these models may be integrated and organised as a systemic planning approach for Siem Reap municipality, with relevance to other comparable cities in the Asia Pacific, and globally. Evaluative criteria from the first learning cycle were applied to strengthen this deliberation. This thesis presents a discussion to lead thinking on planning frameworks that embrace the complexity of heterogeneous urban water and sanitation configurations. It argues that the role of planners is to be genuinely curious about possible endogenous solutions emerging from within this problematical situation. Organising gentle, collaborative interrogation of such purposeful models for change is key to organising water and sanitation as citywide inclusive public services.

Part One: Learning how to compare a possible, desirable, feasible, and inclusive mix of interventions for heterogeneous water and sanitation configurations

Chapter One: Introduction

1.1 Overview

This thesis documents the conception, design, conduct, and evaluation of a purposive, transdisciplinary body of research based on the *outcome spaces framework* (Mitchell et al., 2015). The research focuses on methods for planning interventions within *heterogeneous water and sanitation service configurations* in low- and middle-income countries (LMICs). It is shaped by a *purposeful intention* to devise planning approaches that respond to persistent inequalities in how the benefits and costs of urban water and sanitation services are distributed across cities, arising from this heterogeneity. The inquiry is organised as three action-oriented learning processes aligned with the *three outcome spaces* (Mitchell et al., 2015) that (i) define problematical situations of interest, (ii) explore these situations in the real world, and (iii) critically reflect on what was learned to prompt actions to improve these situations.

This introductory chapter situates this research in response to previous work for a master's dissertation set in Battambang, a secondary city in Cambodia, where the intention for the inquiry arose (Ross 2018). It further positions this work within the broader context of urban water and sanitation planning in cities in LMICs in the Asia Pacific region and globally. I map the key issues, actors, infrastructures, and institutions that shape service delivery in such contexts, and describe how these interact across different scales to produce uneven service outcomes. I then make my own positionality in relation to these dynamics explicit to support my claim to conduct a reflexive, action-oriented, transdisciplinary inquiry (Mitchell et al., 2015). From this perspective, I articulate how my motivations shaped each cycle of action-oriented research, and how these motivations align with the ontological and epistemological assumptions underpinning the study to support its integrity.

Chapter One concludes by outlining how the four papers arising from this research are woven into a coherent, compelling thesis. By adopting the outcome spaces framework, this thesis effectively begins at the end (Mitchell et al., 2015), defining desired improvements to a problematical¹ situation of interest upfront. This means that the theoretical assumptions and methodological decisions discussed in Chapter Two are as integral to the contribution of this thesis as the findings discussed in Chapter Seven and the reflections in Chapter Eight.

1.2 Research context

The conceptualisation of this thesis arose through the completion of an unpublished dissertation for the award of a Master of Integrated Water Management (Ross, 2018). This work considered the guiding principles of the Dublin Statement on Water and Sustainable Development (UNCED, 1992) to analyse the *urban metabolism* of Battambang Municipality. The work examined how the infrastructure configurations that provide water and sanitation services acquire social and political identities with the power to shape who benefits from planning decisions, and who does not.

The study collected qualitative data from *twenty-five* in-depth interviews with societal actors ranging from Provincial and Municipal officials, service providers, health care workers, residents, and peri-urban farmers. These actors all related in some way to downstream flows of wastewater from the city, characteristic of many secondary cities in the Mekong region (Ross, 2018). In particular, the work considered whether infrastructure-led planning norms for the development of urban water and sanitation services resulted in disproportionate impacts for marginalised urban areas (Middleton & Krawanchid, 2014).

¹ Checkland and Poulter (2010) defined a *problematical* situation, as opposed to a more conventional term of *problem situation*, to distinguish between complex situations that are not amenable to being objectively *solved out of existence* and require a soft systems approach to improving the situation. This convention is used consistently in this thesis even when referring to methods such as *critical systems heuristics* (Ulrich, 2000) that are focused on these contexts but do not explicitly use this terminology.

1.2.1 Framing heterogeneous water and sanitation service configurations

Although widely acknowledged in the Battambang case study (Ross, 2018), inequalities arising from the planning of basic municipal services through the management of urban water resources were rarely addressed meaningfully. The master's dissertation drew attention to the perceived inevitability of such disproportionate impacts, and how local effort to resolve this problematical situation was constrained by political inertia (Ross 2018). Structuring the master's dissertation through an *urban political ecology* lens linked this inquiry to others within broader literature characterising urban water and sanitation planning in this way as a basis for accessing insights into how more equitable and sustainable futures may be realised.

Urban political ecology has been described as a global *community of practice* (Robins, 2012). By linking studies focused on the political nature of decisions about urban water and sanitation systems and the implications for social and environmental justice, experiences in Battambang, as a secondary city of Cambodia, could be linked to experiences in similar cities of other relevant LMICs, e.g. Bell (2020), Jaglin (2014), Karpouzoglou et al. (2018), Lawhon et al. (2017), Letema (2012), Middleton et al. (2017), and Nakyangaba et al. (2021).

A feature of such studies is a focus on the diverse perceptions of the sustainability of urban water and sanitation planning and governance across an urban-to-periurban continuum. Conflicting worldviews present within such contexts may prioritise intentions ranging from a desire to improve public amenity; to promote tourism and a pleasant urban environment; through to intentions to improve low-quality housing, constrained access to water and sanitation services, and the accumulation of solid waste and wastewater pollution, affecting the urban poor (Middleton & Krawanchid, 2014).

Urban political ecology articulates how unequal power relationships produce winners and losers depending upon which of these conflicting perspectives are prioritised when decisions about the planning of urban water and sanitation services are made. Insights from such studies can shape an understanding of how transformation towards more democratic and just urban water and sanitation systems may emerge (Bell, 2020; Heynen, 2014).

For instance, Jaglin (2014) calls for moving beyond infrastructure-led norms for supplying urban water and sanitation services towards recognising the value of the broad mix of existing, socio-technically diverse service provision models that respond directly to diverse demands. This concept is reflected in Lawhon et al.'s (2017) framing of complex, *heterogeneous infrastructure configurations comprising multiple and partial infrastructures with different coverages, technologies, logics, and ownerships* which has been adopted as an epistemic object in this thesis to support thinking about how planning frameworks might evolve in response.

Interpreting existing water and sanitation service provision arising from such heterogeneous configurations has profound implications. First, it raises the question of how to meaningfully compare components of these systems with inherently different assumptions and functions. Second, it prompts reflection on which components are relevant to a broader urban water and sanitation configuration, how they are interrelated, and what systemic impacts these relationships have over time. Third, it invites inquiry into how arrangements might become more equitable to sustainably benefit society (Jaglin, 2014).

Thus, urban political ecology has contributed *indirectly* to the theoretical and methodological framework of this thesis through its epistemic role in re-structuring urban water and sanitation planning as a *complex problematical situation*. For instance, conceptualising urban water and sanitation configurations as being shaped by uneven

power relationships that produce inequitable socio-technical arrangements necessitates the application of a critical lens when making decisions using the methodological and theoretical framework outlined in *Chapter Two* (Jaglin, 2014).

1.2.2 Urban water and sanitation planning in secondary cities of Cambodia

Socioeconomic development in Cambodia has been linked to poverty reduction and markedly improved access to urban water and sanitation services. However, significant disparities in access to urban water and sanitation services between the better-off and poorest quintiles of the population prevail, particularly in secondary cities (Mosello & O'Leary, 2017; Smets, 2015; WaterAid, 2015). In recent years, there has been an increasing focus on the heterogeneity of such service outcomes (Mosello & O'Leary, 2017; Nou et al., 2018; Rhodes-Dicker et al., 2022; Thuon & Cai, 2019; WaterAid, 2018). Inequalities in these contexts, particularly for urban sanitation services, are described as being shaped by latent unresolved conflicts that persist over extended periods and are often deprioritised by donors, government, and non-government actors, who tend to prioritise more visible issues at the political and economic core of cities (Mosello & O'Leary, 2017; Rhodes-Dicker et al., 2025; Smets, 2015; WaterAid, 2015).

This situation is linked to an array of complexities in secondary Cambodian cities, arising within a context of rapid urbanisation and climate vulnerability (Lord & Prior, 2024; Mosello & O'Leary, 2017; WaterAid, 2015). Circumstantially, the most significant investment in improving urban water and sanitation services in this situation is sourced from households, through contributions to the self-supply of household water and sanitation infrastructures and their maintenance (Danert & Hutton, 2020; Kingdom of Cambodia, 2024; Mosello & O'Leary, 2017; Smets, 2015).

These aspects of the development of heterogeneous water and sanitation service provision configurations can make monitoring such real-world service outcome disparities and the socio-technical arrangements that produce them challenging. Constraints to service provision are often masked by the way knowledge about these systems is produced, which tends to exclude the experiences of how households and individuals access self-supplied or other less formal service configurations. [Mosello and O'Leary \(2017\)](#) describe a risk that pockets of marginal peri-urban housing with constrained water supplies and unsanitary containment systems may reproduce without an effective means of including these experiences within planning frameworks ([WaterAid, 2015](#)).

In the secondary cities of Cambodia, the planning and regulation of socio-technically diverse components of urban water services have been somewhat integrated, following successes in the capital, Phnom Penh, as well as in Siem Reap ([WaterAid, 2024](#)). However, this is not the case for urban sanitation services ([Kingdom of Cambodia, 2024](#); [Mosello & O'Leary, 2017](#); [Smets, 2015](#)). To date, most publicly financed interventions have focused on the development of conventional networked sewer infrastructure and wastewater treatment plants in wealthier urban areas that are more convenient to service. These investments are heavily subsidised compared to those supplied by informal service providers or households themselves at full cost recovery. Infrastructure also operates with significant latent capacity due to capital maintenance issues and low connection rates ([IRC & WaterAid, 2016](#); [Kingdom of Cambodia, 2024](#); [Mosello & O'Leary, 2017](#)).

The extent to which these interventions are integrated with existing non-networked faecal sludge management and solid waste collection services in Cambodia is limited. Such services, in contrast, have been accessed via informal private business and self-supply practices at full cost recovery, which have emerged in direct response to demands for

services (Frenoux & Tsitsikalis, 2012; Global Green Growth Institute, 2019a; IRC & WaterAid, 2016). Cambodia's decentralisation and deconcentration process has faced limitations in transferring autonomy and public finances to Municipal and Sangkat Authorities. Meanwhile, local institutions, being closer to the point of service consumption, are often perceived as better equipped to understand and facilitate improved water and sanitation service delivery at this scale (WaterAid, 2024).

Existing regulations reinforce this fragmentation. For instance, *Sub-Decree 235 on the Management of Drainage System and Wastewater Treatment System* provides clear directives on the disposal of wastewater to a sewer and onsite treatment systems used by commercial operations and new urban development and housing projects. It requires building plans to be approved prior to construction (Kingdom of Cambodia, 2013). However, these regulations were not designed to support local authorities to transition existing households or businesses toward safely managed sanitation, nor to regulate faecal sludge collection and transport for existing urban communities (Kingdom of Cambodia, 2024; Global Green Growth Institute, 2019a; 2019b).

As a result, although some utilities provide faecal sludge treatment services, collection and transport are often carried out by informal or private operators without a formal regulatory framework. This often leads to uncertainty regarding service quality, accountability, and long-term sustainability, reinforcing fragmented and uneven service outcomes (Kingdom of Cambodia, 2024). Each of these issues constrains relationships between service authorities, service providers and households within secondary cities. This results in gaps between the nominal role of local institutions and their actual capacity to fulfil their mandate (Mosello & O'Leary, 2017; Smets, 2015).

1.2.3 Urban water and sanitation planning in low- and middle-income countries

The dynamic, multifaceted context in which interventions for heterogeneous urban water and sanitation service provision configurations are planned in Cambodia is a complex situation replicated across cities of LMICs globally (Tayler, 2018). Service outcome inequalities have been shown to persist for the lowest income quintiles of urban households in heterogeneous configurations, who are more vulnerable to the impacts of rapid urbanisation and climate change (Andersson et al., 2016; Bayu et al., 2020; Gambrill et al., 2020; Hutton & Andrés, 2018; UNICEF & WHO, 2019). Further, there are also many hidden gaps that lead to disparate access to water and sanitation services for the same subgroups identified in the Cambodian context, which are less visible when monitoring global indicators (Dickin & Gabrielsson, 2023; Evans, 2007).

Such persistent inequalities continue to result in disparities in water and sanitation service outcomes in marginalised populations in cities of LMICs. Significant proportions of urban citizens are reliant on informal or self-supplied arrangements in these contexts that produce fragmented service outcomes (UNICEF & WHO, 2021). The forecasted scale of investment required to provide safely managed water and sanitation services to such urban populations is vast (Hutton & Varughese, 2016; WHO & UNICEF, 2021). Moreover, tangible estimates of the required investment in infrastructure largely under-represent the perspective of low-income and marginalised households. Even where planned service options are in reach of these residents, they often fully bear opportunity costs associated with transitioning from informal configurations necessary to realise improvements in service outcomes (Hutton et al., 2014; Hutton & Andrés, 2018; Danert & Hutton, 2020).

In addition to these tangible determinants of service outcome inequalities, a range of less tangible, non-monetary costs are rarely acknowledged in formal planning frameworks.

These include the additional time spent by those accessing informal configurations to treat and dispose of water of variable quality and maintain self-supplied means of doing so; addressing safety and privacy concerns, and the stigma associated with accessing unreliable or unsafe water and sanitation services (Sclar et al., 2018; Sinharoy et al., 2019). Studies across LMIC urban contexts globally highlight that these burdens fall disproportionately on marginalised groups including women, renters, low-income households, and residents of peri-urban or informal settlements (Dickin & Gabrielsson, 2023; McGranahan, 2015; Narain et al., 2023). While these costs are substantial, and widely documented, they are inconsistently incorporated into existing quantitative approaches.

Costs that are less visible and measurable significantly contribute to the persistence of service-outcome inequalities due to their influence on household decisions. Societal actors interact differently with urban water and sanitation configurations determined by where they are positioned within a city. Nonetheless, this existing context is challenging to account for within formal urban water and sanitation planning frameworks. This heterogeneity raises important questions about how comparative economic analyses of urban water and sanitation are currently framed and whose costs they include. This context justifies the research questions posed by this thesis and motivates the context specific, pluralist, transdisciplinary orientation of the research.

1.2.3.1 The need to respond to a fragmented service provision context

One factor that has influenced this situation is a historical focus on the infrastructure-led supply of services, as opposed to directly monitoring and responding to demands related to the operation and maintenance of water and sanitation services *as they exist* across service chains and within households (Andersson et al., 2016; Hawkins et al., 2013). A need for supply strategies that respond more effectively to this demand in fragmented,

heterogeneous water and sanitation service configurations is evident. A response should be led by a more disaggregated understanding of the economic, spatial and social determinants of service outcome inequalities (Dickin & Gabrielsson, 2023; Gambrill et al., 2020; McGranahan, 2015).

Urban water and sanitation planning in heterogeneous contexts requires a more holistic, contextual understanding of the factors influencing a *without-project situation*, including how they interact to influence the ways in which services are provided. This framing includes (i) the existing physical infrastructures within a configuration both at a household scale and across the service chain, by which wholesale water and sanitation services are provided; (ii) the endogenous capacities and resources available to provide services, including self-supply; (iii) the nature of unmet demands for services and how they manifest differently across a city; (iv) the formal and informal means of regulating service provision; (v) the broad enabling environment including capacity for local collective action; and (vi) the projected life cycle costs of how existing and possible service provision models may evolve over time (Evans, 2007; McGranahan, 2015; Ramôa et al., 2018; Tayler, 2018).

1.2.3.2 How inclusive planning frameworks have emerged in response

Arguments for more adaptive, dynamic, and holistic planning approaches that integrate the supply of formal publicly financed systems of water and sanitation service provision with options that meet the demands for more basic services in pockets of marginal areas across a city are not new (Evans, 2007; Hawkins, Blackett & Heymans, 2013). For instance, a broad range of *conceptual frameworks* and approaches for the planning and design of *citywide* or *inclusive sanitation* have been proposed and iterated by the water and sanitation sector over several decades. Four prominent frameworks drawing upon planning principles established by the World Bank during the *International Decade of Drinking Water*

Supply and Sanitation in the 1980s have been heavily profiled, developed with a realisation that conventional centralised infrastructure would not align with demand in all urban areas of LMICs (Julius, 1979; Kalbermatten et al., 1980; 1982a; 1982b).

Overall, these frameworks express a need for a holistic perspective, integrating the planning of both urban water and sanitation services, and going beyond infrastructure to include an array of other factors influencing demand for water and sanitation services at the community or household scale; in particular, the inclusion of the perspectives of low-income and marginalised users (Evans, 2007; Hawkins et al., 2013; Kennedy-Walker et al. 2014; Rosenqvist et al., 2016; Schertenleib et al., 2021; Spuhler & Lüthi, 2020). While such approaches represent important progress in recognising heterogeneous demand and diverse service provision models, their translation into planning practice has remained limited. One significant limitation of these frameworks is the limited methodological guidance on how household-level impacts, including non-monetary costs, should be interpreted within comparative economic planning. As a result, informal and self-supplied service experiences often remain weakly embedded in comprehensive decision-making processes.

Each framework has addressed the need to balance gaps between the supply and demand for water and sanitation services across urban areas in different ways. For instance, the *Strategic Sanitation Approach* introduced the idea of negotiating with communities with an established *willingness to pay* for services to address these gaps by identifying which of a broader mix of options might be desirable or alternatively made desirable to such users (Wright, 1997). However, the approach relied heavily on existing demand for these options. Decisions about the strategic *unbundling of* service components were supported by providing diverse alternative options in relevant geographical areas to facilitate choice, or to

stage investments incrementally to plan supply in closer alignment with expected demand. Both horizontal and vertical unbundling were intended to balance desired service levels and affordability. However, in practice, the approach was limited to providing principles to guide how such unbundling might occur, rather than practical advice. Further, the focus on the commercial principles of cost recovery might be questioned as prioritising financial sustainability over social sustainability. The approach may be criticised for not reaching marginalised users without the capacity to pay for existing options (Kennedy-Walker et al., 2014; Wright, 1997).

In contrast, a *Household-Centred Environmental Sanitation* (HCES) approach advocated for a stronger bottom-up, integrated planning of *urban water and sanitation* to be organised. This was promoted as a means of more directly responding to demand for service provision in homogeneous zones at different scales, but as close as possible to the problem that planning is intended to resolve (Eawag: Swiss Federal Institute of Aquatic Science and Technology, 2005; Kalbermatten et al., 1999; Lüthi et al., 2010).

Community-Led Urban Environmental Sanitation Planning (CLUES) attempted to enhance this idea by extending household demand to community scale demand. This iteration focused on the establishment of an enabling environment to better align and integrate bottom-up planning efforts with broader institutional frameworks. For example, a demand creation step at the start of a planning process could be used to identify local leadership that might be able to unite actors around a plan (Lüthi et al., 2011).

However, the limitation of both of these approaches was the reliance on framing zones or communities as having unified or consistent demands, with minimal friction between actors. While highly participatory and well suited to shifting local behaviours and practices, this also limited the areas where this approach could be applied within a city,

raising questions about the scalability and capacity to access finance to implement outcomes of planning processes.

Another influential planning framework, *Sanitation 21*, considered the complexity of needing to balance heterogeneous demands for urban water and sanitation services across different urban domains, particularly at the household and community scale. The approach characterised service provision contexts as dynamic, and driven by rapid urbanisation, where gaps between the perspectives, experiences, and priorities at the *household and community domains* and a *city domain* were persistent. The approach assumed that demand was driven by complexities arising primarily at a local scale. This approach identified a lack of flexibility and capacity to accommodate these shifting demands to address the institutional inertia constraining local action. *Sanitation 21* proposed to address this inertia by simplifying this context (Evans & Saywell, 2006).

The framework defined a range of generic service provision models applicable to most situations to streamline how these options might match the demands of clusters of households. Further, the framework focused on identifying broader capacity needs at a *city scale* for resourcing selected options while considering a holistic range of external factors that might affect their sustainability. The approach highlighted the need for incremental changes to prompt longer-term behavioural shifts to help balance demand and supply and a more relational approach between institutions and communities (Evans & Saywell, 2006; Parkinson & Lüthi, 2014). However, while the framework outlined a need to assess the costs of disaggregated plans for service delivery, it remains largely conceptual.

1.2.3.3 The challenge of embracing complexity through planning

At present, the translation of planning frameworks for urban water and sanitation into planning processes used in practice within municipalities in LMICs remains limited. Further

work to achieve traction within the real-world complexity of urban water and sanitation contexts is required (Hawkins et al., 2013; Scott et al. 2017; Kennedy-Walker et al. 2014; van Welie et al., 2018). For instance, Evans & Saywell (2006) described *Sanitation 21* as an *embryonic approach* representing an intention to enhance conventional sanitation planning. While the framework was later revised, the identification of possible options in diverse urban contexts remains somewhat prescriptive and limited in how effectively it may accommodate diverse perspectives (Spuhler & Lüthi 2020).

Kennedy-Walker et al. (2014) suggest that the influence of rational water and sanitation planning in these contexts is lower than it needs to be, calling for investing more time and focus in better understanding the context in which interventions are planned. Rosenqvist et al. (2016) go further to suggest that not only the contextual complexity requires deeper reflection, but also the complexity of the diverse perspectives that urban water and sanitation professionals bring to these situations.

The extent to which household demand for urban services, especially for marginalised users, has been embraced and integrated with the perspectives of service providers and service authorities within urban water and sanitation planning frameworks also remains limited. Detailed practical guidance on how urban water and sanitation professionals might work towards offering a dynamic blend of disaggregated, socio-technical service options that provide users with a genuine choice between acceptable and desirable service outcomes and affordability remains aspirational. In this light, pathways transitioning towards more equitable and sustainable arrangements require a focus on the capacity of users to pay for services as well as a shift in perspectives about a collective capacity to supply them (Abey Suriya et al. 2015; Abey Suriya et al. 2019; Abey Suriya et al., 2008; van Welie et al., 2019).

The way water and *sanitation cityscapes* are perceived as systemic, as opposed to linear means of providing water and sanitation services to meet heterogeneous demands is still evolving, alongside the definition of the *citywide inclusive sanitation* agenda (Lüthi et al., 2020; Schertenleib et al., 2021; Scott & Cotton, 2020). That is, to: (i) prioritise urban sanitation as a human right; (ii) achieve safely managed sanitation service outcomes across an entire urban water cycle via a diverse, adaptive, and incremental mix of service provision models; (iii) recognise the tangible and intangible contributions of sanitation to economic development; and (iv) commit to partnerships between formal and grassroots actors to transparently deliver *integrated urban services*, including water supply, drainage, and solid waste management (Lüthi et al., 2020). This thesis adopts an action-oriented learning approach to exploring this situation in the context of Siem Reap municipality in Cambodia to inform practice globally in LMICs.

In summary, despite evidence of the heterogeneity of service outcomes in Cambodia, as well as globally constraining planning efforts; methodological guidance on how urban planners can systematically compare, assess and make evidence-based decisions about complex, socio-technically diverse water and sanitation configurations remains limited. Existing frameworks identify problems associated with uneven service delivery. However, they provide little practical advice on how to interpret bottom-up household demand, integrate intangible costs, or evaluate diverse service typologies within a coherent least-cost comparative analysis. This constrains the ability of planners to design economically equitable and contextually appropriate interventions in heterogeneous urban environments in LMICs.

1.2.4 Knowledge gaps

Despite the extensive global literature defining the problematical situation of how to plan heterogeneous water and sanitation configurations in LMICs, three important gaps remain unresolved. First, while studies identify inequities between networked, informal, and hybrid service arrangements, there is limited understanding of how to systematically compare these configurations in a way that meaningfully reflects their societal implications.

Second, existing comparative economic analyses tend to assume homogeneity in service conditions. Moreover, intangible and non-monetary burdens, such as time, dignity, safety, and psychosocial stressors, that shape how households experience and evaluate services are often omitted or not addressed in a context-sensitive way as part of economic evaluations. Addressing these inequalities is not only a technical or economic challenge but raises concerns about urban environmental justice. When conventional least-cost planning frameworks assume homogeneous conditions, they obscure how the impacts of service configurations are distributed across diverse socio-economic groups. Integrating such considerations, particularly the uneven distribution of costs and risks is a key motivator for this thesis. It aims to develop a planning approach that can engage more equitably with heterogeneity.

Third, although the context in Siem Reap is broadly representative of many secondary cities globally, such contexts remain underexamined when considering comparative economic appraisals of urban water and sanitation interventions. Case studies that meaningfully compare mixed interventions under conditions of rapid urbanisation, fragmented governance, reliance on household self-supply and informal service provision, and spatially heterogeneous service outcomes remain limited. Consequently, new knowledge is required regarding how to adapt least-cost and integrated resource planning

principles to such heterogeneous contexts and develop a methodology capable of integrating the social and technical dimensions of service provision in decisions. This thesis addresses this gap by developing and testing a systemic comparative economic analysis methodology as part of a broader transdisciplinary case study.

1.2.5 Positioning myself as a researcher in this problematical situation

As an early career researcher, I position myself within the problematical situation described above in Cambodia and, more broadly, in the context of urban water and sanitation planning in LMICs. I intend to address persistent inequalities in how the benefits and costs of providing urban water and sanitation are distributed across secondary cities in Cambodia and in LMIC contexts. Thus, it is important to openly reflect on my position, the motivations guiding this research, and the intentions shaping its design, including how my relationship to the context has evolved over time. While I remain an outsider in many visible ways, through my nationality, racial profile, and academic privilege, years of engagement have drawn me into the everyday social and institutional dynamics of the setting. I have come to understand my role not only as an external observer, but as someone embedded, in part, in the ongoing flow of life in the research context (Checkland & Poulter, 2010).

In 2003, at the age of 24, I made the decision to withdraw from a confirmed PhD candidature in Chemical Engineering. While I had demonstrated academic aptitude and progressed well in a technically focused field, I increasingly found myself feeling out of step with the context and expectations of that environment. Having grown up in various regional towns in Northern New South Wales, shaped by complex early life experiences that fostered a strong sense of independence, I was beginning to question how best to align my skills with my evolving interests in social and environmental development.

At the time, I was navigating challenges in social communication and self-understanding that I now recognise, with the benefit of hindsight and a later formal diagnosis, as characteristics of autism. Although I was not aware of this at the time, these differences influenced the ways I processed emotions, engaged with others, and interpreted the academic environment around me. This experience significantly shaped the trajectory of my career and my motivations for engaging in research that acknowledges diverse ways of knowing, communicating, and participating in knowledge creation.

I was discouraged from further study and guided towards establishing my own *community development praxis*, informed by a *dialogical approach* and supported by a broader *community of practice* in Brisbane, Queensland (Westoby & Kaplan, 2014). I was encouraged to apply this praxis, not in a traditional social work setting but within *community spaces* in Australia, where social development needs existed. I was advised to seek out inter-cultural spaces with open, flexible boundaries inviting dialogue and relevant social enterprise that would provide opportunities to work reflexively (Burkett & McDonald, 2005).

I spent ten years prioritising my intention to *make a difference*, working and volunteering across multiple intercultural spaces in Brisbane, Australia, using this framework. This included work in neighbourhood centres, a publicly accessible urban community farm, a disability worker's co-operative, arts venues and community cafes, various social enterprises, as a *conversation partner* at an English language college, as a social research interviewer at a university, and similar experiences. Through this practice, I collaborated with a vast range of vulnerable perspectives different to my own, which has strongly influenced my worldview.

In 2013, aged 34, I translated this praxis, prioritising the observation, listening, reflection, and prompting of critical dialogue (Burkett & McDonald, 2005; Westoby & Kaplan, 2014) to address social development needs in Cambodia, where I would remain for a decade. At this time, I was motivated to integrate my aptitude for engineering into my praxis by focusing on *community spaces* relevant to water and sanitation service provision. Compared to my work in Brisbane, where it was necessary to seek out spaces to practice, in Cambodia, they were ubiquitous (Burkett & McDonald, 2005). I worked in a breadth of new social development contexts with this focus, facilitated through various connections with local development organisations in rural and urban settings.

Outside these roles, I also worked as an editor, primarily for emerging researchers focused on water governance and development across the Mekong region to finance this endeavour. This experience enabled me to explore these areas of interest in depth through local perspectives (Middleton et al., 2016). At this time, I was also engaged in studying for an interdisciplinary *Master of Integrated Water Management*. This study allowed me to apply my praxis through targeted *problem-based learning* assessments, broadening my knowledge and experience of local contexts and spheres of influence as I engaged with various societal actors within government and non-government institutions and local practitioners. This experience included the process of completing the dissertation described when defining the context of the research (Ross, 2018).

By the time I had decided to pursue a PhD, I had, to an extent, become embedded within the *everyday flux of life* in Cambodia, as might be expected when engaging in a praxis intended to prompt mutual learning over an extended period (Checkland & Poulter, 2010). I actively pursued every available opportunity to travel to *community spaces* across all *twenty-five* provinces in Cambodia. I engaged in a wealth of unplanned but purposeful

chance meetings, using these opportunities as a chance to practice language and cultural skills through observing and interacting. Through this experience, I met my life partner, who became my wife, and I began living with my family by marriage. I had also become skilled in communicating in Khmer language, developing the capacity to form diverse independent relationships less encumbered by translation.

These experiences have made me much more explicitly aware of the beliefs, thinking, social norms, perspectives, and culture I was embedded within. The *continually changing, on-rushing, turbulent stream of happenings, ideas, emotions, and actions, mediated through the slippery agency of language* in this context, had become more personally meaningful, as had my intention to improve it (Checkland & Poulter, 2010; Mitchell et al., 2015). Like all lenses, my perspective about the complex context of this research is partial and subject to implicit biases and preferences as to what I am likely to focus on, shaped by a cultural lens. I did not spend my childhood in Cambodia or a similar context.

I identify with having a privileged identity and perspective as a *third-culture individual*. However, my inherent associations with the research context go beyond a professional interest and are shaped by the culture co-developed with my partner, family-by-marriage, and the relatively unique duality arising from my formative experience of becoming a water and development professional in the Cambodian, rather than the Australian context. With this background in mind, I go beyond positioning my work in this research chapter with this qualification when I define my motivations and conceptual, ontological, and epistemological positioning concerning the thesis as a source of reflexive practice (Mitchell et al., 2015). These lived experiences reinforce my motivation to explore

transdisciplinary, action learning-oriented planning methodologies that integrate diverse knowledge systems and actively respond to inequalities.

1.3. Research motivations

This section outlines three interrelated motivations that guided the development of the research questions and design. These motivations emerged from extended engagement with the study context and the broader literature on comparative economic analysis of *heterogeneous water and sanitation systems*. The integrity of this research is supported by being transparent about the *intention to address persistent inequalities in how the benefits and costs of managing urban water and sanitation service are distributed across secondary cities in Cambodia, and in LMICs globally*. Being explicit about these motivations and their intended outcomes during the conceptualisation of the research questions of the thesis is important for supporting a reflexive approach to the study. Moreover, establishing and maintaining a clear line of sight between these motivations, the research plan, honed towards addressing them, the criteria for evaluating the research, and the underlying ontological and epistemological assumptions framing the research are important for guiding research practice with integrity (Mitchell et al., 2015).

1.3.1 Least-cost and integrated resource planning principles

The first motivation arising from the problematical situation I observed in previous work was understanding the economic basis of decision-making regarding urban sanitation planning (Ross, 2018). I was driven by the apparent contradiction of prioritising high-cost interventions at the economic and political core of a city that had significant downstream impacts while deprioritising low-cost alternative interventions that might have a more meaningful impact on citizens' needs, which, from my perspective, were more compelling (Mosello & O'Leary, 2017; Ross, 2018; WaterAid, 2015).

This investigation led me to the literature on urban sanitation planning, particularly the seminal work of [Julius \(1979\)](#) and [Kalbermatten et al. \(1980; 1982\)](#) in proposing least-cost economic principles to guide decision-making about selecting appropriate interventions. This thinking has emerged from the realisation that, unlike the iterative development of universal conventional waterborne sewage in high-income countries, this position was most untenable for the provision of basic sanitation services for all in LMICs ([Kennedy-Walker et al., 2014](#); [Öberg et al., 2020](#); [Weiss, 2006](#)). Furthermore, there was a lack of tangible knowledge about the costs of alternative technical options to support the sustainable, integrated planning of new approaches ([Kalbermatten et al., 1980; 1982](#); [McIntyre et al. 2014](#))

In reviewing this work, I identified a trend for subsequent conceptual frameworks to focus more on the broader planning principles of this work and less on the application of least-cost planning principles to supporting decision-making ([Hawkins et al., 2013](#); [Kennedy-Walker et al., 2014](#); [Rosenqvist et al., 2016](#); [Schertenleib et al., 2021](#)). The literature identified focused on the lack of available broad cost-effectiveness data for all possible interventions within the mixes of options, including those that extend beyond infrastructure, and the constraints this places on planning at a municipal scale ([Hutton et al., 2014](#); [Hutton & Chase, 2016](#); [Daudey, 2018](#); [Mills et al., 2020](#); [Sainati et al., 2020](#); [Tilley et al. 2014](#)). While the complexity of these service provision contexts was recognised and, in part, the context-specific determinants of cost existing within relatively small urban areas, there were still methodological gaps in how to produce and employ this data locally ([Daudey, 2018](#); [Hutton, 2001](#); [Sainati et al., 2020](#)).

My perspective is that there is value in deriving generalised heuristics about the costs of existing urban water and sanitation interventions to facilitate the vast investments in service

provision required to achieve the water-related targets of the Sustainable Development Agenda. However, these heuristics are less relevant to resolving the persistent inequalities in urban service provision at a municipal scale. Contextual guidance on methodologies that may be applied to such contexts is fragmented in the literature and limited to components of least-cost economic comparison, such as life-cycle costing (Fonseca et al., 2011; McIntyre et al., 2014).

Drawing inspiration from a set of *Integrated Resource Planning* principles developed by the Institute for Sustainable Futures in consultation with a range of Australian stakeholders in the urban water sector in the mid-2000s (Fane & Mitchell, 2006; Mitchell et al., 2007), I became motivated to learn about how this more comprehensive set of least-cost and integrated resource planning principles may be translated to resolving persistent inequalities for both water and sanitation service outcomes. These principles have been tested in the context of planning sanitation service options for a simplified ‘*greenfield*’ site in Can Tho, Vietnam (Willettts et al., 2010; Retamal et al., 2011; Willettts et al., 2013). However, they have not been used to plan options for the more complex context of existing heterogeneous service provision configurations. This motivation to consider how these principles might be applied to a context with existing service outcome inequalities is addressed in *Chapter Three* of this thesis.

1.3.2 Defining a heterogeneous *without-project* case for inclusive comparison

The second motivation for this research was to define a without-project situation, or basis of comparison, that reflects the complexity of the real-world service provision context in cities of LMICs such as Siem Reap in Cambodia. Evans (2007) refers to the degree of *inertia* in recognising the impacts of rapid urbanisation and climate change on *business-as-usual* approaches to urban water and sanitation planning. These conditions are framed as a

new normal that needs to be embraced within planning frameworks. They identify a need to define a more realistic model of urban populations, or a more holistic understanding of the determinants of demand for water-related services, and how this is likely to emerge from this context in the future. This concept recognises that an existing least-cost scenario for the provision of services is seldom if ever, *doing nothing*, even if this is how planning approaches frame an existing context (Hutton, 2001).

The principle that a *without-project scenario* should represent the most cost-effective situation that would have otherwise emerged without an intervention to account for the local opportunity costs of existing informal infrastructures and practices is rarely applied in practice (Julius, 1979; Sacristán et al., 2020). To do so requires a more contextual, dynamic, and holistic understanding of all existing sub-components of a water and sanitation configuration, how these components are interrelated, and what impacts this has on how an urban water and sanitation configuration behaves (Evans 2007; Mitchell et al., 2007). Such an approach brings into perspective a debate about which parts of an urban water and sanitation system are relevant to a reference case as a basis for decision-making (Franco et al., 2020; Mitchell et al., 2007) and how socio-technically diverse service provision models, emerging from inherently different perspectives might be compared meaningfully.

Conventional comprehensive rational planning frameworks, common in practice, assume a unified system objective, which is how existing practice models are defined to support decisions (Abey Suriya et al., 2019; ISF-UTS & SNV, 2016). In contrast, this thesis intends to define the complexity of a heterogeneous service provision context that integrates the existence of divergent service provision models and their underlying assumptions about the existing problematical situation within the same systems model (Mitchell et al., 2007; Ramôa et al., 2018). *Chapter Five* of this thesis reflects this motivation

by outlining a process of how diverse service provision experiences are integrated into the same water end-use demand model as a physical basis for an economic comparison in the context of a case study in Siem Reap, Cambodia (Ross et al., 2025). *Chapter Six* is also linked to this motivation by outlining how the cognitive assumptions and worldviews representing diverse perspectives may be integrated into a systems model in the same case study context (Ross et al., preprint).

1.3.3 Building relational capacity to respond to inertia

The third motivation for this thesis is to outline a systemic planning approach that intends to shape iterative decisions towards urban water and sanitation arrangements becoming more equitable and sustainable (Jaglin, 2014). To do so requires building the relational capacity and confidence of societal actors to engage in planning processes that aim to address latent conflicts regarding service provision outcomes in a culturally feasible way. This function includes a shared capacity to promote ideas, experiment, negotiate power relationships, and champion and realise improved service outcomes.

This motivation embodies the *collaborative planning paradigm* focused on dialogue, mutual learning, and accommodating the perspectives of others, as well as the *advocacy paradigm* intended to improve arrangements for less powerful societal actors described by ISF-UTS & SNV (2016). Such an approach is focused on longer-term shifts in the political will of these actors to work towards future-oriented, shared urban water and sanitation objectives (Abey Suriya et al., 2019). Such an approach represents a direct response to the inertia described by Evans (2007) and characterised in detail more recently in the Indonesian context by Kösters et al., (2019).

Rational comprehensive planning frameworks often oversimplify decision-making by limiting its scope and, thus, the factors that may be addressed through participation

(McConville et al., 2011; McConville et al., 2014). This approach may be fit-for-purpose for some objectives; however, prescriptive participation has been shown to be less successful in shifting perspectives necessary to realising a citywide inclusive planning agenda (Abey Suriya et al. 2019; Gambrill et al., 2020). For such shifts to occur, there is a need for decision-making processes that access knowledge about competing priorities, interests, and power relationships (Abey Suriya et al., 2019; Ramôa et al., 2018).

Planning processes are required with the capacity to respond to epistemological uncertainty regarding decision-making in inequitable service provision contexts. This is necessary in such situations, where there are winners and losers, and a lack of transparency, accountability, trust, as well as a clear rationale for making ethical decisions (Abey Suriya et al., 2019; ISF-UTS & SNV, 2016). For example, uncertainty arises about how to frame decisions about the distribution of the economic benefits and costs from public financing, what constitutes an acceptable service outcome, what is affordable, and which types of downstream impacts arising from centralised infrastructure in marginal urban environments are included in a decision (Evans 2007; Hawkins et al., 2013).

Assuming a single universal objective with narrow decision criteria limits the inclusion of knowledge of the context-specific needs of communities and the types of assumptions that may be tested in planning frameworks (McConville et al., 2014; ISF-UTS & SNV, 2016). Processes are required to organise societal actors to understand the situation from different epistemologies (or *ways of knowing*) to counter symptoms of inertia. For instance, when service users become disengaged and disinterested in working collaboratively to improve the situation, which, in turn, dulls the political incentives for local institutions to act (Abey Suriya et al., 2019). Some issues regarding water and sanitation services are not well-suited to being resolved solely by the institutions that possess nominal accountability for

decisions (McIntyre et al., 2014). For instance, less tangible issues experienced individually or as part of a household, associated with feelings of futility, anxiety, shame, or embarrassment (Sclar et al., 2018)

Developing a relational capacity to address such issues necessitates greater flexibility for water and sanitation planning frameworks than rational comprehensive planning (ISF-UTS & SNV, 2016). This thesis responds to prompts by Abeysuriya et al., (2019) to adopt *learning experiments* to respond to the complex, ill-defined and rapidly changing urban contexts within cities that produce inequalities. This motivation contributed to the decision to apply soft systems methodology in *Chapter Six* and shaped the discussion in *Chapter Seven* about how context-specific iterative testing of assumptions at local scales may shape citywide water and sanitation planning (Ramôa et al., 2018).

1.4. Research ontology, epistemology and worldview

In this section, I clearly outline the ontological and epistemological assumptions that I adopt and how they shape the worldview I bring to problem-focused research on the complex societal challenge of *persistent inequalities in how the benefits and costs of managing urban water and sanitation service provision are distributed across secondary cities in Cambodia, and in LMICs globally*. Mitchell et al. (2015), following Ison (2008), describe this practice as an obligation because of the process of conducting transdisciplinary research being a somewhat contested concept.

1.4.1 Ontology

I have organised the observation of a complex real-world problematical situation, from multiple perspectives to facilitate knowledge production in this thesis. This approach aligns with the position of *bounded relativism*. It assumes that the problematical situation that is the focus of the research represents a shared reality that may be best understood by

considering the diverse realities of different societal actors connected to it (Moon & Blackman, 2014). Thus, I perceive that the real-world situation of urban water and sanitation management in LMICs comprises a *complex adaptive system*, its subcomponents, and inter-relationships, with the planning of this system being a key interest (Ison, 2008; Neely, 2015; 2019).

I frame this system as open, complex and messy, comprising interdependent, heterogeneous elements with rich interactions with factors outside its boundaries (Franco et al., 2020; Jackson, 2000). From the perspective of a single observer, this reality is unpredictable and does not appear to respond to interventions in a linear way. However, it appears to behave in a way that systemically creates inequalities (Jackson, 2000). This real-world situation has a social memory and constantly evolves. It is full of contradictions, tensions, and conflicts, which are integral to its function (Franco et al., 2020; Heynen 2014). This knowledge may be captured and recovered via *mental models* that facilitate knowledge generation through learning about a shared reality (Moon & Blackman 2014).

For these reasons, the characterisation of the heterogeneous urban water and sanitation configuration in Siem Reap (Lawhon et al., 2018), broadly representative of heterogeneous contexts in other cities in LMICs globally, as a *complex adaptive system* is appropriate. Such systems may be distinguished by multiple actors, non-linear feedback, self-organisation, and emergent behaviours that cannot be fully explained or predicted from the perspective of an individual element alone (Pahl-Wostl, 2007; 2009). Individual system components such as diverse wastewater sinks and treatment facilities, drainage canals or sewers, containment systems, water storage vessels, or household appliances may be considered as designed artefacts. Thus, they are *complicated* or demonstrate behaviours that may become known. However, the behaviour of the contested socio-technical

configurations or service typologies that emerge around these elements are inherently unknowable. They behave in ways that are *relational, contingent* on political factors that are unpredictable, and *adaptive*.

Lawhon et al.'s (2018) framing of diverse, competing socio-technical configurations in such contexts is aligned with systemic practices that identify systems as ways of knowing about dynamic problematical situations, rather than fixed entities that may be observed from a single perspective (Ison, 2010). Water and sanitation services are understood in this case as an emergent outcome of interactions among diverse, technological options, institutions, everyday practices, informal service typologies and latent socio-political tensions. Multiple actors, including diverse household typologies, informal pit-emptiers, water and wastewater utilities, municipal authorities, and civil society make decisions with a partial understanding of the situation, uneven access to resources, and changing incentives. These decisions co-evolve under uncertain complexities such as rapid population growth and urbanisation, climate impacts, and shifts in governance as discussed previously in this chapter. Such conditions give rise to heterogeneous service arrangements that distribute the costs and benefits of urban water resources unevenly over time (Lawhon et al., 2018).

Features such as distributed, multi-level governance; non-linear behaviour, self-organisation, interdependency and emergent inequalities are consistent with established ways of understanding *complex adaptive systems in water governance* (Pahl-Wostl, 2007; 2009). While physical infrastructures are planned, broader *service configurations* are socio-technically and politically influenced and not amenable to prediction or control. Adopting an ontological perspective of this problematical situation of interest as a complex adaptive system justifies a methodology that integrates hard, soft and critical systems approaches outlined in *Chapter Two*.

1.4.2 Epistemology

Related to this ontological position, I adopt an *epistemologically plural perspective*, ascribing value to multiple *ways of knowing* about this shared reality based on their capacity to contribute to integrating different knowledges from different disciplines, and diverse perspectives. This preference acknowledges that giving equal value to diverse knowledges without compromising their integrity is key to mutual learning and obtaining a more complete understanding of a problematical situation, increasing the likelihood of meaningful change (Miller et al. 2008; Mitchell et al., 2015). Making this epistemological assumption also enables a flexible and adaptive approach to conducting participatory transdisciplinary research within a dynamic problematical situation, where understanding what is contextually relevant may change.

For instance, the value of accommodating multiple epistemics in the research is evident in several ways. An *objectivist epistemology* was used in this thesis in several ways. This *way of knowing* was valued in drawing from proven, *replicable knowledge* about least-cost economic principles to help validate the evaluative criteria presented in *Chapter Three*. It was also used to generate tangible knowledge about the heterogeneous water end-use behaviours in the context of *Chapter Five* of the case study. The replicability of this approach means that these parameters might be meaningfully compared to knowledge generated using the same methodologies in other cities of LMICs. A *constructivist epistemology* was valued in development as *recoverable knowledge* in the form of contextual artefacts (*mental models* and *rich pictures*) that could be used to access and apply local knowledge to facilitate learning in the case study context in *Chapter Six*. Related to this work, a *subjectivist epistemology* was valued in applying the semi-structured interview and observation protocol used to create the root definitions as the basis for constructing the *mental models*.

Being able to access knowledge about the personal experiences of different societal actors and how this shaped thinking, feelings, and worldviews was integral to exploring how inertia affected the actors in the same case study (Moon & Blackman, 2014).

Research integrity is maintained when adopting an epistemologically pluralist perspective by being explicit about the motivations and values that underpin the research and using them as a guide for justifying the use of *mechanistic*, *contingent*, and *narrative* approaches to improving different aspects of a problematical situation where they are most relevant (Miller et al. 2008; Mitchell et al., 2015). This position implies that a reflexive approach has been taken to provide a foundation for this flexibility, which will be demonstrated in later chapters. These motivations underpin the choice of *soft systems methodology* and *critical systems heuristics* as flexible, learning-oriented tools to iteratively engage with planning challenges in Siem Reap. In particular, the injustice of the persistent inequalities motivating this thesis requires this epistemological orientation. Lived experiences and relational knowledge are key to understanding the intangible costs of service provision, which are not directly measurable. Yet, they are critical to understanding the behaviour of heterogeneous urban configurations, which means an epistemologically pluralist perspective is necessary to ensure they are not excluded from the research.

1.4.3 Worldview

In adopting outcome spaces as a conceptual, practice-oriented framework for this thesis, recognising the tension that exists within the confines of a PhD thesis, I have adopted a *pragmatic* and *transdisciplinary worldview* in negotiating the conception, design, implementation and evaluation of this research (Mitchell et al., 2015). A *pragmatic worldview* closely aligns with an *epistemologically pluralist* way of knowing and adopting a focus on a problematical situation of interest. Emphasising the problem of *persistent*

inequalities in how the benefits and costs of providing urban water and sanitation services are distributed across secondary cities in Cambodia, and in LMICs globally calls for the use of a research approach that focuses on *what works* in this context. Throughout the research, I have been purposeful and engaged in ongoing reflection on all possible approaches to identifying meaningful improvement in this problematical situation (Creswell, 2003; Mitchell et al., 2015). This *pragmatic* philosophical preference is underpinned by a commitment to curating knowledge from multiple relevant disciplines in a way that facilitates the strongest possible relational understanding between the roles of clients, practitioners and issue owners (see Checkland & Poulter, 2010) associated with the real-life problematical situation (Mitchell et al., 2015; Mobjörk, 2010) .

1.5. Research aim, objectives and questions

1.5.1 Research aim

Considering the problematical situation described in *Section 1.2*, the overarching aim of this thesis is to explore methodological approaches to *urban water and sanitation planning* in LMICs. I hope to guide water and sanitation professionals on how they collaborate with other societal actors to address persistent inequalities in the benefits and costs of providing urban water and sanitation services and support equitable and sustainable outcomes. I aim to provide insights into systemic approaches that enable the integrated planning of the socio-technically diverse components of the *heterogeneous water and sanitation configurations* that provide services across urban environments in these contexts. This intention extends beyond the *multiple and partial infrastructures*, including their *diverse coverages, technologies, operations, logics and ownerships* (Lawhon et al., 2017) in a case study of two villages in Siem Reap, representative of similar cities in LMICs globally.

1.5.2 Research objectives

I have devised three research objectives to provide a greater focus on achieving this overall research aim and align with the motivations for this research outlined in *Section 1.3*. The *first objective* is to scope, synthesise, and validate a set of comprehensive least-cost comparative economic analysis principles relevant for application to heterogeneous urban water and sanitation configurations in LMICs. These principles are not readily applied within urban water and sanitation planning frameworks and have not been comprehensively reviewed in the literature for over 40 years. Guidance specific to this context remains fragmented. I seek to evaluate how such principles are currently applied to decision-making in this context before considering how any gaps in practices might be addressed. These principles are discussed in depth in *Chapters Three and Four* (Ross et al., 2024a, 2024b).

The second objective is to collaboratively define the demand for water and sanitation services for an existing *without-project context*, as the most cost-effective situation that would have otherwise emerged without an intervention (Sacristan et al., 2020), for a case study of a discrete heterogeneous water and sanitation configuration in Siem Reap municipality in Cambodia. I intend to provide a contextual, dynamic, and holistic definition of the components of the end-use demand for water for service provision, how demand for these components is interrelated, and provide an account of how diverse determinants of demand for service provision might evolve in the future in the case study. The details of this *system definition* are presented in *Chapters Five and Six* (Ross et al., *under review a, b*).

The third objective is to outline how an ongoing flexible, iterative planning framework adopting a learning orientation might emerge in Siem Reap to improve the relational capacity and confidence of societal actors. This objective intends to address the *inertia* causing gaps in the infrastructure-led supply of water and sanitation services and the

diverse determinants of demand for these services within households and across an entire service chain. Further, the aim extends to informing the initial development of an integrated planning framework for heterogeneous water and sanitation configurations in LMICs based on the learning that occurred in the case study. The nature of this planning framework is discussed in *Chapter Seven*.

1.5.3 Research questions

Overall research question

What planning approaches might be suitable for addressing persistent service outcome inequalities when planning interventions for heterogeneous water and sanitation service provision configuration in Siem Reap, Cambodia and other similar contexts?

Research question #1a

What might a set of comprehensive least-cost integrated resource planning principles for comparative economic costing of equitable and sustainable urban water and sanitation interventions look like?

Research question #1b

In reference to the existing literature presenting comparative economic appraisals of urban water and sanitation interventions, what gaps exist in applying these principles, and how might they best be addressed?

Research question #2a

How might residential water end-use demand analysis characterise a heterogeneous without-project case for an urban water and sanitation configuration in Siem Reap to inform an inclusive planning approach?

Research question #2b

How might a systems thinking approach identify possible desirable and feasible options for heterogeneous urban water and sanitation configurations in Siem Reap from diverse societal actor perspectives?

Research question #3

How might systemic, learning-oriented approaches to urban water and sanitation planning enhance the relational capacity of societal actors to address the inertia constraining equitable and sustainable water and sanitation service provision in Siem Reap, Cambodia and other similar contexts?

The aims and objectives were translated into the above research questions to guide this transdisciplinary inquiry, characterised by a purposeful intention to address a complex problematical situation of interest. The *overall research question* for the inquiry represents this research aim. The *first research questions #1a and #1b* focus on scoping, synthesising and re-purposing fragmented evidence from a range of theoretical disciplinary perspectives on relevant principles for least-cost comparative economic analysis for planning interventions for heterogeneous water and sanitation service provision configurations to support the inquiry; for instance, from the fields of economics, engineering, governance, and social planning. This knowledge was used to establish several relevant methodological gaps constraining the inclusive and sustainable planning of these configurations in practice.

The *second research questions #2a and #2b* were used to shape a participatory case study methodology, bringing together a diverse range of service users, service providers, and service authorities in an action-oriented, mixed-methods learning approach to define and articulate possible endogenous improvements to the problematical situation. For the

third research question #3, the case study was used as an empirical foundation for proposing a planning framework for the selection of interventions for heterogeneous water and sanitation service provision configurations in cities in LMICs.

Responding to these questions represents three significant contributions to knowledge about urban water and sanitation planning for interventions in heterogeneous water and sanitation service provision configurations. One is the proposal of evaluative criteria that may be used by water and sanitation professionals to support the planning or evaluation of least-cost comparative economic analysis studies to support decision-making about appropriate interventions. Another is the presentation of two innovative modelling approaches for understanding the future resource demands for water to provide water and sanitation services in heterogeneous contexts in LMICs. The first is a quantitative approach to deriving disaggregated water end-use parameters for such a context, where formal and informal service provision typologies are integrated within the same water balance. The second is a systemic approach to the collaborative definition of possible options and decision criteria for use in planning processes.

The final contribution is the insights developed from experimenting with a context-responsive planning approach that integrates diverse types of knowledge to support inclusive decision-making in heterogeneous urban water and sanitation configurations. Instead of proposing a prescriptive planning framework, this shows how adopting a transdisciplinary case study approach, and integrating systems thinking, comparative economic appraisal, and participatory modelling can support a more relational understanding of an existing context. This type of understanding is significant as it prompts endogenous actions in response. This contribution is novel because it is grounded in empirical work in Siem Reap, Cambodia, whereas existing frameworks often fail to reflect

the systemic, plural, and evolving nature of real-world service configuration in LMICs as the basis for planning.

1.6. Thesis structure

I will now conclude this chapter by providing an overview of this manuscript. This *thesis by compilation* has been structured in accordance with the University of Technology Sydney's Graduate Research Candidature Management, Thesis Preparation and Submission Procedures 2023 (*Section 10.1.2*). The thesis comprises two published journal articles and two publishable works. The latter have been submitted to relevant journals, which have been accepted for review by relevant experts. I was the lead author of these works, making a substantial contribution, as verified by my co-authors in the declarations presented in the preface of this manuscript. Each paper is a unique contribution to knowledge, with a distinct theoretical framework, methodology, and analysis. The studies presented in these papers have been coherently compiled within chapters in this thesis. An outline has been included prior to each paper to situate each work within the broader transdisciplinary inquiry. A reflection on the contribution of each paper in response to the research question(s) relevant to their purpose has also been included at the end of each embedded paper.

The thesis is presented in three parts, comprising eight chapters in total. Each part represents a phase of action-oriented learning intended to address the complex societal issue of persistent service outcome inequalities within heterogeneous water and sanitation infrastructure configurations in LMICs.

Part One focuses on learning how to compare an inclusive mix of possible, desirable, and feasible interventions for heterogeneous water and sanitation configurations. This introductory *Chapter One* provides an overview of the problematical situation as the focus of the research, situating it within the case study context, the broader issue of planning

interventions within heterogeneous water and sanitation configurations in LMICs, and my own context as a researcher. I outline how this problematical situation and context has shaped the motivations, aim, objectives and research questions of the thesis. *Chapter Two* outlines the approach taken to answering the research questions using the *transdisciplinary outcome spaces* framework. Within this framework, I scaffold the theoretical and methodological approach taken for the research, outlining relevant methods and analytical tools that are applied in support. *Chapter Three* demonstrates how I scoped, synthesised and validated fragmented knowledge from different disciplines to establish evaluative criteria for least-cost comparative analysis of urban water and sanitation interventions in LMICs in response to *Research Question #1a*. *Chapter Four* then systematically applies this framework to the existing academic literature, presenting comparative economic analyses of integrated urban water and sanitation interventions in practice in response to *Research Question #1b*. This contribution to knowledge was used to identify gaps in existing practice to help plan and evaluate the approach proposed in this research in *Chapter Seven*. Moreover, this contribution served the dual purpose of being used as a theoretical framework for researchers and water and sanitation professionals intending to conduct similar analyses.

Part Two focuses on learning about the heterogeneous demand for water and sanitation services in Siem Reap municipality, Cambodia, in response to *Research Question #2*. This section applies a transdisciplinary case study methodology across two distinct studies that are used to characterise an existing without-project context for service provision, identify possible interventions, and shape context-specific decision criteria that increase the likelihood that an inclusive mix of service options will become available to service users. *Chapter Five* presents a residential water end-use analysis for two villages

comprising the case study area representing a heterogeneous water and sanitation service provision configuration, answering *Research Question #2a*. *Chapter Six* presents a study applying soft systems methodology to identify possible options for the same heterogeneous water and sanitation service provision configuration in response to *Research Question #2b*, establishing criteria that may be used in a multi-stakeholder decision-making process.

Part Three focuses on learning how to disseminate, translate, and implement this research within the case study to increase the likelihood of improvement in the problematical situation in response to *Research Question #3*. *Chapter Seven* considers the theoretical framework outlining the *four waves of systems thinking approaches* to apply insights derived from the Cambodian case study in Part II of the thesis. I discuss how these insights may shape a systemic adaptive urban water and sanitation planning framework for municipal administrations in cities of LMICs. *Chapter Eight* revisits the intended outcome spaces and transdisciplinary case study methodology described in *Chapter Two*. An assessment of the contributions to each outcome space is offered, as well as suggesting opportunities for future research.

Chapter Two: Theoretical and methodological framework

2.1. Overview

In *Chapter One*, three distinct motivations for this thesis were established, informed by a reflexive approach that clearly articulated their underlying ontological and epistemological assumptions (Ison, 2008; Mitchell et al., 2015). The context of the research was defined as a *real-world* urban water and sanitation planning situation in Siem Reap, a secondary city in Cambodia. This situation was framed as an open and messy *complex adaptive system*, comprising interdependent, heterogeneous elements with rich interactions and uncertain behaviour. Given this, it was relevant to bring an *epistemologically plural* perspective, *pragmatic worldview*, and commitment to reflexivity to this work.

Chapter Two translates these motivations into three waves of action-oriented learning: (i) problem framing; (ii) problem analysis; and (iii) exploration of (emerging) impact, each linked to a distinct outcome space and aligned with the transdisciplinary integration model of Pohl et al. (2021). A transdisciplinary case study methodology is articulated in this chapter, cognisant of the fact that the meaning of *transdisciplinarity* is often contested. The perspectives and preferences brought to this problematical situation, and the theoretical and methodological framework adopted for this inquiry are explained. This includes a description of the research design, methods and analytical tools applied to answer the three research questions.

Table 1 (in *Section 2.4.4*) summarises how each aspect of the transdisciplinary inquiry is integrated. The table links each element to supporting literature, and to the chapter of the thesis in which each theory and method is discussed.

2.2. The transdisciplinary outcome spaces framework

This section introduces the *transdisciplinary outcome spaces* framework and explains how it guided the theoretical framing of this inquiry. First, the three outcome spaces proposed by Mitchell et al. (2015) are defined, to describe how they inform the design of the transdisciplinary case study. Then, an outline of how backcasting was applied to conceptualise how the desired contributions relevant to each outcome space could be realised is provided.

Chapter One positioned my disciplinary and experiential background as a transition from a post-positivist perspective as a Chemical Engineer, to reflexive, dialogical community development from a *social constructivist* perspective (Burkett & McDonald, 2005; Westoby & Kaplan, 2014); before integrating these experiences through interdisciplinary work in water and sanitation in Cambodia (McIntosh & Taylor, 2013; Ross, 2018). I demonstrated how this had shaped a pragmatic preference for what Lawrence et al. (2022) describes as the *social engagement school* of transdisciplinarity.

This may be contrasted with the form of *transdisciplinarity* applied in this thesis. In this case, there was also a need to learn how to compare heterogeneous water and sanitation infrastructure configurations. Address service outcome inequalities required a more robust approach. It needed to bridge both the *social engagement* and theoretical *unity-of-knowledge* schools of transdisciplinarity (Lawrence et al., 2022). In other words, it required a unified approach, that integrated knowledge about the economic comparison of such systems from multiple disciplinary perspectives, alongside the active engagement of the diverse perspectives of societal actors in a real-world case study (Jahn et al., 2012; Lawrence et al., 2022; Mitchell et al., 2015; Pohl, 2011; Pohl et al., 2021).

To scaffold such an approach, the *transdisciplinary outcome spaces* framework (Mitchell et al. 2015) was adopted to conceptualise, design, implement, and evaluate the research. This framework offers a systems perspective that brings together diverse collaborators and components of the transdisciplinary approach, and organises them in alignment with three *outcome spaces*: (i) an improvement in the situation; (ii) a contribution to stocks and flows of knowledge; and (iii) mutual and transformational learning (see *Figure 1*).

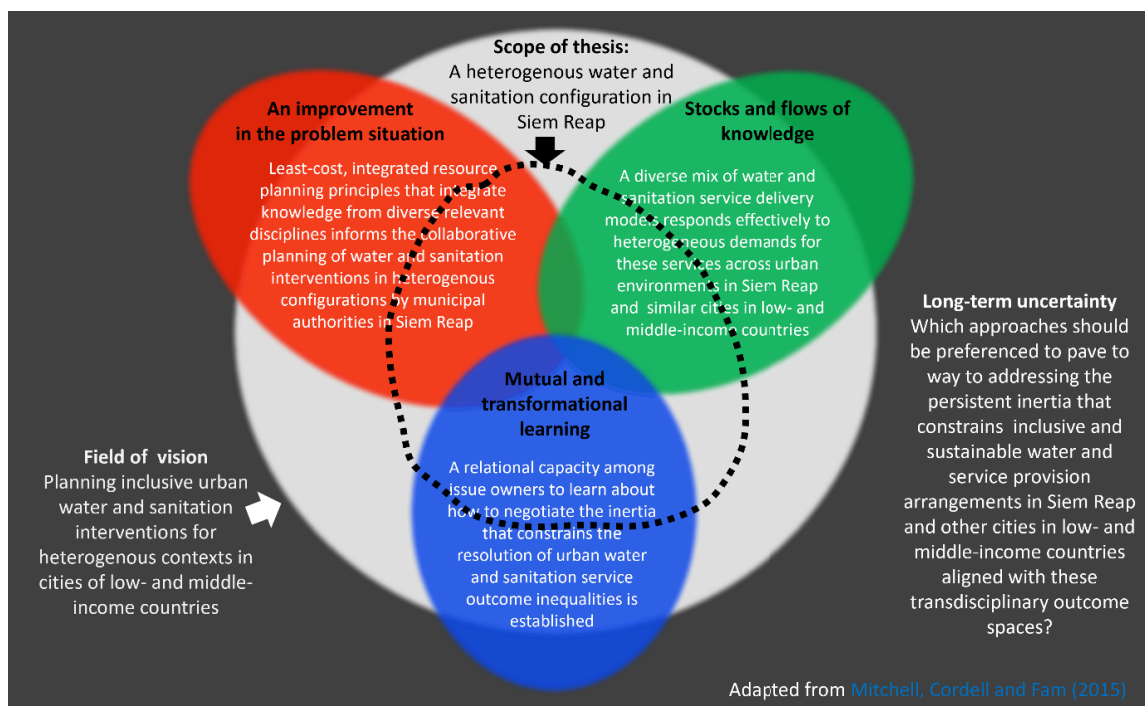


Figure 1: A conceptual map of the transdisciplinary outcome spaces of this thesis, adapted from Mitchell et al. (2015)

To begin with, applying the framework is shaped by a researcher defining a desirable improvement to a complex problematical situation aligned with their ontological and epistemological preferences, as defined in *Chapter One*. Then, as the inquiry progresses, the comparison and integration of other *ways of knowing* about this situation is enabled. Knowledge artefacts from additional perspectives are used as prompts for reflexive learning about the situation to support a *flexible methodology* (Wickson et al., 2006). Combined, the

approach supports the pragmatic, coherent integration of theoretical perspectives from different academic disciplines in a way that also accommodates shifts in the perspectives of different societal actors, as they are engaged in action research (Mitchell et al., 2015).

The framework works backwards from these three desirable outcome spaces, aligned with the motivations of the research, in a process called *backcasting* (Dreborg, 1996; Mitchell & White, 2003). In this thesis, *backcasting* was applied in two distinct ways. In *this chapter*, when applied within the outcome spaces framework, backcasting is aligned with an extended version of Scholz et al's (2006) *backward planning* approach that uses the three outcome spaces in place of *goal formation* and *case faceting* steps (Mitchell et al., 2015). Backcasting serves as a tool to guide decisions about the design of an adaptive, transdisciplinary case study methodology working backwards from these *three outcome spaces* (as case facets) to guide a reflexive and emergent approach to assessing, comparing, modelling, and integrating different epistemological approaches to knowledge co-production (Jahn et al., 2012; Scholz et al., 2006).

Backcasting supported collaborative deliberation with supervisors and research partners about how each outcome space should be pursued, and which should be prioritised, as depicted in Figure 1 (Dreborg, 1996; Mitchell et al., 2015; Scholz et al., 2006). These decisions took into account: (i) the constraints of situating transdisciplinary research within a PhD thesis; (ii) the broader *field of vision* focused on urban water and sanitation planning in heterogeneous contexts in practice; and (iii) the coherence of integrating different theoretical frames and methodological approaches in response to problematical situation from multiple perspectives (Mitchell et al., 2015).

A second more orthodox form of backcasting is applied later in *Chapter Seven* (Dreborg, 1996; Mitchell & White, 2003). This form is more linear and analytical. It begins defining a

longer-term vision for an *integration concept* (see *Section 2.4.3*) defining how a systemic comparative economic analysis methodology might be applied to the problematical situation. And then, guides revisions to inform an approach to adaptive planning for heterogeneous water and sanitation configurations. The resulting framework supports more inclusive planning outcomes by considering the evaluative criteria presented in *Chapters Three and Four* of this thesis (Ross et al., 2024a, 2024b). Backcasting is used to arrange how various elements in the integration concept (i.e. end-use modelling, cost modelling, soft systems methodology) might be coherently sequenced based on the transdisciplinary case study.

While the two applications of *backcasting* differ in logic and purpose, both align with the criteria defined by Dreborg (1996) to justify backcasting as an approach. They both address (i) a complex, real-world problem characterised by competing heterogeneous perspectives; (ii) a dominant paradigm (i.e. one-size fits all, infrastructure-led supply of water and sanitation services); (iii) a persistent complex problem (i.e. how to counter service outcome inequalities in heterogeneous configurations); (iv) over an extended time horizon. They are disambiguated here to avoid confusion about how the term is used in this thesis (Dreborg, 1996; Mitchell et al., 2015; Mitchell & White, 2003; Scholz et al., 2006)

The remainder of Chapter Two describes in more detail how backcasting using backwards planning (i.e. Mitchell et al's (2015) extension of Scholz et al's (2006) approach) from three *outcome spaces* (as case facets) shaped the theoretical and methodological design of this thesis. Although presenting this approach retrospectively may give the appearance of a methodology that was clearly defined from the outset, in practice, the research encountered real-world limitations and tensions between each outcome space (Willetts et al. 2012). Coherence and theoretical alignment were achieved by reflecting on

these tensions, and adapting the approach accordingly, as described in the following sub-sections.

While all three outcome spaces were pursued in this inquiry, they are realised in different ways and to different degrees. Specifically, contributions to Outcome Space 1 (improvements in the problematical situation) were less direct and primarily realised through reframing and adapting how planning is perceived and assessed. Whereas, more direct empirical contributions are made to Outcome Space 2 (knowledge stocks and flows) and Outcome Space 3 (mutual and transformative learning).

2.2.1 A tangible improvement in the problematical situation

The first outcome space is concerned with a tangible and articulable improvement in a real-world problematical situation and field of inquiry (Mitchell et al. 2015). As discussed in *Chapter One*, the conceptualisation of this complex situation, and how it might be improved, arose from lived experience (Checkland & Poulter, 2010).

A dissertation completed prior to this thesis (Ross, 2018) defined the problematical situation through interviews in Battambang, a comparable city to Siem Reap. In this context, inertia resulting from fragmented relationships across different levels of governance and formal and informal institutions created uncertainty about how water and sanitation service outcome inequalities could be resolved (Kingdom of Cambodia, 2024; Mosello & O'Leary, 2017; Ross, 2018; WaterAid, 2015). Unequal power relationships shaped a city with a social identity, capable of making decisions that produce winners and losers, resulting in disproportionate access to services (Bell, 2020; Heynen, 2014).

Two approaches for assessing this outcome space (or case facet) were backcast to improving how interventions are planned for heterogeneous water and sanitation service provision configurations, as follows (Mitchell et al., 2015; Scholz et al., 2006).

2.2.1.1 Transforming how the problematical situation is perceived

The first action was to define the research focus by applying Lawhon's (2017) *concept of heterogeneous urban infrastructure configurations* to transform how urban water and sanitation services are perceived. This epistemological lens provided a means of critically examining the heterogeneous arrangement of infrastructures, formal and informal institutions, relationships, and practices that characterise service provision in LMICs. This perspective helps to think through how physical, institutional, and regulatory elements of the urban water and sanitation configuration, and their conflicting objectives, influence how services are supplied, governed and experienced.

Jaglin (2014) extends this framing to move beyond the idea that infrastructure-led planning, typical of high-income countries, represents a norm for planning equitable services. Further, that its absence in cities of LMICs should not be interpreted as a failure, distortion, or deficiency. Instead the existing planning context can be understood as *heterogeneous infrastructure configurations comprising multiple and partial infrastructures with different coverages, technologies, logics, and ownerships* (Lawhon et al. 2017).

Reframing the *problematical situation* through this lens recognises the plural values, intentions, and diverse socio-technical arrangements embedded within the existing system, and how they have evolved in response to uneven and context specific demands. This perspective makes it clear that improvements to this real-world situation requires addressing both socio-technical and socio-political dimensions, with each necessary for realising inclusive and adaptive planning.

Applying this overarching epistemic lens also reveals persistent mismatches between the supply and demand of services in cities of LMICs (Lawhon et al., 2017), raises questions with practical and theoretical implications. First, how might heterogeneous configurations

with inherently different assumptions and functions by meaningfully compare. Second, how might relevant entities within a configuration be characterised and grouped (along with their underlying assumptions and perspectives) to understand how they shape system behaviour (Jaglin 2014).

These questions underscore the relevance of explicitly accommodating heterogeneity when considering appropriate planning approaches. This aligns with van Welie et al (2018) who distinguish between *sectoral regimes* (established, or dominant infrastructure-led planning norms); and *service regimes* (real-life practices, technologies, and logics that shape on-the-ground service delivery). Understanding this distinction is important to explaining why some arrangements persist and how they may or may not support equitable and sustainable services (e.g. McConville et al., 2019; Mdee et al., 2023; and Narain et al., 2023).

2.2.1.2 Transforming how a tangible improvement in the situation is assessed

The second action was to explore how improvements to heterogeneous urban water and sanitation service provision configurations (Jaglin, 2014; Lawhon et al., 2017) could be assessed by drawing on economic and planning theories repurposed for this task (Mitchell et al., 2015; Scholz et al., 2006). Re-framing the problematical situation as a *socio-technically diverse configuration*, better reflects the situation observed in the Cambodian context. This enables the research to move beyond planning approaches that normalise infrastructure-led planning that disproportionately distribute economic benefits and costs of urban water resources (Mosello & O’Leary, 2017; Ross, 2018; WaterAid, 2015). Instead, it more closely aligns with the emerging *citywide inclusive sanitation planning* agenda, which emphasises integrating the diverse perspectives of service authorities, formal and informal service providers, and service users (Lüthi et al., 2020).

The repurposed framing of this assessment drew on *least-cost* and *integrated resource planning principles*, as well as the application of *planning theory* to urban water and sanitation systems. *Least-cost* planning principles were first applied to *urban sanitation* planning frameworks for LMICs in the 1980s. They encourage decision-making that considers all possible service provision alternatives, including informal and decentralised arrangements, to select the most cost-effective interventions to meet service demands (Julius 1979; Kalbermatten et al. 1980, 1982). However, reviews evaluating urban sanitation planning frameworks that have followed suggest that this economic theory has not significantly influenced decision support frameworks (Hawkins et al., 2013; Hutton, 2001; Kennedy-Walker et al., 2014; Rosenqvist et al., 2016; Schertenleib et al., 2021). Revisiting *least-cost planning* theory for *heterogeneous urban configurations* therefore remains relevant.

Integrated resource planning principles extend *least-cost planning* by incorporating systems thinking, recognition of the interdependency of *urban water* and *urban sanitation* services and broader sustainability criteria including the equity of outcomes when responding to heterogeneous demands (Beecher, 1991; Mitchell et al., 2007; Willetts et al., 2010). The work of McConville (2010), ISF-UTS & SNV (2016), and Abey Suriya et al. (2019) also demonstrates how different planning theories may influence how decisions inform shifts in such complex service provision contexts (Hudson et al., 1979). The integration of both economic and systems-based principles enables a more holistic framing of how urban water and sanitation planning frameworks may be transformed to better reflect *heterogeneous service provision configurations*, rather than infrastructure-led norms

2.2.2 Contribution to knowledge stocks and flows

The second outcome space concerns contributing to *knowledge stocks* and *flows* (Mitchell et al., 2015). This refers not only to how knowledge is generated but also to how it is made accessible and interpretable across the perspectives of researchers, *clients*, *practitioners*, and *issue owners* to support meaningful change (Checkland & Poulter, 2010; Mitchell et al., 2015). Within a doctoral thesis, this objective can be difficult to balance. Academic expectations to publish peer-reviewed articles may conflict with the time and flexibility to co-produce and mobilise knowledge for real-world impact (Willetts et al., 2012). This thesis produced four published (or publishable) articles (see *Chapters Three to Six*). It also produced context-specific learning artefacts intended to prompt practice-based social learning within the case study. The balance between these knowledge products may have shifted if the research was shaped by other drivers.

Urban water and sanitation planning often applies cost effectiveness analysis shaped by infrastructure-led norms that adopt a narrow, single financial cost perspective, typically that of a utility. Such reductionist framing often fails to reflect the complexity of adaptive, heterogeneous service configurations (Hutton, 2001; Sainati et al., 2020). As a result, planning frameworks frequently overlook context-specific cost determinants, creating significant gaps between the economic basis for decision-making and everyday practices (Daudey, 2018; Hutton, 2001; Sainati et al., 2020). Much of the existing literature focuses on gaps in *knowledge stocks* (i.e. available national or global-scale cost effectiveness data about networked service configurations) and the implications for the allocative efficiency of investments (Hutton et al., 2014; Hutton & Chase, 2016; Daudey, 2018; Mills et al., 2020; Sainati et al., 2020; Tilley et al., 2014). Far less attention has been paid to how local knowledge about costs and their determinants flows between formal, informal, community-

based, self-supplied, hybrid, or other non-conventional configurations to shape their behaviours.

Thus, to guide contributions as to how this second outcome space could be *assessed*, a theoretical frame was again backcast aligned with the extended transdisciplinary case study approach of [Scholz et al. \(2006\)](#), as described by [Mitchell et al. \(2015\)](#). As outlined previously, heterogeneous water and sanitation service provision configurations ([Jaglin, 2014](#); [Lawhon et al. 2017](#)) embed diverse and conflicting epistemological perspectives within existing service arrangements. These worldviews are shaped by the roles, positions, and access to knowledge of societal actors in which they are embodied. In such contexts, urban water and sanitation planning requires better alignment between top-down disciplinary frameworks and bottom-up perspectives. Enabling meaningful knowledge flows at this interface depends on integrating different ways of knowing, including those grounded in lived experience and practice, which are often excluded from formal planning processes.

From this premise, and as foreshadowed in *Section 1.4.1* the theoretical frame for this outcome space begins with the ontological assumption that heterogeneous service configurations function as complex adaptive systems. That is, they are characterised by uncertainty, non-linearity, and emergent change ([Neely, 2015](#)). Understanding such configurations requires an *epistemologically plural* approach that values mechanistic, contingent, and narrative forms of knowledge ([Miller et al. 2008](#)). No single epistemology can fully explain system behaviour or support transformation alone. Each worldview offers partial insights that must be engaged with collectively and reflexively to engender systemic shifts.

Epistemological pluralism therefore suggests drawing on diverse systems approaches including objective (hard systems), interpretive (soft systems), and emancipatory (critical systems) methodologies (Cabrera et al., 2021; Ison, 2008; Jackson, 2000; Reynolds & Holwell, 2010). Each embodies different assumptions, values, and methods for understanding complex problematical situations. Integrating these approaches within an inquiry requires an overarching concept for guiding how different forms of knowledge co-production are recognised, organised, and unified. This requires a reflexive process to shape how each way of knowing contributes meaningfully to a shared understanding of the situation.

In this thesis, epistemological pluralism is supported through applying meta-*theoretical framework* developed by Cabrera et al. (2021), known by the mnemonic DSRP. This framework identifies four core patterns of systems thinking, *Distinctions, Systems, Relationships, and Perspectives*, required for a *minimum viable contribution* to a systemic understanding. Knowledge flowing from academic disciplines or lived experiences can be integrated to support mutual transformative learning if thinking is arranged to embody these four patterns. DSRP enables comparisons across diverse knowledge systems via a shared cognitive structure that supports the flexible use of shared learning artefacts to integrate or *co-produce unified ways of knowing*.

Even if planners, service providers or householders are not consciously or explicitly applying systems thinking when engaging in knowledge co-production, their insights still contribute to systemic learning if they articulate DSRP patterns. Namely (D) distinctions between (S) systems (e.g., different service provision typologies within a configuration); (R) relationships (e.g. determinants of how service outcomes are affected by costs); or (P) perspectives (e.g. regarding criteria to determine desirable and feasible service levels)

(Cabrera et al., 2021) (see Figure 2). When knowledge embodying these four patterns is made visible and reflexively compared across epistemological positions, it contributes to the co-production of more inclusive and context-specific planning approaches.

This theoretical framing supports a systemic and epistemologically plural approach to understanding and assessing contributions to knowledge stocks and flows. It positions informal, tacit, and experience-based knowledge as valid and valuable for informing decisions about interventions in heterogeneous service configurations.

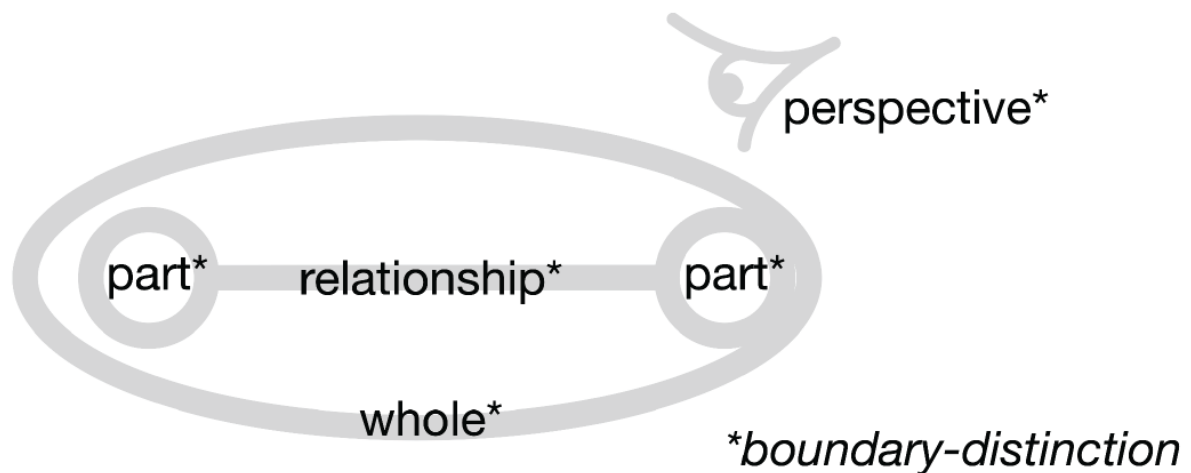


Figure 2: Cabrera et al's (2021) concept of a minimum viable contribution to systemic knowledge

This theoretical framing shaped the flexible methodology applied to organise transdisciplinary knowledge integration in this thesis through applying various systems thinking approaches. This influenced decisions such as how fragmented disciplinary knowledge was consolidated (i.e. via the inclusion and exclusion criteria applied in the review in *Chapter Three*); who it was intended to engage (i.e. prioritising dissemination in journals likely to be read by practitioners); and how knowledge was co-produced (i.e. applying bottom-up, action-oriented learning approaches flexibly to increase the likelihood of an inclusive understanding of the real-world situation).

Collectively, such decisions reflect the intention to support contribution to knowledge stocks and flows in a way that engage heterogeneous systems and actors. Thus, reflexive practice informed scholarly and pragmatic knowledge co-production, both aimed at shifting how complex service provision configurations are perceived. These contributions overlap with the next outcome space of *mutual and transformative learning* (see *Figure 1*).

2.2.3 Mutual and transformative learning

The third outcome space focuses on the intent of transdisciplinary research to foster *mutual and collaborative learning* (Mitchell et al., 2015). In this inquiry, this concerns *how* urban water and sanitation planning frameworks may be enhanced via systemic knowledge flows derived from diverse epistemological perspectives. Such relational knowledge supports real-world shifts in practice in Siem Reap within this study, with implications for similar contexts in LMICs globally.

This dimension of mutual social learning seeks to strengthen relational capacity, and confidence of societal actors to think creatively, experiment with negotiating power relationships, influence decisions, and champion innovation to advocating for real-world improvements in the problematical situation (Checkland & Poulter, 2010). It moves beyond an objective understanding of the situation, towards critical reflection that compares different *ways of knowing* about how to improve heterogeneous configurations. Thereby, shifting how the complex situation is perceived (Lawrence et al., 2021). *Critical systems thinking* supports this process by encouraging action-oriented learning to identify and compare possible desirable, feasible, and context-specific innovation, particularly in contexts where relational understandings may be undervalued (Jackson, 2000; Midgley, 2003; Ulrich, 2010; Reynolds & Holwell, 2010).

The theoretical framing used to assess *mutual and transformative learning* (Mitchell et al., 2015; Scholz et al., 2006), adopts the same ontology (i.e. complex adaptive systems) and epistemological pluralist stance of the second outcome space. However, the emphasis here shifts from defining the system from diverse epistemological positions to modelling these perspectives to prompt social learning. Such learning emerges when inclusive *hard systems* models that structure the problematical situation objectively are compared to interpretive (*soft*) or emancipatory (*critical*) systems models that reveal the assumptions, values, and emotions through which societal actors experience the problematical situation (Checkland & Poulter, 2010; Ison, 2008; Jackson, 2000; Reynolds & Holwell, 2010).

Structured learning activities support these comparisons by juxtaposing existing heterogeneous service configurations (Jaglin, 2014; Lawhon et al., 2017), with perceptions, structured as *human activity models* (Checkland & Poulter, 2010), of the diverse ways participants understand that this problematical situation should be improved. Systems thinking approaches that surface insights into how the *metabolism* of these configurations leads to persistent inequalities in service outcomes (Ulrich, 2010). These activities prompt reflexive shared learning about how such outcomes manifest, with the potential to generate endogenous shifts in how actors perceive the situation and influence systemic changes in how configurations are organised.

Mutual and transformative learning is also conceptualised using the DSRP heuristic (Cabrera et al., 2021; Mitchell et al., 2015; Scholz et al., 2006). However, here this extends beyond whether *unity of knowledge*, or a shared understanding of the situation emerges (Lawrence et al., 2021) to whether this shared knowledge challenges assumptions, values, and emotions. Evidence should be sought regarding whether relationships between clients,

practitioners, and issue owners shift in ways that increase the likelihood of actions to improve the situation.

DSRP is used to assess whether the three commitments of *critical systems thinking* were upheld: (i) whether critical awareness of taken for granted assumptions and systems boundaries emerged; (ii) whether issues of power were addressed, indicated by shifts in who contributes to defining the problem and possible solutions; and (iii) whether methodological pluralism, or the adaptive use of diverse methods, responded to evolving needs, perspectives, and tensions in the research context (Midgley, 1996; 2003; Ulrich, 2010; Wickson et al., 2006).

These commitments may be appraised through collaborative boundary critique, which iteratively tests and refines the assumptions underpinning how system boundaries are defined, which knowledge is considered to be legitimate, and who controls decisions (Lawrence et al., 2021; Midgley, 1996; Ulrich, 2000). This assessment should not only consider the content of the critique, but also whether it resulted in relational shifts. Mitchell et al. (2015) suggests using Mobjörk's (2010) characterisation of *participatory transdisciplinarity* to guide the depth of collaboration required. Ideally, the lived experiences of *issue owners* should be wholly included in knowledge co-production and afforded equal value to inter-disciplinary academic knowledge (Mobjörk, 2010).

2.3. Research design

Urban water and sanitation service provision in low- and middle-income countries is increasingly understood as a *complex adaptive system* characterised by uncertainty, non-linearity, and interdependence (Carey et al., 2015; Currie et al., 2018; Neely, 2019; Moallemi et al., 2021). In response, systems thinking approaches have proliferated across research and practice for their capacity to interpret the complex interactions shaping service

outcomes (Liddle & Fenner, 2017; Valcourt et al., 2020). However, this proliferation has also led to fragmentation, with limited reflection on how different systems paradigms relate to one another or can be coherently integrated within applied planning processes (Neely & Valcourt, 2024). This diversity risks obscuring core systems thinking principles and weakening their accessibility and influence in heterogeneous urban contexts where integration across perspectives is critical (Cabrera et al., 2021; Srivastava & Nambiar, 2022).

These challenges motivate the need for an explicit integration concept capable of organising epistemologically diverse systems approaches within a single, learning-oriented research design. Accordingly, this section outlines how the transdisciplinary outcome spaces (or case facets) proposed by Mitchell et al. (2015) were operationalised to inform the research design and structure of this thesis and aligned with the three-phase model for transdisciplinary integration proposed by Pohl et al. (2021). Together, these frameworks informed a single *transdisciplinary case study design* iteratively applied in Siem Reap, Cambodia, as documented in *Chapters Five and Six* (Ross et al., 2024a, 2024b).

As Pohl et al. (2021) argue, transdisciplinary research should link two concurrent and iterative processes. One focused on producing academic knowledge about a sustainability issue, and the other concerned with integrating this knowledge into real-world learning experiments aimed at improving a problematical situation. These processes co-evolve rather than unfold linearly: a theoretical frame informs methods; methods are applied in a real-world context; and what occurs in practice generates new knowledge that reshapes how the theory is understood (Mitchell et al., 2015; Pohl et al., 2021). There is no one-size-fits-all approach for integrating these processes. Accordingly, this thesis was guided by an ideal-typical structure comprising three phases: (i) problem framing (or problem transformation);

(ii) problem analysis; and (iii) exploration of impact (Jahn et al., 2012; Lang et al., 2012; Pohl et al., 2021).

In this thesis, these phases were operationalised as three distinct but interconnected waves of action-oriented learning within a single transdisciplinary case study (Mitchell et al., 2015; Scholz et al. 2006; Wickson et al., 2006). This research design responds to the contextual complexity of heterogeneous urban water and sanitation service provision in Siem Reap, Cambodia, representative of other LMIC contexts in the Asia-Pacific region and globally. Each *wave* aligns with different research motivations and outcome spaces. Collectively, they serve the overarching objective of addressing persistent urban water and sanitation service outcome inequalities by improving how heterogeneous configurations are represented and planned.

Figure 3 summarises the three waves of action-oriented learning in the thesis and illustrates their alignment with the research questions in *Chapter One*, the outcome spaces in *Section 2.2*, and the methodological decisions described in *Section 2.4*. A consolidated summary of each wave's theoretical framing, associated transdisciplinary characteristics, component methods, and evidence base is provided in *Table 1* at the end of this chapter.

2.4. Methodological framework

This methodological framework aims to co-produce knowledge from an *epistemologically pluralist* perspective across three integrated *waves* of transdisciplinary research. The three waves correspond to the three phases of transdisciplinary integration described by Pohl et al. (2021), that is, problem framing, problem analysis, and exploration of impact. For each wave, this section explains its purpose, its alignment with a transdisciplinary outcome space (Mitchell et al., 2015), the key knowledge artefacts and methods employed, and how it contributes to answering the research questions and

structuring subsequent chapters. The methodology adopts a reflexive, evolving design shaped by a real-world problematical situation of Siem Reap municipality, Cambodia (Wickson et al., 2006).

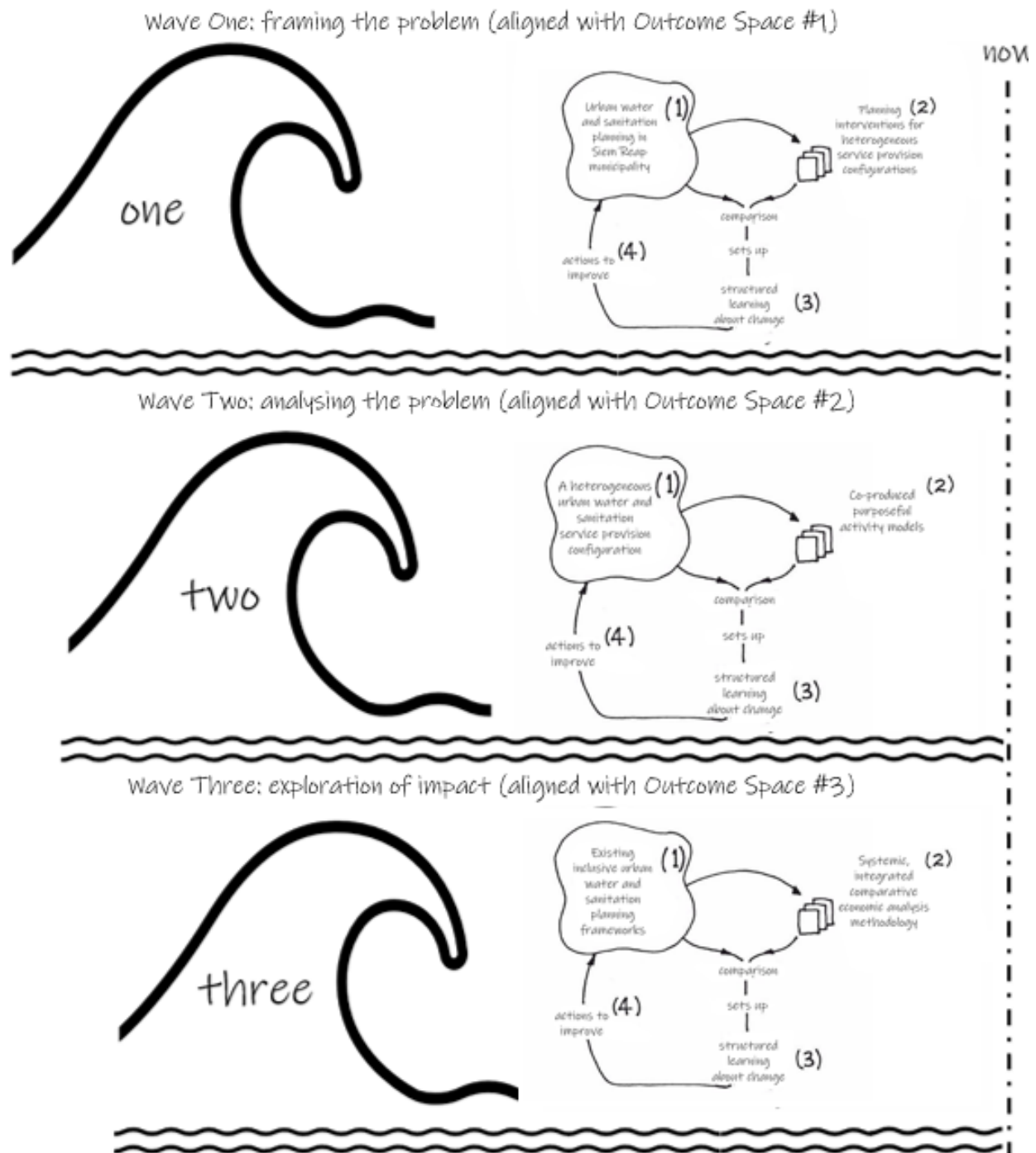


Figure 3: Three waves of action-oriented learning in this thesis. Learning cycles adapted from Checkland and Poulter (2010)

2.4.1 Wave One: Problem framing

The *first wave* of this research focused on the collaborative framing of the problematical situation about persistent service outcome inequalities in heterogeneous urban water and sanitation configurations. It corresponds with the first outcome space, *a tangible improvement in the problematical situation*, and is supported by a synthesis of least-cost and integrated resource planning theory re-purposed in response to this context (Ross et al., 2024a, 2024b).

The *wave* established what would be researched, who would be engaged in the research, and what research questions would guide the inquiry. It aligns with what Pohl et al. (2021) and Lang et al. (2012) describe as *problem framing*, or *problem transformation* (Jahn, Bergmann & Keil 2012), linking a societal problem with gaps in academic knowledge through a shared research object. Following Jahn et al. (2012), this wave involved framing a societal problem, relating it to academic knowledge, and transforming it into boundary and epistemic objects that structured the inquiry.

2.4.1.1 Framing a societal problematical situation

The societal problem concerns persistent urban water and sanitation outcome inequalities in Cambodia, which is established in *Section 1.2* of this thesis. The motivation to address this problem emerged from prior exploratory work involving in-depth interviews with households, service providers and local authorities in Battambang, Cambodia (Ross, 2018). As the research questions for this doctoral thesis were refined, further informal discussions were held with actors across community, municipal, provincial, and national levels in Cambodia. These discussions revealed a shared interest in better understanding the economic basis of decision-making related to urban water and sanitation planning at the municipal scale in secondary cities.

Two consistent issues were raised: (i) limitations in the cohesion and alignment of existing planning processes with the breadth of urban water and sanitation service demands; and (ii) ongoing constraints in institutional capacity and financing needed to extend universal services at the subnational scale (Ross, 2018). Together, these issues reflect the absence of a consensus on how this complex problematical situation should be addressed, consistent with Jahn et al.'s (2012) criteria for a transdisciplinary research object.

2.4.1.2 Relating the societal problem to academic knowledge

Ongoing discussions with these societal actors and my supervisory team led to a focus on the academic problem of how *least-cost* and *integrated resource planning* principles might be applied to heterogeneous urban contexts in LMICs. This work built on earlier transdisciplinary experimentation with these principles in the Australian water sector (Fane & Mitchell, 2006; Mitchell et al., 2007) and their subsequent application to the planning of a greenfield development site in *Can Tho, Vietnam*. While this study provided useful insights, the application to a relatively homogeneous setting did not enable the complexities of an existing heterogeneous urban water and sanitation configuration (Willetts et al., 2010; Retamal et al., 2011; Willetts et al., 2013).

Relevant academic literature reveals ongoing uncertainty about how to apply *least-cost principles* to planning equitable interventions for urban water and sanitation services across different disciplinary perspectives (Julius, 1979; Kalbermatten et al., 1980, 1982). As shown in Chapter Three, although least-cost principles influenced sanitation planning frameworks in the 1980s, this was largely conceptual and did not significantly change how economic principles impacted planning frameworks (Hawkins et al., 2013; Hutton, 2001; Kennedy-Walker et al., 2014; Rosenqvist et al., 2016 Schertenleib et al., 2021). Efforts to apply least-cost and integrated resource planning have remained somewhat fragmented, drawing

narrowly on aspects such as *life cycle costing* in clearly defined rural or peri-urban contexts (Fonseca et al. 2011; McIntyre et al. 2014) , leaving methodological gaps unresolved for complex heterogeneous urban configurations, particularly at the municipal scale (Hutton, 2001; Hutton & Andrés, 2018; Willetts et al., 2010, 2013).

Repurposing this fragmented body of academic knowledge to better fit real-world heterogeneous urban service provision was therefore identified as a legitimate pathway for the research and defined the first action-oriented learning cycle of the thesis (Mitchell et al., 2015). Informed by Khalil and Tricco's (2022) evidence synthesis ecosystem, *Wave One* examined how a scoping and systematic review methods could best respond to *Research Question #1*.

Research Question #1a, regarding the development of evaluative criteria for comparative economic analysis grounded in least-cost and integrated resource planning principles, was addressed through a scoping review presented in Chapter Three (Ross et al., 2024a) extending earlier work by Hutton (2001) mapping gaps in established comparative economic analysis methodologies. *Research Question #1b* examined the extent to which existing studies apply these principles in practice and was addressed through a systematic review of comparative economic analyses of urban sanitation interventions presented in Chapter Four (Ross et al., 2024a, 2024b)

Although these reviews focused nominally on urban sanitation interventions, they were analysed using criteria that treat such arrangements as broad configurations, that integrate sanitation with broader urban systems, including water supply, drainage, and solid waste (Lüthi et al., 2020; Jaglin, 2014; Lawhon et al., 2017). This focus on integrated systems means that the evaluative criteria appropriately respond to heterogeneous water and

sanitation service provision configurations referred to in Research Question #1a (Ross et al., 2024a).

Together the review papers helped to define the focus for the second wave of action-oriented learning in this thesis. Specifically, they identified the need to: (i) incorporate diverse cost perspectives in planning processes, particularly those of marginalised groups; (ii) develop an inclusive definition of an existing citywide *without-project case* across an entire water and sanitation service chain as the basis of comparison; (iii) meaningfully integrate both tangible and intangible economic costs and outcomes into planning to the fullest extent possible; and (iv) project disaggregated costs and outcomes associated with mixtures of formal and informal service provision configurations so that persistent service outcome inequalities may be addressed. These insights clarified the methodological requirements for addressing Research Question #2 and directly informed the design of Wave Two (see Figure 3).

2.4.1.3 Identifying a boundary object for the research

Following Jahn et al. (2012) linking the societal problematical situation with relevant academic knowledge required identification of a suitable boundary object to coordinate the transdisciplinary inquiry. *Siem Reap municipality* was selected as the boundary object through early discussions primarily with networks within the Ministry of Public Works and Transport, who initially acted in the role of clients for the research (Checkland & Poulter, 2010).

As a secondary city in Cambodia, Siem Reap was considered most appropriate case study site base on several criteria: (i) local officials had the most capacity to engage with the problematical situation, due to recent training on citywide inclusive sanitation planning; (ii) the city was experiencing rapid population growth, alongside pronounced and persistent

water and sanitation service outcome inequalities (iii) multiple donor-supported projects were underway or in planning, creating overlapping and sometimes conflicting objectives; and (iv) the municipality was receptive to collaborative transdisciplinary research. Further justification for the selection of Siem Reap as the boundary object, and its application within the embedded transdisciplinary case study, is provided in *Chapters Five and Six* (Ross et al. 2025; Ross et al, [preprint]).

2.4.1.4 Transforming the boundary object into *epistemic objects*

The final decision in Wave One concerned how the boundary object would be transformed into epistemic objects capable of driving inquiry in response to the research question (Jahn et al., 2012; Pohl et al., 2021). As outlined in *Section 2.2.2*, this was achieved by adopting the concept of *socio-technically diverse, heterogeneous urban water and sanitation service provision configurations* (Jaglin, 2014; Lawhon et al., 2017).

This concept enabled existing service arrangements to be reframed not as linear infrastructure systems but as complex adaptive socio-technical configurations. It provided a basis for *thinking through* how least-cost and integrated resource planning principles might respond to heterogeneous service demands and the real world constraints that this manifests.

Throughout the research, this concept functioned in a dual role. It provided a stable reference point for interpreting the existing citywide without-project case (as a boundary object), while also operating as a *soft systems model* through which alternative configurations could be co-produced and explored from diverse perspectives (as epistemic objects). This dual role supported both comparative economic analysis and reflexive learning about how heterogeneous configurations are planned and governed. Applying this epistemic framing shaped the methodological choices in subsequent waves of action-

oriented learning and guided how diverse forms of knowledge were integrated within the transdisciplinary case study.

2.4.2 Wave Two: Problem analysis

The second wave of this research is problem analysis, specifically the co-production of new knowledge about persistent water and sanitation service outcome inequalities in *heterogeneous urban water and sanitation service configurations*. This wave corresponds with the second outcome space, contributing to knowledge stocks and flows. Lang et al. (2012) refers to this wave as involving the co-creation of solution oriented transferable knowledge. A central design feature of Wave Two was the use of an *integration concept* (Jahn et al., 2012), as discussed in more detail in Section 2.4.3.2, to organise how diverse forms of knowledge would be co-produced and compared through the boundary and epistemic objects introduced in Wave One.

In the intended design, a residential water end-use analysis and model was to function as a *boundary object*, providing a consistent reference point for representing the existing citywide *without-project case* in Siem Reap. In contrast, purposeful activity models developed through individual and collective semi-structured interviews were designed as epistemic objects, articulating the values, assumptions, and intentions of different societal actors (Jahn et al., 2012). The structured comparison of these objects within a transdisciplinary case study was expected to prompt reflection on the determinants of persistent inequalities in water and sanitation service outcomes..

Wave Two was therefore supported by two embedded studies. The residential water end-use analysis (*Chapter Five*) represents an objective, hard systems approach, while the purposeful activity models (*Chapter Six*) represent an interpretive, soft systems approach (Cabrera et al., 2021; Ison, 2008; Jackson, 2000; Reynolds & Holwell, 2010). Together, these

methods were intended to support epistemologically plural knowledge co-production, consistent with the theoretical framing outlined in *Section 2.2*.

The roles of researchers and societal actors were organised in line with the meta-level integration model proposed by [Jahn et al. \(2012\)](#) and the related concept of a *thought collective* ([Pohl et al., 2021](#)). This framing provided a shared understanding of how different forms of knowledge would contribute to addressing the problematical situation, and supported flexible collaboration between researchers and societal actors through participation and inclusiveness ([Jahn et al., 2012](#); [Wickson et al., 2006](#)).

In practice, however, several constraints affected how this design could be implemented. While the residential end-use survey generated substantial insights into heterogeneous demand for water and sanitation services, the associated model was not finalised until after this phase due to delays arising from the COVID-19 pandemic. As a result, the planned use of the end-use model as a boundary object within participatory workshops was not feasible at the time of implementation..

The workshops were therefore adapted to use alternative participatory tools to represent the real-world problematical situation. In particular, a collaboratively developed *rich picture* was used to convey key insights from the end-use analysis, whereas it was originally planned to play a secondary role to the end-use model. This pivot from the intended to the implemented integration strategy, and its implications for transdisciplinary knowledge integration, are examined in detail in *Chapter Seven*.

2.4.2.1 Clarifying the roles of researchers and societal actors

The first step in Wave Two involved clarifying the roles of researchers and societal actors, specifically clients, practitioners, and issue owners, within the transdisciplinary inquiry. Defining these roles helped to clarify how the boundary and epistemic objects

established in Wave One would be applied to structuring subsequent knowledge co-production activities (Jahn et al., 2012).

This process was supported by *Soft Systems Methodology* as an action-oriented learning approach, drawing on the finding out phase described by Checkland and Poulter (2010) and documented in detail in *Chapter Six*. In terms of the research design, the *finding out* process was operationalised through three interrelated analyses intended to align the inquiry to roles, norms, and power relations within the problematical situation.

Analysis One focused on clarifying the roles of clients (researchers and officials enabling the inquiry), practitioners (the research team working alongside local officials), and issue owners (societal actors contributing experiential knowledge through interviews, surveys, and participatory modelling activities). *Analysis Two* was intended to support reflexivity regarding formal and informal roles, prevailing norms of behaviour, and the values shaping how actions and decisions were judged. *Analysis Three* introduced a critical lens, focusing on how power was held and exercised within the real-world situation and how this influenced whose knowledge shaped system definitions and intervention options (Checkland & Poulter, 2010).

These analyses were initially facilitated through transect walks (see Chapter Six) and continued to inform methodological decisions throughout Wave Two. They enabled structured and inclusive engagement and context-specific engagement in ways that were meaningful across different epistemological positions. (Checkland & Poulter, 2010; Jahn et al., 2012; Mobjörk, 2010; Pohl et al., 2021). They also provided a foundation for thinking through how power, roles, and assumptions shaped knowledge integration in practice in Chapter Seven

2.4.2.2 Design of an (emergent) integration concept

In retrospect, the development of an *integration concept* capable of meaningfully organising and communicating the epistemologically plural knowledge generated during *Wave Two* was difficult to conceptualise without prior experience in transdisciplinary research of this depth. Initially, the nature of this concept was only partially understood. It gradually emerged through practice and was later consolidated when the research was written up as a transdisciplinary case study methodology. This process reflects the theoretical framing introduced in *Section 2.2*, where boundary objects and epistemic objects structure the integration of diverse forms of knowledge

The integration concept needed to align with the assessment criteria for the three outcome spaces in the theoretical framework (Jahn et al., 2012; Mitchell et al., 2015; Pohl et al., 2021). It took the form of a *transdisciplinary case study methodology* used both to organise and structure the research activities, and to integrate different *ways of knowing* and engaging with the complex real-world problematical situation.

The transdisciplinary case study focused on a single, intrinsic case to explore how epistemologically diverse methods might be arranged in contexts, in which their sequencing to address the problematical situation is not yet clearly defined (Scholz et al., 2006). The case study remained flexible and emergent, enabling ‘what if’ questions to evolve, while the embedded methods it contains are epistemologically well-defined and applied with rigour. The case study thus provided an overarching frame in which methods could be arranged, applied, and tested in a coherent and recoverable way. This makes their contribution to improving a complex problematical situation transparent and open to scrutiny (Scholz et al., 2006).

In this research, the transdisciplinary case study focused on developing a systemic comparative economic analysis methodology to develop an enhanced planning approach for heterogeneous configurations in Siem Reap municipality. The integration concept embedded two distinct methods corresponding to the boundary object and the epistemic objects defined in *Wave One*.

The boundary object was intended to be the residential water end-use demand analysis and model (Ross et al. 2025). It would generate objective knowledge, used as a consistent without-project case and a point of reference for comparison, directly addressing *Research Questions #2a* in *Chapter Five*. The *epistemic objects* were the co-produced *purposeful activity models* (Ross et al. [preprint]), which articulated subjective soft systems knowledge about the cognitive assumptions, feelings, and culturally grounded understandings of how a system might be improved, directly addressing *Research Question #2b* in *Chapter Six*. Together, these artefacts supported a multi-dimensional, collaboratively constructed understanding of the problematical situation.

2.4.2.3 Insights from testing and reframing the integration concept

The initial integration concept (*Figure 4*) was developed as a flexible design to support an evolving systems approach to transdisciplinary inquiry, guided by the outcome spaces framework (Mitchell et al. 2015). It articulated how boundary and epistemic objects introduced in *Wave One* were intended to be sequenced across three phases: system discovery, system definition, and system comparison; within the transdisciplinary case study.

When implemented in practice, several aspects of this integration concept proved difficult to operationalise in the heterogeneous urban context of Siem Reap. These challenges did not invalidate the overall methodological approach but revealed important

tensions between conceptual design and real-world application in a complex adaptive system. Rather than being treated as methodological failures, these tensions became a source of learning that informed subsequent refinement of the integration concept.

Insights arising from testing and adapting the integration concept are discussed in detail in *Chapter Seven*, where what occurred in practice, and the implications for transdisciplinary knowledge integration is reflected on and used to develop a revised integration concept informed by both the intended design and the real-world constraints encountered. These reflections also provide the basis for *Wave Three*, which shifts from knowledge co-production to critical assessment of how integration was achieved and how it might be strengthened in future applications.

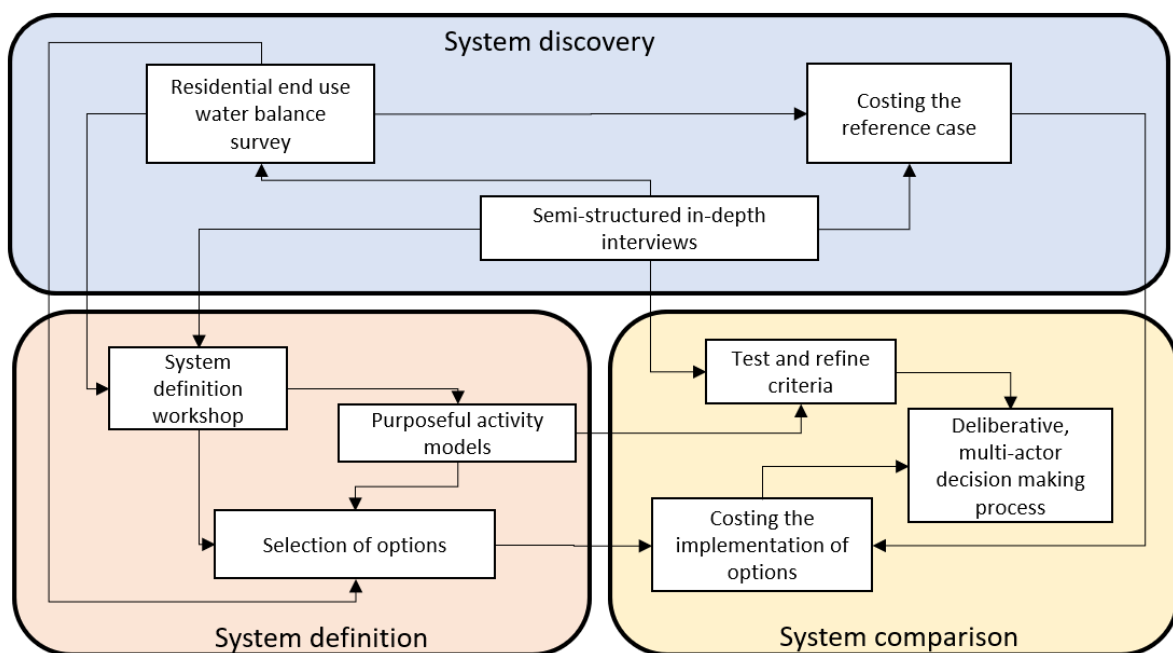


Figure 4: The initial implementation strategy proposed for the transdisciplinary case study

2.4.2.4 Ethical considerations

Ethical considerations were an important part of the design and implementation of Wave Two, as it focused on participatory knowledge co-production with diverse human participants in a complex and uncertain real-world context. Ethical commitments shaped

not only formal research ethics approval, but also methodological decisions about how participants engaged in these research activities.

The research was designed in accordance with the Australian National Statement on Ethical Conduct in Human Research (NHMRC, 2018) and the ACFID Principles and Guidelines for Ethical Research and Evaluation in Development (ACFID, 2017). At the time of designing this research, Cambodia did not have a formal mechanism for approving human research ethics approval, so formal agreements about the nature of the research were sought from relevant national and local authorities, as outlined in *Chapter Six*. High-risk human ethics approval was granted by the University of Technology Human Research Ethics Committee (ETH205222) following submission of a detailed risk management plan.

A significant risk associated with this research was that it was conducted in the context of uncertainty regarding the COVID-19 pandemic, and the research approach remained flexible and responsive to emerging public health guidance throughout its duration.

The research also adhered to the ethical principles of beneficence and non-maleficence, with a focus on minimising harm, inconvenience, and burden on participants, and was shaped in response to locally determined research objectives, and particularly the needs of vulnerable issue owners.

The scope and format of participation were revised to ensure efficient and respectful engagement with those contributing to the research. Those participating in the workshops were compensated for their time with per diem payments aligned with local expectations. All respondents were briefed about the study before providing written consent to participate. Additionally, all data was anonymised to maintain confidentiality and prevent individual respondents from being identified.

2.4.3 Wave Three: Exploration of (emerging) impact

The third wave of the research, *exploration of (emerging) impact*, focused on the integration of co-produced knowledge generated during the earlier phases of the transdisciplinary case study (Jahn et al., 2012). Lang et al. (2012) refers to this phase as the *reintegration and application* of knowledge. Wave Three aligns primarily with the outcome space of mutual and transformative learning and thinks through how structured learning interactions among societal actors supported reflexive shifts in understanding and decision-making.

This wave employed *critical systems thinking* to facilitate reflexivity among issue owners, practitioners, and researchers, with particular attention to how different perspectives, assumptions, and values interacted when knowledge artefacts were brought into critical dialogue. Rather than seeking to measure impact through a linear or causal analysis, *Wave Three* explored how learning processes unfolded during the workshops and how these processes reshaped how the problematical situation was perceived and discussed.

Wave Three involved two main steps. First, contributions to the three transdisciplinary outcome spaces defined in *Section 2.2* were critically assessed (Mitchell et al., 2015; Pohl et al., 2021). While this wave aligns most directly with mutual and transformative learning (*Outcome Space 3*), improvements in the problematical situation (*Outcome Space 1*) were also evaluated indirectly, through evidence of reframing, learning, and changes in how planning challenges were understood and negotiated by diverse societal actors. This assessment was informed by the three participatory workshops referred to earlier, and these were designed to make the process of transdisciplinary integration observable to researchers, practitioners, and issue owners.

These workshops supported collective reflection on how different forms of knowledge contributed to learning, including the interplay between insights from lived experience, various systems models, and comparative economic analysis. Organising the workshops in this way enabled critical examination of how knowledge was integrated in practice and how this integration influenced how participants interpreted persistent service outcome inequalities.

It is important to note here that some aspects of the co-produced knowledge were not able to be directly integrated as part of these workshops, due to the limitations discussed in the previous section, and as outlined in *Chapter Seven*. For example, constraints in directly integrating data on the costs of possible interventions, and the data from the residential water end-use model. However, many aspects of this knowledge about the heterogeneous demand for water and sanitation services within the case study were able to be integrated indirectly through rich pictures and the representative participation of societal actors who contributed to the household survey and in-depth interviews. The implications of this indirect integration are examined further in *Chapters Seven and Eight*.

The second step of *Wave Three* concerned assembling the outcomes of the transdisciplinary knowledge co-production for academic use and broader use by society. As anticipated by [Willetts et al. \(2012\)](#) and [Mitchell et al. \(2015\)](#), and discussed in *Chapter Seven*, constraints associated with conducting transdisciplinary research within a PhD resulted in the prioritisation of academic knowledge outputs ([Ross et al., 2024a, 2024b](#); [Ross et al., 2025](#); [Ross et al., \[preprint\]](#)). However, continued engagement with clients and practitioners involved in the research has enabled opportunities for future outputs focused on embedding learning outcomes in practice. Consistent with the nature of interventions in *complex adaptive systems*, some impacts are expected to emerge in non-linear and non-

intuitive ways that emerge beyond the scope of this thesis (Jahn et al., 2012; Pohl et al., 2021).

2.4.3.1 Assessment of the integration concept through collaborative workshops

The assessment of transdisciplinary integration was informed by a series of three participatory workshops, drawing on *Soft Systems Methodology* (Checkland & Poulter, 2010) and *Critical Systems Heuristics* (Ulrich, 2000; Ulrich & Reynolds, 2010). The workshops were designed as real-world learning experiments that translated knowledge produced from household surveys and interviews to surface collaborative insights from integrating knowledge across different perspectives arising from the transdisciplinary case study (Pohl et al., 2021). In particular, the workshops enabled the opportunity to observe and assess outcomes related to *mutual and transformational learning*, albeit somewhat constrained by the time available to facilitate this knowledge co-production (Mitchell et al., 2015). As discussed above, these learning experiments intended to integrate different *ways of knowing* did not directly include insights from the residential water end-use demand model. The implications of this constraint are discussed in *Chapter Seven*.

Each of the workshops is described in detail in *Chapter Six* of this thesis (Ross et al., [preprint]), with a summary of the contribution of each workshop to the integration included below. The *first workshop* was structured to co-produce a rich picture of the problematical situation (Berg, 2015; Checkland & Poulter, 2010). In the case of *Wave Three*, the rich picture acted as a proxy boundary object, in this case prioritising the capacity of this artefact to represent an objective understanding of the complex problematical situation.

The second workshop facilitated a structured discussion to compare differences in the rich picture (as a boundary object) and a series of purposeful activity models derived from root definitions developed during the in-depth interviews, and from societal actors

participating in the workshops (as epistemic objects). During the workshop, actors were tasked with collaboratively articulating the differences between the real-world situation and the purposeful activity model. This prompted a structured discussion about how the model may be transformed to represent a shared conceptualisation of each model. One that accommodated questions about desirability and feasibility, the intention of activities, decision criteria, and the assumptions embodied in each model (Checkland & Poulter, 2010).

The third workshop applied a similar structure to the second to apply Ulrich's (2000) twelve *critical systems heuristics* as a boundary critique of the purposeful activity models. This workshop prompted a deeper reflection on how different commodities of power are held and distributed within the case study to structure a gentle critique. It was used to challenge how normative assumptions about the planning of urban water and sanitation services may affect the viability of each model. This approach helped to establish alignment between the ideas emerging from within the problematical situation and the evaluative criteria for least-cost comparative analysis of citywide inclusive sanitation service provision (Ross et al., 2024a).

Overall, these workshops functioned as a participatory approach to facilitating and collaboratively reflecting on transdisciplinary learning driven by the integration of epistemologically diverse knowledge. The knowledge artefacts co-produced in these workshops are interpreted in *Chapter Six* to inform the development of the systemic urban water and sanitation planning framework discussed in *Chapter Seven*.

2.4.3.2 Assembly of knowledge products for science and society

The final step of *Wave Three* and this methodological framework is to synthesise the insights and reflections generated through the framing, analysis, and integration of co-produced knowledge in the workshops. The intention of this step was to inform a revised

integration concept to structure a systemic comparative economic analysis methodology to support the planning of water and sanitation interventions for heterogeneous configurations in LMICs. Such an approach was expected to inform the development of new integrated urban water sanitation planning frameworks. As discussed in *Chapter Seven*, the assembly of the knowledge produced in this thesis articulates how the decision-making principles incorporated in this research, grounded in diverse real-world perspectives from Siem Reap municipality, Cambodia might be structured and applied in practice.

The transdisciplinary case study methodology in this thesis has been mostly successful in integrating knowledge co-produced through a collaborative focus on a boundary object and epistemic objects as intended by the integration concept. However, some knowledge co-produced in this thesis could not be directly integrated. For example, insights from the residential end-use demand model, as well as the fragmented cost data obtained through the in-depth interviews. In these cases, knowledge that could only be indirectly tested through real-world experimentation was instead evaluated through a reflexive assessment in *Chapter Seven*, as recommended by [Pohl \(2021\)](#).

This contribution to knowledge is coupled with the compilation of academic publications as outlined in the preface of this thesis arising from this methodological framework. An evaluative criteria proposed in one of these publications for the least-cost economic analysis for citywide inclusive sanitation ([Ross et al., 2024a](#)) has been used to structure and evaluate the proposed methodological approach in *Chapter Seven*.

2.4.4 Research methods

To conclude the outline of this methodological framework, *Table 1* summarises how the outcome spaces framework was used as a basis for backcasting. This includes: (i) the theoretical frame used to assess the contribution to each outcome space; (ii) the

methodological frame used to compare different ways of knowing about the problematical situation; (iii) the methods used to co-construct various systems models; and (iv) the evidence base used to support knowledge co-production.

Table 1 also indicates which wave of action-oriented learning the method contributes to, and which chapter the method is documented within, supporting transparency and reflection on the approach taken to the transdisciplinary case study methodology. It also provides a frame of reference for tracing how each method contributed to different types of knowledge production, integration, and research impact.

2.5 Limitations

The theoretical and methodological framing adopted in this thesis has several strengths for addressing a complex problematical situation where social, technical, institutional, and economic implications are messy and interdependent. The use of a single, intrinsic, embedded case study methodology was well suited to an inquiry focused on understanding how different types of knowledge may be integrated within a unified planning approach where it is not straightforward to separate the problem from the real-world context (Scholz et al., 2006). The purposeful selection of a *heterogeneous urban water and sanitation service provision configuration* in Siem Reap municipality enabled the co-production of rich contextual insights into the nature of this situation and the practical challenges of planning within it.

At this same time, the scope and design of this research impose limitations on what can be claimed as a contribution to knowledge. The evaluative criteria for the least-cost comparative economic analysis developed in this thesis drew from a breadth of global, yet fragmented literature (Ross et al., 2024a) and have been validated in comparison to diverse studies in a range of international contexts (Ross et al., 2024b).

Table 1: How the transdisciplinary outcome spaces framework (Mitchell et al., 2015) was used to incorporate different characteristics of transdisciplinarity Lawrence et al. (2022) when backcasting the theoretical and methodological framing of the research.

Outcome Space (Wave)	Characteristics of a transdisciplinary praxis	Theoretical framing	Methodological framing	Methods	Evidence base
Transdisciplinary outcome spaces framework (Integration of Wave One, Two and Three) (Mitchell et al., 2015)	All transdisciplinary characteristics (Lawrence et al., 2022)	Transdisciplinary integration (Pohl et al., 2021)	Participatory transdisciplinary case study methodology (Jahn et al., 2012; Scholz et al. 2006; Pohl, 2021; Mobjörk, 2010)	Transdisciplinary integration (Pohl et al. 2021) with an evolving methodology (Wickson, Carew & Russell 2006)	As outlined below
Improving the situation (Wave One)	A focus on specific, complex, societally relevant, real-world situation that transcends disciplinary boundaries	Heterogeneous urban water and sanitation service provision configurations (Jaglin, 2014; Lawhon et al., 2017; van Welie et al., 2018)	Evidence synthesis ecosystem (Khalil & Tricco, 2022)	Scoping review: Evaluative criteria for least-cost economic analysis of citywide inclusive sanitation (Ross et al., 2024a) (Chapter Three)	38 sources were synthesised in the evaluative criteria (Ross et al., 2024a) (Chapter Three)
	An orientation toward the common good	Least-cost, and integrated resource planning (Beecher 1991; Hutton 2001; Julius 1979; Kalbermatten et al., 1982; Mitchell et al., 2007;; Willetts et al., 2010, 2013)		Systematic review: Comparative economic analysis of urban sanitation interventions in low- and middle-income countries (Ross et al., 2024b) (Chapter Four)	
Contributing to knowledge stocks and flows (Wave Two)	The inclusion of multidisciplinary and interdisciplinary academic research	Heterogeneous urban water and sanitation service provision configurations (Jaglin, 2014; Lawhon et al., 2017; van Welie et al., 2018)	Residential water end-use demand analysis and modelling (Mazzoni et al., 2023; Tamason et al., 2016)	Transect walks, grey literature review, and informal interviews (Chapters Five & Six)	3 transect walks were conducted as part of defining the case (Chapter Five & Six) (Ross et al., under review a, b).

		Hard vs soft systems thinking / DSRP framework (Cabrera et al., 2021; Ison, 2008; Jackson, 2000; Reynolds & Holwell, 2010)	Soft systems methodology (<i>Analysis One, Two and Three</i> , and CATWOE as a problem structuring approach) (Checkland & Poulter, 2010)	Household residential end-use survey (<i>Chapter Five</i>) <hr/> In-depth semi-structured interviews (<i>Chapter Six</i>)	Surveys in 97 out of 1,630 households (<i>Chapter Five</i>) (Ross et al., under review a). <hr/> 32 interviews informing 9 purposeful activity models (<i>Chapter Six</i>) (Ross et al., under review b).
<i>Mutual and transformational learning (Wave Three)</i>	A focus on theoretical unity of knowledge, to transcend disciplinary boundaries The involvement of (non-academic) societal actors as process participants Working in a transformative manner Reflexivity	Heterogeneous urban water and sanitation service provision configurations (Jaglin 2014; Lawhon et al. 2017; van Welie et al. 2018) Hard vs soft systems thinking / DSRP framework (Cabrera et al., 2021; Ison, 2008; Jackson, 2000; Reynolds & Holwell, 2010) Critical systems thinking (Jackson, 2000; Midgley, 2003; Ulrich, 2010)	Soft systems methodology (Rich pictures and purposeful activity models) (Checkland & Poulter, 2010) Critical systems heuristics (Ulrich & Reynolds, 2010)	Workshop: Rich Picture co-construction (Berg 2015; (Checkland & Poulter, 2010) (<i>Chapter Six</i>) <hr/> Workshop SSM Learning Cycle: Using Models to Structure-Discussion About the Situation and Its Improvement (Checkland & Poulter, 2010) (<i>Chapter Six</i>) <hr/> Workshop: Boundary critique (Ulrich & Reynolds, 2010) (Chapter 6)	<i>Workshop One</i> comprised 15 issue owners co-producing 3 rich pictures (<i>Chapter Six</i>) (Ross et al., under review b). <hr/> <i>Workshop Two</i> comprised 15 issue owners comparing 9 purposive activity models with 3 rich pictures (<i>Chapter Six</i>) (Ross et al., under review b). <hr/> <i>Workshop Three</i> comprised 15 issue owners comparing 9 purposive activity models with 12 critical system heuristics (<i>Chapter 6</i>) (Ross et al., under review b).

In contrast, the methods embedded within the transdisciplinary case study to co-produce contextual knowledge, such as the heterogeneous water end-use analysis and the purposeful activity models, are inherently context specific. This aspect of the research is well-suited to exploring how different ways of knowing may be integrated with a heterogeneous urban configuration. However, it does not allow for the definition of generalisable end-use parameters, or a claim that the resulting models are representative of other cities in LMICs, or even other areas within Siem Reap municipality. Replication at a larger scale or across multiple cases would be required to support such claims.

The design of the research was also shaped by the practical constraints of conducting a transdisciplinary inquiry within the timeframe and resource limits of a PhD thesis. Ideally, such transdisciplinary research would be facilitated by a larger and more diverse team of researchers, enabling deeper and more consistent engagement with societal actors across all waves of the inquiry. However, the requirement for an individual doctoral contribution, combined with time, mobility, and resource constraints, including disruptions associated with the COVID-19 pandemic, necessarily limited the scale and intensity of participation that could be supported across all research activities.

Furthermore, reflexivity was a significant component of the theoretical and methodological framing. This it is important to acknowledge that the complexity of coordinating multiple embedded methodologies, alongside the task of reflecting on their integration, constrained the extent to which this deliberation could be undertaken at all stages of the research. The framework outlined in *Section 2.2* provided guidance for maintaining coherence across methods, but the design did not always allow sufficient opportunities to properly analyse and deliberate on emerging research findings and recalibrate the approach, where it may have been useful.

These limitations are identified not to diminish the contribution of the research, but to clarify the boundaries within which the methodological framework was developed and applied. They define the scope of what this thesis can reasonably claim at the level of research design. A more detailed reflection on how these constraints shaped the knowledge produced, the integration achieved, and the contributions to each of the three transdisciplinary outcome spaces is provided in *Chapters Seven and Eight*.

2.6. Summary

This chapter establishes the theoretical and methodological foundations of this transdisciplinary inquiry into the planning of interventions for heterogeneous urban water and sanitation configurations to address persistent service outcome inequalities. The thesis adopts the *transdisciplinary outcome spaces framework* (Mitchell et al., 2015) to frame the objectives of this research as a system of three interdependent contributions including: (i) a tangible improvement in a problematical situation; (ii) contributions to both knowledge stocks and flows; and (iii) mutual and transformative learning. This framing makes the ontological assumption that heterogeneous urban water and sanitation service provision configurations function as *complex adaptive systems* and thus may only be understood using an *epistemologically plural* approach. Each outcome space represented a facet of the case study, which was backcast to identify a specific theoretical framing that may be used to assess how to research the integration of diverse ways of knowing about the problematical situation. This process was guided using an extended version of the *backward planning approach* proposed by Scholz et al. (2006), as recommended by Mitchell et al. (2015).

The research was organised using a three-wave, action-oriented, embedded transdisciplinary case study methodology, aligned with the ideal-typical stages of *problem framing (or transformation), problem analysis, and exploration of (emerging) impact* (Jahn

et al., 2012; Lang et al., 2012; Pohl et al., 2021). Wave One articulated the real-world problematical situation and repurposed fragmented knowledge about least-cost and integrated resource planning principles to guide a purposeful response. *Wave Two* focused on the co-production of new knowledge using the objective (hard) systems approach and residential water end-use demand analysis (as a *boundary object*); and the interpretive (soft) systems approach of constructing purposeful activity models (as an *epistemic object*). These were structured using an initial integration concept that compared these objects to facilitate learning across different perspectives within the case study. *Wave Three* used a series of three workshops to observe how this knowledge was integrated in the real-world problematical situation in real-time to reflect on how these diverse knowledges may inform a systemic comparative economic analysis methodology that might inform an inclusive planning framework.

The chapter concludes with a summary table that demonstrated the links between each outcome space and its transdisciplinary characteristics, and the theoretical and methodological framing, methods, and evidence base for each *wave*. This synthesis informs how reflexive decisions are structured to support a flexible methodology that is responsive to the complex, real-world problematical situation of persistent service outcome inequalities in the case of Siem Reap, Cambodia. While some limitations in the implementation of this framework were encountered due to the complexity and heterogeneity of the case study, the outcome spaces framework has proved to be effective for structuring the four studies presented in the chapters that follow.

Chapter Three: Evaluative criteria for least-cost comparative economic analysis of urban water and sanitation interventions in low- and middle-income countries

3.1 Overview

Chapter Three is a knowledge output produced in response to the *first wave* of action-oriented learning in the *transdisciplinary case study* (see *Figure 3*). This wave contributes to the first *transdisciplinary outcome space*: making a *tangible improvement in a real-world problematical situation*. In this case, the *societal problem* is defined as persistent water and sanitation service outcome inequalities in secondary cities in Cambodia. The problem was linked to the academic challenge of effectively applying *least-cost* and *integrated resource planning principles* to decisions about the most cost effective urban water and sanitation interventions from a societal perspective (see *Sections 1.2* and *2.2.1* for a detailed description of this context and process). More specifically, the challenge responded to in this *chapter* was the need to *re-purpose* fragmented academic literature to inform tangible improvement in this real-world context. A scoping review, published in the *Journal of Water Sanitation and Hygiene for Development*, is compiled in this chapter to respond to *Research Question #1a* (Ross et al., 2024a). As outlined in Section 2.4.1.2, the focus on this paper on citywide inclusive sanitation is consistent with this questions as CWIS refers to integrated water and sanitation configurations inclusive of a breadth of basic urban services.

Within the context of Siem Reap municipality in Cambodia, the concept of heterogeneous urban water and sanitation service provision configurations (Jaglin 2014; Lawhon et al. 2017) served as central, implicit driver in *reframing* or *transforming* the problematical situation investigated in the scoping review. Specifically, the review focused

on how comparative economic analysis methodologies may be applied to such configurations. As described in *Section 2.2.1*, the methodology acted as a *boundary object* and the concept of heterogeneous service provision configurations as an *epistemic object* (Jahn et al., 2012). These conceptual tools informed the framing of the review through a collaborative definition of the aim, objectives, and questions of the thesis, developed in consultation with the *clients* of this research from the *Ministry of Public Works and Transport in Cambodia* and associated entities (Ross, 2018); and the supervisory team from the *Institute for Sustainable Futures* in Sydney (Fane & Mitchell, 2006; Mitchell et al., 2007; Retamal et al., 2011; Willetts et al., 2010, 2013). This co-framing ensured relevance of this paper to both academic and societal objectives (Pohl et al., 2021; Lang et al., 2012).

The compiled paper makes several theoretical and methodological contributions, which are summarised here and discussed in further detail in *Chapter 8*. Firstly, it implicitly reframes the challenge of planning CWIS in LMICs, through the lens of a *heterogeneous socio-technical configuration* (Jaglin, 2014; Lawhon et al., 2017), aligning with citywide inclusive planning principles (Lüthi et al., 2020). Second, it synthesises evidence about the application of *least-cost* and *integrated resource planning* principles to such heterogeneous configurations. Third, it proposes a set of evaluative criteria for least-cost economic analysis of citywide inclusive sanitation, which refer to integrated water-related services are provided in a way that was previously underdeveloped in the academic and practitioner focused literature. At the time of thesis submission, the publication had been viewed ~650 times and downloaded by ~120 unique readers from doi.org/10.2166/washdev.2024.209, highlighting the reach of this paper and its practical relevance.

Publication: Evaluative criteria for least-cost economic analysis
of citywide inclusive sanitation: A scoping review

This journal article is included in this thesis as the *peer-reviewed manuscript accepted for publication* by the *Journal of Water Sanitation and Hygiene for Development* on the 30th of October 2024, with edits in the typesetting process included. This version has been compiled within the thesis to enable plagiarism checking software to be applied and to facilitate a transparent overall word count for the thesis. To aid navigation of the thesis, the headings, figures, and tables of this publication have been embedded within the structure of the overall thesis and are not in the same format as the published version. The published version of the journal article is available via an open access agreement and is available for free download via accessing the link <https://doi.org/10.2166/washdev.2017.130>.

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Evaluative criteria for least-cost economic analysis of citywide inclusive sanitation: a
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Abstract:	Compared to health interventions, where evaluative criteria have been established, uncertainty about best practices for the comparative economic analysis of urban sanitation interventions in low- and middle-income countries persists. Identified gaps in applying economic least cost principles to these methodologies constrain emerging citywide inclusive sanitation (CWIS) planning frameworks. Further, a scarcity of comparable evidence about the economic efficiency of heterogenous service provision interventions impacts the delivery of urban sanitation as an inclusive public service. This review scopes evidence about applying methodologies representing least-cost economic principles to the comparative economic analysis of urban sanitation interventions in two iterations. We devise and discuss evaluative criteria, embodying CWIS principles, that will improve the quality of these methodologies, including (i) the inclusion of diverse cost perspectives, particularly those with marginal access to sanitation; (ii) how a context-specific without project case may be used as an appropriate basis for comparison; (iii) how tangible and intangible costs and outcomes may influence decisions; and (iv) how diverse mixtures of interventions at different scales may be compared with integrity. The resulting evaluative criteria define principles that may be charted in future systematic reviews to inform practices that enhance CWIS planning frameworks.
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Evaluative criteria for least-cost economic analysis of citywide inclusive sanitation:

a scoping review

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Abstract

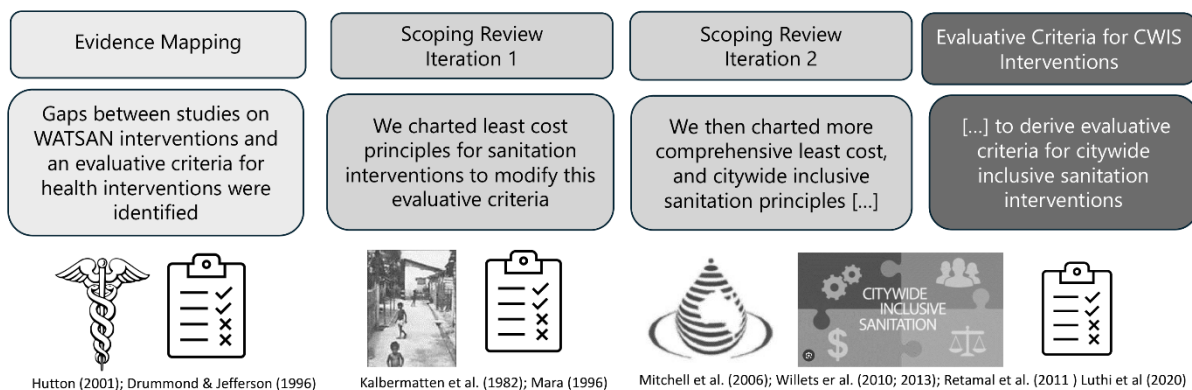
Compared to health interventions, where evaluative criteria have been established, uncertainty about how comparative economic analysis methodologies should be applied to heterogeneous urban sanitation interventions in cities of LMICs persists. Gaps between least-cost principles and current approaches constrain emerging citywide inclusive sanitation (CWIS) planning frameworks. Further, a lack of comparable evidence about the economic efficiency of service provision interventions impacts the delivery of urban sanitation as an inclusive public service. This review scopes how least-cost principles may be applied to methodologies for urban sanitation interventions in two iterations. We devise and discuss evaluative criteria, embodying CWIS principles, that will improve the quality of these methodologies. They include how (i) the inclusion of diverse cost perspectives, particularly populations with marginal access to sanitation, are accommodated within an analysis; (ii) a context-specific *without-project case* may be used as an appropriate basis for comparison; (iii) tangible and intangible costs and outcomes may influence decisions; and (iv) diverse mixtures of interventions at different scales may be compared with integrity. The resulting evaluative criteria define principles that may inform future systematic reviews on practices that enhance CWIS planning frameworks.

Keywords: cost analysis, heterogeneity, least-cost planning, integrated resource planning, urban sanitation, urban water

Highlights

- Evidence of the allocative efficiency of context-specific sanitation investments is scarce in low- and middle-income countries.
- We devise evaluative criteria for the comparative economic analysis of urban sanitation interventions.
- These criteria may inform methodologies for prioritising the right mix of service provision models for achieving citywide inclusive outcomes.

Graphical abstract



Proposed evaluative criteria for the comparative economic appraisal of citywide inclusive sanitation interventions

Study Design		Data Collection		Analysis and Interpretation	
1.1	A research question that balances economic efficiency and equity outcomes	4.1	The source of effectiveness data is specific to the without-project case	8.1	The time horizon and discount rate applied are stated and justified.
1.2	A societal cost perspective is disaggregated by subgroup cost perspectives	4.2	A justification for the comparison of data across different contexts is provided		
2.1	Options are compared against a least cost without-project standard	5.1	Unit costs expressed in TACH or TACC are used to measure cost-effectiveness.	9.1	Confidence intervals are presented for stochastic data.
2.2	Consistent and appropriate system boundaries are applied	5.2	Benefit valuation methods are described and justified for the study population	9.2	Sensitivity and scenario analyses are used to enhance the use of modelled data.
		5.3	Intangible benefits are reported separately and appraised deliberately	9.3	Deliberative methods are used to allow for epistemic uncertainty
3.1	An appropriate economic analysis methodology is adopted	6.1	Average incremental costing is used to structure life cycle costs over time.	10.1	Reported outcome measures (TACH/TACC) align with the basis of comparison
		6.2	Adjustments for inflation and currency conversion are made explicit.	10.2	Outcome measures are presented in an aggregated and disaggregated format
		7.1	Assumptions within the costing model are justified and contextually relevant	10.3	Conclusions arise from multiple cost perspectives informed by multiple criteria

3.2 Introduction

The *Kalbermatten model* of least-cost sanitation planning (Mara, 1996) was developed from World Bank guidance in the 1980s about the comparative economic analysis of sanitation projects (Kalbermatten et al. 1980, 1982). It embodied a *theory of economic costing* used to select public infrastructure projects at the World Bank (Julius, 1979; Squire & van der Tak, 1975). Kalbermatten et al. (1980) promoted prioritising cost-efficient, intermediate sanitation interventions that directly responded to demands for improved sanitation service outcomes within cities of LMICs. Governments with limited capacity to use taxation and subsidies to finance projects might instead select least-cost interventions that leverage local factors of production to distribute the benefits of economic development projects more equitably (Perard, 2018; Squire & van der Tak, 1975).

In a review paper, Kennedy-Walker et al. (2014) describe the influence of the *Kalbermatten model* in shaping the economic aspects of urban sanitation planning frameworks in LMICs (Schertenleib et al., 2021). For instance, it drove a shift in focus from economic to allocative efficiency and challenged an *induced bias* towards the selection of conventional waterborne sewerage (Mills et al., 2020; Rosenqvist et al., 2016; Squire & van der Tak, 1975). However, the diverse range of paradigms about the inclusive planning of urban sanitation services that have emerged since have not been used to adapt comparative economic analysis methodologies for urban sanitation projects (Rosenqvist et al., 2016). For instance, the least-cost approach promoted by Kalbermatten et al. (1982) is still applied in contemporary studies, e.g. Manga et al. (2020).

Methodological constraints to producing comparable evidence of how urban sanitation interventions distribute costs and benefits at a municipal scale persist (Mills et al.,

2020). Available data on the economic performance of competing options and their capacity to respond to Sustainable Development Targets 6.1 & 6.2 exist on a global (Hutton & Varughese, 2016) or national scale (Hutton et al., 2014). However, these data are not suited to informing decisions about the most appropriate mix of municipal-level projects (Hutton, 2016). The scarcity of cost-effectiveness data for the mixed sanitation options used in practice at this scale has been widely reported (Daudey, 2018; Hutton & Chase, 2016; Hutton et al., 2014; Mills et al., 2020; Sainati et al., 2020).

Thus, comparative economic analysis methodologies for urban sanitation interventions in these heterogeneous contexts are attracting growing interest (Carrard et al., 2021). The transition from the Millennium to the Sustainable Development Agenda has prompted the development of different ways of conceptualising urban sanitation systems, with the intent to facilitate the more equitable distribution of the costs and benefits of interventions (Kennedy Walker et al., 2014; Rosenqvist et al., 2016; Schertenleib et al., 2021; Scott et al., 2017). Recent iterations of urban sanitation planning frameworks have highlighted the importance of mitigating the negative societal impacts of not providing appropriate sanitation services to everyone in a city. The need for heterogeneous service models that match the diverse service demands and cost preferences across different population clusters in cities has been highlighted (Hutton & Andrés, 2018).

To date, these frameworks have yet to be applied as effectively as they might have been to inform decisions in practice (Scott & Cotton, 2020). The scale at which safely managed sanitation services are needed tends to drive rule-of-thumb comparisons between existing feasible options (Sainati et al., 2020; Willetts et al., 2010). Current economic and financial analysis approaches promote what Spuhler and Luthi (2020) describe as a persistent *one-size-fits-all approach* to decision-making, where novel, cost-effective

approaches are less likely to be compared evenly. The depth of analysis required within comparative economic analysis methodologies to understand the complexity of context-specific drivers of cost-effectiveness within an urban LMIC context is rarely achieved (Daudey, 2018; Hutton & Andrés, 2018).

This situation makes the findings of Hutton (2001), who mapped gaps between comparative economic analysis methodologies for water and sanitation interventions and the available evaluative criteria that might improve them, increasingly salient. Such criteria are essential to developing a capacity to compare the economic performance of heterogeneous mixtures of sanitation configurations with variable service outcomes. The methodological uncertainty about how to compare heterogeneous urban sanitation interventions has been identified as a key constraint to the delivery of CWIS as a municipal public service (Lüthi et al., 2020; Mills et al., 2020; Schrecongost et al., 2020).

To address this uncertainty, methodologies enhanced by more comprehensive least-cost principles are needed to assist urban sanitation planners in interpreting the complex economic relationships that exist within cities of LMICs (Scott et al., 2017). As Scott and Cotton (2020) observes in presenting the emerging *sanitation cityscape* framework, the extent to which the complexity of the household demand for urban sanitation services has been embraced in planning frameworks is limited. Thus, how the bottom-up demand for services from women, girls, and those who are poor or experience marginal living environments can be poorly understood by planners (Hutton & Andrés, 2018; Spuhler & Lüthi, 2020). Understanding the complex interface of mixed service provision typologies and household demand profiles is critical to distributing the costs and benefits of seemingly fragmented urban sanitation configurations more equitably (Scott et al., 2020).

While this *sanitation cityscape* may be interpreted in different ways, the conceptualisation is well aligned with the four principles of the evolving CWIS planning framework (Schertenleib et al., 2021; Scott et al., 2020). Namely to (i) prioritise urban sanitation as an equitable and inclusive human right; (ii) achieve safely managed sanitation service outcomes across an entire urban water cycle via a diverse, adaptive, and incremental mix of service provision models; (iii) recognise the tangible and intangible contributions of sanitation to economic development; and (iv) commit to partnerships between formal and grassroots actors to transparently deliver integrated urban services (Lüthi et al., 2020).

With this background in mind, this paper has three objectives: (i) to establish evaluative criteria for the comparative economic analysis of *sanitation interventions* based on principles embodied in the *theory of economic costing* (Julius, 1979) promoted in the *Kalbermatten model*, as a reference case; (ii) to chart evidence from a more comprehensive set least-cost, integrate resource planning principles for urban water systems (Mitchell et al., 2007; Willetts et al., 2010, 2013) about how comparative economic analysis methodologies may better analyse and interpret how urban sanitation configurations distribute costs and benefits across a *sanitation cityscape*; (iii) to scope and discuss enhanced evaluative criteria for the economic analysis of CWIS interventions.

3.3 Methodology

Evaluative criteria for the comparative economic analysis of CWIS interventions have the potential to (i) facilitate the selection of least-cost urban sanitation configurations, (ii) provide a consistent lens for assessing the quality of studies, (iii) assist with making coherent comparisons across different contexts within cities, and (iv) enhance the capacity of municipal authorities, civil society, and grassroots actors to make inclusive and evidence-

based decisions (Luthi et al., 2020). While it was identified that these principles were not sufficiently comprehensive for the comparison of water and sanitation interventions, they would be useful in understanding the additional principles that would be necessary to apply. Our objective is to inform methodologies that compare urban sanitation configurations more meaningfully.

Hutton (2001) applied a deductive review to map evidence about gaps in existing evaluative criteria for the comparative economic analysis of water and sanitation interventions. *Twenty-four* methodologies were used to compare these interventions and mapped against existing evaluative criteria for health interventions. In this case, those used to appraise studies in the *British Journal of Medicine* (Drummond & Jefferson, 1996). Hutton (2001) identified that these principles were not sufficiently comprehensive for the comparison of water and sanitation interventions, but they would be useful in understanding the additional principles that would be necessary to apply. The rationale used was that they represented consensus among health economists about what had a demonstrated capacity to improve the quality of studies. By identifying the gaps, Hutton (2001) intended for future work to shape more fit-for-purpose methodologies.

To build upon this gap analysis, we apply an inductive scoping review with two iterations, as outlined in *Figure 5* (Khalil & Tricco, 2022). We aim to understand how more comprehensive, *least-cost* principles may enhance how the allocative efficiency of emergent mixtures of heterogeneous CWIS interventions are compared. The review acknowledges that we have selected evaluative criteria for health interventions as a point of reference that has since been subject to two major reviews (Drummond & Jefferson, 1996; Husereau et al., 2022). However, the review by Hutton (2001) is useful as a pivot, as it clearly distinguishes gaps between the principles and practices relevant to the comparative economic analysis of

water and sanitation interventions from those of health interventions. This trait enables a discussion about how to scope how these limitations may be addressed in enhanced evaluative criteria for urban sanitation and, more specifically, CWIS.

The first iteration of the evaluative criteria for health interventions in Column 1 of *Appendix C* is conducted by charting principles from the literature presenting the *theory of economic costing* (Julius, 1979; Kalbermatten et al., 1980, 1982; Mara, 1996; Squire & van der Tak, 1975) that address gaps identified by Hutton (2001). To support this iteration, we also considered additional literature reviewing the application of this theory in planning frameworks retrospectively (Kennedy-Walker et al., 2014; Rosenqvist et al., 2016; Schertenleib et al., 2021; Scott et al., 2017; Spuhler & Lüthi, 2020).

A second iteration of the evaluative criteria was conducted with an explicit objective of charting more comprehensive and up to date least-cost principles for sustainable urban water management and a related *cost-effectiveness analysis methodology* applying them to urban sanitation interventions (Mitchell et al., 2007; Retamal et al., 2011; Willetts et al., 2010, 2013). To support this iteration, we referred to related resources providing more in-depth coverage of particular concepts (Beecher, 1996; Fane et al., 2003; Hanley & Spash, 1993). We also extended the scope of the criteria to consider how they might embody CWIS principles (Luthi et al., 2020; Scott et al., 2020). To do so, we sourced additional updated literature on least-cost principles for urban water and sanitation. We searched the titles, abstracts, and keywords of English language literature published between 2001 and 2021, recorded in the *SCOPUS* and *Google Scholar* databases, including any included papers' citations and reference lists. We applied the search terms *urban, sanitation*, permutations of the terms *plan**; *cost**, *economic, financial, citywide, inclusive*, as well as specific keywords from the least-cost planning framework. Namely *cost-effectiveness analysis, cost-*

benefit analysis, multicriteria decision analysis, sustainability assessment, resource efficiency, societal cost perspective, reference case, systems thinking, system boundaries, complex system, life cycle cost*, average incremental cost*, externalities; & and uncertainty.*

Our inclusion criteria were based on the participant, concept, context (PCC) mnemonic (Khalil & Tricco, 2022). We defined the participant as the evaluative criteria and the concept as the least-cost principles. The context was defined as the application of a comparative economic analysis methodology to CWIS interventions in LMICs. As each included paper was read in full, relevant principles for the evaluative criteria were extracted. The intention of the scoping review was primarily to consolidate and tabulate fragmented literature about this complex and interdisciplinary context as a precursor to a systematic review. If applied comprehensively, the risk of bias from this method of scoping the literature is not significant (Khalil & Tricco, 2022). An outline of the approach is provided in

Figure 5.

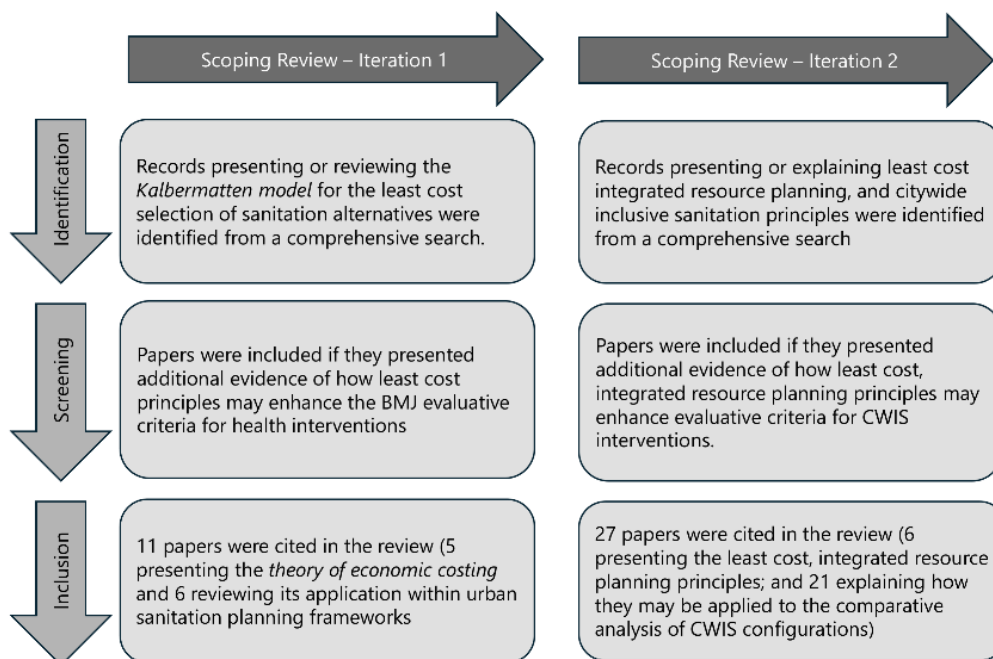


Figure 5: Scoping review methodology

3.4 Results and discussion

The evaluative criteria for the comparative economic analysis of CWIS interventions derived from this methodology are presented in *Appendix C*. They are consolidated in *Table 2* and interpreted in the discussion that follows. This discussion is supported by a companion paper that systematically reviews the application of the evaluative criteria to existing comparative economic analysis methodologies, citing practical examples of how they may be applied from relevant literature (Ross et al., 2024b).

Table 2: Evaluative criteria for the comparative economic analysis of CWIS interventions

Study design
Research question
1.1 A research question is outlined that balances economic efficiency, equity, and sustainability outcomes inclusive of low-income households, women, girls, and those facing insecure land tenure"
1.2 The study adopts a societal cost perspective, disaggregated by the cost perspectives of key societal actors and relevant subgroups
The rationale for the comparison of alternatives
2.1 All alternative supply and demand-led interventions that might meet a defined service outcome are compared against the opportunity costs of forgoing the least-cost standard that would have emerged without a project
2.2 The without-project case and alternatives are framed within consistent and critically defined system boundaries that are explicit about the people, time, and service dimensions adopted in the analysis and relevant to key decision-makers.
Economic analysis methodology
3.1 The economic analysis methodology comprises (i) a comparable cost-effectiveness analysis, (ii) optimisation of each alternative, and (iii) end user(s), especially marginalised end users, making a final cost-benefit or cost-effectiveness determination of the least-cost alternative based on broad qualitative criteria.
Data collection
Effectiveness data
4.1 Sources used to derive outcome measures are stated, and the study design is specific to the study context and the system boundaries of the comparative economic analysis.
4.2 If outcome measures from multiple cost-effectiveness studies are compared, a method of synthesis or meta-analysis is provided, including a justification for why the results are comparable.

Benefit valuation

- 5.1 A primary outcome measure is reported in units of total annualised costs, or net present value (NPV) per household or capita (TACH/TACC), along with an explicit account of the costs and outcomes included in the measure.
-
- 5.2 If tangible and quantifiable benefits have been valued, the method adopted is relevant to the context in which the estimate is made explicit.
-
- 5.3 Intangible and unquantifiable benefits are reported separately in a format that enables their relevance to be determined by decision-makers
-

Cost data

- 6.1 Quantities of resources are reported separately from unit costs and used to determine relevant life cycle costs using average incremental costing
-
- 6.2 Currency and price data are recorded, and details of adjustments for inflation or exchange rates are given.
-

Modelling

- 7.1 A contextually relevant resource flow model is described and justified as the basis for estimating the economic costs over the time horizon of analysis for a hybrid mixture of service provision interventions, with any assumptions applied made explicit, recoverable, and testable
-

Analysis and interpretation of results

Adjust for the timing of costs and benefits.

- 8.1 The time horizon and discount rate(s) used in the analysis are stated and justified
-

Account for uncertainty

- 9.1 Details of statistical tests and confidence intervals are given for all stochastic data.
-
- 9.2 Methods, such as sensitivity or scenario analysis, are used to explore and describe uncertainties, and their implications can be interpreted by diverse subgroups.
-
- 9.3 Deliberative multistakeholder decision-making methods, inclusive of marginal users, address epistemic uncertainty as part of the design of economic analysis methodology and increase the likelihood that root causes of gender and social inequity shape decisions.
-

Present results transparently

- 10.1 Relevant, mutually exclusive alternatives optimised to meet the same service outcome are compared in incremental units of TACH/TACC against a cost-effective, without-project standard.
-
- 10.2 An aggregate primary outcome measure is also presented in a disaggregated form for each stage of the sanitation service chain, life cycle cost component and for each cost and subgroup perspective
-
- 10.3 A non-prescriptive conclusion is presented in response to the study question arising from the reported data, accompanied by appropriate caveats describing uncertainties to enable societal actors, especially marginalised users, to interpret the study outcomes independently.
-

3.4.1 Defining urban sanitation from a societal cost perspective.

While [Drummond and Jefferson \(1996\)](#) imply that a well-defined comparative economic analysis of health interventions may be designed from a single cost perspective, CWIS interventions require a societal cost perspective aggregating multiple viewpoints. The legitimacy of inclusive decisions is shaped by the capacity of analysis to accommodate the cost preferences of societal actors and related subgroups. This requirement is reflected by [Kalbermatten et al. \(1982\)](#), stating that '*all costs to the economy are included within the scope of an analysis, no matter who incurs them*' ([Julius, 1979](#)).

Framing a comparative economic analysis from a societal perspective enables the financial costs and benefits of an intervention appraised to have the least societal cost to an economy to be disaggregated and distributed equitably ([Julius, 1979](#); [Kalbermatten et al., 1982](#); [Squire & van der Tak, 1975](#)). For instance, the allocative efficiency of interventions prioritising user convenience, such as conventional waterborne sewerage, will differ from those intended to provide basic, safely managed services at a low cost of ownership ([Kalbermatten et al., 1980](#); [Lawhon et al., 2017](#)). In LMIC contexts, this might include options that extend to the use of formal, centralised interventions beyond their intended objectives or those informal services that arise in response to unmet demand ([Lawhon et al., 2017](#)).

A societal cost perspective differs from a conventional utility perspective, which selects options based on the capacity to recover costs from additional service users from a predetermined intervention ([Willetts et al., 2013](#)). Adopting multiple perspectives within a societal lens enables service outcomes to be negotiated, accommodating a greater range of options within an analysis. However, adopting a societal perspective increases the complexity of comparative economic analysis and the data required to describe the economic impacts of interventions. The breadth of costs included expands and may include

data not systematically collected in LMICs (Scott et al., 2020). For instance, data about social and environmental externalities, such as the climate impacts of service provision that institutions may be reluctant to adopt within an analysis (Kalbermatten et al., 1980).

Data about subgroup cost perspectives, such as those of women and girls or those with marginal housing tenure, are also not typically considered for disaggregation by utilities in LMICs (Hutton & Andres, 2018). For instance, Danert and Hutton (2020) juxtapose the significance of household expenditure on the self-supply of sanitation services in many countries with the typical lack of inclusion of this knowledge in feasibility studies. Hutton (2001) identified the potential for *subgroup analysis* to enhance the capacity of comparative economic analysis to generate cost-effectiveness data for interventions that are more specific to clusters of households. This extends the capacity of an analysis to consider equity outcomes of decisions in more detail (Hutton & Andres, 2018; Kohli-Lynch & Briggs, 2019; Narayanan et al., 2018; Squire & van der Tak, 1975).

Comparative economic analysis methodologies for CWIS interventions may use data about disaggregated subgroups to develop more robust models to better understand the performance of urban sanitation configurations from a societal lens. For instance, *multiple technical approaches that are adaptive, mixed, and incremental and operate under different ownerships at different economies of scale* (Schrecongost et al., 2020) may be compared iteratively to consider different financial trade-offs that may work towards outcomes where everyone benefits (Schrecongost et al., 2020). Residential end-use modelling approaches, as discussed later in this paper, are one approach that may be used to facilitate data collection and analysis that might enable subgroup analysis (Retamal et al., 2011). Others are articulated in a companion paper presenting a systematic review of the evaluative criteria (Ross et al., 2024).

3.4.2 A consistent basis for comparing alternative CWIS interventions.

Kalbermatten et al. (1982) referred to two key findings from studies about the cost-effectiveness of sanitation alternatives in Asia and Africa to support their model. The first was that at least two feasible low-cost alternatives to conventional waterborne sewerage could provide universal access to adequate sanitation service outcomes. Secondly, incrementally sequencing the implementation of these interventions over time is typically more cost-effective than conventional waterborne sewerage due to the capacity to employ local labour and resources.

Both observations make the basis of the comparison of alternatives important. For comparing health interventions, a *before and after* basis is often used for comparing mutually exclusive alternatives to enable an assumption that the opportunity costs of forgoing the existing intervention are *doing nothing* and negligible (Drummond & Jefferson, 1996). However, this is rarely, if ever, the status quo for water and sanitation interventions and makes the basis for comparison of alternative service provision models more uncertain (Hutton, 2001). For this reason, Julius (1979) asserted that, in principle, sanitation intervention should instead be compared to a *without-project scenario* to represent the local opportunity costs of existing service provision approaches. Sacristán et al. (2020) further clarify this principle by defining a *without-project reference case* as representing the most cost-effective situation that would have otherwise emerged without an intervention.

While it is more complex to define this without-project situation, it is important to ensure the integrity of an economic analysis that claims that '*no alternative use of resources consumed by a project would secure a lower societal cost*' (Squire & van der Tak, 1975). A comparison with a local cost-effective standard is essential for understanding the local resource implications arising from all possible options that may be selected. These include

supply-led interventions that enable access to additional resources and demand-led or behavioural approaches that distribute the benefits of existing resources more equitably (Beecher, 1996; Fane et al., 2003; Mitchell et al. 2007; Spuhler & Luthi, 2020; Willetts et al. 2010).

Defining a without-project case as the basis for comparison significantly impacts the outcomes of comparative economic analysis, but it is also subjective. This situation means scoping the *system boundaries* of an appraisal of sanitation alternatives should be conducted with a critical lens (Mitchell et al., 2007; Willetts et al., 2010). Historically, institutional preferences for conventional waterborne sewerage have led to default decisions about the costs and benefits that should be included or excluded from an analysis of sanitation interventions (Hutton, 2001). For instance, household investments and the costs of water for flushing or treating greywater have typically been excluded from least-cost analysis despite the greater relevance of these factors in LMICs (Danert & Hutton, 2020; Kalbermatten et al., 1980).

Willetts et al. (2010) advocate for an explicit justification of the *system boundaries* regarding a study's *people*, *time*, and *service* dimensions. The people dimension refers to a consistent definition of the population considered in a study, including their behaviours and values. The time dimension refers to the time horizon of a study and whether it appropriately accounts for how the life cycle costs of alternative interventions are sequenced over time (Fonseca et al., 2011). The service dimension refers to a consistent definition of which components of a sanitation service chain are being considered by a study. CWIS frameworks are purposive in shifting how system boundaries of a comparative economic analysis are defined so that safely managed service provision is universal and inclusive (Schrecongost et al., 2020). For instance, the *sanitation cityscape* framework Scott

et al. (2020) advocates for the *living environment* to be more explicitly included within the system boundaries of analysis, encompassing the diverse typologies of demand for services that exist within households (Danert & Hutton, 2020).

3.4.3 Selecting an appropriate comparative economic analysis methodology

Comparative economic methodologies for water and sanitation interventions are described as less developed than health interventions (Hutton, 2001). This contributes to there being scarce evidence of the economic efficiency of sanitation alternatives in cities of LMICs (Hutton & Chase, 2016; Hutton et al., 2014). Available data is framed at a global or regional level and is limited to a general conclusion that the economic benefits of urban sanitation outweigh the costs rather than informing decision-makers about how options might be optimised towards CWIS outcomes (Hutton et al., 2014; Hutton & Varughese, 2016; Perard, 2018). A broad range of methodological limitations exist that are specific to comparing the costs and outcomes of water and sanitation interventions at a municipal scale (Hutton, 2001).

Kalbermatten et al., (1982) assert that all comparative economic analysis methodologies are only partially satisfactory for comparing sanitation alternatives. A common approach is to make a *cost minimisation assumption* that the interventions being compared are mutually exclusive and provide equivalent service outcomes to justify the selection of the alternative with the lowest net present value (NPV) as the least-cost. However, as this assumption rarely manifests in practice, uncertainty prevails about any quantitative measure of cost-effectiveness arising from this assumption (Julius, 1979; Squire & van der Tak, 1975).

An implication of not applying this assumption is that it becomes necessary to monetise the benefits of sanitation alternatives to compare them either in (i) absolute

terms within a *cost-benefit analysis*, where tangible benefits are valued by a market or a proxy measure, or (ii) as a standard outcome measure to conduct a *cost-utility analysis*, where costs are defined in relation to a broadly-accepted proxy measure of benefit, such as disability-affected life years (DALYs). Benefit valuation is contentious and has been identified as a significant constraint to the comparative economic analysis of water and sanitation interventions (Hutton, 2001). Well-established methodologies applying these approaches report difficulties in accounting for all intangible and non-monetisable benefits and a lack of local data with which to model valuations at a resolution at a sub-national scale with integrity (Hutton & Chase, 2016; Hutton et al., 2014).

In response to these limitations, Kalbermatten et al. (1982) proposed a multi-method approach to the appraisal of sanitation alternatives, comprising (i) a comparable *cost-effectiveness analysis* of direct and tangible indirect costs, (ii) optimisation of each alternative aligned with the objective of the analysis; and (iii) a process enabling service users to make the final cost-benefit determination to deal with the intangible and non-monetisable impacts of alternatives. Willetts et al. (2013) extend the idea of service users making a final cost-benefit determination by framing deliberative sustainability criteria as an alternate means of dealing with externalities. This work could be further adapted to include households, particularly vulnerable users, in decisions in alignment with CWIS principles.

3.4.4 Generating context-specific effectiveness data

A significant difference between the comparative economic analysis of health interventions and water and sanitation interventions is that randomised controlled trials generate data for the latter, where it is less certain which drivers of change effectiveness data for water and sanitation represents (Hutton, 2001). A reliable, standardised methodology that produces robust, cost-effectiveness data is necessary to improve the capacity to make evidence-based

decisions about selecting least-cost urban sanitation configurations. However, the current focus of the literature is on increasing the volume of available financial unit cost data (Daudey, 2018) and standardising how it is reported to enable a meta-analysis of the costs of established urban sanitation interventions (Sainati et al., 2020). This approach applies broad-brush parametric estimation methods to develop *heuristics* or rules of thumb that may be used to support decisions about infrastructure decisions.

Higher quality and more robust effectiveness data are necessary if the cost determinants of complex mixtures of CWIS interventions are to be understood (Willetts et al., 2010) and a more appropriate basis for comparing interventions established (Hutton et al., 2014). Very few comparative economic analyses of urban sanitation interventions specify a context-specific, least-cost standard as a basis for generating and comparing cost-effectiveness data. This limitation impedes more detailed and flexible analyses that accommodate multiple perspectives and inform more context-specific decisions about CWIS interventions and the systemic causes of inequitable service provision (Willetts et al., 2010).

For this to occur, costing models that are capable of meaningfully representing the least-cost standard, or without-project case need to be developed. Such models require all existing service provision configurations to be defined so that their unit costs and quantities of resources consumed over time can be estimated at their current service level. While these data may or may not be available for formal service provision models from utilities or other service providers, conceptual models that meaningfully represent informal service provision will be required. Further, cost models should attempt to account for the heterogeneity of how services are provided. This will necessitate that the data collected about unit costs and resource consumption used to support a cost model be sampled in a way that holistically represents a citywide water and sanitation system.

Assumptions embedded within costing models associated with concept designs, bill of materials, household and community surveys, or resource flow models need to be made transparent (Ross et al., 2024). Cost-effectiveness models should be considered to be iterative, with built flexibility to test different scenarios over time, whereby significant shifts in the without-project situations are able to be accounted for to facilitate a more robust understanding of the diversity of cost determinants within the least-cost analysis. Multiple methods specific to a city and its heterogeneous contexts, including ongoing household and community surveys in situations where data collection cannot be automated, will be necessary to improve the inclusiveness, flexibility, and certainty of cost estimates (Hutton et al., 2014; Retamal et al., 2011).

3.4.5 Addressing limits to benefit valuation.

The selection of an outcome measure for least-cost analysis that compares the costs of sanitation alternatives with their outcomes is determined by the method of benefit valuation adopted. For example, *benefit-cost ratios* attempt to monetise the value of defined service provision outcomes by collecting empirical data about the price users are willing to pay (Julius, 1979). However, this economic value, especially in LMICs, can be an unreliable indicator of true value or resource costs to the economy due to uncertain social and environmental externalities (Squire & van der Tak, 1975). The *Kalbermatten model* proposes that the costs of projects should be adjusted by a range of shadow factors defined for a national economy. Governments often define shadow rates to account for contextual factors that cause financial variables, such as interest rates, the price of labour, or critical resources such as water, land, or energy, or exchange rates, to vary from their actual economic value (Squire & van der Tak, 1975).

When considering the heterogeneity, this approach is contentious and subject to various objections regarding its accuracy, rigour, impact, feasibility, and desirability. When proposed by Julius (1979), there was awareness of these limitations in accounting for the value of sanitation projects. The rationale for disregarding these concerns was that merely accounting for the variation was sufficient to counter induced biases within least-cost analysis methods and was preferable to doing nothing (Squire & van der Tak, 1975). However, when considering the heterogeneity of demand and the weakness of the market for sanitation services in cities of LMICs, the relevance of such an approach to municipal-level studies is questionable.

The same problems apply to all direct and indirect, or proxy methods, for valuing the benefits of urban sanitation projects based on willingness to pay for a service outcome, such as contingent valuation or hedonic pricing (Hanley & Spash, 1993; Hutton, 2001; Julius, 1979). Significant practical and theoretical constraints limit their use as a standard measure of benefits arising from water and sanitation interventions *at a project scale* (see (Hutton et al., 2014)). In particular, the intangible nature of benefits arising from sanitation, such as dignity, comfort, prestige, security, gender equality, household cleanliness, or aesthetics, is challenging to quantify comprehensively within a study (Ross et al., 2021). A single measure is unlikely to be representative or consistent across a population (Hutton, 2001). The partial nature of benefit valuation and its tendency to misrepresent the scale and distribution of benefits of sanitation limits its use in general decisions about allocating economic resources, at best, to a national scale. This limit applies to the *Economics of Sanitation Initiative* methods, which remains the most rigorous methodology for benefit valuation for urban sanitation (Hutton & Chase, 2016; Hutton et al., 2014).

For these reasons, outcome measures contingent on benefit valuation to any extent are less relevant to decisions about CWIS. Cost-effectiveness measures of total annualised cost per household (TACH) or per capita (TACC) basis are better suited to municipal-level studies (Julius, 1979; Kalbermatten et al., 1982; Sainati et al., 2020). In this case, benefits are defined for the NPV of providing an incremental unit of a service outcome (i.e., treating the next litre of wastewater or cubic metre of faecal sludge) at the scale of a household.

Focusing on a clearly defined service outcome enables a robust, quantifiable comparison of the tangible costs, including those that may be avoided, in a way that is clearly distinguished from intangible and non-monetisable outcomes (Beecher, 1996). This knowledge allows intangible costs to be recorded separately and analysed via broader qualitative decision-making processes such as multicriteria decision analysis or a deliberative sustainability assessment (Mitchell et al., 2007; Willetts et al., 2013).

3.4.6 Representing cost data appropriately

Comparing the costs of alternative sanitation projects involves collecting or estimating both unit costs and the quantities of resources used to supply services over the time horizon of an analysis. This task can be challenging in cities of LMICs, where reliable cost data for urban sanitation configurations can be scarce and difficult to project in the future (Daudey, 2018; Mills et al., 2020; Sainati et al., 2020). Gaps in knowledge related to the units, currency, or year costs were incurred, and other contextual factors are common. For new or innovative approaches to sanitation service provision, context-specific cost data may need to be derived via detailed design work, technology transfer processes, or the endogenous development of service configurations. For example, Willetts et al. (2010) and Retamal et al. (2011) provide a detailed account of how this may be achieved in an urban LMIC context.

Where sufficient data is available for a comparative economic analysis, it should be used to define incremental costs defined in TACH or TACC to help compare assets within a sanitation service configuration over their entire lifetime. An authentic comparison of alternative interventions requires these units to enable costs to be scaled and sequenced over a common time horizon. There can be significant differences in how the costs and benefits of interventions with different asset lives are incurred and benefits, or service outcomes, are realised (Hutton, 2001; Julius, 1979). For this reason, when comparing alternatives against a least-cost, standard, without-project case, life-cycle-cost analysis (LCCA) should be applied. Fonseca et al. (2011) provide a detailed account of an LCCA methodology, while the evaluation of Criterion 10.2 (see Table 2) by Ross et al. (2024b) provides examples of studies that have meaningfully applied LCCA.

LCCA helps to optimise the sustainability of options compared within an analysis by explicitly defining how the total costs of investment and ownership of assets are structured over their lifetime, measured as a net present value (NPV). LCCA enables the capacity to account for costs as they occur up to the time when the asset with the longest asset lifetime is replaced (Mitchell et al. 2007). While frameworks for characterising these costs have been promoted for water and sanitation interventions (see Fonseca et al. (2011)), they are yet to be universally adopted. Developing a benchmark for reporting life cycle costs would help improve the generalisability of cost data for CWIS interventions (Daudey, 2018; Sainati et al., 2020).

The approach by which costs are discounted over time is equally essential to applying LCCA. In practice, *annualised unit costs* are commonly reported for this purpose. This method spreads the *capital costs* of infrastructure linearly, on an annual basis, over its anticipated lifetime, before being combined with an estimate of annual operating costs and

then discounted (Fane et al., 2003; Fonseca et al., 2011). The problem with this measure is that it disproportionately favours centralised alternatives with high initial investment costs and excess capacity for planned growth. Conversely, demand-led options that are more adaptive to changing demand over time and are commonly used to provide CWIS outcomes are disadvantaged (Kalbermatten et al., 1980). The reason for this is that the benefits of matching a service's supply to the demand for that service are not accounted for with *annualised costs* (Fane et al., 2003). Examples of demand-led options include decentralised options that respond directly to specific gaps in service provision or programs that extend the use and purpose of existing infrastructure.

To counter this potential bias, the *Kalbermatten model* adopts *average incremental* or *levelised costs* (Fane et al., 2003). In this case, the sum of the NPV of all life cycle costs is divided by the sum of the present number of households serviced or the volume of water supplied (or wastewater treated) to provide that service (Julius, 1979; Willetts et al., 2010). Using an average incremental cost as the basis for discounting life cycle costs provides a more context-specific, future-oriented, and equivalent basis for comparing all possible options for providing the same service outcome (Fane et al., 2003).

3.4.7 Meaningfully modelling economic costs over time.

Drummond and Jefferson (1996) outline how models used within a comparative economic analysis extend the limits of what can be observed using empirical data. In the case of decisions about sanitation interventions, models are used to understand relationships between key determinants of resource consumption and the distribution of costs over time. Within many LMIC contexts, the quality of available data that may be used as input parameters for a model can be limited, fragmented in nature, and typically focused on

institutional forms of service provision, where material and financial flows are more likely to be monitored (Lawhon et al., 2017).

The integrity of future decisions about how sanitation alternatives are prioritised is shaped by the level of detail in which a model selected can represent the complexity of the interactions between different approaches to service provision. This extent depends on how effectively the *without-project case* of a comparative economic appraisal represents its context and the parameters that determine how the urban sanitation configurations will interact. An ideal model would represent this situation as it exists and include the influence of all relevant cost and subgroup perspectives in any forecast (Kohli-Lynch & Briggs, 2019; Lawhon et al., 2017; Mitchell et al., 2007).

Urban sanitation infrastructure configurations are complex systems because of the heterogeneous demands for service outcomes that emerge from a study population, arising from the diverse mix of interrelated approaches for supplying service outcomes of varying quality (Mitchell et al., 2007; Schrecongost et al., 2020; Willetts et al., 2010). Infrastructure configurations are layered with multiple and partial service provision approaches applied at different scales, comprising '*different coverage, technologies, operations, logics, and ownerships*' (Lawhon et al., 2017). Their integrated behaviour is inherently complex to forecast spatially and over time in a way that accounts for these differences.

The essential requirement for any model used within a comparative economic analysis is that the modelling method adopted is explicit and aligned with the objective of an appraisal. The assumptions used to extend available empirical data should fit the context in which the appraisal is conducted and be reported transparently (Drummond & Jefferson, 1996). Regarding CWIS interventions, decisions about the definition of system boundaries have uncertain implications. The potential impact of including and excluding perspectives,

preferences, and behaviours of different cost and subgroup perspectives at different scales can result in significant variation in how a *without-project case* is defined (Beecher, 1996; Mitchell et al., 2007; Retamal et al., 2011; Willetts et al., 2010).

A model might structure different infrastructures, cost, and subgroup perspectives within an urban sanitation configuration as part of different sub-systems within broader system boundaries (Narayanan et al., 2018). Systemic modelling approaches require a robust and flexible basis for building up projections of the behaviour of the without-project case and sanitation alternatives from disaggregated empirical data. End-use analysis and modelling approaches effectively represent incremental cost-effectiveness and have been applied successfully to this task (Mitchell et al., 2007) in cities of LMICs (Retamal et al., 2011). End-use models enable material flows to be shaped by the behaviour of different costs and subgroup perspectives. They enable assumptions about interactions between CWIS service provision models to be tested iteratively and made explicit to promote shared knowledge with which to inform decisions. The benefits and disadvantages of a range of other less robust modelling approaches applied to urban sanitation contexts in LMICs are discussed in Ross et al. (2024)

3.4.8 Adjusting for the timing of costs and benefits

Discounting the future costs and outcomes of water and sanitation interventions is more complicated than health interventions (Hutton, 2001; Squire & van der Tak, 1975). First, urban sanitation configurations comprise interdependent components with diverse asset lives. This variation means there is a trade-off necessary between including the life cycle costs of these components within the system boundaries of analysis and the certainty in which they can be estimated over an extended time horizon (Ilg et al., 2017). Second, discount rates that are appropriate to a household cost perspective are likely to be different

to those of investors in infrastructure, with the opportunity cost of capital being much lower for households (Fonseca et al., 2011). Historically, central governments set discount rates strategically at a national level and are rarely questioned within a comparative economic analysis at a municipal scale Hanley & Spash (1993). As such, a heterogeneity of cost perspectives concerning the discount rate is rarely, if ever, tested in sensitivity analyses (Ilg et al., 2017) for appraisals of urban sanitation interventions, and a greater focus testing a range of rates and then on justifying the choices made is required for CWIS interventions

3.4.9 Dealing with uncertainty

Drummond & Jefferson (1996) emphasise the importance of considering how decision-makers might interpret risk and uncertainty associated with the outcomes of a comparative economic analysis (Willetts et al., 2013). Risk and uncertainty perceptions are different. Both are associated with deciding about an unknown future consequence of a scenario. However, risks are associated with probabilities that may be known or measured. At the same time, uncertainty is related to aspects of a decision where the probability of a consequence cannot be known (Ilg et al., 2017). Urban sanitation configurations in LMICs have many uncertain cost determinants (Daudey, 2018; Mills et al., 2020), characterised by heterogeneity related to access to water resources, sanitation service provision models, experiences, and aspirations.

Because of this, the outcomes of urban sanitation interventions may not be known at a citywide scale, as they are inherently unpredictable, particularly over the time horizon adopted for comparative economic analysis. In existing practice, most studies focus on the *aleatoric* aspects of uncertainty that may explain what is known and unknown statistically, e.g. by specifying confidence intervals for empirically collected data or by conducting a

sensitivity analysis to test uncertain relationships between model parameters (Ilg et al., 2017). This type of uncertainty is accounted for in existing evaluative criteria.

However, this is different for *scenario uncertainty*, which relates to ambiguity about how a comparative economic analysis is designed. For example, decisions about the costs and outcomes included in a without-project case or the system boundaries of analysis. This type of uncertainty is *epistemic* and relates to whether the right questions are being asked to make all relevant knowledge available to inform a decision (Ilg et al., 2017). Epistemic uncertainty is not easily measurable, and efforts to manage it often result in decision-makers applying intuitive or subconscious reasoning derived from known past experiences (see Sclar et al., 2018). Decisions about the design of a study may draw on intangible social, cultural, or political biases to derive greater confidence in predicting an unknown future outcome.

A critical gap in the evaluative criteria for CWIS is the need to include more diverse knowledge of costs and outcomes in the without-project case or system boundaries used as a basis of comparison in a study. Deliberatively including the preferences, aspirations, and worldviews of people without formal access to land tenure or access to safely managed services and the cost perspectives of subgroups, including women and girls, in the design of a comparative economic analysis is well aligned with the principles of CWIS (Lüthi et al., 2020; Schrecongost et al., 2020). Including criteria prompting epistemic or scenario uncertainty is thus an essential addition to evaluative criteria (Willetts et al., 2013).

Studies should be explicit about how social equity and gender objectives are designed into planning processes and how this might lead to more inclusive outcomes. For instance, economic analysis models may be designed with the capacity to disaggregate the cost perspectives of subgroups representing differences in the social and behavioural

determinants of sanitation interventions, in addition to physical determinants (Lambe et al., 2020; Mitchell et al., 2007). Such an approach helps to make the assumptions and biases underpinning an analysis more explicit and mutually understood to transform how outcomes are interpreted.

3.4.10 Presenting results transparently

Hutton (2001) identified that few published economic evaluations had reported the economics of selecting alternative water and sanitation interventions comprehensively or satisfactorily, with implications on how decisions are shaped. Transparent reporting of the outcomes of a comparative economic analysis is indicated in three main ways. Firstly, aggregated results for the cost-effectiveness of different options should also be presented in a disaggregated format. Ideally, an analysis would be documented clearly, including details about how alternative interventions were selected for comparison and optimised and then how they may be interpreted from all key cost and subgroup perspectives (Kalbermatten et al., 1982). Transparent reporting also assists in determining how outcomes may be interpreted in other comparable contexts to support decisions beyond the scope of the objectives of the appraisal. Secondly, outcome measures should not be reported prescriptively or imply consensus about a least-cost outcome from a societal perspective. While outcome measures may help broadly rank interventions, decisions should consider whether outcomes have disproportionate impacts from different financial cost and subgroup perspectives (Kalbermatten et al., 1980). Ideally, economic outcome measures should be interpreted collaboratively, incorporating broader sustainability criteria representing intangible social, environmental, and political impacts not able to be included within an appraisal (Willettts et al., 2013). Thirdly, decision-makers should be made explicitly aware of any caveats arising from the design of a study. In addition, outcome measures

should only be validated by the results of other studies if similarity in the methods and the study context can be demonstrated (Drummond & Jefferson, 1996).

3.5 Conclusion

Compared to methodologies for the comparative economic analysis of health interventions, those for water and sanitation, and in particular urban sanitation interventions, remain underdeveloped. This scoping review considers evidence about how least-cost economic principles may address identified gaps in evaluative criteria intended for health interventions to make them more fit-for-purpose for urban sanitation interventions in LMICs.

The results of this scoping review are intended to clarify and provide insights into how least-cost analysis methodologies might better reflect CWIS principles, including (i) the inclusion of diverse cost perspectives, particularly those with marginalised access to the benefits of urban sanitation investments in prioritising urban sanitation interventions (ii) the representation of the existing *without-project case* across an entire citywide sanitation service chain as the basis of comparison; (iii) distinguishing tangible and intangible economic costs and outcomes and integrating both into sanitation planning frameworks; and (iv) the projection of costs and outcomes of mixtures of formal and grassroots sanitation service provision models into the future in a disaggregated form so context-specific impacts of decisions about urban sanitation interventions are more visible.

The resulting evaluative criteria are not claimed to be consensus-based. The review scopes comprehensive, up to date, least-cost economic principles to enhance the application of comparative economic methodologies to CWIS interventions in practice. We recommend that researchers and practitioners further review and iterate these criteria. For instance, the criteria may be applied as a charting tool in a systematic literature review to

highlight gaps in existing best practices for the least-cost analysis of urban sanitation interventions and provide more specific guidance on how these principles may be applied in practice.

Data availability statement

All relevant data are included in the paper or supplementary material.

Conflict of interest

The authors certify that none of the authors are affiliated with or involved with any organisation or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this paper.

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Chapter Four: Comparative economic analysis of (integrated) urban sanitation interventions in low- and middle-income countries: a systematic review

4.1 Overview

Chapter Four compiles the second knowledge output arising from *Wave One* of action-oriented learning within the *transdisciplinary case study* (see *Figure 3*). Like the scoping review in *Chapter Three*, it contributes to the first *transdisciplinary outcome space* of a *tangible improvement in a real-world problematical situation*. While the systematic review presented here is global in scope, analysing 22 unique methodologies comparing integrated urban sanitation interventions employed across 44 cities in 23 countries, it is driven by a *societal concern* grounded by experiences in secondary cities of Cambodia, where there are persistent water and sanitation service outcome inequalities (Ross, 2018). This societal challenge was linked to an academic motivation of addressing the limited application of *least-cost* and *integrated resource planning principles* in real world planning decisions. These principles were conceptualised as *boundary objects*, while the complex nature of service provision in these contexts was framed as an *epistemic object*: namely, *heterogeneous service provision configurations* (Jaglin, 2014; Lawhon et al., 2017). Thinking through these constructs guided the research design and shaped the objective to supporting a transition toward more equitable and cost-effective urban water and sanitation interventions (see *Sections 1.2 and 2.2.1* for further discussion).

The systematic review compiled in this chapter and published in the *Journal of Water Sanitation and Hygiene for Development* directly responds to *Research Question #1b* (Ross et al., 2024b). It explores the extent to which the evaluative criteria for comparative economic analysis proposed in *Chapter Three* have been reflected in existing real-world

studies comparing urban sanitation interventions that are integrated with water supply and wastewater drainage services, and more critically, what gaps remain. By focusing on the Cambodian context, while reviewing the global literature, this chapter informs the design of planning tools that are responsive to the practical needs of decision-makers in LMICs.

The review also draws on literature highlighting the dearth of context-specific cost data for municipal scale service provision models (Daudey, 2018; Hutton, 2013; Hutton & Chase, 2016). This lack of data results in some service configurations poorly understood, or excluded from consideration in formal decision making processes. This is particularly true for configurations that respond directly to user demand for services, and are sensitive to local cost determinants (Danert & Hutton, 2020; Hutton et al., 2014). This invisibility reinforces the fragmentation of service provision in urban contexts in heterogeneous urban environments, limiting effective planning at a scale where it is most needed (Hutton & Chase, 2016; Lawhon et al., 2017; Lüthi et al., 2020; van Welie et al., 2018).

This chapter makes three key contributions: (i) it identifies opportunities to strengthen decision support processes by addressing methodological gaps that limit recognition of diverse urban water and sanitation needs in LMICs; (ii) it highlights the value of conducting studies that respond to real-world contexts to improve comparative economic analysis practices, beyond heuristic approaches that are less context-specific (Sainati et al., 2020); and (iii) it encourages more inclusive and context-aware planning, recognising that the drive for efficient decisions needs to be balanced with properly addressing local complexities and the diversity of perspectives that influence municipal planning decisions (Lüthi et al., 2020). At the time of thesis submission, the publication had been viewed ~1,300 times and downloaded by ~230 unique readers from doi.org/10.2166/washdev.2024.313, showing interest in this research output and its practical relevance.

Publication: Comparative economic analysis of urban sanitation interventions in low- and middle-income countries: a systematic review

This journal article is included in this thesis as the *peer-reviewed manuscript accepted for publication* by the *Journal of Water Sanitation and Hygiene for Development* on the 13th of August 2024, with edits in the typesetting process included. This version has been compiled in the thesis to enable plagiarism checking software to be applied and to facilitate a transparent overall word count for the thesis. To aid navigation of the thesis, the headings, figures, and tables of this publication have been embedded within the structure of the overall thesis and are not in the same format as the published version. The final version article is published under an open access agreement and is available for free download by accessing the link doi.org/10.2166/washdev.2024.313.

Journal of Water, Sanitation and Hygiene for Development
**Comparative economic analysis of urban sanitation interventions in low- and middle-
income countries: a systematic review**
--Manuscript Draft--

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Comparative economic analysis of urban sanitation interventions in low- and middle-income countries: a systematic review

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Abstract

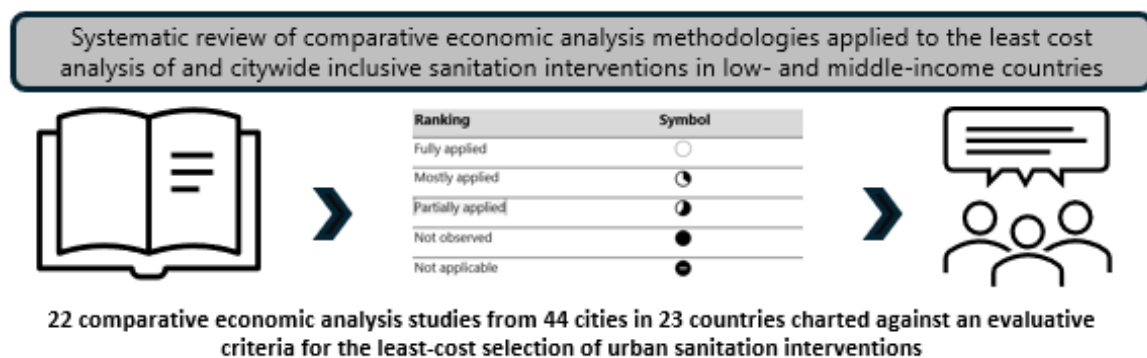
This review assesses evaluative criteria for least-cost economic analyses of citywide inclusive sanitation (CWIS) interventions, focusing on their alignment with the practical needs for decision support in low- and middle-income countries. We examined literature from 2003 to 2022 that compares costs and benefits of urban sanitation interventions to analyse their capacity to select cost-efficient and equitable urban sanitation options. The analysis reveals that finer disaggregation of cost perspectives could better articulate the diverse demands for services. Furthermore, options for comparison should be framed in addition to the diverse service provision models already existing within a context to ensure these perspectives are included. Developing the capacity to forecast a context-specific without-project scenario, using locally derived cost data as a basis of comparison will be essential for adhering to CWIS planning principles. Additionally, involving marginalized users more effectively in decision-making processes within economic analyses is essential for advancing equitable service provision. The resulting evaluative criteria define principles that may inform future reviews of methods aimed at enhancing CWIS planning frameworks.

Keywords: cost analysis; cost-effectiveness; economic principles; social equity; sustainability

Highlights

- Related literature studies are collated on the comparative economic analysis of urban sanitation interventions.
- Gaps in existing practices were appraised when applied to heterogeneous urban sanitation configurations in low- and middle-income countries.
- This study highlights how economic principles may be used to adapt methods for prioritising the selection of citywide inclusive sanitation interventions.
- Assumptions within existing planning approaches are challenged and what this means for best practice is discussed.

Graphical abstract



4.2 Introduction

Sustainable Development Goal (SDG) Target 6.2 aims to achieve access to adequate and equitable sanitation and hygiene for all and end open defecation by 2030. It also pays particular attention to the needs of women, girls, and vulnerable populations (United Nations, 2015). Achieving SDG Target 6.2 requires cost-effective decisions about sanitation investments. Estimated annual investments range from \$6.1 to \$22.6 billion for basic services and \$26.1 to \$72.7 billion for safely managed services in LMICs from 2020 to 2030 (Hutton & Varughese, 2016). Requirements for urban sanitation

financing are increasing and are estimated to be double that needed for rural areas until 2030 (WHO & UNICEF, 2021). Fifty percent of urban investments will need to target low-cost services for the two poorest quintiles of populations in LMICs (Hutton & Varughese, 2016). The scale of these investment decisions is immense. The supply rate of basic sanitation services must double by 2030. For safely managed services, it needs to quadruple to meet SDG 6.2 (UN Water, 2021).

At present, cost-effectiveness data for sanitation options in LMICs are limited to order-of-magnitude estimates (Hutton, 2013). Such data are insufficient for making municipal-level decisions about urban sanitation standards (Hutton & Chase, 2016). Inclusive selection of least-cost sanitation options and standards must account for the heterogeneity of cost determinants in LMICs. These include population density, topography, existing service models, socio-demographic profiles, and household practices and behaviors (Daudey, 2018). Existing data only partially reflects user experiences (Hutton et al., 2014). Evidence-based decisions often overlook unknown costs associated with informal service provision in LMIC cities. This includes services not provided by utilities, especially self-supplied systems (Danert & Hutton, 2020). This limitation leads to fragmented service outcomes, unevenly distributing investment benefits (Lawhon et al., 2017; Luthi et al., 2020). Such outcomes are challenging to characterize (Hutton & Chase, 2016; van Welie et al., 2018).

Current best practices use a heuristic model to simplify comparing urban sanitation options at the municipal level (Sainati et al., 2020). However, the assumptions facilitating comparisons in LMIC cities are limited. These include: (i) using existing service provision models to characterize infrastructure configurations, (ii) assuming the outcomes of these models are acceptable and equivalent, (iii) that life cycle costs can be reported in a

standardized format, and (iv) that equitable decisions can arise from a single cost perspective. Such assumptions are limited in their capacity to account for the complexities within urban sanitation contexts in LMICs. These assumptions aligned with a generalised comparison of the feasibility of existing alternatives (Sainati et al., 2020), rather than fully embodying CWIS principles (Luthi et al., 2020).

Complementary approaches are needed to address the complex urban contexts in LMICs, where diverse service provision models coexist (Lawhon et al., 2017; van Welie et al., 2018). Deliberating trade-offs between multiple competing priorities for CWIS interventions is also necessary in these situations (Luthi et al., 2020). It is important to clarifying how heuristic rules of thumb about selecting sanitation options is integrated with detailed analytical decision support to address issues in complex, evolving local systems (Lawhon et al., 2017; van Welie et al., 2018). Such integration is vital for comparative economic analysis to foster a transition to more inclusive outcomes (Sainati et al., 2020). Therefore, it is important to discuss how effectively comparative economic analysis studies embody CWIS principles.

Recently, evaluative criteria aimed at enhancing the quality of least-cost economic analyses of CWIS interventions were devised from a scoping review (Ross et al., under review). This paper applies these criteria as a charting tool within a *systematic review* (Khalil & Tricco, 2022). It appraises the methods used to design, implement, analyse, and interpret comparative economic analysis studies for urban sanitation configurations within LMICs over the past 20 years. The insights from this review will shape fit-for-purpose methodologies that complement more generalised comparisons and work towards achieving CWIS principles. Specifically, the review emphasizes the need to: enable diverse mixtures of interventions at different scales to be compared; represent the complexity of

the existing context as a basis for comparison; enable both tangible and intangible determinants of life cycle costs and benefits to inform decisions; and accommodate diverse cost perspectives within decisions, particularly for those with marginal access to sanitation services (Luthi et al., 2020).

4.3 Methodology

This paper adheres to PRISMA guidelines (Page et al., 2021), as outlined in *Figure 6*.

4.3.1 Eligibility Criteria

The review builds on previous work that examined the costs of urban sanitation interventions in LMICs (Daudey, 2018). This earlier work highlighted the scarcity of relevant lifecycle cost data with equivalent objectives, timeframes, and scales of analysis (Whittington et al., 2012). The eligibility criteria structured using the participant, comparator, intervention, outcome (PICO) format (Khalil & Tricco, 2022). We defined the participant as the economic analysis methodologies, and the intervention as comparing cost-effectiveness data for urban sanitation options in LMIC cities. The comparator was the evaluative criteria from Ross et al. (under review), and the outcome focused on how well the methodologies embodied CWIS principles.

4.3.2 Information sources and search strategy

We defined search terms to identify and expand on comparative cost analysis studies identified by Daudey (2018) that aligned with our criteria. We searched the *Scopus* database, using combinations of the search terms 'urban', 'sanitation', 'cost*', 'economic', 'financial', 'appraisal', and 'method*' to find English-language literature from 2003 to 2022. Broader terms resulted in many irrelevant results, so we refined our terms to 'sanitation', 'cost*', and 'method*', yielding 1,365 records.

4.3.3 Screening

We scanned the titles and abstracts of 1,365 records, yielding 200 results. Of these, 17 were inaccessible or not in English. After reviewing 183 reports, 17 were found to have met the criteria.

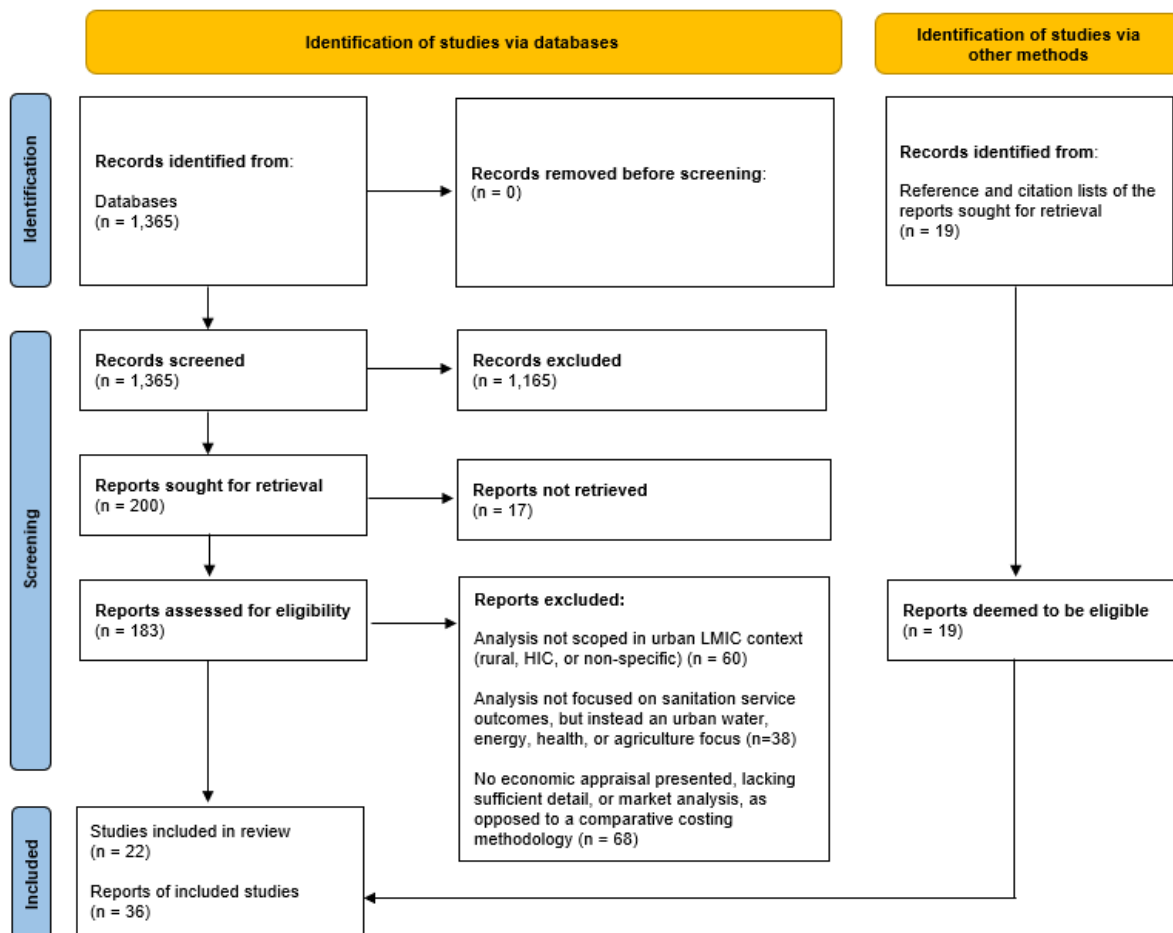


Figure 6: PRISMA flowchart (Page et al., 2021) for the systematic review of comparative economic analysis studies applied to urban sanitation intervention

Studies were excluded for several reasons. Some focused on high-income countries or rural contexts (n=60). Others had objectives not aligned with sanitation outcomes (n=38) or lacked detailed economic analyses (n=68). We included 19 additional studies identified via reference and citation lists of the 183 retrieved studies.

4.3.4 Evaluation

We conducted a detailed review of each study (see *Table 3*) using evaluative criteria from a previous scoping review (Ross et al., 2024a). Refer to *Table 4* and *Table C1* in the Appendix for details. We ranked criteria responses on a four-point scale: fully applied, mostly applied, partially applied, and not present, considering the study context, methodology, and supplementary material without seeking additional author insights. No attempt was made to weigh each criterion or evaluate the overall quality of each study retrospectively.

4.4 Results

Our search strategy and screening method identified 36 diverse and comprehensive range of economic analysis methodologies. These papers encompass 22 different economic appraisal methodologies for urban sanitation interventions. They span 44 cities across 23 countries, covering developments over the past 20 years.

Table 3: Summary of included literature

Study	Methodology and study location	Cost perspective(s)	Outcome measure(s)
Meddings et al. (2004)	Economic CEA for a latrine construction and rehabilitation program (Kabul, Afghanistan)	Societal (disaggregated by NGO perspective)	Costs per death averted
Dahiya et al. (2006)	Financial cost comparison of HH hygiene improvement and traditional vs ventilated pit latrine options (Ulaanbaatar, Mongolia)	HH	Costs per household
von Münch & Mayumbelo (2007)	Financial CEA of a VIP latrine vs UDDT option (Lusaka, Zambia)	HH and utility	TACC, 10-year NPV
Prihandrijanti et al. (2008)	Economic CBA of two decentralised options vs a simplified sewer option (Surabaya, Indonesia)	Societal (defined by an institution)	B-C ratio, 20-year NPV
Kerstens et al. (2009)	Financial cost comparison of four innovative, resource-oriented sanitation alternatives for a greenfield site (Changzhou, China)	Institutional	20-year NPV
Schuen & Parkinson (2009)	Financial and economic cost comparison of UDDT vs VIP & centralised sewerage options (Kabala, Uganda; eThekweni, South Africa; & Ouagadougou, Burkina Faso)	Societal (disaggregated by low & high-income HHs and projects)	10-year NPV
Willets et al. (2010); Retamal et al. (2011); & Willets et al. (2013)	Financial CEA for four hybrid (centralised and decentralised component) options (Can Tho, Vietnam)	HH, Utility, Developer & Gov't	30-year NPV, TACV, TACH
Hutton et al. (2014)	Economic CBA, CUA, and CEA for sanitation options in 17 urban contexts in Cambodia, Indonesia, Laos PDR, the Philippines, Vietnam, and Yunnan, China.	Societal (disaggregated by HH income levels, gov't, private sector)	B-C ratios, Cost per DALY, case, death, 20-25-year NPV & TACH
Dodane et al. (2012)	Financial CEA for a sewer-based and FSM system within the same geographical area (Dakar, Senegal)	HH, service provider, Utility & Gov't	TACC
Mburu et al. (2013)	Financial CEA for a WSP and constructed wetland (Juja, Kenya)	Institutional	TACPE
Peal (2013)	Financial CEA for four hybrid CWIS scenarios (Dhaka, Bangladesh)	Institutional; and low & non-low-income HHs	30-year NPV & TMCH
Tilmans et al. (2015)	Financial CEA for a public ecosan latrine and CBS option (Cap Haitien, Haiti)	Institutional (NGO)	Total cost per kg of faeces per 13 weeks.

Ketema et al. (2015); Ketema and Langergraber (2015; 2016)	Financial CEA for four diverse, hypothetical urban sanitation interventions, defined by cost functions (Arba Minch & Bahir Dar, Ethiopia)	Societal (User, service provider, and externalities)	25-year NPV
Kennedy-Walker et al. (2016)	Financial CEA for seven FSM transportation and treatment configurations (Lusaka, Zambia)	Utility/community water trust	TMCH & 25-year NPV
Ross et al. (2016)	Economic CUA and Financial CEA for four hypothetical low-cost off-site urban sanitation configurations (Dhaka, Bangladesh)	Societal (low-income HHS and institutional)	Cost per death & illness & DALY averted; TACH
Jung et al. (2018)	Financial cost comparison of centralised vs decentralised WWM systems (Alibag, India)	Fixed and floating HHS, Institutional	30-year NPV
Shi et al. (2018)	Economic cost comparison of four resource-oriented public toilet options (Beijing, China)	Societal (institutional & environment)	20-year NPV
McConville et al. (2019)	Financial CEA sewer and FSM service regimes. (Kampala, Uganda)	HH, utility, informal businesses	TACC
Furlong et al. (2020)	Financial CEA of four hybrid urban sanitation FFM (Pokhara, Nepal)	Various (dependent on FFM)	30-year NPV
Manga et al. (2020)	Financial & economic CEA of three simplified sewer scenarios, with VIP and UDDT options (Soweto, South Africa)	HH & Institutional (all costs attributed to HHS)	TACH, TACC, & 25-year NPV
Delaire et al. (2020)	Economic cost comparison for options meeting SDG 6.2 targets by 2030 and the economic value users are willing to pay (Kisumu, Nakuru, & Malindi, Kenya; Rangpur, Bangladesh; & Kumasi, Ghana)	Societal (low-income HHS and service providers)	10-year NPV
Carrard et al. (2021)	Financial CEA of resource-oriented sanitation option (Balangoda, Sri Lanka)	HHS; local authorities; & Gov't	10-year NPV & TACC

Legend: CBA = cost-benefit analysis; CEA = cost-effectiveness analysis; CUA = cost-utility analysis; FFM = financial flow model; FSM = faecal sludge management; VIP = ventilated improved pit latrine; UDDT = urine dry diverting toilet; CBS = container-based sanitation; HH = household; NPV = net present value; DALY = disability affected life-year; B-C ratio = benefit-cost ratio; TACH = total annual cost per household; TMCH = total monthly cost per household; TACC = total annual cost per capita; TACPE = total annual cost per person equivalent; WSP = waste stabilisation pond; WWM = wastewater management.

Table 4: Abridged evaluative criteria (Ross et al., 2024a) and analysis of the included literature

Criteria	1.1	1.2	2.1	2.2	3.1	4.1	4.2	5.1	5.2	5.3	6.1	6.2	7.1	8.1	9.1	9.2	9.3	10.1	10.2	10.3	
1.1 A research question balances economic efficiency and equity outcomes																					
1.2 A societal cost perspective is disaggregated by subgroup perspectives.																					
2.1 Options are compared against a least-cost <i>without-project standard</i>																					
2.2 Consistent and appropriate system boundaries are applied																					
3.1 A comprehensive economic analysis methodology is adopted																					
4.1 The source of effectiveness data is specific to the study context.																					
4.2 A justification for comparisons of cost effectiveness across different contexts is provided																					
5.1 An incremental analysis in units of TACH/TACC is presented as a primary outcome measure.																					
5.2 Benefit valuation methods are described and justified for the study population.																					
5.3 Intangible benefits are reported separately and interpreted within the analysis.																					
6.1 Average incremental costing is used to structure life cycle costs over time.																					
6.2 Adjustments for inflation and currency conversion are made explicit.																					
7.1 Assumptions within the costing model are justified and contextually relevant.																					
8.1 The time horizon and discount rate applied are stated and justified.																					
9.1 Confidence intervals are presented for stochastic data.																					
9.2 Sensitivity and scenario analyses are used to enhance the use of modelled data.																					
9.3 Deliberative methods are used to allow for epistemic uncertainty.																					
10.1 Reported outcome measures (TACH/TACC) align with the basis of comparison.																					
10.2 Outcome measures are presented in an aggregated and disaggregated format.																					
10.3 Conclusions arise from multiple cost perspectives informed by multiple criteria.																					
Legend	Fully applied	Mostly applied				Partially applied				Not observed				Not applicable							
Study / Criteria	1.1	1.2	2.1	2.2	3.1	4.1	4.2	5.1	5.2	5.3	6.1	6.2	7.1	8.1	9.1	9.2	9.3	10.1	10.2	10.3	
Meddings et al. (2004)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Dahiya et al. (2006)	●	●	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	●	●	☐	☐	☐	☐	☐
von Münch & Mayumbelo (2007)	●	☐	●	☐	☐	☐	☐	☐	☐	●	☐	☐	☐	☐	●	●	●	☐	☐	☐	●
Prihandrijanti et al. (2008)	☐	●	●	☐	☐	☐	☐	●	☐	☐	☐	☐	☐	☐	●	☐	●	●	●	☐	●

Kerstens et al. (2009)	●	●	◐	●	◐	◑	◐	●	●	◑	◐	●	◐	○	●	○	●	●	◐	●	
Schuen & Parkinson (2009)	◑	◑	●	●	◐	◐	◐	●	◐	◐	◐	○	◐	◑	●	○	●	●	◐	◐	
Willettts et al. (2010 ; 2013) ; Retamal et al. (2011)	○	◑	◑	○	◑	○	◐	○	◐	○	○	○	○	○	○	●	◑	◑	◑	◐	◑
Hutton et al. (2014)	○	○	◑	◐	◐	◑	◑	○	◑	◐	○	◐	○	○	●	○	●	◐	○	○	
Dodane et al. (2012)	●	◑	●	◑	◐	◑	◐	◑	◐	◑	○	◐	○	○	●	◐	◐	◐	○	◐	
Mburu et al. (2013)	●	●	●	◑	◐	◑	◐	◐	◐	●	◐	●	◑	●	●	●	◐	◐	◐	●	
Peal (2013)	●	◑	●	○	◐	◑	◐	◑	◐	●	◐	○	◑	○	●	◑	◐	◐	◐	◑	
Tilmans et al. (2015)	●	◐	◐	◐	◐	◑	◐	◐	◐	●	●	◑	◐	◐	◐	●	●	◐	◐	◐	
Ketema et al. (2015)	●	●	●	◑	◐	◑	●	●	◐	●	●	○	◐	◑	●	◑	●	●	◐	●	
Kennedy-Walker et al. (2016)	●	●	◑	○	◐	◑	◐	○	◐	●	○	◐	◐	○	●	○	●	○	◐	●	
Ross et al. (2016);	◐	◑	●	◐	◐	◐	◐	◑	◐	◑	●	○	◐	●	●	●	◐	◐	◑	◐	
Jung et al. (2018)	●	●	●	◐	◐	○	◐	●	◐	●	●	○	◑	○	○	○	●	●	◐	●	
Shi et al. (2018)	◐	●	◐	◑	◐	◑	◐	●	◐	◑	◐	○	◑	○	●	◑	●	●	◐	●	
McConville et al. (2019)	●	◑	●	●	◐	◑	◐	◑	◐	●	●	◐	◐	○	●	◑	◐	◐	○	◐	
Furlong et al. (2020)	●	◐	◑	○	◑	◑	◐	●	◐	●	●	◐	◐	○	●	◑	◐	●	◑	◑	
Manga et al. (2020)	◐	●	●	◑	◐	○	◐	○	◐	○	○	◑	○	○	●	○	●	◐	◐	●	
Delaire et al. (2020)	◑	◑	◑	○	◑	○	●	●	◑	◑	◐	○	◐	○	◐	○	◐	●	○	◑	
Carrard et al. (2021)	●	◐	◑	◑	◐	○	◑	◑	◐	◐	◑	○	◐	◑	◐	◐	◐	◑	○	◑	

Note: These criteria are presented in full in Ross *et al.* (under review) and Table D1 in the Appendix.

4.5 Discussion

In this section, we analyse the extent to which each study's methodology responds to each evaluative criterion for CWIS interventions.

4.5.1 Study Design

4.5.1.1 A research question balances economic efficiency and equity outcomes.

Criterion 1.1 assesses whether the methodology balances the selection of the most economically efficient option with the equitable distribution of financial costs and benefits of that option. *Table 4* demonstrates that three studies *partially apply* this criterion. These methodologies adjusting each option's net financial costs to partially account for their net economic costs. For example, [Manga et al. \(2020\)](#) calculate the economic value of options using shadow pricing for capital, land, and water. [Prihandrijanti et al. \(2008\)](#) and [Ross et al. \(2016\)](#) consider *averted health costs*, i.e. costs no longer incurred because of a sanitation intervention, in their analysis. [Shi et al. \(2018\)](#) trade off the financial value of different interventions against a measure of their environmental impact. However, these studies are limited as they only consider how cost are perceived from a single institutional perspective, not how they are distribution.

Studies that *mostly apply* this criterion analyse the economic efficiency of each option, and how each option distributes financial costs and benefits to different parties. For example, [Meddings et al. \(2004\)](#) and [Schuen & Parkinson \(2009\)](#) consider the benefits of reducing child mortality and the net economic per capita costs of providing sanitation services in Africa, respectively. They also analysing how the financial costs of each option are distributed to a project, and household perspective. Similarly, [Delaire et al. \(2020\)](#) compare the economic efficiency by which different options may achieve adequate citywide, safely managed urban sanitation by 2030. Then they use a *willingness-to-pay*

survey to analyse how users and government subsidies may cover the financial costs of each option.

Studies that *fully apply* this criterion analyse how the financial costs of an economically preferred option are perceived by subgroups, such as women, girls, or those living in informal settlements. For example, the *Economics of Sanitation Initiative* (ESI) in Southeast Asia (Hutton *et al.*, 2014) comprehensively measure the economic efficiency of different options. Then determines how the financial costs of these interventions are distributed to households from different income quintiles. Willetts *et al.* (2010; 2013) demonstrate an alternative approach to fully applying this criterion by integrating a financial cost benefit analysis for different options into a deliberative economic appraisal. In this case, options are prioritised based on broader economic criteria, including financial and non-financial costs and benefits. Both studies respond effectively to CWIS principles (Lüthi *et al.*, 2020) by explicitly accounting for the distribution of costs to marginal groups.

4.5.1.2 A societal cost perspective is disaggregated by subgroup perspectives.

Criterion 1.2 complements Criterion 1.1 and assesses whether a study adopts a *societal cost perspective* that includes all relevant costs, irrespective of who incurs them. This perspective helps to consider whether the measure of economic efficiency used to prioritise options is comprehensive, which is key to defining a *least-cost-to-society* ranking. An example of a study that *fully applies* this criterion is Hutton *et al.* (2014). They account for the tangible and intangible economic costs and benefits of various options, from multiple financial cost and subgroup perspectives. However, although the net costs were derived from municipal data, they aimed for national comparisons, making the data less context-specific than in other studies.

Studies that *mostly apply* the criterion limit the scope of a societal cost perspective. The scope may be limited to particular urban areas. For example, [Ross et al. \(2016\)](#) and [Delaire et al. \(2020\)](#) compared the economic efficiency of options for a 'slum' and 'low-income' context, respectively. However, this analysis is also limited to this cost perspective, so financial trade-offs with other parties in an urban population cannot be considered. An alternative method limits the societal cost perspective by focusing solely on financial efficiency. This approach assumes that economic outcomes for each option are equivalent. For example, [Peal & Georges \(2013\)](#) and [Willetts et al. \(2010\)](#) compare hybrid mixtures of sanitation interventions aimed at providing services to all cost perspectives within a specific population. These approaches required detailed forecasting of each option's financial costs and benefits to test assumptions over the time horizon of each study. Another method of applying this assumption is to divide an urban area into different *service regimes* ([van Welie et al., 2018](#)), or characteristic service provision models. Thus, enabling different cost perspectives to be disaggregated from a broader societal cost lens. Proponents assume that *service regime* that exists in the same geographical area will have the same economic determinants of costs justifying a financial comparison. Both [Dodane et al. \(2012\)](#) and [McConville et al. \(2019\)](#) apply this approach. However, in both examples, it is unlikely that costs are spatially or temporally homogeneous across the study context. This variability limits how meaningful a financial comparison is in practice. This limitation persists even where [McConville et al. \(2019\)](#) attempts to optimise the comparison by scaling options to full capacity. Cost determinants in this case are unlikely to be consistent even within the same service regime. [Carrard et al. \(2021\)](#) further demonstrate how even the boundaries of a single service configuration are challenging to define in terms of geography or population.

Studies that best apply Criterion 1.2 are those that balance the inclusion of all costs to society and how meaningfully they can be disaggregated and analysed (Lüthi et al., 2020). The examples above illustrate how challenging accounting for heterogeneity within the context of studies of CWIS options can be.

4.5.1.3 Options are compared against a least-cost, without-project standard.

Criterion 2.1 evaluates whether urban sanitation options are compared against meaningful and realistic without-project standards. These standards represent cost-effective situations that would likely occur without any intervention, according to the context of the study. To facilitate compelling decisions, options should be defined in addition to this standard (Willetts et al., 2010). Each option should be mutually exclusive, meaning selecting one precludes the selection of others. *Table 4* indicates that no studies *fully apply* Criterion 2.1. This result reflects the challenges discussed in response to Criterion 1.2 of framing an objective and meaningful basis of comparison.

To illustrate these challenges, we consider Willetts et al. (2010). They *mostly apply* this criterion by systematically defining a *reference case* using an *end-use model* (see Criterion 7.1) (Retamal et al., 2011). They compare costed sanitation service provision scenarios based on detailed concept designs aligned with local policies for new greenfield developments. However, they neglected to include the cost perspectives of existing urban users. This omission makes it less certain whether a least-cost without-project standard (see *Criterion 1.2*) was fully defined. The local status quo likely included a mix of informal service provision, as well as plans for developing conventional centralized services. This definition is crucial because it affects the inclusivity and relevance of the options compared in the analysis. When faced with the challenges of collecting data to represent a least-cost *without-project standard* (see Criterion 2.1), many studies define a *do-nothing scenario*. This

assumes that the existing context remains the same over time. The difference in these definitions is nuanced but significant. Defining a do-nothing scenario excludes the opportunity costs of forgoing existing practices from consideration.

Other studies that *mostly apply* Criterion 2.1 comprise various attempts to define a meaningful without-project context. For instance, [Kennedy-Walker et al. \(2016\)](#) compare various modeled scenarios of faecal sludge collection and transportation to results from an existing pilot study. [Dahiya et al. \(2006\)](#) and [Hutton et al. \(2014\)](#) compare iterative improvements in sanitation service levels against a sanitation service ladder. [Delaire et al. \(2020\)](#) define investments that would have been made by households and institutions *without a project*, based on results from a willingness-to-pay survey. [Furlong et al. \(2020\)](#) attempt to contextualise *financial flow models* validated in a comparable city. At the same time, [Carrard et al. \(2021\)](#) define a without-project case without comparing it to alternative interventions. Any approach may introduce subjective biases, making a critical evaluation of whether a meaningful basis of comparison has been selected as necessary (see Criterion 9.3).

4.5.1.4 Consistent and appropriate system boundaries are applied.

Criterion 2.2 assesses whether the system boundary of comparative economic analysis is clearly defined and consistently applied ([Willettts et al., 2010](#)). This idea aligns with the standard, generalisable system boundary proposed by [Sainati et al. \(2020\)](#) for comparing unit costs across different urban sanitation contexts. This system boundary specifies the cost perspectives (Criterion 1.2), life cycle cost components (Criterion 6.1), and components of a sanitation service chain (Criterion 7.1) relevant to an analysis.

Some studies that *fully apply* Criterion 2,2 like [Peal and Georges \(2013\)](#), [Delaire et al. \(2020\)](#), and [Furlong et al. \(2020\)](#) adopt comprehensive system boundaries. Others, like i.e.

Kennedy-Walker et al. (2016) may adopt more discrete boundaries specific to a context, such as the collection and treatment of faecal waste for low-income users. Carrard et al. (2021) demonstrate that system maps are valuable for visually depicting the costs and benefits within a system boundary, as well as external factors that might influence a study's results.

4.5.1.5 A comprehensive economic analysis methodology is adopted.

Criterion 3.1 evaluates a study's adherence to three required elements of a comparative economic appraisal. These include conducting a cost-effectiveness analysis, optimizing each alternative towards a defined service outcome, and engaging end users in the final cost-benefit determination. All studies meeting the review's eligibility criteria fulfill the first two requirements of Criterion 3.1. Therefore, our analysis focuses on how effectively studies engage end users in decision-making processes. Based on this criterion, only the study by Dahiya et al. (2006) fully applied Criterion 3.1. They adopted an informed choice approach, enabling service users to trade off perceived benefits of various household containment options against their financial cost.

Other studies *mostly apply* Criterion 3.1 by demonstrating methods that engage institutions in a decision using approaches that may also be used to engage service users. For example, Furlong et al. (2020) conducted workshops with local service providers to contextualise how different *financial flow models* may accurately represent the study context. Willetts et al. (2013) engaged local authorities in deliberating a least-cost option. Delaire et al. (2020) indirectly engaged low-income households in a least-cost determination via a willingness-to-pay survey. Studies fully meeting this criterion should consider how these approaches engage service users in decision-making. Such engagement builds demand for safely managed sanitation, aligning with CWIS principles (see Criterion 10.3).

4.5.2 Data collection

4.5.2.1 The source of effectiveness data is specific to the study context.

Criterion 4.1 assesses how specific data sources deriving cost-effectiveness measures, to a context, focus on the relevance of input variables, models, and assumptions. *Table 4* indicates that the extent to which different studies describe caveats associated with their data sources varies.

4.5.2.2 A justification for comparisons across different urban contexts is provided

Criterion 4.2 assesses how meaningful cost-effectiveness comparisons across diverse urban sanitation contexts are. In general, urban sanitation interventions in LMICs feature heterogeneous cost determinants, making direct comparisons difficult to justify (Carrard et al., 2021). For instance, Sainati et al. (2020) recommend using generalised estimates with a minimal error of $\pm 25\%$ for broad comparisons. Standardised comparisons, like those in case-control studies, pose challenges for urban sanitation. They require specifying a single cost-effectiveness measure that encompasses all relevant costs and benefits (Ross et al., 2022). *Table 4* indicates that no studies fully apply this criterion. However, several acknowledge the limitations of these comparisons (Meddings et al., 2004; Hutton et al., 2014; Carrard et al., 2021). Hutton et al. (2014) suggest using generalized comparisons mainly in broad national contexts. In contrast, the heterogeneous contexts of LMIC cities demand more detailed analyses.

4.5.2.3 An incremental analysis in units of TACH/TACC is presented.

Criterion 5.1 assesses if studies use standardized unit costs, specifically total annualized cost per household (TACH) or per capita (TACC), to compare sanitation options. This method is advocated by Sainati et al. (2020). These units facilitate an incremental comparison of the *life cycle costs* of relevant options in addition to a without-project case (see Criterion 2.1). In

this case, instead of assuming a linear change, the net present value of each option varies as households or individual users gain access to water-related services (see Criterion 6.1). This approach enables more meaningful comparisons of diverse urban sanitation interventions, from capital-intensive infrastructure projects to lower-cost, intermediate options with more intermediate service outcomes. Incremental analysis also aids in evaluating demand-side management options and the potential for avoided costs from delaying infrastructure-led options.

Studies that *fully apply* Criterion 5.1 include [Kennedy-Walker et al. \(2016\)](#), who analysed different faecal sludge collection and transport options for urban poor communities. [Manga et al. \(2020\)](#), who compared simplified sewer configurations against onsite options. In addition, [Retamal et al. \(2011\)](#) modelled the financial performance of various hybrid sanitation interventions. These studies exemplify the application of average incremental costing (AIC) (see Criterion 6.1) for projecting detailed life cycle costs to inform future service provision models.

4.5.2.4 Benefit valuation methods are described and justified for the study population.

Criterion 5.2 assesses whether benefit valuation methods for economic efficiency are clearly defined and appropriate for the study context. Benefit valuation for urban sanitation can be contentious due to the potential for bias by only partially including all relevant outcomes of an intervention. The *ESI methodology* ([Hutton et al. 2014](#)) is an example that *comprehensively applies* Criterion 5.2 via the range of benefits it attempts to quantify using rigorous methods. Typically, benefit valuation methods are most effective in homogeneous settings where they can be applied consistently to yield reproducible results. In heterogeneous urban contexts in LMICs, justifying benefit valuation methods is more

difficult, as demonstrated in *Table 4*, where few studies attempt this. For example, [Meddings et al. \(2004\)](#) conducted a case-control study, [Prihandrijanti et al. \(2008\)](#) estimated averted health expenditures, [Delaire et al. \(2020\)](#) utilized a willingness-to-pay survey, and [Schuen & Parkinson \(2009\)](#) assumed a generic health benefit for Sub-Saharan Africa.

4.5.2.5 Intangible benefits are reported separately.

Criterion 5.3 evaluates whether studies distinguish between intangible costs and benefits and economic efficiency measures in reported results. Urban sanitation systems often include diverse intangible benefits that are difficult to define and measure. Studies that *fully apply* Criterion 5.3 systematically differentiate between factors that can and cannot be quantified to support clearer decisions. For instance, [Hutton et al. \(2014\)](#) effectively categorised benefits as valued, quantified, and tangible. Another example is [Willettts et al. \(2010; 2013\)](#), who embedded a quantitative measure of cost-effectiveness within a deliberative sustainability assessment of sanitation options conducted with local authorities. The latter approach further exemplified Criterion 5.3 by transparently aligning their approach for defining and handling externalities with global sustainability frameworks.

4.5.2.6 Average incremental costing is used to structure life cycle costs over time.

Criterion 6.1 assesses whether AIC has been applied to structure life cycle costs within a study. *Table 4* shows that [Kennedy-Walker et al. \(2016\)](#), [Manga et al. \(2020\)](#), [Retamal et al. \(2011\)](#), and [Willettts et al. \(2010\)](#) fully applied this method. These studies determined the cost of the next additional unit of service provision for either households or users (see Criterion 5.1).

4.5.2.7 Adjustments for inflation and currency conversion are made explicit.

Criterion 6.2 evaluates whether a study adjusts prices to a common year and currency, explicitly citing conversion factors. As indicated in *Table 4*, this *criterion fully applied* to most of the included literature.

4.5.2.8 A contextually relevant resource flow model is used to estimate economic costs.

Criterion 7.1 assesses the effectiveness of economic models in representing the specific contexts of urban sanitation interventions within cities of LMICs. Models that fully apply this criterion need to scale and integrate data accurately to forecast cost and benefit changes over time. This will require reconciling fragmented data and ensuring assumptions align closely with real-world behaviours and their impact on demand for urban water resources.

Table 4 indicates that resource flow models most effectively apply Criterion 7.1, as they more closely determine the broader economic impacts of urban sanitation interventions. Six reviewed studies utilise water balance models to estimate economic costs in alignment with this intention. [Retamal et al. \(2011\)](#) and [Willetts et al. \(2010\)](#) demonstrate a rigorous approach to meeting this criterion by conducting a residential water end-use analysis model based on representative household surveys. This method enables the bottom-up prediction of wastewater flows over the entire timeframe of their analysis, derived from end-use practices within households, such as bathing or flushing. This approach allows the model to test the impact of context-specific assumptions on urban sanitation interventions from diverse perspectives ([Retamal et al., 2011](#)) (see Criterion 1.2).

Other studies either *mostly* or *partially apply* this criterion, depending on the rigour of the model applied. For instance, studies may represent resource flows using generalised per capita assumptions about total residential wastewater production ([Jung et al., 2018](#); [Manga](#)

et al., 2020), empirical cost functions (Peal & Georges, 2013), or existing standard design parameters (Mburu et al., 2013; Shi et al., 2018) to predict the future costs of urban sanitation interventions. Studies that evaluate non-sewered urban sanitation options adopt resource flow models that estimate volumes of faecal sludge, as opposed to wastewater. For example, Tilmans et al. (2015) evaluate a container-based sanitation option using a model derived from empirical measurements. In contrast, Furlong et al. (2020), Kennedy-Walker et al. (2016), and von Münch & Mayumbelo (2007) determine resource flows based on per capita faecal sludge generation rate estimates derived from other contexts.

An alternative method of modelling the costs of urban sanitation interventions that partially applies Criterion 7.1 is financial flow modelling, as adopted by Carrard et al. (2021), Dodane et al. (2012) and McConville et al. (2019). These studies utilise historical financial data from the records of utilities, local authorities, and other service providers to project future costs. However, while the analysis facilitates a valuable financial comparison, the approach does not meaningfully account for the physical impacts of resource flows from changes to populations over time. This impacts how accurately they represent the actual context of the study.

4.5.3 Analysis and interpretation of results

4.5.3.1 The time horizon and discount rate applied are stated and justified.

Criterion 8.1 assesses whether studies clearly define and justify the applied discount rates and time horizons. Most studies *fully applied* this criterion, typically applying discount rates of 4% to 12% across time horizons of 10 to 30 years.

4.5.3.2 Confidence intervals are presented for stochastic data.

Criterion 9.1 evaluates whether confidence intervals are included for stochastic data used as model inputs in comparisons of urban sanitation interventions. Although this was

not common in the reviewed literature, this criterion helps decision-makers to clearly understand the level of certainty of the results of an economic analysis. Confidence intervals indicate the variability parameters such as unit costs and resource quantities, which can vary widely across different urban settings and result in significant errors and poor decision outcomes.

An example that *fully applies* Criterion 9.1 is [Jung et al. \(2018\)](#), who define confidence intervals for various input variables, including the discount rate, cost of electricity, and the degree to which modelled wastewater treatment configurations were decentralised. These intervals inform more certain decisions about the planning of wastewater treatment configurations in this context. Other examples partially apply Criterion 9.1 by providing confidence intervals only for critical variables with uncertain values. For instance, the sale price of reuse products ([Carrard et al., 2021](#)), the mass of faecal waste produced per day ([Tilmans et al., 2015](#)), the willingness to pay for sanitation services, [Delaire et al. \(2020\)](#), and an overall outcome measure of cost per death averted ([Meddings et al., 2004](#)).

4.5.3.3 Sensitivity and scenario analyses are used to enhance the use of modelled data.

Criterion 9.2 evaluates how sensitivity and scenario analyses enhance the use of modelled data to address uncertainties. Seven studies fully apply this criterion, as detailed in Table 4, although they apply these tools in varied ways. Sensitivity analysis tests assumptions about significant input parameters over a defined range. Some analyses focus on a key parameter, such as the discount rate or time horizon of a study ([Dodane et al., 2012](#); [Prihandrijanti et al., 2008](#); [Willets et al., 2010](#)), the cost of fuel or electricity ([Jung et al., 2018](#); [Manga et al., 2020](#)), the level of subsidy provided ([Delaire et al., 2020](#)), the sale of

reuse products (Carrard et al., 2021; Schuen & Parkinson, 2009), or non-monetary benefits, such as averted health costs (Hutton et al., 2014). Other analyses are more comprehensive and are used to determine the parameters with the most potential to impact a decision (Hutton et al., 2014; Jung et al., 2018; Ketema & Langergraber, 2015).

Scenario analysis poses *what-if* questions to a model to consider the impact of assumptions on a model over time and how this scenario may impact multiple parameters at the same time. This method is primarily used to appraise the impact of uncertain future scenarios when comparing sanitation service options (Furlong et al., 2020; Kennedy-Walker et al., 2016; Jung et al., 2018; Schuen & Parkinson, 2009; Prihandrijanti et al., 2008; Kerstens et al., 2009). Other applications are more specific, seeking to validate a cost function model (Ketema & Langergraber, 2015), test and optimise assumptions about the population assumed to be serviced by a service provision model (Carrard et al., 2021; McConville et al., 2019), or structure life cycle costs over time with greater certainty (Willetts et al., 2010).

4.5.3.4 Deliberative methods are used to address aspects of epistemic uncertainty.

Criterion 9.3 assesses the use of deliberative methods in urban sanitation studies to address uncertainties from diverse perspectives. This criterion highlights the importance of incorporating a broad range of viewpoints to enhance the equity of economic analyses and prevent biased decisions in service provision. Intentionally including these perspectives helps align studies with CWIS principles (Lüthi et al., 2020), fostering deeper reflection on and addressing the root causes of disparities in service access.

While no studies have *fully applied* Criterion 9.3, some enabling practices with the capacity to enhance the participation of traditionally excluded groups in economic appraisals were identified. For example, Willetts et al. (2013) implemented a sustainability

assessment that brought together various stakeholders to discuss complex issues of social equity and environmental sustainability, prompting discussions about challenges in reaching consensus. Similarly, [Dahiya et al. \(2006\)](#) employed an informed choice approach, enabling informal households to actively evaluate trade-offs between costs and the intangible benefits of different service options. Future methodologies should further these practices, ensuring comparative economic analysis shapes inclusion in urban sanitation planning decisions.

4.5.3.5 Outcome measures (TACH/TACC) are reported against a least-cost standard.

Criterion 10.1 assesses whether an economic analysis measures outcomes in incremental units of TACH or TACC (see Criterion 5.1) and compares these against an existing least-cost without-project standard (see Criterion 2.1). Among the studies reviewed, only [Kennedy-Walker et al. \(2016\)](#) *fully applied* Criterion 10.1 by conducting an incremental analysis. This study compared faecal waste transportation and treatment costs to those of a least-cost pilot study in comparable units of total monthly cost per household.

4.5.3.6 Outcome measures are presented in an aggregated and disaggregated format.

Criterion 10.2 evaluates whether economic appraisals of urban sanitation report aggregated outcome measures that are then disaggregated to detail significant cost and subgroup perspectives (see Criterion 1.2), life cycle cost components (see Criterion 6.1) and stages of a sanitation value chain. Studies that fully apply Criterion 10.2 include [Carrard et al. \(2021\)](#), [Delaire et al. \(2020\)](#), [Dodane et al. \(2012\)](#), [Hutton et al. \(2014\)](#), and [McConville et al. \(2019\)](#).

4.5.3.7 Conclusions arise from multiple cost perspectives informed by multiple criteria.

Criterion 10.3 extends the principles of Criterion 10.2 by evaluating whether economic analyses facilitate supports flexible interpretation from diverse urban perspectives and scales. This criterion stresses the importance of transparent and non-prescriptive reporting, avoiding sole reliance on quantitative measures. It advocates for an iterative and collaborative analysis process that adapts to the diverse and evolving economic relationships among various cost and subgroup perspectives.

While current practices often fall short of involving participants directly in analysing results, several studies illustrate emerging approaches that enhance collaborative decision-making. For example, [Delaire et al. \(2020\)](#) suggest that considering the spatial heterogeneity of cities could refine economic analyses, optimising sanitation costs for different urban contexts. [Schuen and Parkinson \(2009\)](#) and [Peal and Georges \(2013\)](#) demonstrate how what-if scenarios may be used to explore how changes in urban sanitation configurations might impact different cost perspectives. Additionally, [Furlong et al. \(2020\)](#) conducted participatory workshops to ensure that a financial flow model adapted from another context resonated with the diverse experiences of users and service providers before its implementation in economic analysis. Future methodologies should develop tools that allow decision-makers across an urban spectrum to relate to and interpret results on their own terms. This may facilitate a more inclusive and comprehensive understanding of economic analyses, aligned with CWIS principles.

4.5 Conclusion

This review examined how methods from costing studies over the past two decades align with evaluative criteria for least-cost comparative economic analysis of CWIS interventions in LMICs. By analysing how each criterion was applied, this paper provides valuable insights

for planners aiming to design comparative economic analyses to select equitable and sustainable urban sanitation configurations.

Several challenges emerged from applying these criteria. Local authorities will need practical support to reframe economic analysis from first principles to an inclusive societal cost perspective. This support should facilitate defining a problem that includes all relevant subgroup perspectives in an analysis. It will require negotiating a collaborative definition of an existing without-project standard for sanitation service provision and collecting context-specific data for meaningful comparison. CWIS principles imply the need to take calculated risks to transition from focusing on existing infrastructure options to focusing on a diversity of approaches and outcomes. This will require longer-term economic analysis methodologies to compare context-specific innovations that respond to persistent unmet service demands. Decision support models should aspire to engage service users in this process critically.

The primary contribution of this review is highlighting opportunities to enhance economic analysis methodologies to better address the diverse needs for sanitation in LMIC cities. The evaluative criteria require broader discussion within the urban water and sanitation sector to improve how they are defined and weighted in an overall evaluation. This activity should be coupled with additional context-specific economic analysis studies aligned with these criteria, complementing more generic heuristic comparisons.

Declaration of competing interests

The authors declare no competing financial interests.

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Part Two: Learning about the diverse *ways of knowing*
about heterogeneous demand for water and sanitation
services in Siem Reap Municipality, Cambodia

Chapter Five: Residential end-use water demand analysis for a heterogeneous urban water and sanitation configuration in Siem Reap, Cambodia

5.1 Overview

Chapter Five presents the third knowledge output of this thesis, and the first study embedded within the *transdisciplinary case study methodology*, aligned with *Wave Two* (see *Figure 3*). This *wave* contributes to the second transdisciplinary outcome space, focusing on *generating knowledge stocks and flows*. Here, knowledge is co-produced using *hard systems* tools to explore how some of the methodological gaps identified in *Chapter Four* may be resolved by testing an empirical approach to residential end-use demand modelling. The chapter compiles a paper published in the *Journal of Cleaner Production*, detailing the design and implementation of a residential water end-use survey and demand analysis in two peri urban villages in Siem Reap municipality, Cambodia. This work directly responds to *Research Question #2a*, which asks how to characterise a heterogeneous *without-project case* as a basis for comparison for an economic analysis to inform the inclusive planning of *heterogeneous water and sanitation service configurations*.

The residential end-use model developed in this chapter was developed using a *hard systems* approach to empirically explore a context where demand for water and sanitation services is highly fragmented, and formal infrastructure is only partially accessible. Conceptualised as a *boundary object*, the model was intended to provide a shared, consistent point of reference that could be used to shape later integration activities (outlined in *Section 2.2.2* and *Section 2.4.2*) in *Wave Three* of this inquiry through participatory workshops (discussed in *Chapter Six*).

From a comparative economic perspective, the residential end-use model developed in this chapter provides the empirical basis for defining a heterogeneous *without-project case*,

enabling least-cost comparison of alternative service configurations against existing patterns of demand, access, and household behaviours. In this way, the model operationalises the economic planning principles articulated in *Chapters Three and Four* within a real-world, heterogeneous service provision context. While the water end-use model was not ultimately integrated as part of these workshops due to constraints arising due to the COVID-19 pandemic, it was designed with this purpose in mind. In lieu of having the model prepared for the workshops, insights into how it may have been integrated with other co-produced knowledge from other epistemological perspectives were guided using a rich picture model as a proxy, which is discussed in more detail in *Chapters Two and Seven*.

The study identifies a gap in the literature on residential water end-use analysis. There are few studies performed at a granular scale in cities of low- and middle-countries that analyse water demand in heterogeneous service provision contexts (Di Mauro et al., 2021; Mazzoni et al., 2023; Roshan & Kumar, 2020). This situation arises because applying standard methodologies relies on metering approaches that are not suitable for these contexts, while the reliability of *socially generated* data is often questioned (Morrison & Friedler, 2015). However, this study addresses this gap by applying a flexible methodology that co-produces residential water end-use data from a *societal perspective* (i.e., purposefully including diverse urban needs within a single model), aligned with the least-cost, integrated resource planning principles established in *Chapters Three and Four* (Ross et al., 2024a, 2024b).

The model enables the analysis of water demand data for different end-use component systems (e.g., drinking, washing, toilet flushing) comprising multiple water sources, diverse household water access typologies, household infrastructures, and wastewater sinks. To ensure the case study was representative, stratified random sampling for 14 enumeration

zones across the two villages was used to survey 97 of 1,630 households, generating highly disaggregated, context-specific end-use demand data. This knowledge was used to model a without-project case that may be used in a systemic comparative economic analysis of different scenarios, characterised by inclusive end-use parameters (frequency, duration, intensity).

The research conducted in this chapter lays claim to three significant contributions: (i) it explores how a collaborative heterogeneous urban residential water end-use demand model may theoretically be used as a *boundary object* in a systemic comparative economic analysis methodology to support participatory, integrated, least-cost urban water and sanitation planning; (ii) it describes and tests a novel, flexible *methodology* that co-produces *residential end-use water demand data* across heterogeneous service provision configurations; and (iii) it practically demonstrates how diverse formal, semi-formal and informal service provision configurations may be integrated into a least-cost *without-project case* through the determination of heterogeneous *end-use parameters*.

These contributions inform the adaptive development of a revised integration concept for accommodating systems thinking arising from epistemologically plural perspectives, building on an initial approach described in *Section 2.4.3*. While the residential end-use model was not integrated as part of the participatory workshops described in *Chapter Six*, the adaptive use of *rich pictures*, as a proxy, highlights the potential for objectively defined knowledge to contribute to a more holistic understanding of systemic behaviour in a complex heterogeneous water and sanitation configurations to better support decisions. *Chapter Seven* reflects more deeply on how such models can support inclusive planning frameworks in complex, heterogeneous urban contexts in LMICs.

Publication: Residential end-use water demand analysis for a heterogeneous urban water and sanitation configuration in Siem Reap, Cambodia

This journal article is included in this thesis as the *peer-reviewed manuscript accepted for publication* by the *Journal of Water Sanitation and Hygiene for Development* on the 27th of September 2025. This version has been compiled within the thesis to enable plagiarism checking software to be applied and to facilitate a transparent overall word count for the thesis. To aid navigation of the thesis, the headings, figures, and tables of this publication have been embedded within the structure of the overall thesis and are not in the same format as the published version. The published version of the journal article is available via an open access agreement and is available for free download via accessing the link <https://doi.org/10.1016/j.jclepro.2025.146757>

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Residential end-use water demand analysis for a heterogenous urban water and sanitation configuration in Siem Reap, Cambodia

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Abstract:	<p>A significant limitation when planning urban water and sanitation in low- and middle-income countries is the capacity to define what services already exist. This paper demonstrates how residential end-use analysis may be applied to model a detailed without-project situation and help to identify contextually relevant least-cost interventions. We present an end-use analysis of a heterogeneous infrastructure configuration in Siem Reap Municipality, Cambodia. This analysis sampled end-use consumption data from 97 of 1630 geographically stratified households from 14 enumeration zones in two adjacent villages. It represents a socio-technically diverse population accessing services from a mix of service provision types and household infrastructures at a high spatial resolution. A semi-structured survey questionnaire, observation protocol, and empirical flow measurements were used to socially collect end-use parameter data (frequency, duration, and volume or flow rate). Our analysis effectively disaggregates daily per capita demand for socio-demographic attributes, including income level, household size, length of tenure, different water access typologies and wastewater sinks. Bottom-up water balances of this nature provide a flexible and inclusive basis for identifying, forecasting and comparing how possible water and sanitation options may impact urban households differently in a Southeast Asian context.</p>

Residential end-use water demand analysis for a heterogeneous urban water and sanitation configuration in Siem Reap, Cambodia

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Abstract

A major limitation in planning urban water and sanitation in low- and middle-income countries is the capacity to define what services already exist in contexts that are challenging to meter. This paper demonstrates how residential water end-use analysis may be applied to model a detailed without-project situation and help to identify contextually relevant least-cost interventions. We present such an end-use analysis for a heterogeneous infrastructure configuration in Siem Reap Municipality, Cambodia. This analysis sampled end-use consumption data from 97 of 1630 geographically stratified households from 14 enumeration zones in two adjacent villages. The study represents a socio-technically diverse population accessing services from a mix of service provision types and household infrastructures at a high spatial resolution. A semi-structured survey questionnaire, observation protocol, and empirical flow measurements were used to collect end-use parameter data (frequency, duration, and volume or flow rate). Our analysis effectively disaggregates daily per capita demand for socio-demographic attributes, including income

level, household size, length of tenure, different water access typologies and wastewater sinks. Bottom-up water balances of this nature provide a flexible and inclusive basis for identifying, forecasting and comparing how possible water and sanitation options may impact urban households differently in a Southeast Asian context.

Keywords: integrated resource planning, least-cost principles, micro-component analysis, socio-technical systems, water demand forecasting

Highlights

- Outlines a method for the social generation of residential water end-use data.
- Samples from a heterogeneous urban water and sanitation configuration.
- Defines a context-specific without-project case for comparing possible interventions.
- Discusses how RWEUA may help evaluate interventions in heterogeneous contexts.
- Prompts further studies to define water end-use parameters in other LMIC contexts.

Graphical abstract

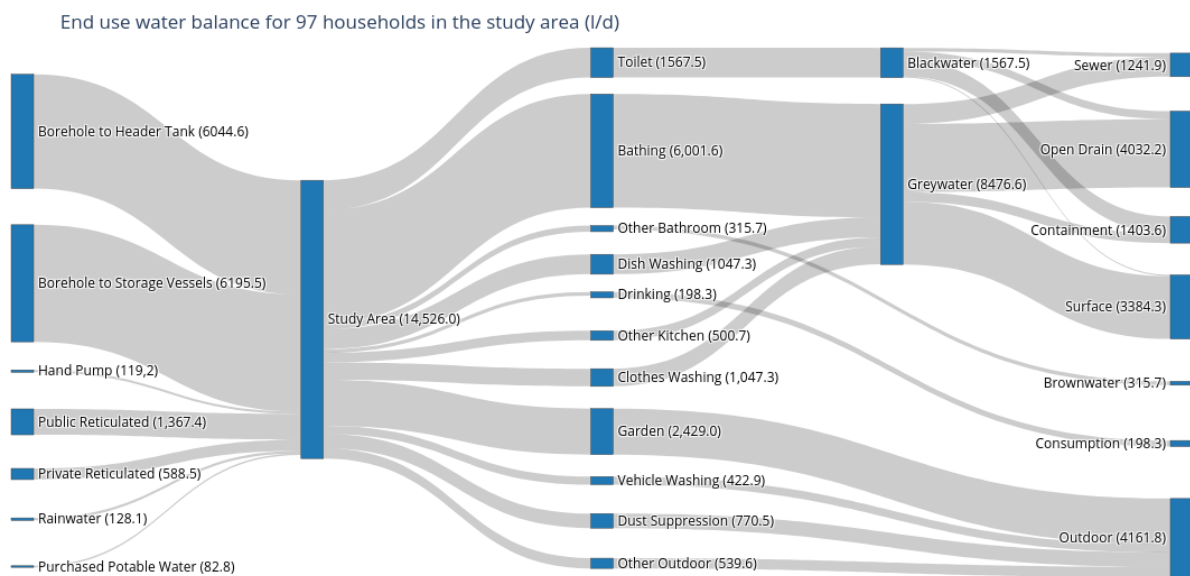


Figure 7: Aggregated water end-use balance for the case study area

5.2 Introduction

Residential water end-use analysis (RWEUA) collects and disaggregates water demand data into discrete events, representing services provided in households such as toilet flushing, bathing, or washing clothes (Beecher 1991; White & Fane 2002). End-use models typically define three parameters characterising these events: frequency, duration, and intensity (volume or flow rate) (Rathnayaka et al., 2011). Planners use these data to forecast the impacts of interventions for water and wastewater services, improving understanding of factors influencing urban water configurations at various scales (Fane et al., 2006). These parameters define how water is supplied and demanded for different household services.

Bottom-up residential water end-use models, based on local water service experiences, enhance the validity of planning decisions (Mukheibir et al., 2013). Since the 1990s, such models have become increasingly used by urban water utilities in high income countries (HICs) for demand forecasting and options development. RWEUA has evolved alongside innovations in smart meter technology for relatively universal service provision contexts to support resource efficient service delivery (Mazzoni et al. 2023). However, in rapidly urbanizing secondary cities in low- and middle-income countries (LMICs), demand for water-related service provision can be inherently heterogeneous and challenging to enact universal metering.

Planning approaches supported by RWEUA become complex due to the presence of multiple, and intermittent water sources, delivered by divergent infrastructures, artefacts, and practices, underpinned by diverse household perspectives (Lawhon et al., 2017; van Welie et al., 2018). Understanding disaggregated water end-use parameters in such contexts is important, as it allows for a more inclusive account of the performance of urban water systems. In particular, for accommodating the experiences of marginalised urban

populations. Such knowledge may aid municipal authorities to balance cost-efficient water service delivery with public health, social, and environmental outcomes, while ensuring services are affordable for all (McGranahan, 2002; Mills et al., 2020; Schwartz et al., 2018).

Despite the potential to better inform this situation, the application of RWEUA to heterogeneous service provision contexts has not attracted significant attention. Relatively fewer documented studies in urban LMIC contexts are available (Di Mauro et al., 2021; Mazzone et al., 2023; Roshan & Kumar, 2020) due to standard methods of collecting and analysing end-use data being less fit-for-purpose (Morrison & Friedler 2015). The inability to universally meter households has constrained insights in areas where universal piped water access is not present, and assumptions about household fixtures and water demand are less reliable (Araral & Wang, 2013; Mayer & DeOreo, 1999; Zapana-Churata et al., 2022). This situation has persisted since the earliest attempts to apply standard RWEUA approaches from HICs (i.e. San Francisco, USA) to LMIC contexts (i.e. Bangkok Thailand) by Darmody et al., (1999), where household water-use practices deviate from standard assumptions.

RWEUA methodologies that collect high-resolution time series data from a single meter are preferred, as they mitigate recall biases (Tamason et al., 2016). However, in urban LMIC contexts, metering is only partially relevant to select piped water access typologies (Kumpel et al., 2017). As a result, studies often focus on small, homogeneous samples of high-income households in upper-middle-income countries, and still require supplementary socially generated data for validation (Hammes et al., 2020; Ghisi & Mengotti de Oliveira, 2007; Meyer et al., 2021).

Alternative metering approaches for collecting time series data such as water level meters on household header tanks (Guragai et al., 2018); or directly metered taps or fixtures within households specific to a particular end-use type (Bao et al., 2013; Otaki et al.,

2008; 2011; 2013, 2022; Sivakumaran & Aramaki, 2010; Vieira & Ghisi, 2016), also have limited applicability. Such methods are limited to a partial range of specific microcomponent end-uses (Muniina et al., 2017; Welling et al. 2020) and tend to demonstrate poor correlation with results obtained socially generated data, such as questionnaire surveys (Otaki et al., 2017; Kumar et al., 2021).

Socially generated data collection methods including recall-based questionnaires, observation protocols, and water diaries have prevailed LMIC contexts, as they enable flexibility in accommodating different demographics, water access typologies, and household infrastructures (Tamason et al., 2016). Initially, RWEUA approaches in LMICs adopted generic, recall-based questionnaire surveys. They were used to produce stratified total end-use consumption per capita data for different socio-demographic groups, or housing types at a city scale (Adekalu., 2002; Zhang & Brown, 2005; Shaban & Sharma, 2007; Jethoo & Poonia, 2011; Damodaran 2011; Pasakhala et al., 2013). Over time, they transitioned towards estimate end-use parameters of *frequency, duration and intensity* to model context-specific planning scenarios (Ghosh et al., 2016; Hussien et al., 2016; Sadr et al., 2016).

Various methods have been applied to increase the spatial resolution at which household experiences are examined by RWEUA studies. Such approaches include training student cohorts to self-administer surveys (Bari et al., 2015; Ibrahim et al., 2021), and co-producing data using water diaries to produce more granular, citywide end-use parameter data. For example, Alharsha et al., (2022) collected diurnal end-use parameters, sampling from 1 in 50 households in Sirte, Libya. Meanwhile other studies in LMICs have focused on specific urban neighbourhoods to model water end-use demand and produce detailed forecasts of potential future development scenarios (Retamal et al., 2011).

Despite the emergence of RWEUA studies with precise objectives focusing on both the quality and quantity of water demanded ([Marinoski et al., 2014](#); [Katukiza et al., 2015](#)), sampling has been largely limited to communities with homogenous income levels or housing types. Recent studies have tended to disaggregate water end-use data, with a primary focus on low-income communities ([Sultana et al., 2022](#); [Utami et al., 2023](#); [Lewis et al., 2024](#)). It is rare for RWEUA studies in LMICs to explore the heterogeneity of urban water and sanitation infrastructure configurations. Higher resolution studies considering diverse household typologies have tended to samples from discrete homogeneous communities from different areas within a city, rather than the same heterogeneous sample ([Rondinel-Oviedo & Sarmiento-Pastor, 2020](#)).

Granular RWEUA studies that collect residential end-use data from a broader societal perspective have potential for enhancing urban water planning. Such analyses may produce models that act as a comparator for the inclusive prioritisation of water supply and sanitation options in heterogeneous contexts, accommodating diverse subgroup perspectives ([Ross et al., 2024a, 2024b](#)). Thus, the present study aims to demonstrate this potential by analyzing data from a heterogeneous water and sanitation infrastructure configuration in Siem Reap Municipality, Cambodia. We apply RWEUA to explore how diverse consumption practices and behaviours, socio-demographic attributes, and household infrastructures distribute demand for water and wastewater services in a single model. In doing so, we wish to demonstrate how such data can provide more inclusive forecasts of water demand by accommodating diverse perspectives.

5.3 Methodology

5.3.1 Study location

Siem Reap (Figure 1B) was selected as our case study city, as Cambodia's second most populous municipality, after the capital Phnom Penh. The city has experienced significant post-conflict urbanisation and population growth, characteristic of secondary cities in Southeast Asia, expanding from ~50,000 in the early 1990s to ~250,000 today (Corbane et al., 2018). A major driver of this growth is tourism associated with the Angkor World Heritage site, attracting millions of tourists annually, causing notable increases in rural-to-urban migration. Unplanned development has resulted in vulnerable households in peri-urban areas experiencing constrained access to water and sanitation services (Green et al., 2017; Liu et al., 2019; Mosello & O'Leary, 2017; IRC & WaterAid, 2016).

At present, sub-national democratic development reforms aim to transfer technical and financial capacity for urban water and sanitation planning to municipal authorities closer to the point of service provision (Royal Government of Cambodia, 2021). The Siem Reap municipal administration plans water-related services supported by 12 suburban Sangkat and 103 Village authorities, as well as separate water and wastewater utilities. However, at present, a major factor limiting the universal delivery of services in this context is the extent to which disaggregated water demand data is available across the diversity of household experiences within the municipality. Master planning strategies foreshadow the expansion of centralised water and wastewater services. However, self-supplied access to groundwater from private, unmetered wells was still predominant at the time of the study, and likely to continue for many villages for at least several decades (Cities Development Institute for Asia, 2019; Siem Reap Urban Development Project, 2010).



Figure 8: Location of the selected study area

5.3.2 Selection of the case study site

We purposively sought a case study area from which a heterogeneous water and sanitation service provision configuration could be sampled at high spatial resolution (Jaglin, 2014; Lawhon et al., 2017). Available grey literature, as well as microdata from the 2019 Commune Databook, and microdata from 2019 General Population Census and enumeration maps were used to shortlist five possible case study sites in collaboration with local partners (National Institute of Statistics, 2023).

Zone	Pop. (pp)	Pop. (hh)	Area (ha)	Pop. Dens. (pp/ha)	Strata sample size	Enumeration Zones
WS1	662	121	31.8	20.8	7	
WS2	652	113	17.3	37.7	7	
WS3	542	81	7.1	75.9	5	
WS4	301	45	2.8	107.1	3	
WS5	441	77	27.0	16.3	5	
WS6	739	177	23.5	31.5	10	
WS7	544	96	9.1	60.0	6	
WS8	894	193	28.2	31.7	11	
WS9	435	88	16.5	26.2	5	
WS Total	5,209	991	163.4	31.9	57	
KK1	437	88	28.6	15.3	6	
KK2	1,053	200	48.5	21.7	13	
KK3	376	79	11.4	33.0	5	
KK4	906	176	42.4	21.3	11	
KK5	503	96	61.8	8.1	6	
KK Total	3,275	639	192.8	17.0	40	
Overall	8,484	1,630	356.2	23.8	97	
Zone	Brief description of the without-project situation in the area of each enumeration zone					
WS1	Sparsely populated area earmarked for development after new road and drainage infrastructure					
WS2	Mixed housing and commercial area (factories and businesses). New infrastructure and planning standards require integration with existing community-led sewer and drainage infrastructure.					
WS3	Area with shopfronts facing a busy road along the river. Established sewer and stormwater drainage					
WS4	A more densely populated, urbanised area with higher-income households and concrete roads					
WS5	Low-lying, sparsely populated area. Lower priority for development except along main roads					
WS6	Area of established, mixed housing and government facilities between two large pagodas					
WS7	An area with rapidly increasing population density and remnant areas of low-quality housing. Conflicts over drainage make it difficult for some households to connect to new infrastructure.					
WS8	Area under active development. Private road, drainage and housing infrastructure.					
WS9	Area with a higher prevalence of ID-poor households. New infrastructure replacing open drains					
KK1	A lower-lying, sparsely populated, high groundwater area. Significant problems with pits overflowing.					
KK2	Area with laterite roads, limited formal drainage, and a higher proportion of older vernacular housing. An increasing mix of newer types of development is occurring in this area.					
KK3	Lower-density commercial area with a mixture of shopfronts and a mixture of how and lower-income households along a busy road facing the Siem Reap River. Established stormwater drainage.					
KK4	Low-density residential area. Laterite roads and limited drainage. No development restrictions					
KK5	Area with restricted development due to management of cultural heritage the APSARA Authority.					

Figure 9: Enumeration zones in the study area used for stratified random sampling

At each site, transect walks were conducted with village officials, utility representatives, private service providers, and community leaders to identify community-scale risks associated with water and sanitation services (Ross et al., 2025). Knowledge about administrative borders, drainage infrastructure, local governance structures, the diversity of service provision typologies in different zones of the study area were also documented, aligned with the approach described by Narayanan et al. (2018).

This knowledge was used to select a case study site based on the criteria (i) being heterogeneous, comprising a mixture of socio-demographic characteristics, housing types, water access typologies, and water-related service provision configurations; and (ii) the area being subject to an urban water and sanitation planning framework, i.e., not at risk of relocation.

The two adjacent villages of Wat Svay and Kakranh, as mapped in Figure 1A, were selected for the case study, comprising 1,630 households and 8,484 people (National Institute for Statistics, 2023). The case study represents an urban to peri-urban area downstream of the centre of Siem Reap. A ring road that diverts traffic around the city defines the border between the villages. Wat Svay is zoned as urban and, at the time of the study, was experiencing major upgrades of centralised reticulated water supply, drainage, road and sewer infrastructure as part of a project supported by international partners. Kakranh is zoned as peri-urban, where the development of municipal water, sanitation, and drainage infrastructure is a lower priority and driven mainly by community-led projects or self-supplied services (Siem Reap Urban Development Project, 2010).

5.3.3 Sampling

To obtain a heterogeneous sample, we applied random stratified sampling of 14 census enumeration zones across the two villages (see Figure 2). A minimum sample size of 91 out

of 1,630 households was selected to achieve a 95% confidence interval and $\pm 10\%$ error margin. In total, 97 household surveys were conducted to exceed these parameters. A grid was placed over each enumeration zone across the study area. Households were randomly sampled, proportional to the number of households in each zone, as indicated in Figure 2. This process ensured that the households were representative of diversity of service provision typologies and contexts within the case study area (United Nations, 2005).

5.3.4 Household survey

Water end-use data was collected from the sampled households using a semi-structured survey and observation protocol over five weeks (February 7 to March 11, 2022). Data collection occurred following a series of lockdown events due to the COVID-19 pandemic between July and September 2021, with minimal impact on survey outcomes. The survey prompts were designed to be interpretive to accommodate non-standard household contexts and collect data from all households within the sample, as presented in the supplementary material. A pre-survey tool informed by in-depth interviews (Ross et al., 2025) was tested on ten diverse households immediately outside the study area, prior to its use in the study. Pre-testing helped to appraise the fit of the tool to the study context. Where possible storage vessels, appliances, and artefacts such as scoops, buckets, jars, tanks typical for Khmer households were pre-measured to limit the level of intrusion of the data-collection process.

The validated survey tool comprised questions regarding the (i) demographic characteristics of each household member (gender, age, income level, occupation, education level, housing type, and length and type of tenure; (ii) water access typology; (iii) water storage capacity; (iv) household appliances and fixtures; (v) frequency, duration, and intensity for indoor (toilet, bathroom, kitchen, laundry) and outdoor (garden, vehicle

washing, dust suppression) end-use events; (vi) other end-uses not included the question prompts; (vi) wastewater sinks associated with each event; and (vii) in lieu of household level consumption data area not being available from the *Siem Reap Water Supply Authority*, whether the household has access to total monthly household consumption from a recent water bill (Supplementary material). Each survey was conducted over 45–75 min, depending on the size and complexity of each household configuration.

Multiple methods were adopted to collect data, including prompted recall, structured observations, and empirical measurements of flow rates and water storage inventories, as appropriate to each household context. If consent was provided, bathroom, laundry, and toilet fixtures and appliances were photographed to enable cross-referencing with available manuals and standards. Where unavailable, estimates were made based on appliances with the same or similar capacity in other households. To ensure consistency, end-use events occurring outside the household (i.e. services performed by a laundromat or carwash) were excluded from the analysis.

5.3.5 Data analysis

The data collected from the 97 households surveyed were coded to ensure anonymity, before being transcribed into a Microsoft Excel spreadsheet for analysis. Householders from the participating households were categorised by village (Wat Svay or Kakranh), gender (male or female) age (< 18 yrs or ≥ 18 yrs), income level (high, medium, or low), and tenure length (< 10 yrs, 10 ≤ yrs < 20, 20 ≤ yrs < 30 or ≥ 30 yrs) and type (owner, tenant or owned by family member). Low-income households were defined via the possession of ID Poor status, a Khmer standard used to administer welfare to households. Medium- and high-income households were distinguished based on housing quality and ownership of assets such as vehicles, among other effects. This approach is an indicative and reliable measure

consistent with practices used by the Royal Government of Cambodia ([National Institute of Statistics, 2023](#)).

Following the component end-use parameters (frequency, duration, and volume or flow rate) for each household being imported into Microsoft Excel, the following approach was adopted. First, each end-use parameter was used to determine water demand for each specific end-use event in each household in litres per capita per day (lpcd). Then, descriptive statistics were calculated (median, mean and distribution) to analyse these results for various water access typologies, total and disaggregated end-use components, and wastewater sinks. Box plots were created using Plotly Chart Studio (chart-studio.plotly.com/create) to examine outliers and clean the data by checking for transcription errors.

Following this, a residential end-use water balance model was developed for the entire case study area, disaggregated by village. Discrete end-use flows from each household aggregated at various scales, were traced from each water access typology (reticulated water from public utilities, reticulated water from private landlords, borehole to a header tank, borehole to storage vessels, hand pump, rainwater, and packaged water); to microcomponent end-use; to various wastewater sinks (black water, greywater and brown water (i.e. water from bathroom taps, where it is unclear whether the flow may be attributed to a blackwater or greywater flow)). Wastewater sinks were further disaggregated based on the destination of the flow (sewer, open drain, containment in a pit, surface flows, consumption, and outdoor use). The end-use model was represented as a Sankey diagram also produced in Plotly Chart Studio, with flows disaggregated by village to aid the analysis of the heterogeneity of the urban water and sanitation configuration in the case study.

Validation of the water end-use parameters data collected was attempted. Total water consumption data was sourced either directly from recent water utility bills (n = 6 households), or from estimates based on recall of recent payments and tariffs paid to landlords (n = 4 households). However, this data was constrained to a small proportion of households surveyed in Wat Svay village due to the predominance of self-supplied access to groundwater for service provision across the case study area. Further, in most cases, data were available for either one or two past bills, or recollections of recent payments, used to estimate monthly consumption based on knowledge of tariffs. This constrained the extent to which survey results could be verified, particularly when considering expected monthly and seasonal variation in water demand.

Notwithstanding this, a disaggregated analysis of the end-use water demand data for the various socio-demographic determinants characterised by study (village of residence, income level, household size, and length of tenure) was conducted. This analysis is supported by drawing conclusions from box plots depicting mean, median, standard deviation and outliers for each microcomponent flow. Further, a disaggregated set of each end-use parameters (frequency, duration, and intensity) underlying the water balance is presented and discussed.

The study aimed to analyse how various socio-demographic determinants influence how water access typologies, household infrastructures, and preferences for water use practices affect how heterogeneous water demand is distributed in the case study. To support this objective, sampled households were characterised by village of residence, household income, household size, and length and type of tenure, as presented in Table 1.

5.4 Results

5.4.1 Characteristics of the sampled households

The study aimed to analyse how various socio-demographic determinants influence how water access typologies, household infrastructures, and preferences for water use practices affect how heterogeneous water demand is distributed in the case study. To support this objective, sampled households were characterised by village of residence, household income, household size, and length and type of tenure, as presented in Table 1.

Table 5: Socio-demographic characteristics of surveyed households and residents

Village	Wat Svay		Kakranh		Total	
	Frequency (n)	Percentage (%)	Frequency (n)	Percentage (%)	Frequency (n)	Percentage (%)
Total Households	57		40		97	
Household size (survey)	5.39		5.68		5.51	
Household size (2019) *	5.25		5.13		5.20	
No. Householders	307		227		534	
Female	155	50.5	118	52.0	273	51.1
≥ 18 yrs old	104	33.9	81	35.7	185	34.6
< 18 yrs old	51	16.6	37	16.3	88	16.5
Male	152	49.5	109	48.0	261	48.9
≥ 18 yrs old	97	31.6	73	32.2	170	31.8
< 18 yrs old	55	17.9	36	15.8	91	17.0
Income level						
High-income	11	19.3	6	15.0	17	17.5
Middle-income	30	52.6	22	55.0	52	53.6
Low-income	16	28.1	12	30.0	28	28.9
Tenure						
< 10 yrs	18	31.6	13	32.5	31	32.0
10 ≤ yrs < 20	17	29.8	7	17.5	24	24.7
20 ≤ yrs < 30	9	15.8	5	12.5	16	14.4
≥ 30 yrs	13	22.8	15	37.5	25	28.9
Owner	44	77.2	31	77.5	75	77.3
Tenant	7	12.3	5	12.5	12	12.4
Owned by family member	6	10.5	4	10.0	10	10.3

As a result of geographically stratified sampling from each enumeration zone, the number of households surveyed was in proportion to the number of households in each village of residence. Household size was defined as people who live together in a single dwelling, sharing common living arrangements (i.e. eating together). These parameters were found to be comparable with those from the 2019 Cambodian General Population Census ([National Institute of Statistics, 2022](#)) for both case study villages (see *Table 1*).

A slightly higher proportion of high-income households and lower proportion of low-income households were observed in Wat Svay. This was expected and is in alignment with description of the case study area in *Section 2.2*, with the village being located closer to the political and economic centre of Siem Reap municipality than Kakranh. Results for the length and type of tenure for households in the study area should be interpreted considering the historical context of the abolishment of private property and collectivisation of land ownership during the Khmer Rouge period (1975-1979). This situation fundamentally altered land tenure patterns and their evolution since this time. Post-conflict reclamation of land has resulted in higher levels of land ownership, and a different relationship to tenure than might be expected in other similar LMICs.

Overall, the proportion of owners, or those living on land owned by family members, compared to tenants is very high, and comparable in both *Wat Svay* and *Kakranh*. However, the extent to which households with legal tenure have been displaced by higher land prices, modern housing and infrastructure types is more pronounced in *Wat Svay* (*Table 1*). As is the proportion of households who relocated to Siem Reap to take advantage of the expanding tourism economy ($10 \leq \text{yrs} < 20$). Thus, while the proportion of *newcomers* (< 10 yrs) is similar in each village, the extent to which households who have maintained tenure since land re-distribution following the Pol Pot regime (≥ 30 yrs) is substantially higher in

Kakranh. As demonstrated later in Section 3.2.4, these contextual factors influence the prevalence of water access typologies; wastewater sinks in each village, and preferences for household configurations and water use practices.

5.4.2 The influence of household characteristics on end-use water demand

5.4.2.1 Village of residence

Table 2 presents results that demonstrate how village of residence influences the volume of water demanded for various microcomponent end-uses in the case study based on water access typology.

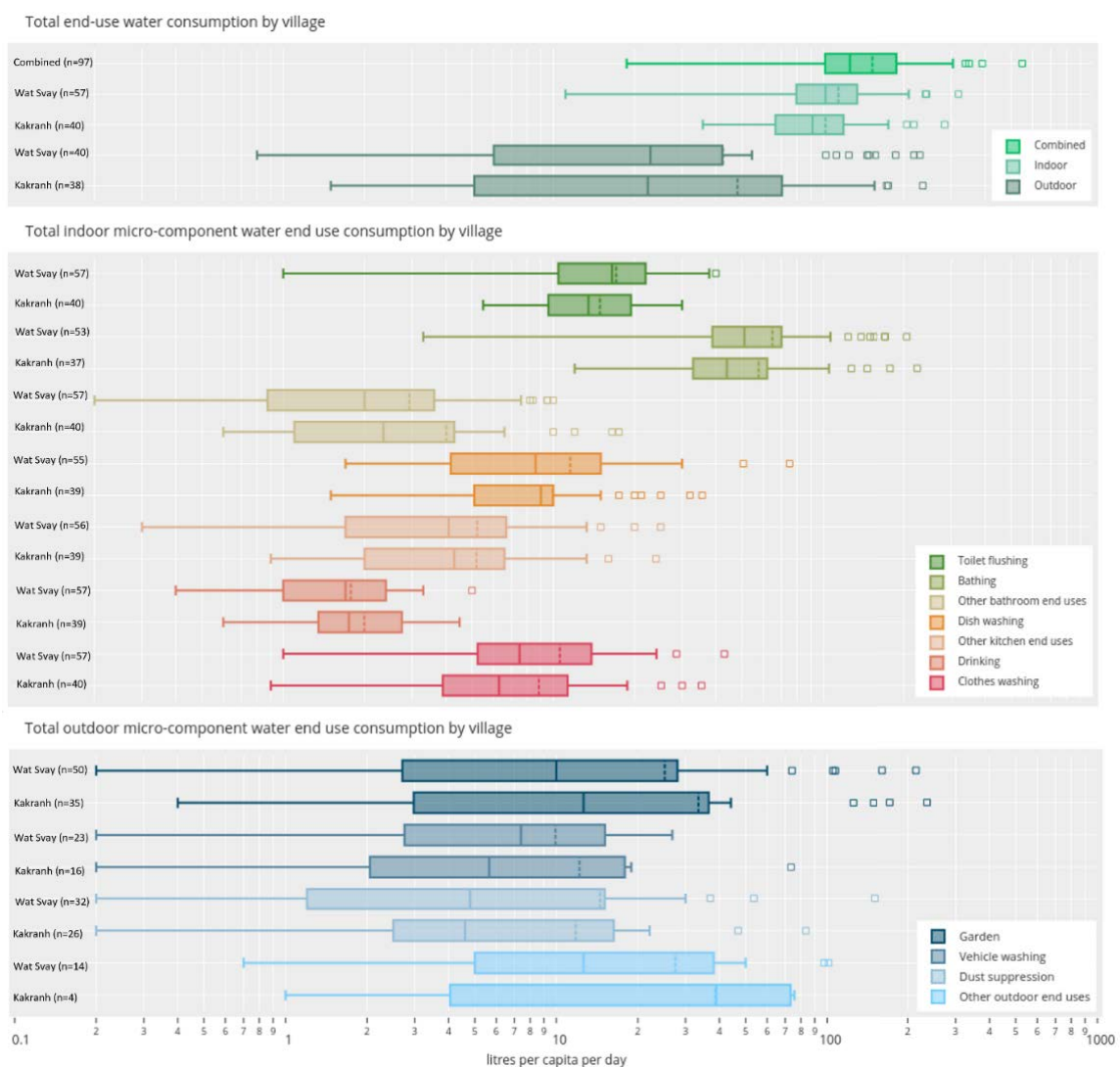
Table 6: The influence of water access typology on end-use demand by village

Village	Wat Svay		Kakranh		Total	
	Frequency n (%)	Average Volume (lpcd)	Frequency n (%)	Average Volume (lpcd)	Frequency n (%)	Average Volume (lpcd)
By water access typology						
Combined average	57 (100%)	154.4	40 (100%)	147.6	97 (100%)	151.6
Public reticulated	6 (10.5%)	158.7	2 (5.0%)	235.5	8 (8.2%)	177.9
<i>Indoor component</i>	"	131.4	"	229.6	"	160.3
Private reticulated	2 (7.0%)	147.1	0 (0.0%)	-	2 (4.1%)	147.1
<i>Indoor component</i>	"	140.6	"	-	"	140.6
All reticulated	8 (18.5%)	155.8	2 (5.0%)	235.5	10 (12.3%)	171.7
<i>Indoor component</i>	"	135.0	"	229.6	"	150.8
Private borehole to header tank	23 (38.6%)	163.2	16 (40.0%)	154.6	39 (39.2%)	159.7
<i>Indoor component</i>	"	117.1	"	115.3	"	116.4
<i>Storage volume (header tank)</i>	26	1,519.2 l	14	1642.9 l	40	1,562.5 l
<i>Not specified</i>	5	-	4	-	9	-
<i>Total storage volume (vessels)</i>	19	97.4 l	14	60.0 l	33	81.5 l
Private borehole to storage vessels	26 (47.4%)	126.9	20 (52.5%)	132.7	46 (49.5%)	129.4
<i>Indoor component</i>	"	102.3	"	82.8	"	93.6
<i>Total storage volume (vessels)</i>	25	394.8 l	18	166.1 l	43	299.1 l
<i>Not specified</i>	1	-	2	-	3	-
Hand pump	0 (0.0%)	-	2 (5.0%)	59.6	2 (2.1%)	59.6
<i>Indoor component</i>	"	-	"	57.0	"	57.0
<i>Storage volume</i>	0	-	2	90.0 l	2	90.0 l
Rainwater	15 (26.3%)	6.9	6 (15.0%)	4.8	21 (21.7%)	6.3
Purchased drinking water	29 (50.9%)	1.8	17 (42.5%)	1.8	46 (47.4%)	1.8

The table shows that in *Wat Svay*, 56.1% of households have access to water via a reticulated supply or a borehole pumped to a header tank, compared to just 45.0% of households in Kakranh (Table 2). Access to water supplied by these access typologies is noteworthy, as piped water enables the adoption of appliances such as cistern flushed toilets, showers, washing machines, as well as the use of taps rather than the practice of *scooping* water from an indoor vessel for different microcomponent services. Within the case study, the transition to either type of piped supply tends to shift household water consumption practices, resulting in increased water demand for similar service outcomes, albeit with an enhanced level of convenience. For instance, in *Wat Svay*, which is designated as an urban, mean (indoor and outdoor) end-use demand is 154.7 lpcd, while in *peri-urban* Kakranh it is 147.6 lpcd, compared to 151.8 lpcd for the entire case study (Table 2).

This result is more pronounced for primary focus of most RWEUA studies discussed in the introduction. Specifically, ~73% (113.7 lpcd) of water demand could be attributed to indoor water end-use demand in *Wat Svay*, in contrast to ~69% (101.9 lpcd) in Kakranh, and in comparison, to ~71% (108.8 lpcd) over the entire study area. Indoor water demand is shown to be strongly impacted by water access typology. Overall, households that access water primarily via a reticulated supply (12.3 %, 150.8 lpcd) or header tank (39.2%, 116.4 lpcd) demonstrate higher than average indoor water demand. Meanwhile, households that access water via groundwater pumped to indoor storage vessels (49.5%, 93.6 lpcd) or the few households reliant on hand pumps (2.5%, 57.0 lpcd) demand substantially less (Table 2). Thus, planned infrastructure projects intended to rapidly expand the availability of reticulated water in *Wat Svay* (Cities Development Institute for Asia, 2019), will likely be coupled with a commensurate increase in water demand and wastewater production.

Box plots presented in Figure 4 demonstrate that the tendency for water demand for indoor end-use events to be higher in Wat Svay than in Kakranh is consistent for the four most substantial end-use microcomponents (toilet flushing, bathing, dishwashing, and clothes washing). Of these microcomponent demand profiles, toilet flushing and drinking demonstrate fewer outliers and are closer to being normally distributed. This is likely due to these events being recalled more precisely, as their use being regulated by a non-continuous flow for all household configurations (i.e. a cistern or a scoop) (see Table 3).



NB Boxplots show the median (solid line), the mean (dotted line), interquartile range, outliers, for each category.

Figure 10: Total indoor and outdoor microcomponent end-use consumption by village

For toilet flushing, lower daily per capita water demand in *Kakranh* is likely associated with an intent to reduce the cost of desludging containment units, particularly in lower-lying areas

with a high groundwater table, and lower access to nearby open drains. In these contexts, some households reported minimising water demand for flushing (see Table 5) (Global Green Growth Institute, 2019).

Table 7: The influence of household fittings and practices on indoor end-use demand by village

Village	Wat Svay		Kakranh		Total	
	Frequency n (%)	Mean Volume (lpcd)	Frequency n (%)	Mean Volume (lpcd)	Frequency n (%)	Mean Volume (lpcd)
Combined <i>indoor</i>	57 (100.0%)	113.4	40 (100.0%)	101.9	97 (100.0%)	108.7
Toilet Flushing						
Combined toilet	57 (100.0%)	17.1	40 (100.0%)	14.9	97 (100.0%)	16.2
Cistern	23 (40.4%)	15.7	15 (37.5%)	15.0	38 (39.2%)	15.4
Dual flush	7 (12.3%)	16.7	2 (5.0%)	16.4	9 (9.3%)	16.6
Single flush	16 (28.1%)	15.3	13 (32.5%)	14.9	29 (29.9%)	15.1
Scoop	34 (59.6%)	17.7	25 (62.5%)	14.1	59 (60.8%)	16.1
Pedestal	15 (26.3%)	18.7	6 (15.0%)	15.6	21 (21.6%)	17.5
Squat	19 (33.3%)	17.0	19 (47.5%)	13.5	38 (39.2%)	15.4
Bathing						
Combined bathing	57 (100.0%)	64.9	40 (100.0%)	57.6	97 (100.0%)	61.9
Shower only	8 (14.0%)	116.6	6 (15.0%)	106.5	14 (14.4%)	112.3
Both	9 (15.8%)	58.0	1 (2.5%)	41.7	10 (10.3%)	56.2
Scoop only	40 (70.2%)	56.0	33 (82.5%)	50.9	73 (75.3%)	53.7
Bathroom storage volume	44 (77.2%)	150.9 l	35 (87.5%)	89.4 l	79 (81.4%)	123.7 l
Other Bathroom						
Combined	53 (93.0%)	2.9	40 (100.0%)	4.0	93 (95.9%)	3.4
Dish Washing						
Combined	57 (100.0%)	11.6	39 (97.5%)	10.0	96 (99.0%)	10.9
Running Tap	7 (12.3%)	24.8	4 (10.0%)	28.5	11 (11.3%)	26.1
Both	1 (1.8%)	50.6	-	-	1 (1.0%)	50.6
<i>Jaan Dyke</i>	49 (86.0%)	8.8	35 (87.5%)	7.8	84 (86.6%)	8.4
Not applicable	0 (0.0%)	-	1 (2.5%)	-	1 (1.0%)	-
Drinking						
Combined drinking	57 (100.0%)	1.8	40 (100.0%)	2.0	97 (100.0%)	1.9
Other Kitchen						
Combined	57 (100.0%)	5.2	39 (97.5%)	5.2	96 (99.0%)	5.2
Indoor Storage	23 (40.4%)	37.9 l	16 (40.0%)	53.1 l	39 (40.2%)	44.0 l
Outdoor Storage	10 (17.5%)	417.0 l	9 (22.5%)	211.3 l	19 (19.6%)	325.6 l
Clothes Washing						
Combined laundry	55 (96.5%)	10.6	39 (97.5%)	8.8	94 (96.9%)	10.9
Machine	11 (19.3%)	14.9	2 (5.0%)	18.3	13 (13.4%)	15.4
Both	8 (14.0%)	8.7	6 (15.0%)	8.9	14 (14.4%)	8.8
By Hand	36 (63.2%)	9.7	31 (77.5%)	8.2	67 (69.1%)	9.0
Laundry Service	2 (3.5%)	-	1 (2.5%)	-	3 (3.1%)	-

For bathing, dishwashing, and clothes washing, daily per capita end-use volumes have broader distributions, skewed towards higher end-use volumes, with more outliers (see *Figure 4*). This indicates an uneven demand for water for services related to these end-uses, with the capacity of these households to consume water and dispose of wastewater tending to be more heterogeneous.

Figure 4 also demonstrates that the distribution of water demand for these types of end-uses is broader in *Wat Svay* than in *Kakranh*. Across the sampled households, the primary water source of ~80% of the sample is not directly regulated by price but rather by the capacity to self-finance water access and electricity costs for pumping. This insight may suggest that the degree of heterogeneity of water consumed for these end-uses in *Wat Svay* is greater, where, on average, there is a higher capacity to invest in more convenient water access typologies.

Table 8: The influence of water end-use practices on outdoor water consumption

Village	Wat Svay		Kakranh		Total	
	Frequency n (%)	Average Volume (lpcd)	Frequency n (%)	Average Volume (lpcd)	Frequency n (%)	Average Volume (lpcd)
Combined outdoor	57 (100.0%)	41.0	40 (100.0%)	45.7	97 (100.0%)	42.9
Gardening						
Combined garden	50 (87.7%)	25.1	35 (87.5%)	33.5	85 (87.6%)	28.6
Hose	27 (47.4%)	41.3	21 (52.5%)	39.8	48 (49.5%)	44.6
Bucket	23 (40.4%)	6.2	13 (32.5%)	7.7	36 (37.1%)	6.8
Both	0 (0.0%)	-	1 (2.5%)	235.5	1 (1.0%)	235.5
No garden	7 (12.3%)	-	5 (12.5%)	-	11 (11.3%)	-
Vehicle Washing						
Combined	23 (40.3%)	9.9	16 (40.0%)	12.2	39 (40.2%)	10.8
Hose	17 (29.8%)	11.0	13 (32.5%)	13.1	30 (30.9%)	12.2
Bucket	6 (10.5%)	4.6	3 (7.5%)	3.8	9 (9.3%)	4.3
Service Provider	31 (54.4%)	-	19 (47.5%)	-	50 (51.5%)	-
Not applicable	3 (5.3%)	-	3 (7.5%)	-	6 (6.2%)	-
Dust Suppression						
Combined	32 (56.1%)	14.5	26 (65.0%)	11.8	58 (59.8%)	13.3
Hose	24 (42.1%)	18.1	19 (47.5%)	14.4	43 (44.3%)	16.5
Bucket	8 (17.6%)	3.5	7 (22.5%)	4.6	15 (15.5%)	4.0
Not applicable	23 (40.4%)	-	12 (30.0%)	-	35 (36.1%)	-

In contrast to indoor water demand, lower outdoor water demand is observed in *Wat Svay* (41.0 lpcd) than in *Kakranh* (45.7 lpcd) compared to an overall average for the entire case study (42.9 lpcd). Outdoor water demand is also shown to be impacted by water access typology. Approximately 88.7% of households access water primarily from private boreholes (excluding consumption of rainwater, purchased packaged water, and greywater reuse) and are shown to consume substantially more water than 12.3% of households that access publicly or privately reticulated and metered supplies (*Table 2*). This general trend is consistent across both villages. It is unclear whether plans to expand reticulated supply in the municipality will decrease water demand for outdoor uses ([Cities Development Institute for Asia, 2019](#)). Typically, houses that connect to the reticulated supply maintain their borehole for select non-potable uses.

Table 4 demonstrates that households in *Kakranh* consistently demonstrate higher daily per capita water demand for garden, vehicle washing, and dust suppression microcomponent uses. This tendency may be due to multiple factors. Firstly, there is a lower proportion of reticulated and priced water access typologies in *Kakranh* (see *Table 3*). Flows from pumps, particularly those not connected to a header tank, are often poorly regulated, with relatively high flow rates (see *Table 6*).

Second, there is both a capacity and behavioural norm for households to allow sullage, blackwater, as well as other water used for outdoor purposes to be disposed of as surface flows into open drains or rice fields. In *Kakranh*, a lower population density, and a greater prevalence of vernacular stilted or raised houses resilient to flooding events facilitate this practice.

In *Wat Svay*, where localised conflicts over the impacts of outdoor water use, stormwater, wastewater, and the disposal of municipal solid waste are more common. This

is due to a greater prevalence of higher-density housing that may not have access to adequate or resilient drainage infrastructure, acting as a driver of reduced outdoor water demand that is less compelling in *Kakranh* (Global Green Growth Institute, 2019).

5.4.2.2 Income level

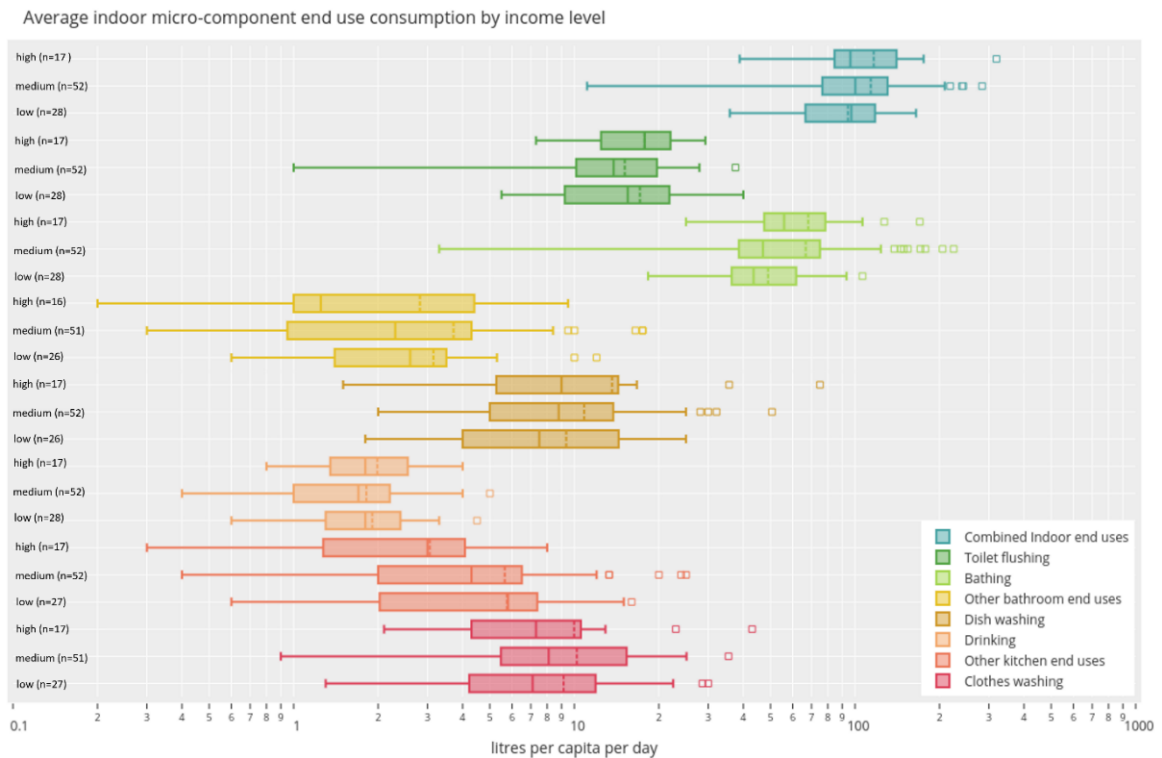
Overall, across the study area, higher income levels typically indicate higher-than-average indoor water consumption. ID-Poor households (94.4 lpcd) demand less water than medium-income (113.8 lpcd) and high-income households (116.6 lpcd) (see Figure 5). As with results disaggregated by village, water demand for toilet flushing and drinking is closest to being normally distributed. Low-income households demonstrate narrower, normally distributed demand distributions for each major end-use type, with fewer outliers. Uneven demand for toilet flushing, bathing, dishwashing, and clothes washing is more prevalent in medium and high-income households. Households often opt to exploit opportunities to adopt options for more convenient water consumption practices differently depending on factors such as the cost of connecting to a reticulated supply, purchasing household appliances, electricity bills, age or the presence of stay-at-home family members.

Higher water demand in medium- and high-income households may be attributed to greater volumes used for *bathing, washing, and washing clothes* (see Table 3). This increase is likely associated with a reticulated supply or header tank and the capacity to transition to showers and bidets rather than scooping water or bucket bathing. The same transition occurs when households wash dishes under a running tap or a washing machine instead of hand-washing clothes in a bucket. Table 3 demonstrates that high-income households have a narrower water demand distribution than middle-income households for these end-uses, as they can more easily transition to more convenient practices.

Table 9: The influence of containment and transportation infrastructure on blackwater sinks

Village	Wat Svay		Kakranh		Total	
	Frequency n (%)	Average Volume (lpcd)	Frequency n (%)	Average Volume (lpcd)	Frequency n (%)	Average Volume (lpcd)
By containment typology						
Septic tank	2 (3.5%)	7.1	1 (2.5%)	21.6	3 (3.1%)	12.0
Double pit latrine	31 (54.4%)	16.6	25 (62.5%)	15.1	56 (57.7%)	15.9
First pit lined	28 (49.1%)	16.5	23 (57.5%)	15.0	51 (52.6%)	15.8
First pit unlined	3 (5.3%)	18.3	2 (5.0%)	15.8	5 (5.2%)	17.3
Second pit lined	3 (5.3%)	14.5	2 (5.0%)	16.0	5 (5.2%)	15.1
Second pit unlined	25 (43.9%)	16.6	21 (52.5%)	14.9	46 (47.4%)	15.9
Single pit latrine	24 (42.1%)	18.1	14 (35.0%)	12.5	38 (39.2%)	16.0
Lined	3 (5.3%)	23.1	0 (0.0%)	-	3 (3.1%)	23.1
Unlined	21 (36.8%)	15.4	14 (35.0%)	12.5	35 (36.1%)	14.3
By faecal sludge disposal method						
Direct sewer connection	3 (3.5%)	40.9	1 (2.5%)	21.6	4 (3.1%)	34.5
Sewer	5 (12.3%)	18.3	0 (0.0%)	-	5 (7.2%)	18.3
Open drain	9 (15.8%)	24.0	6 (15.0%)	19.5	15 (15.5%)	22.2
Faecal sludge collection	25 (43.9%)	14.1	8 (20.0%)	13.1	33 (35.1%)	13.9
Surface disposal	4 (7.0%)	14.8	7 (17.5%)	12.1	11 (11.3%)	13.1
Unspecified	11 (19.3%)	13.6	18 (45.0%)	13.9	29 (29.9%)	13.8
By septage disposal method						
Sewer	8 (3.5%)	22.3	1 (2.5%)	14.3	9 (3.1%)	21.4
Open drain	6 (8.8%)	13.8	6 (15.0%)	14.9	13 (7.2%)	14.3
Leaches into soil	25 (56.1%)	14.6	19 (47.5%)	12.8	44 (50.5%)	14.1
Pit overflows in the wet season	18 (31.6%)	18.1	14 (35.0%)	16.1	32 (39.2%)	17.2

For *toilet flushing*, where water demand is equally well-regulated by both scooping and flushing practices, higher water demand may be attributed access to a sewer or open drain in *Wat Svay*; or the capacity to direct septage contained within pits to a surrounding rice field in less densely populated areas in both villages (see Table 5). Community-led efforts to raise funds and obtain institutional support for drainage projects in both villages were observed to be more likely to be enacted in areas with a greater concentration of high-income households. Some low-income households reported limiting flush volumes to mitigate the costs of pit-emptying or self-transferring waste to an open drain.



NB Boxplots show the median (solid line), the mean (dotted line), interquartile range, outliers, for each category.

Figure 11: Total indoor and microcomponent end-use consumption by income level

5.4.2.3 Household size

From previous studies in contexts that are more homogeneous (i.e. focused on a single socio demographic grouping), it might be expected that per capita water demand would demonstrate an economy of scale as a function of household size (Sadr et al. 2016). However, this was not observed in the data. Average per-capita water demand was lowest for small households (98.6 lpcd, 1 to 2 people) and extended households (99.3 lpcd, > 9 people). Each of these subgroups demonstrated a narrower distribution compared to households comprising 3 to 5 people (102.8 lpcd) and 6 to 8 people (122.8 lpcd). The latter categories demonstrated a broader and more heterogeneous range of estimates for per capita demand.

The heterogeneity of the sample explains the difference in expected results. The sample's dominant grouping of small households (1-2 people) was low-income, *newcomer* households, of which a portion lived in rental accommodation. Meanwhile, the largest

households in the sample (> 9 people) are all landowners, with few low-income households or *newcomers*. Further, 46% of the households in this cohort had been established for more than 20 years, and most were medium-to-high-income with well-established end-use practices. Larger households (6 to 8 people) were the most heterogeneous group with no specific cluster dominating, accounting for the broad distribution of per capita water consumption and being more likely to transition to more convenient but less water-efficient end-use practices. Medium-sized households (3 to 5 people) had relatively fewer high-income households and a high proportion of newly established households.

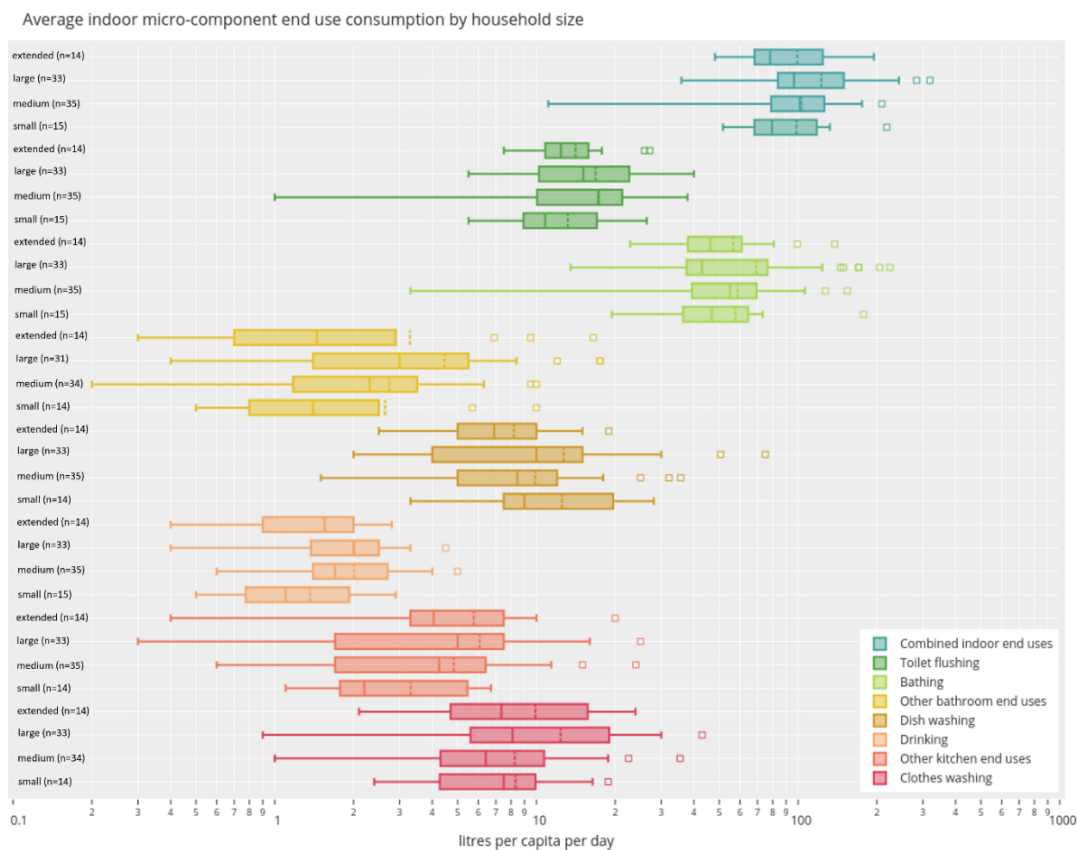


Figure 12: Total indoor and microcomponent end-use consumption by household size

Water demand for *toilet flushing*, *bathing*, *dishwashing*, and *clothes washing* produced less discernible trends in relation to household size. As with village of residence and income level, the distribution of water demand for toilet flushing and drinking was well-regulated and relatively consistent across different household sizes. Bathing and dishwashing water

demand for medium-sized (3 to 5 people) and large (6 to 8 people) households demonstrated a broader distribution, with higher numbers of outliers. This result further supports the idea that these households have less fixed, and more heterogeneous water consumption profiles and are more likely to transition to new end-use typologies.

5.4.2.4 Length of tenure

Water demand associated with indoor usage supported knowledge collected from households about the impact of length of tenure. Typically, households with a tenure of greater than 30 years demonstrated lower overall water demand (100.0 lpcd), as well as for *toilet flushing, bathing, dishwashing, and clothes washing* (see Figure 7). This result is consistent with interactions during surveys where households with long-term tenure strongly preferred *vernacular* housing and water management approaches.

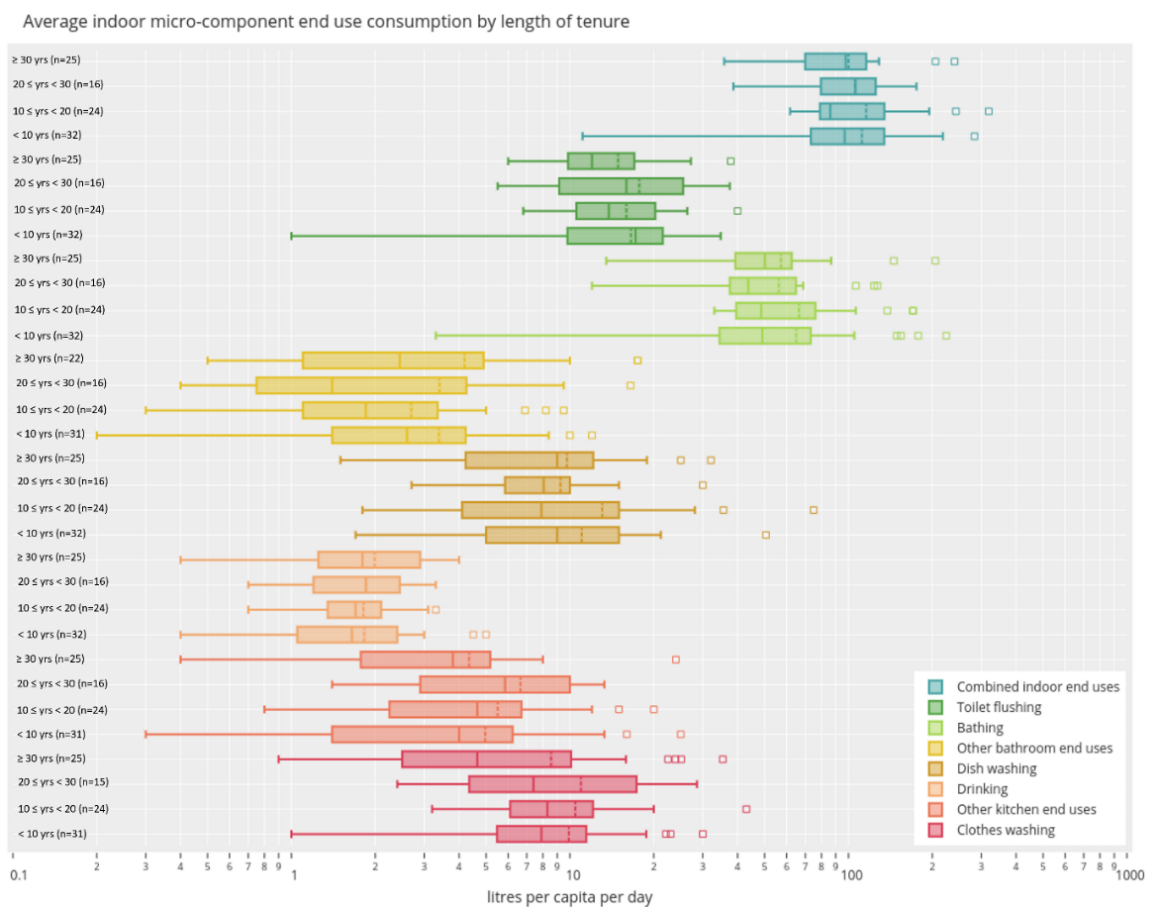


Figure 13: Total indoor and microcomponent end-use consumption by length of tenure

This approach is aligned with a preference for no fences dividing households, raised housing, and open areas below houses allowing people and water to move freely. This culture is associated with a greater likelihood of shared water infrastructure, including boreholes and pumps and wastewater sinks such as rice fields.

These practices were most strongly distinguished from *newcomers* (< 10 years, 111.6 lpcd) and other *recently established* households ($10 \leq \text{years} < 20$, 115.9 lpcd), primarily drawn to Siem Reap Municipality by the tourism economy. These households typically resided in newer or more modern housing with clearly defined boundaries. This housing is more likely to be securely fenced, with housing types that impede the flow of water, people, and the sharing of community resources. In these zones, planning drainage infrastructure was more important to avoid problems with flooding. In contrast, households repatriating to the study area in the 1990s *post-conflict period* ($20 \leq \text{years} < 30$, 105.4 lpcd) were more likely to align with vernacular end-use consumption practices.

Newcomers to the study area demonstrated the most diverse characteristics, roughly comprising two subgroups. The first are low to medium-income households with five or fewer people. The second was medium to high-income households with 6 or more people. These subgroups account for the broad water end-use distribution for most key microcomponents in the study area. Households repatriated in the study area in the post-conflict period in the 1990s comprised fewer low-income households and were typically larger. The subgroup primarily drawn to the study area by the tourism economy, while still mainly comprising larger households, had a broader mix of income levels and a larger proportion of households with ID Poor status.

5.4.3 A heterogeneous end-use water balance

As outlined in the introduction of this paper, the aim of this study was to conduct a RWEUA for a heterogeneous urban water and sanitation configuration by sampling a socio-technically diverse range of households within the same water balance. In doing so, we aimed to more accurately represent the existing, or without-project situation in Siem Reap Municipality, enabling the water and sanitation planning context to be perceived from a broad, inclusive, societal perspective. Adopting this lens was expected to shift the boundaries of how these configurations are typically understood in urban water planning.

Prior to this study, knowledge of the systemic behaviour of water and wastewater services in Siem Reap Municipality was based on historical census data recording differences in access typologies in different areas of a city ([National Institute of Statistics, 2023](#)). Planning practices typically forecast demand for water supply infrastructure based on available metered data, disaggregated by resident and tourist populations (personal communication, utility representative). Projections for wastewater infrastructure are based on per capita estimates made for maximum blackwater and greywater production from households assumed to be serviced by standardised off-site or on-site configurations ([Ministry of Public Works and Transport, 2023](#)). These assumptions often diverge from the heterogeneous service realities observed in the municipality. Water and sanitation planning has therefore remained framed largely through the institutional lenses of the *Siem Reap Water Supply Authority* and *Siem Reap Wastewater Treatment Plant Unit*, focusing on the provision of centralised piped water, sewerage, and faecal sludge treatment services.

Complementary analyses, such as those using faecal waste flow diagrams, have aimed to identify service gaps from the perspective of different actors across the sanitation service chain ([IRC & WaterAid, 2016](#); [Global Green Growth Institute, 2019a](#)). While valuable, these

approaches are also constrained by their reliance on relatively static and homogenous estimates of water demand (Scott & Cotton, 2020). In contrast, this study accesses a more context-sensitive understanding of water and sanitation system behaviour by grounding analysis in observed end-use data from diverse households.

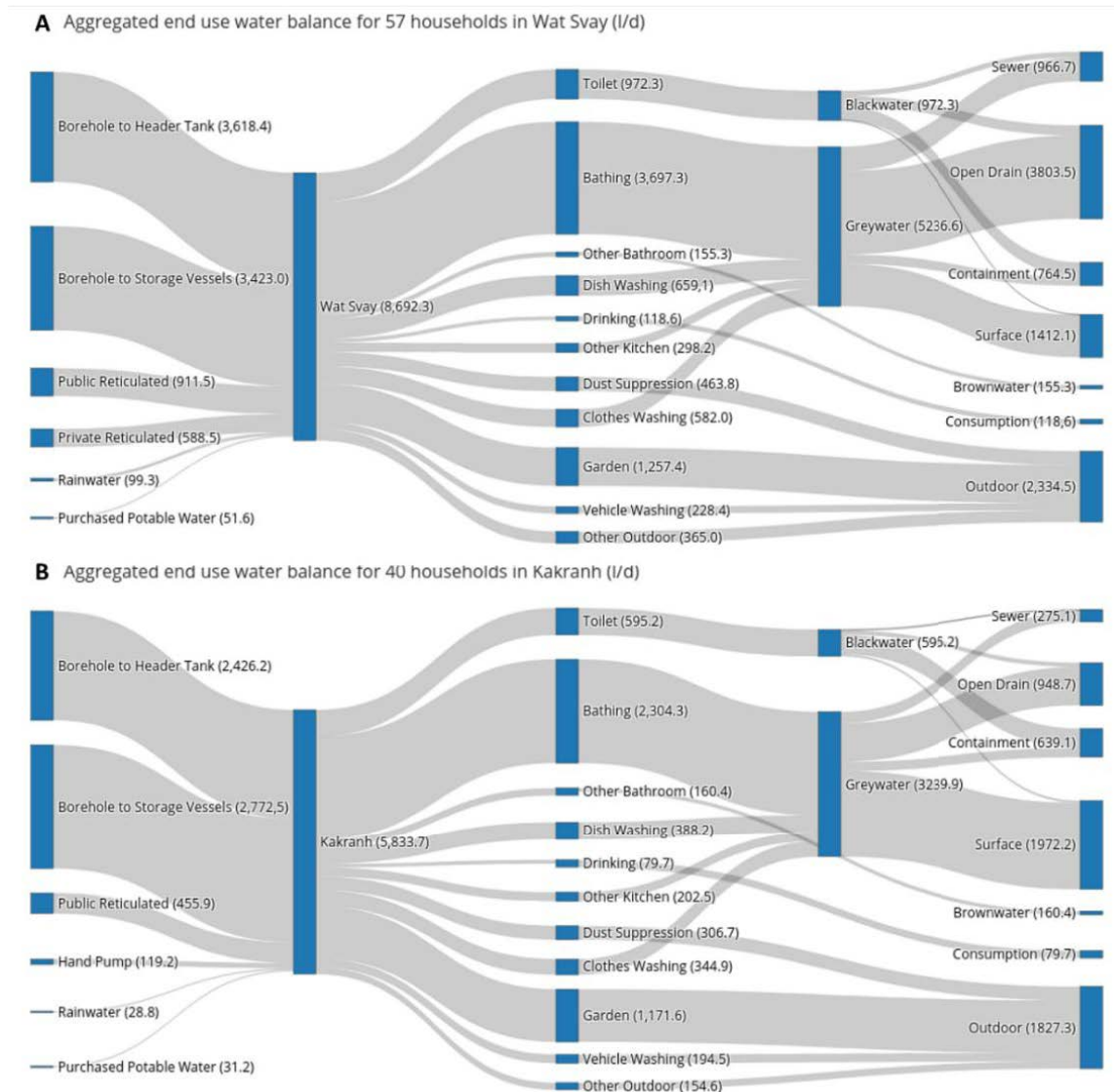


Figure 14: Water end-use balance disaggregated for (A) Wat Svay and (B) Kakranh village

The two Sankey diagrams in *Figure 14* present an overall water balance for the study site that captures the existing, heterogeneous demand for discrete water-related services. Aggregated microcomponent end-use volumes for all sampled households are represented at the centre of each diagram (in litres per day), enabling a visualisation of how water is

allocated across multiple service needs in each village. This representation of the data collected during the survey and observation protocol for the RWEUA offers an aggregated bottom-up perspective of the dynamic interface between water is demanded, and services are supplied. By focusing on discrete end-use events, this approach enables critical public water, sanitation, and hygiene services to be analysed in terms of the actual water resources required for their provision. As such, it provides a robust basis for comparing household service configurations and planning for more inclusive and adaptive infrastructure solutions.

The end-use parameters (see *Section 3.4*) that underpin the water balance provide a foundation for scaling and comparing household typologies and consumption practices across the heterogeneous mix of service configurations found in Siem Reap municipality. These data may also be scaled to analyse broader resource impacts from drawing from urban water resources and returning wastewater sinks. In doing so, the analysis supports a more holistic interpretation of how services are experienced and perceived by households, informal or formal service providers, and their enabling environments.

5.4.4 Bottom-up end-use parameters for modelling future scenarios

This section presents the results of the RWEUA as a disaggregated set of average end-use parameters (frequency, duration, and intensity) for each water-related service reported via the survey. These parameters are the empirical basis for the model depicted in the Sankey diagram and are detailed in [Table 6](#). They provide a foundation for discussing the strengths and limitations of this data and how the co-production of this knowledge may be improved. In particular, the potential of these parameters to act as a *without-project* comparator to support the identification and prioritisation of context-specific interventions that may otherwise not be visible to planners.

Table 10: Average micro-component parameters for end-use events by water demand typology

Village	Wat Svay				Kakranh				Total			
Parameter	Freq.	Dur.	Flow	Vol.	Freq.	Dur.	Flow	Vol.	Freq.	Dur.	Flow	Vol.
Indoor end-use parameters												
Toilet flushing end-use parameters												
Units	events per capita per day	flushes per event	litres per flush	litres per capita per day	events per capita per day	flushes per event	litres per flush	litres per capita per day	events per capita per day	flushes per event	litres per flush	litres per capita per day
Flush (Urine)	2.55	1.00	3.79	9.66	2.41	1.00	3.79	9.13	2.49	1.00	3.79	9.44
	(n=124)	(n=124)	(n=124)	(n=124)	(n=87)	(n=87)	(n=87)	(n=87)	(n=211)	(n=211)	(n=211)	(n=211)
<i>Female</i>	2.80	1.00	3.78	10.58	2.82	1.00	3.88	10.95	2.81	1.00	3.82	10.72
	(n=64)	(n=64)	(n=64)	(n=64)	(n=42)	(n=42)	(n=42)	(n=42)	(n=106)	(n=106)	(n=106)	(n=106)
<i>Male</i>	2.28	1.00	3.80	8.68	2.02	1.00	3.71	7.50	2.17	1.00	3.76	8.17
	(n=60)	(n=60)	(n=60)	(n=60)	(n=45)	(n=45)	(n=45)	(n=45)	(n=105)	(n=105)	(n=105)	(n=105)
<i>< 18 yrs old</i>	2.07	1.00	3.95	8.18	2.35	1.00	3.91	9.20	2.09	1.00	3.85	8.04
	(n=48)	(n=48)	(n=48)	(n=48)	(n=29)	(n=29)	(n=29)	(n=29)	(n=77)	(n=77)	(n=77)	(n=77)
Flush (Faeces)	1.13	1.00	4.06	4.59	1.21	1.00	3.82	4.61	1.16	1.00	3.96	4.60
	(n=124)	(n=124)	(n=124)	(n=124)	(n=87)	(n=87)	(n=87)	(n=87)	(n=211)	(n=211)	(n=211)	(n=211)
<i>Female</i>	1.16	1.00	4.02	4.64	1.27	1.00	3.91	4.98	1.20	1.00	3.97	4.78
	(n=64)	(n=64)	(n=64)	(n=64)	(n=42)	(n=42)	(n=42)	(n=42)	(n=106)	(n=106)	(n=106)	(n=106)
<i>Male</i>	1.10	1.00	4.12	4.53	1.14	1.00	3.74	4.28	1.12	1.00	3.95	4.42
	(n=60)	(n=60)	(n=60)	(n=60)	(n=45)	(n=45)	(n=45)	(n=45)	(n=105)	(n=105)	(n=105)	(n=105)
<i>< 18 yrs old</i>	1.06	1.00	4.16	4.42	1.12	1.00	3.68	4.13	1.08	1.00	3.98	4.31
	(n=48)	(n=48)	(n=48)	(n=48)	(n=29)	(n=29)	(n=29)	(n=29)	(n=77)	(n=77)	(n=77)	(n=77)
Units	events per capita per day	scoops per event	litres per scoop	litres per capita per day	events per capita per day	scoops per event	litres per scoop	litres per capita per day	events per capita per day	scoops per event	litres per scoop	litres per capita per day
Scoop (Urine)	2.33	2.77	1.54	9.93	1.79	3.18	1.49	8.48	2.10	2.95	1.52	9.38
	(n=185)	(n=185)	(n=185)	(n=185)	(n=139)	(n=139)	(n=139)	(n=139)	(n=324)	(n=324)	(n=324)	(n=324)
<i>Female</i>	2.45	2.84	1.52	10.58	1.74	3.09	1.48	7.98	2.14	2.95	1.51	9.49
	(n=101)	(n=101)	(n=101)	(n=101)	(n=79)	(n=79)	(n=79)	(n=79)	(n=180)	(n=180)	(n=180)	(n=180)
<i>Male</i>	2.20	2.70	1.55	9.17	1.86	3.29	1.50	9.17	2.06	2.94	1.53	9.24
	(n=84)	(n=84)	(n=84)	(n=84)	(n=60)	(n=60)	(n=60)	(n=60)	(n=144)	(n=144)	(n=144)	(n=144)
<i>< 18 yrs old</i>	2.15	2.73	1.56	9.13	1.69	3.20	1.52	8.19	1.93	2.95	1.54	8.76
	(n=61)	(n=61)	(n=61)	(n=61)	(n=56)	(n=56)	(n=56)	(n=56)	(n=117)	(n=117)	(n=117)	(n=117)

Scoop (Faeces)	1.12	3.93	1.54	6.75	1.01	3.49	1.49	5.26	1.07	3.74	1.52	6.08
	(n=185)	(n=185)	(n=185)	(n=185)	(n=139)	(n=139)	(n=139)	(n=139)	(n=324)	(n=324)	(n=324)	(n=324)
<i>Female</i>	1.15	3.92	1.52	6.87	0.98	3.42	1.48	4.97	1.08	3.70	1.51	5.99
	(n=101)	(n=101)	(n=101)	(n=101)	(n=79)	(n=79)	(n=79)	(n=79)	(n=180)	(n=180)	(n=180)	(n=180)
<i>Male</i>	1.08	3.94	1.55	6.61	1.06	3.57	1.50	5.66	1.07	3.78	1.53	6.20
	(n=84)	(n=84)	(n=84)	(n=84)	(n=60)	(n=60)	(n=60)	(n=60)	(n=144)	(n=144)	(n=144)	(n=144)
<i>< 18 yrs old</i>	1.11	3.79	1.56	6.57	0.99	3.43	1.52	5.16	1.06	3.62	1.54	5.87
	(n=61)	(n=61)	(n=61)	(n=61)	(n=56)	(n=56)	(n=56)	(n=56)	(n=117)	(n=117)	(n=117)	(n=117)

Bathing end-use parameters												
Units	events per capita per day	minutes per event	litres per minute	litres per capita per day	events per capita per day	minutes per event	litres per minute	litres per capita per day	events per capita per day	minutes per event	litres per minute	litres per capita per day
Shower (annualised)	2.31 (n=93)	8.41 (n=93)	5.84 (n=93)	110.97 (n=93)	2.36 (n=45)	7.13 (n=45)	9.38 (n=45)	159.54 (n=45)	2.33 (n=138)	7.99 (n=138)	7.00 (n=138)	126.81 (n=138)
<i>Shower (typical)</i>	2.39 (n=93)	8.41 (n=93)	5.84 (n=93)	114.83 (n=93)	2.42 (n=45)	7.13 (n=45)	9.38 (n=45)	163.65 (n=45)	2.40 (n=138)	7.99 (n=138)	7.00 (n=138)	130.75 (n=138)
<i>Shower (cold season)</i>	1.94 (n=93)	7.85 (n=93)	6.36 (n=93)	95.59 (n=93)	2.06 (n=45)	6.71 (n=45)	8.99 (n=45)	124.92 (n=45)	1.98 (n=138)	7.48 (n=138)	7.21 (n=138)	105.61 (n=138)
<i>Female (annualised)</i>	2.26 (n=38)	9.78 (n=38)	4.59 (n=38)	101.35 (n=38)	2.43 (n=21)	7.81 (n=21)	10.03 (n=21)	190.25 (n=21)	2.32 (n=59)	9.08 (n=59)	6.53 (n=59)	132.99 (n=59)
<i>Male (annualised)</i>	2.35 (n=55)	7.46 (n=55)	6.71 (n=55)	117.62 (n=55)	2.31 (n=24)	6.53 (n=24)	8.81 (n=24)	132.68 (n=24)	2.34 (n=79)	7.18 (n=79)	7.53 (n=79)	122.20 (n=79)
<i>< 18 yrs old (annualised)</i>	2.30 (n=20)	7.93 (n=20)	5.76 (n=20)	105.43 (n=20)	2.36 (n=12)	6.32 (n=12)	8.87 (n=12)	137.14 (n=12)	2.32 (n=32)	7.32 (n=32)	6.93 (n=32)	117.32 (n=32)

Units	events per capita per day	scoops per event	litres per scoop	litres per capita per day	events per capita per day	scoops per event	litres per scoop	litres per capita per day	events per capita per day	scoops per event	litres per scoop	litres per capita per day
Scoop (annualised)	2.36 (n=173)	13.52 (n=173)	1.57 (n=173)	50.13 (n=173)	2.25 (n=117)	12.17 (n=117)	1.53 (n=117)	41.67 (n=117)	2.32 (n=290)	12.97 (n=290)	1.55 (n=290)	46.72 (n=290)
<i>Scoop (typical)</i>	2.50 (n=173)	13.52 (n=173)	1.57 (n=173)	52.98 (n=173)	2.36 (n=117)	12.17 (n=117)	1.53 (n=117)	44.84 (n=117)	2.44 (n=290)	12.97 (n=290)	1.55 (n=290)	49.29 (n=290)
<i>Scoop (cold season)</i>	1.85 (n=173)	13.26 (n=173)	1.59 (n=173)	38.95 (n=173)	1.91 (n=117)	8.69 (n=117)	1.53 (n=117)	35.55 (n=117)	1.87 (n=290)	12.82 (n=290)	1.56 (n=290)	37.58 (n=290)
<i>Female (annualised)</i>	2.40 (n=87)	14.02 (n=87)	1.53 (n=87)	50.08 (n=87)	2.26 (n=65)	12.75 (n=65)	1.49 (n=65)	42.99 (n=65)	2.34 (n=152)	13.47 (n=152)	1.51 (n=152)	47.88 (n=152)
<i>Male (annualised)</i>	2.32 (n=86)	13.01 (n=86)	1.61 (n=86)	43.40 (n=86)	2.23 (n=52)	11.45 (n=52)	1.57 (n=52)	40.02 (n=52)	2.29 (n=138)	12.42 (n=138)	1.59 (n=138)	45.43 (n=138)

<i>< 18 yrs old (annualised)</i>	2.46 (n=50)	12.33 (n=50)	1.47 (n=50)	44.71 (n=50)	2.35 (n=45)	12.17 (n=45)	1.58 (n=45)	32.33 (n=45)	2.41 (n=95)	10.61 (n=95)	1.52 (n=95)	38.84 (n=95)
Units	events per capita per day	buckets per event	litres per bucket	litres per capita per day	events per capita per day	buckets per event	litres per bucket	litres per capita per day	events per capita per day	buckets per event	litres per bucket	litres per capita per day
Bucket (annualised)	2.31 (n=64)	1.46 (n=64)	19.56 (n=64)	65.84 (n=64)	2.14 (n=75)	1.32 (n=75)	19.56 (n=75)	54.78 (n=75)	2.22 (n=139)	1.38 (n=139)	19.53 (n=139)	59.87 (n=139)
<i>Bucket (typical)</i>	2.39 (n=64)	1.46 (n=64)	19.56 (n=64)	68.04 (n=64)	2.19 (n=75)	1.32 (n=75)	19.56 (n=75)	56.21 (n=75)	2.28 (n=139)	1.38 (n=139)	19.53 (n=139)	61.66 (n=139)
<i>Bucket (cold season)</i>	1.92 (n=64)	1.46 (n=64)	19.56 (n=64)	54.83 (n=64)	1.86 (n=75)	1.32 (n=75)	19.56 (n=75)	47.61 (n=75)	1.89 (n=139)	1.38 (n=139)	19.53 (n=139)	50.93 (n=139)
<i>Female (annualised)</i>	2.33 (n=59)	1.39 (n=59)	19.73 (n=59)	63.58 (n=59)	2.02 (n=152)	1.36 (n=152)	19.73 (n=152)	54.14 (n=152)	2.16 (n=81)	1.37 (n=81)	19.73 (n=81)	58.45 (n=81)
<i>Male (annualised)</i>	2.29 (n=79)	1.56 (n=79)	19.32 (n=79)	68.93 (n=79)	2.31 (n=138)	1.26 (n=138)	19.19 (n=138)	55.68 (n=138)	2.30 (n=58)	1.40 (n=58)	19.25 (n=58)	61.85 (n=58)
<i>< 18 yrs old (annualised)</i>	2.45 (n=32)	1.28 (n=32)	19.02 (n=32)	59.82 (n=32)	2.28 (n=95)	1.18 (n=95)	19.02 (n=95)	49.37 (n=95)	2.35 (n=50)	1.23 (n=50)	18.82 (n=50)	52.97 (n=50)

Other bathroom end-use parameters

Units	estimate per day		litres	litres per household per day	estimate per day		litres	litres per household per day	estimate per day		litres	litres per household per day
Other Personal Hygiene	1.00 (n=53)	-	2.92 (n=53)	2.92 (n=53)	1.00 (n=40)	-	4.01 (n=40)	4.01 (n=40)	1.00 (n=93)	-	3.39 (n=93)	3.39 (n=93)

Units			litres per minute				litres per minute				litres per minute	
Bidet	-	-	5.45 (n=9)	-	-	-	5.82 (n=5)	-	-	-	5.60 (n=14)	-

Kitchen end-use parameters

Dishwashing end-use parameters

Units	events per household per day	minutes per event	litres per minute	litres per household per day	events per household per day	minutes per event	litres per minute	litres per household per day	events per household per day	minutes per event	litres per minute	litres per household per day
Running Tap	2.86 (n=7)	5.28 (n=7)	7.26 (n=7)	134.24 (n=7)	2.50 (n=4)	6.81 (n=4)	10.00 (n=4)	161.82 (n=4)	2.73 (n=11)	5.83 (n=11)	8.64 (n=11)	134.24 (n=11)

Units	events per household per day	buckets per event	litres per bucket	litres per household per day	events per household per day	buckets per event	litres per bucket	litres per household per day	events per household per day	buckets per event	litres per bucket	litres per household per day
By hand	2.35 (n=49)	2.52 (n=49)	7.77 (n=49)	42.66 (n=49)	2.22 (n=35)	2.41 (n=35)	7.93 (n=35)	40.00 (n=35)	2.31 (n=84)	2.48 (n=84)	7.77 (n=84)	42.66 (n=84)
Drinking end-use parameters												
Units	estimate per day		litres	litres per household per day	estimate per day		litres	litres per household per day	estimate per day		litres	litres per household per day
All sources	1.00 (n=57)	-	1.77 (n=57)	1.77 (n=57)	1.00 (n=40)	-	1.90 (n=40)	1.90 (n=40)	1.00 (n=97)	-	1.87 (n=97)	1.87 (n=97)
Other kitchen end-use parameters												
All other end-uses	1.00 (n=57)	-	5.23 (n=57)	5.23 (n=57)	1.00 (n=40)	-	5.19 (n=40)	5.19 (n=40)	1.00 (n=97)	-	5.22 (n=97)	5.22 (n=97)
Laundry end-use parameters												
Clothes washing end -use parameters												
Units	events per household per day	cycles per event	litres per cycle	Litres per household per day	events per household per day	cycles per event	litres per cycle	Litres per household per day	events per household per day	cycles per event	litres per cycle	Litres per household per day
By machine	0.78 (n=12)	1.00 (n=12)	85.42 (n=12)	66.85 (n=2)	1.21 (n=2)	1.00 (n=2)	96.00 (n=2)	122.36 (n=2)	0.84 (n=14)	1.00 (n=14)	86.93 (n=14)	74.78 (n=14)
Both (combined)	0.61 (n=8)	-	-	37.72 (n=8)	1.09 (n=7)	-	-	72.53 (n=7)	0.86 (n=15)	-	-	54.69 (n=15)
Both (by machine)	0.26 (n=8)	1.00 (n=8)	76.57 (n=8)	19.53 (n=8)	0.64 (n=7)	1.00 (n=7)	73.38 (n=7)	46.62 (n=7)	0.46 (n=15)	1.00 (n=15)	74.87 (n=15)	34.28 (n=15)
Units	events per household per day	buckets per event	litres per bucket	litres per household per day	events per household per day	buckets per event	litres per bucket	litres per household per day	events per household per day	buckets per event	litres per bucket	litres per household per day
Both (by hand)	0.35 (n=8)	2.75 (n=8)	16.88 (n=8)	18.19 (n=8)	0.45 (n=7)	2.79 (n=7)	20.71 (n=7)	25.91 (n=7)	0.40 (n=15)	2.77 (n=15)	18.67 (n=15)	20.41 (n=15)
By hand	0.74 (n=36)	2.87 (n=36)	19.92 (n=36)	42.96 (n=36)	0.85 (n=29)	2.86 (n=29)	18.99 (n=29)	45.15 (n=29)	0.79 (n=65)	2.86 (n=65)	19.52 (n=65)	43.94 (n=65)

Outdoor end-use parameters												
Garden												
Units	events per household per day	minutes per event	litres per minute	litres per household per day	events per household per day	minutes per event	litres per minute	litres per household per day	events per household per day	minutes per event	litres per minute	litres per household per day
Hose (wet season)	2.00 (n=1)	5.00 (n=1)	10.00 (n=1)	100.00 (n=1)	-	-	-	-	2.00 (n=1)	5.00 (n=1)	10.00 (n=1)	100.00 (n=1)
Hose (dry season)	0.74 (n=24)	19.60 (n=24)	29.92 (n=24)	435.77 (n=24)	0.64 (n=19)	20.92 (n=19)	31.79 (n=19)	425.04 (n=19)	0.70 (n=43)	20.19 (n=43)	30.78 (n=43)	431.03 (n=43)
Units	events per household per day	buckets per event	litres per bucket	litres per household per day	events per household per day	buckets per event	litres per bucket	litres per household per day	events per household per day	buckets per event	litres per bucket	litres per household per day
Bucket (wet season)	0.89 (n=14)	1.00 (n=14)	38.16 (n=14)	34.07 (n=14)	0.92 (n=7)	1.00 (n=7)	93.15 (n=7)	85.39 (n=7)	0.90 (n=21)	1.00 (n=21)	56.49 (n=21)	51.18 (n=21)
Bucket (dry season)	0.91 (n=24)	1.00 (n=24)	34.70 (n=24)	31.50 (n=24)	0.99 (n=13)	1.00 (n=13)	56.76 (n=13)	56.14 (n=13)	0.94 (n=37)	1.00 (n=37)	42.45 (n=37)	40.15 (n=37)
Vehicle Washing												
Units	events per household per day	minutes per event	litres per minute	litres per household per day	events per household per day	minutes per event	litres per minute	litres per household per day	events per household per day	minutes per event	litres per minute	litres per household per day
Hose (wet season)	0.12 (n=18)	17.08 (n=18)	29.44 (n=18)	61.70 (n=18)	0.08 (n=13)	18.62 (n=13)	38.02 (n=13)	56.15 (n=13)	0.73 (n=31)	17.73 (n=31)	33.08 (n=31)	61.22 (n=31)
Hose (dry season)	0.11 (n=18)	17.08 (n=18)	29.44 (n=18)	54.98 (n=18)	0.08 (n=13)	18.62 (n=13)	38.02 (n=13)	56.15 (n=13)	0.68 (n=31)	17.73 (n=31)	33.08 (n=31)	56.68 (n=31)
Units	events per household per day	buckets per event	litres per bucket	litres per household per day	events per household per day	buckets per event	litres per bucket	litres per household per day	events per household per day	buckets per event	litres per bucket	litres per household per day
Bucket (wet season)	0.15 (n=6)	1.00 (n=6)	166.67 (n=6)	25.29 (n=6)	0.09 (n=4)	1.00 (n=4)	215.00 (n=4)	19.20 (n=4)	0.10 (n=10)	1.00 (n=10)	186.00 (n=10)	19.42 (n=10)
Bucket (dry season)	0.15 (n=6)	1.00 (n=6)	166.67 (n=6)	25.29 (n=6)	0.06 (n=4)	1.00 (n=4)	215.00 (n=4)	13.44 (n=4)	0.10 (n=10)	1.00 (n=10)	186.00 (n=10)	17.98 (n=10)

Dust Suppression												
Units	events per household per day	minutes per event	litres per minute	litres per household per day	events per household per day	minutes per event	litres per minute	litres per household per day	events per household per day	minutes per event	litres per minute	litres per household per day
Hose (wet season)	0.39 (n=2)	6.50 (n=2)	30.00 (n=2)	76.61 (n=2)	-	-	-	-	0.39 (n=2)	6.50 (n=2)	30.00 (n=2)	76.61 (n=2)
Hose (dry season)	0.39 (n=23)	14.17 (n=23)	29.41 (n=23)	162.86 (n=23)	0.44 (n=19)	10.03 (n=19)	30.69 (n=19)	134.44 (n=19)	0.41 (n=42)	12.30 (n=42)	29.99 (n=42)	151.80 (n=42)
Units	events per household per day	buckets per event	litres per bucket	litres per household per day	events per household per day	buckets per event	litres per bucket	litres per household per day	events per household per day	buckets per event	litres per bucket	litres per household per day
Bucket (wet season)	-	-	-	-	1.00 (n=1)	1.00 (n=1)	127.50 (n=1)	127.50 (n=1)	1.00 (n=1)	1.00 (n=1)	127.50 (n=1)	127.50 (n=1)
Bucket (dry season)	0.53 (n=9)	1.00 (n=9)	74.44 (n=9)	39.59 (n=9)	0.66 (n=7)	1.00 (n=7)	79.90 (n=7)	53.08 (n=7)	0.59 (n=16)	1.00 (n=16)	76.83 (n=16)	45.31 (n=16)

5.5 Discussion

This is one of the first RWEUA studies to purposively sample from a *heterogeneous water and sanitation configuration* in an LMIC. However, several factors constrain how effectively these parameters represent the actual *without-project situation* in Siem Reap. The semi-structured survey tool should be considered a first iteration, requiring further refinement in the future for Siem Reap Municipality as a whole. Utilities or municipal authorities in other cities could also replicate and adapt the approach as a planning and asset management tool specific to their context.

The most notable limitations of the survey were the time requested from participants (~1 hour) and associated concerns about beneficence. These factors limited the depth of information reasonably requested in a questionnaire survey and what could be learned from service users. Nevertheless, the approach yields valuable insights into how water and sanitation services are demanded across different service configurations. This knowledge demonstrates cleaner production principles can be supported in an inclusive way.

RWEUA helps to identify interventions that optimise how water and wastewater resources are managed efficiently at the household level, while also being sensitive to the heterogeneous costs and benefits that emerge from how these resources are distributed at a broader urban scale. When RWEUA is used to quantify how actual end-use practices vary across household contexts, it reveals diverse opportunities reduce unnecessary water consumption and wastewater generation. This, in turn, enables diverse demand profiles to be explicitly linked to resource-efficient options that are responsive to these needs and prioritized accordingly.

5.5.1 End-use parameters for events in the bathroom

Bathroom and personal hygiene end-use events are specific to individuals rather than households. Thus, it is possible to disaggregate these parameters by examining individual attributes such as gender or age. Previous studies that have adopted this approach have required time to develop a strong rapport between researchers and participants (e.g. [Sultana et al., 2022](#)). There is a need to adapt data collection for end-uses that are more personal and sensitive. In this study, one family member would often answer questions on behalf of other household members. This situation made it harder for surveys to have the capacity to disaggregate information about the demand for water-related services for end-uses, such as anal washing or menstrual hygiene ([Tamason et al. 2016](#)). Well-designed self-administered surveys and water use diaries may address these limitations (e.g. [Alharsha et al. 2022](#)). Future innovations in direct measurement may also improve the accuracy and level of detail of end-use data.

5.5.1.1 Toilet flushing

Recall-based survey tools were well-suited for data collection for toilet flushing end-use events. Water consumption practices comprised two standard user interfaces (a squat and pedestal toilet) and two standard flushing practices (scooping from a storage vessel inside a bathroom or a cistern). In both cases, users were able to recall discrete flushing events governed by a standardised water volume that regulates water consumption. For instance, scoops used for flushing were standard sizes ranging from 1 to 2 litres, while flush volumes were often specific on cistern labels. Even if the entire scoop or flush volume was not used, the measure still offered a reproducible and reliable proxy for end-use demand. The end-use parameters for toilet flushing in *Table 6* demonstrate that both end-use practices (flushing using a scoop and cistern) produce consistent results. Female users were shown to

use water for flushing urine more frequently than men, while in general, flushing faeces with a cistern was more water efficient than using a scoop. The toilet end-use parameters may have several applications, from scaling the impact of possible sanitation service provision options, including portable septic tanks in high groundwater areas, scheduled emptying (Global Green Growth Institute, 2019), and faecal sludge treatment services or decentralised treatment options that extend the benefits of new sewer infrastructure (Chea et al. 2023).

5.5.1.2 Bathing

Bathing demand in the water balance was characterised by three practices: the use of a showerhead (facilitated by a reticulated supply or header tank), the use of a scoop from an indoor water storage vessel (such as a water jar, plastic, or concrete tank), and bucket bathing. The latter two practices, while similar, result in different per capita end-use volumes, most likely due to the less efficient use of the remaining volume in the bucket for rinsing. Ideally, the first practice, the least water-efficient service provision type, would have been further disaggregated into showering from a hot water machine, and showering from a non-standard cold-water shower head. Many households with a hot water machine declined to use it except in the cold season, preferring washing with a scoop due to the low flow rate. A large variation in flow intensity was identified for shower events in *Wat Svay*, where hot water machines are more prevalent, compared to *Kakranh*, where these flows are less likely to be regulated by appliance or price.

To account for seasonal differences in flows for showers and other end-use typologies identified in the pre-survey, users defined differences in end-use consumption for a 'cool season' of two months (mid-November to mid-January), where many households nominated reduced water consumption for bathing if they did not have a hot water

machine. This change was accommodated by a simple modification to the questionnaire survey. These prompts may be refined in future tools to more accurately account for seasonal variations in water usage for bathing. As with toilets when end-use volumes were estimated individually, the survey could also account for gender and age differences within end-use parameters. In the case of bathing, gender differences in water demand were less prevalent than for toilet flushing. Meanwhile, children (< 18 yrs old) were found on average to use much less water per capita for bathing (*Table 6*).

The other aspect that may be addressed in future studies is the likelihood of higher rates of error associated with measurements from shower heads. Scoop and bucket bathing end-uses were estimated primarily through recall-based methods based on standard measures of scoops and buckets that are discrete and relatively easier to recall. Estimates of per capita volume for shower events, in contrast, are based on empirical measurements. The error anticipated from these results is expected to be larger due to flow rates being measured with taps being fully opened and uncertainty whether these matched flow rates are used in practice ([Tamason 2016](#)). Shower duration is also a less discrete measure than the standardised volumes used to estimate water usage for other practices. Still, increased awareness of the factors influencing water demand that create such inefficiencies may inform interventions leading to more resource-efficient service delivery configurations aligned with cleaner production principles.

5.5.1.3 Other bathroom end-uses

Participants in the pre-survey distinguished between end-use events for bathing, showering, and toilet flushing, as opposed to other personal hygiene end-use events such as hand washing, anal cleansing, menstrual hygiene, and cleaning the bathroom. While the intensity of bidet flowrates was measured in 14 households, it was difficult to estimate and

disaggregate these flows to specific events in the context of a brief survey, where the rapport to ask questions about more intimate end-uses could not be meaningfully established (Sultana et al. 2022). This issue is more pronounced for this study because of the heterogeneity of households sampled. Thus, to simplify the survey tool, these events were aggregated in a question specifying *other bathroom end-uses*, enabling these volumes to be accounted for in general. In future studies, such end volumes may be estimated more effectively via self-administered surveys and water-use diaries.

A further consideration for *other bathroom end-uses* is the nature of the wastewater produced, with the destination ranging from a containment pit to an open drain, sewer, or surface flow. Sophisticated methodologies used in previous studies may provide insights into how these wastewater flows may be disaggregated more meaningfully (Welling et al., 2020). However, in the context of the end-use water balance in this study these were defined as *brownwater*.

5.5.2 End-use parameters for events in the kitchen

While it was possible to convert results for bathroom end-uses to units of per capita water demand, many estimates, including for kitchen end-uses, were necessarily made on a per-household basis.

5.5.2.1 Dishwashing

The primary kitchen end-use for households in the study area was for *washing dishes*. Dishwashing and clothes-washing water usage were measured based on the number of standard wide-mouthed buckets ranging from 5 to 25 litres in volume used. Both dishes and clothes were cleaned using a wash-rinse-rinse cycle, which was the basis for prompts in the survey tool. The other end-use practice modelled was using a running tap to wash dishes based on an estimate of *the frequency* of dishwashing events, the *duration* the tap was in

use, and an empirical measurement of the *flow rate* of the tap. The end-use parameters (Table 6) for dishwashing suggest that more than three times the amount of water is demanded for washing dishes using a running tap. This finding highlights the necessity for local authorities to promote water efficiency alongside improving access to safely managed water services. Such approaches may mitigate any waste associated with urban water resource plans, better aligning with cleaner production principles.

5.5.2.2 Drinking

The predominant methods of accessing potable drinking water in the study area was from 20-litre blue plastic bottles widely distributed commercially via small shops or access for free or a small donation from local pagodas. Water accessed by this practice was determined by estimating the number of these bottles used per week in a household. Some high-income households were identified to have invested in reverse-osmosis filters, supplying their household and others in immediate proximity with water in the same bottles. Other methods of obtaining potable water included boiling or using a *tonsai* (rabbit) brand ceramic filter.

5.5.2.3 Other kitchen end-uses

As with bathroom water usage, the survey tool was simplified to account for various other kitchen end-uses, including water used for washing vegetables, cooking, and cleaning. A daily estimate of other kitchen end-uses was included in the survey tool to simplify the end-use water balance. The total sum of this end-use flow was included as a greywater sink.

5.5.3 End-use parameters for clothes washing events

As outlined previously, the demand for end-use water for clothes washing was lower than for dishwashing (see Table 6). Two main practices were identified. Namely washing with three open-mouthed buckets using a wash-rinse-rinse cycle, and the use of a washing

machine. The former is much more common in the study area, with washing machines used solely in households with a reticulated supply or header tank, except for one instance where a machine was manually filled. The shift towards using machines demands much higher water consumption than hand washing. Such transitions, including the shift from hand washing dishes and clothes, or from scooping to showerheads, suggest that greywater flows are likely to expand rapidly in future years. This presents opportunities to take advantage of low-cost greywater reuse options ([van de Walle et al. 2023](#)). Proactively managing the impacts of increased wastewater flows arising greater user convenience within households supports both developmental and cleaner production goals in heterogeneous urban water and sanitation service configurations.

5.5.4 End-use parameters for outdoor events

Outdoor water consumption is not always included in RWEUA studies in LMICs, nor analysed to the same degree. This study defined three primary end-use typologies: garden irrigation, vehicle washing, and dust suppression. Many households have their vehicles and motorbikes washed outside the home, making estimating the contribution to the water balance difficult. Thus, they were excluded from the analysis. Dust suppression is an end-use type that is rare to see disaggregated in a residential end-use analysis yet is a common and necessary activity in the dry season in Siem Reap Municipality, particularly in our study area, where there are many unsealed laterite roads. Other outdoor end-uses included cleaning pavers and the external areas of the house; running small business selling food, raising animals, or doing laundry for neighbours; or regulating household temperature via evaporative cooling in hot weather. These activities were not sufficiently common enough to determine end-use parameters.

The range of outdoor end-uses is diverse and facilitated by access to unregulated groundwater access. While the sample size for these parameters is not as large as for indoor water consumption, the scale of water demand for these uses is noteworthy, particularly in Kakranh. This intensity of flows from pumps also makes it challenging to collect reliable data about these end-use typologies. Given the significance of issues regarding groundwater recharge deficits, including land subsidence, urban water planners may need to consider regulating consumption from domestic self-supply, alongside developing reticulated water supplies (Buhay Bucton et al. 2022). Supply-oriented planning is commonly prioritised in urban LMIC contexts. However, this is a clear example of how integrating demand management alongside infrastructure interventions can support cleaner production by mitigating preventable environmental degradation.

5.6 Conclusions and recommendations

This study has applied RWEUA to a heterogeneous water sanitation configuration to characterise an existing without-project service provision context in Siem Reap, Cambodia. It is among the first to co-produce residential end-use data from a heterogeneous urban water and sanitation service configuration in an LMIC context. The use of an interpretive, semi-structured survey and observation protocol helped to generate context-specific, empirical data across a diversity of water access typologies, household artefacts and practices, and wastewater sinks. In doing so, the analysis has highlighted the extent to which demand for water and sanitation services varies spatially in such settings, influenced by characteristics, such as income levels, household size, length of tenure, and service provision typologies.

These findings demonstrate that RWEUA, when applied at this scale, is effective in defining a model for an existing heterogeneous *without-project* situation as the basis for

comparing interventions. Moreover, the approach is also beneficial in identifying appropriate, context-sensitive interventions that may otherwise not be visible to decision makers and societal actors. The model derived from the empirical results of this analysis, and the assumptions underlying the end-use parameters, are presented in a way where the uncertainties and limitations of the data collection process are explicit. This transparency enables contextually grounded insights, capable of forecasting the impacts of multiple possible mixed service provision options. It also supported the iterative refinement of the data collection process as system configurations change over time.

This work has several practical implications. It demonstrates that RWEUA is applicable to urban contexts where the use of smart meters to collect high resolution data is constrained. The co-production of meaningful knowledge about the existing without-project situation supports least-cost analysis across a mix of diverse options. In turn, this may help to prioritise inclusive, and adaptive interventions that minimise water consumption and wastewater generation, as well as address the uneven distribution of costs and benefits associated with urban water resources. Urban water and sanitation planning processes that integrate such insights may be better positioned to support collaborative outcomes that are both environmentally sustainable and socially responsive.

It is recommended that future applications of RWEUA to similar heterogeneous water and sanitation service configuration treat the method as a long-term iterative learning process. Such an approach may provide the basis for a collaborative, adaptive planning framework that supports municipal authorities, utilities, and other societal actors to co-develop interventions that respond to diverse demands for water and sanitation services. When integrated into broader adaptive planning framework, RWEUA may contribute to more inclusive and resource-efficient urban water and sanitation service configurations.

Ethics statement

Ethical approval was granted by the University of Technology (ETH205222). All respondents were briefed about the study before providing written consent to participate. Additionally, all data has been anonymised to maintain confidentiality and prevent respondents from being identified.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary material

None

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Chapter Six: Using systems thinking to identify possible water and sanitation solutions for diverse urban needs in Siem Reap, Cambodia

6.1 Overview

Chapter Six presents the fourth knowledge output of this thesis, and the second study embedded within the transdisciplinary case study methodology. It spans *Wave Two (Problem Analysis)* and *Wave Three (Exploration of Impact)* (see Figure 3), contributing to both the second outcome space (*knowledge stocks and flows*), and the third outcome space (mutual and transformative learning). In contrast to *Chapter Five*, which applied a hard systems approach to co-produce objective knowledge, this study applies soft systems tools from *constructivist* and *critical* epistemological perspectives. *Chapter Six* addresses further methodological gaps identified in *Chapter Four* by accessing knowledge about the diverse perceptions about how heterogeneous configurations may be improved, before collaboratively interrogating these perspectives.

The chapter compiles a paper under review with the journal *Environmental Development*. The paper outlines how thirty-two *semi-structured interviews* were used to structure individual root definitions, as the basis for constructing *nine purposeful activity models*. These models were then integrated and interrogated through three participatory workshops, using a collaboratively produced *rich picture*, introduced here as an alternative *boundary object* to the residential end-use model co-produced in *Chapter Five*. This artefact enabled collaborative reflection through its role as a shared, but flexible, reference point for comparing diverse intended models for change.

The paper itself primarily responds to *Research Question #2a* on how systems thinking approaches may integrate diverse actor perspectives into a systemic comparative economic analysis methodology that informs a broader urban water and sanitation planning

approach; and partly to *Research Question #3* on how epistemologically plural, learning-oriented planning approaches may enhance the relational capacity of societal actors to challenge persistent service outcome inequalities. The approach adopts *soft systems methodology* (Checkland & Poulter, 2010), which is extended with *critical systems heuristics* (Ulrich & Reynolds, 2010) to structure reflection, comparison, and questioning of the *purposeful activity models* framed from different societal actor perspectives to improve them. Observable insights from the case study in Siem Reap municipality, and from how a revised integration concept might better sequence and structure knowledge production from different epistemological perspectives are accessed. These insights are used to revise a systemic comparative economic analysis methodology that informs a broader urban water and sanitation planning framework, are accessed, as discussed in *Chapter Seven*.

The study begins by reflecting on the literature applying systems approaches to urban water and sanitation planning in LMICs. *Systems approaches* are attracting growing attention from researchers and professionals for their capacity to embrace the complexity of such planning contexts (Liddle & Fenner, 2017; Neely & Valcourt, 2024; Valcourt et al. 2020). However, in general, this capacity has been limited to the adoption of a *functionalist* or *hard systems* perspective of *'thinking about systems'* (Ison, 2008; Jackson, 2000; Reynolds & Holwell, 2010). Such approaches aim to objectively define water and sanitation systems from a single perspective placing arbitrary limits on what may be understood about heterogeneous urban water and sanitation configurations. Few studies have been found to apply interpretivist systems approaches that recognise the diversity of knowledges about these configurations, and which have the capacity to address the epistemic uncertainty related to service outcomes, which is a key criteria of the least-cost, integrated resource planning principles established in *Chapters Three and Four* (Ross et al., 2024a, 2024b).

To help address this gap, this chapter details how diverse individual perspectives about heterogeneous urban water and sanitation service provision configurations may be co-produced through semi-structured interviews and then be compared and accommodated into collaborative systems models representing feasible and desirable alternative interventions that are inclusive of these perspectives. Through this process, individual *root definitions* and *purposeful activity models* were constructed and used as *epistemic objects*, or learning artefacts in a series of three participatory workshops. These artefacts captured plural viewpoints about how the case study configuration was perceived and intended to be improved. These interpretive models were compared and critiqued against the *rich picture* of the existing situation, which served as a *boundary object*.

The workshops were designed to structure dialogue and reflection to produce types of knowledge that were complementary, yet different to the knowledge co-production described in *Chapter Five*. *Workshop One* involved the facilitated collaborative construction of a *rich picture* of the problematical situation, acting as an alternative representation of the *without-project case* that may be used for comparison. *Workshop Two* compared the rich pictures with a series of nine *purposeful activity models*, derived from semi-structured interviews and root definitions, using structured discussions to enable divergent perspectives to be collaboratively accommodated within the models, thereby improving them, and making them more broadly desirable and feasible. *Workshop Three* applied critical systems heuristics in a further structured and collaborative process to challenge some of the underlying assumptions, power relations, and boundary judgements across each model.

Through these workshops, the compiled paper makes several theoretical and methodological contributions, which are summarised here and discussed in further detail in

Chapters Seven and Eight. First, on a practical level, they produced a range of knowledge artefacts that could be used variably as learning devices. For instance, the *rich picture* could be used as a common reference point in structured discussions; the purposeful activity models could be used to pose questions to prompt systems thinking; and the *critical systems heuristics* applied in Workshop Three prompted questions about fairness and ethical implications. The use of these learning artefacts could be observed directly to shape insights into the tensions between technical feasibility, desirability, and inclusion, providing practical collective insights into what the system objectives should be, who they should benefit, and how they should be evaluated.

Secondly, on a methodological level, the workshops acted as experiments within the broader transdisciplinary case study, enabling reflection on their role and the use of the artefacts in shaping the integration concept outlined in *Section 2.4.3*. The workshops provided an opportunity to observe how epistemologically diverse knowledge may be co-produced, compared, and interrogated within a case study. These observations act as evidence supporting the revision of the integration concept, and the discussion of how a systemic comparative economic analysis methodology might be structured in *Chapter Seven* to conceptualise a *learning-oriented planning framework*.

Thirdly, on a theoretical level, the workshops provided insights into the role of *transdisciplinary integration* in shaping the design of methodologies based on empirical observations in a real-world *transdisciplinary case study*. The results from *Chapter Six* help to evaluate the transdisciplinary outcome spaces framework as a means of conducting purposeful, participatory, transdisciplinary research of this nature. The implications of these findings for refining the integration concept and structuring a systemic urban water and sanitation planning approach are explored in the discussion in *Chapter Seven*.

Publishable Work: Systems as a learning device for identifying and discussing possible interventions for a heterogeneous urban water and sanitation configuration in Siem Reap, Cambodia

This article is included in this thesis as the *manuscript accepted for peer review* by the journal *Environmental Development* on the 20th of March 2025. To aid navigation of the thesis, the headings, figures, and tables of this publication have been embedded within the structure of the overall thesis and are not in the same format as the version submitted to the journal. When accepted, the published peer reviewed article will be available via an open access agreement and available for free download.

Environmental Development

Using systems thinking to identify possible water and sanitation solutions for diverse urban needs in Siem Reap, Cambodia

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Abstract:	<p>Planning interventions for heterogeneous urban water and sanitation configurations in low- and middle-income countries is inherently complex. Systems approaches are increasingly recommended in these contexts to obtain a holistic, functional understanding of the multi-dimensional technical and human factors that impact service delivery. However, an implicit constraint in their application is the partial perception of the system that any analyst brings to an inquiry. A narrow understanding of these systems exacerbates this issue. For instance, where formal service provision arrangements are not universal, assumptions crucial to understanding how informal services arise may not be available to planners. This paper describes an action learning process applied in two urban villages in Siem Reap, Cambodia, adopting soft systems methodology. Nine purposeful human activity models were co-constructed as diverse ways of knowing about how sanitation services might be improved contextually. We demonstrate how such models provide space for collaborative learning about desirable and feasible options as well as real-world constraints. We argue that insights from values-based human activity models combined with functional models, capable of forecasting real-world systemic impacts should inform the integrated planning of urban water and sanitation as an inclusive public service.</p>
Opposed Reviewers:	

Using systems thinking to identify possible water and sanitation solutions for diverse urban needs in Siem Reap, Cambodia

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Abstract

Planning interventions for heterogeneous urban water and sanitation configurations in *low- and middle-income countries* is inherently complex. *Systems approaches* are increasingly recommended in these contexts to obtain a holistic, functional understanding of the multi-dimensional technical and human factors that impact service delivery. However, an implicit constraint in their application is the partial perception of the system that any analyst brings to an inquiry. A narrow understanding of these systems exacerbates this issue. For instance, where formal service provision arrangements are not universal, assumptions crucial to understanding how informal services arise may not be available to planners. This paper describes an action learning process applied in two urban villages in Siem Reap, Cambodia, adopting *soft systems methodology*. Nine *purposeful human activity models* were co-constructed as diverse ways of knowing about how sanitation services might be improved contextually. We demonstrate how such models provide space for collaborative learning about desirable and feasible options as well as real-world constraints. We argue that insights from values-based *human activity models* combined with *functional models*,

capable of forecasting real-world systemic impacts should inform the integrated planning of urban water and sanitation as an inclusive public service.

Keywords: citywide inclusive sanitation, complex adaptive systems, critical systems heuristics, heterogeneity, integrated water management, systems modelling

6.2 Introduction

The delivery of urban water, sanitation and hygiene (WASH) services in LMICs is recognised as a *complex adaptive system* in which patterns of cause and effect and how they are perceived are inherently uncertain (Carey et al., 2015; Currie et al., 2018; Neely, 2019; Moallemi et al., 2021). One reason for this is the *heterogeneity* of existing formal and informal service provision models and the assumptions and beliefs that affirm them (Lawhon et al., 2017; Ross et al., 2024b; Ross et al. *under review b*). Thus, *systems approaches* that collectively probe, make sense of, and respond to these situations are attracting growing attention from researchers and water and sanitation professionals (Liddle & Fenner, 2017; Valcourt et al., 2020). Neely and Valcourt (2024) describe the emergence of *various systems tools and philosophical perspectives* from circa 2005.

Systems approaches aim to embrace the complexity of heterogeneous service provision configurations instead of being *reductionist* (Ison, 2008; Jackson, 2000; Reynolds & Holwell, 2010). Generally, this is approached from one of two epistemological foundations for constructing systems models. The first is from the *functionalist* viewpoint of *thinking about systems*. This perspective gleans an understanding of complexity through constructing *objective* real-world models. This approach is typically goal-oriented, seeking to sweep in as many socio-technical factors as possible that may impact relationships between system sub-components, revealing insights into non-linear or non-intuitive system behaviours (Currie et al., 2018; Valcourt et al., 2020). This lens values such knowledge as it increases the

likelihood that desirable and feasible interventions to support the self-organising behaviour of complex adaptive systems will be identified (Ison, 2008).

The second is from the *interpretivist* (observing a system from diverse perspectives) and *emancipatory* (using diverse perspectives to critique power relations) standpoints of constructing systems as a *learning device* (Jackson, 2000; Reynolds & Holwell, 2010). These paradigms view complex adaptive systems as inherently *messy* and only partially knowable from a single perspective. Thus, learning about complexity is not derived from an objective understanding the real-world situation; instead by *sweeping in* as many partial perspectives of the situation as possible. These viewpoints are not considered to represent *real-world* situations but are constructed as mental models of the cognitive assumptions and worldviews underlying intentions to improve a situation (Reynolds & Holwell, 2010). This knowledge is valued as it enables the epistemological uncertainty of a problematical situation to be interrogated, potentially leading to transformative shifts in how *practitioners* and *issue owners* understand service provision constraints.

Reviews of systems approaches applied to WASH focus heavily on two overlapping applications in LMICs; namely, sustainability assessments for service delivery, largely in rural and occasionally peri-urban contexts (Huston & Moriarty, 2018; Liddle & Fenner, 2017; Neely & Valcourt, 2024; Valcourt et al., 2020), and the evaluation of externally funded programs or projects using *systems-based* conceptual frameworks, or theories of change (Hollander et al., 2020; Huston & Moriarty, 2018; Neely & Valcourt, 2024; Valcourt et al., 2020; Wilkinson et al., 2021; Willetts et al., 2022). These applications primarily adopt a *functionalist* lens, constructing objective models to enhance the understanding of real-world systems. The explicit adoption of an *interpretive* or *emancipatory* lens to frame systems approaches is rare, except for a few studies applied to urban water and sanitation planning

(Liddle & Fenner, 2017; Valcourt et al., 2020). This limits the type of information that may be accessed to support decisions about interventions in complex service provision contexts comprising heterogeneous service provision models (Lawhon et al., 2017).

One way of clarifying the value of *interpretive* and *emancipatory* systems thinking paradigms for urban water and sanitation planning in LMICs is to consider how systems approaches have been applied in the peer-reviewed literature to date. One of the first systems approaches applied to this context was hypothetical, defining a *systems dynamic model* based on an imagined *causal loop diagram* (Nandalal & Simonovic, 2003). This work was intended to prove that *functionalist* systems approaches may be relevant to simulating the dynamic socio-technical factors impacting complex urban water resource management contexts. However, a limitation that has continued to constrain this realisation is the challenge of *holistically* defining the sub-components and variables or factors relevant to the performance of real-world complex, adaptive, urban WASH systems.

An approach that has been adopted in an attempt to meet this challenge is translating *generalised systems models* to a specific context of interest. For example, Spencer (2007) hypothesised a range of factors expected to comprehensively explain the performance of new piped water services for households of different income levels in Can Tho, Vietnam. More specifically, Louis and Magpili (2007) and Henriques and Louis (2011) promoted a *capacity factor assessment* for urban communities to appraise the appropriateness of possible interventions in Kenya and Indonesia, respectively. This method defined eight general factors for a comprehensive self-assessment of the capacity to manage infrastructure for water and wastewater services and plan the financing and implementation of such options. *Building block* or *systems strengthening frameworks* are valued for making systems thinking accessible to local water and sanitation professionals

(Huston & Moriarty, 2018; Kimbugwe et al., 2022; Willetts et al., 2022). However, the benefits of capacity building should always be considered alongside the contextual fit of the model.

Comprehensive, context-specific approaches to system definition are more likely to contribute to producing meaningful insights into relevant sub-systems, the factors determining their relationships, and their dynamic nature (Hollander et al., 2020; Mason et al., 2019). These insights are necessary to manage the uncertainty of models arising from qualitative system definition and their outcomes. The *causal loop diagram* Nandalal and Simonovic (2003) applied to define the hypothetical systems dynamic model exemplifies how system definition may be more flexibly structured, as replicated in a real-world context via the development of a stocks and flows model for a complex integrated urban system in Chiang Mai, Thailand (Asasuppakit & Thiengburanathum, 2014).

Another framework that offers flexibility in how local sub-components and factors influencing system behaviour are defined is described by Weaver et al. (2017), who applied a *complex socio-ecological systems* lens as a heuristic to define a water supply system in Grahamstown, South Africa. Flexibility enables models to be shaped towards specific system objectives. For example, Foster et al. (2021) intended to develop a stronger evidence base about the health impacts of urban sanitation systems. Thus, a *systems model* was defined to limit interactions from factors beyond those of the system of interest; in this case, the validation of two integrated sub-models explaining the dynamics of pathogen transport and the risk of pathogen exposure from faecal waste flows in Dhaka, Bangladesh.

Another approach to developing more compelling objective systems models is to validate them using a theoretical framework. For example, Mukulu et al., (2011) used *resource-based theory* to validate qualitative data about the factors that affect the

sustainability of micro- and small-piped water enterprise systems in Kenya. [Iribarnegaray and Seghezzo \(2012\)](#) used a *governance analytical framework* to validate their insights, explaining five key factors that demonstrate how power relations influence the sustainable governance of an urban water and sanitation system in Salta, Argentina. [Hulland et al., \(2013\)](#) used an *integrated behaviour model* for hand-washing behaviour in infrastructure-constrained urban contexts to validate different psychosocial and technological factors affecting hand-washing practices in Dhaka, Bangladesh. Alternatively, [Simiyu et al. \(2017\)](#) developed an inductive theory about the factors influencing the management of shared sanitation facilities by tenants and landlords in informal settlements in Kisumu, Kenya.

Systems researchers have also strengthened urban water and sanitation system models through meta-analysis to obtain an empirical basis to support claims about relationships between sub-components. For example, [Starkl et al. \(2013\)](#) collected data from local practitioners and experts appraising the success or failure of 60 urban water and sanitation systems across India, Mexico, and South Africa. Causal factors arising from these appraisals were pairwise compared to classification trees, depicting how factors were interrelated at scale. Another example is [Davis et al., \(2019\)](#), who applied a *fuzzy set qualitative comparative analysis* to explain the *factors* leading to local priorities for sanitation services being met or otherwise. Data on priority factors were determined for 20 case studies using data collection methods such as interviews, focus groups, and photovoice. These were coded and listed before being ranked comparatively in an additional focus group.

Nonetheless, *functionalist* systems dynamics models that define a system from a single perspective place arbitrary limits on which system subcomponents, and determinants of behaviour are considered to simplify the analysis of heterogeneous urban water and

sanitation configurations. For example, a systems dynamic model developed by Poustie and Deletic (2014) compared multiple arbitrary infrastructure development scenarios to 2050 in Port Vila, Vanuatu. However, these forecasts were limited to considering pollutant loads in wastewater, and mainly considered physical determinants in the model. Further when modelling interactions between formal and informal components of an urban water supply systems, a lack of data limited Bano et al.,(2022) to using hypothetical systems archetypes to consider potential options.

More advanced functionalist modelling methods are also limited in this regard. The application of *Bayesian network analysis* in Tarawa, Kiribati, to consider the impacts of an idealised co-management approach for an urban water supply on groundwater resources is a case in point (Moglia et al., 2012). Researchers engaged local perspectives to quantify the probability that different sub-components of a model would exist in a certain state. However, this was limited to the factors identified in the researcher-led system definition. The use of *agent-based modelling* in Hubli-Dharwad, India to consider the climate change factors influencing the performance of an intermittent urban water and sanitation system supported by household point-of-use strategies was similarly limited (Mellor et al., 2016). The model considered the diversity of static household practices and their contribution to diarrhoeal disease risks, but stopped short of considering the values, underlying these practices.

Where soft systems approaches have been applied as an alternative to *functionalist* approaches, they have still tended to be applied objectively (Jackson, 2000); that is, analysing a *messy* system of interest rather than *organising the observation and understanding of a problematical situation* from different worldviews (Ison, 2008). For example, Kayaga (2008) nominally applied soft systems methodology (SSM) to analyse the

Ugandan water and sanitation sector. However, it was not applied as might be expected by [Checkland & Poulter \(2010\)](#). Instead, models were constructed from the perspective of the researcher only. They contained the perspectives of multiple stakeholders, however, defined the real-world problematical situation from the single official perspective of the Government of Uganda. In effect, using the models to analyse current policy settings, rather than thinking from the perspective of others. The same is true for [Pan and Armitage \(2011\)](#), who constructed a model considering material, personal, and social dimensions of a proposed water and sanitation improvements in an urban slum in Cape Town, South Africa from a researcher perspective. While it was identified that these might be compared to the perspective of other actors, this was not addressed in the study. More recent uses of SSM in urban water and sanitation planning in Tehran, Iran ([Saeedi et al., 2022](#)) and Riau Province, Indonesia ([Suyeno et al., 2024](#)) also define objective models of a real-world situation, rather than interrogating different perceptions and assumptions of what the real-world might be. [Simbolon \(2017\)](#) does the same when applying *critical systems heuristics* (CSH) to evaluate the impact of power relations on decentralised water management systems in Nauli City in Indonesia. The potential to facilitate dialogue to resolve latent inequalities in the system was missed.

In the peer-reviewed literature, there are few studies construct *systems as learning devices* ([Reynolds & Holwell, 2010](#)). Some of these studies comprise multiple methods and adopt soft systems ideas as part of a broader systems approach. For instance, [Tasca et al. \(2020\)](#) describe a *general systems thinking approach* to the problematical situation of poor water quality in an urban river in Southern Brazil. Key controlling variables and feedback loops were identified collaboratively as part of a *causal loop diagram*. Then, a process where this diagram was iteratively enhanced over five rounds of *member checking*, where

different perspectives are accommodated within the diagram, is described, increasing the likelihood of learning outcomes transforming perspectives within an emergent action plan. [Starkl et al. \(2013\)](#) also describe a pluralistic planning methodology, where different development scenarios and related concept scenarios or interventions were established in a participatory process for a peri-urban area of Mexico City. The approach used interviews with 30 actors representing households and institutions to rank preferences for options in a classification tree. *Social network analysis* was then used to cluster groups with similar preferences to map how changes to concept plans would affect consensus on an overall development scenario.

To our knowledge, only two studies closely aligned with an interpretivist systems approach exist for urban water and sanitation planning. The first applies SSM to learn about managing an urban water resource in Chennai, India, promote learning, and stimulate action for desirable and feasible change ([Bunch, 2003](#)). A soft systems approach is applied in an orthodox way, resulting in a fundamental shift in system objectives arising from comparing purposeful activity models with a shared conceptual model of the real-world ([Checkland & Poulter, 2010](#)). The other example is a participatory systems mapping methodology applied to a household and community-scale water and sanitation system in an informal settlement in Suva, Fiji. Diverse individual narratives about desirable and feasible means of improving the situation derived from interviews were compared with a collective systems map. Collaborative workshops are described as situations where this learning-oriented approach triggers positive systemic responses at multiple scales ([Saunders et al., 2016](#)).

The present paper describes the application of SSM as an action research approach to engage diverse societal actors within a complex heterogeneous water and sanitation infrastructure configuration in Siem Reap, Cambodia ([Checkland & Poulter, 2010](#)). We aim

to provide a clear example of how SSM may be organised as an action research methodology to collaboratively interrogate and transform the various socio-technical perspectives that exist in this problematical situation to enhance them through a relational approach (Carrard et al., 2024). We detail: (i) how local participants were recruited into the process of finding out about the real-world problematical situation, including developing a *rich picture* of this real-world, without-project context; (ii) how purposeful activity models were developed as a learning device via in-depth interviews; (iii) how heuristics were applied to facilitate structured discussions about (a) the *comparison between the real-world situation and the purposeful activity models*; (b) *gently disrupting, unsettling, and provoking new thinking* about how more equitable systems arrangements might be imagined (Checkland & Poulter, 2010; Jackson, 2000). We conclude our paper by providing insights into how this approach may be relevant for improving city-wide inclusive sanitation planning frameworks.

6.3 Soft Systems Methodology

SSM is described as *an action-oriented inquiry into problematical situations in the everyday world* (Checkland & Poulter, 2010). As opposed to conducting an analysis, the methodology is applied to learn both how to (i) conduct the inquiry into the system of interest, in this case, the planning of services for a heterogeneous water and sanitation configuration, as well as how to (ii) find out about the content of a messy, complex adaptive system and how to take actions to improve it (Ison, 2008). The process by which this learning was organised and how various systems models were constructed as *devices* to structure this learning is outlined as follows, aligned closely with the explanation of SSM provided by Checkland and Poulter (2010).

6.3.1 Finding out about the problematical situation

For this study, we frame the urban sanitation context in Siem Reap as a messy, *complex adaptive system* situated within a broader socio-ecological system in which patterns of cause and effect are inherently uncertain. [Checkland and Poulter \(2010\)](#) describe four types of inquiry that can be used to find out about the content of a messy, real-world situation; namely *Analysis One, Two, and Three* (as outlined below), as well as constructing *rich pictures* of the real-world problem, including its sub-components, structure, and perspectives contained within.

6.3.1.1 Analysis One (the intervention itself)

Analysis One clarifies the nature of the systemic inquiry by defining the roles required to *organise the observation and understanding the problem situation from different worldviews* ([Ison, 2008](#)); that is the roles of *clients, practitioners, and issue owners* for the inquiry. Within an SSM inquiry the *client* role causes the learning activities to occur ([Checkland & Poulter, 2010](#)). In this study, this role was fulfilled via a collaboration between the primary authors of this paper and public institutions at multiple levels in Cambodia. For instance, the concept of research on the inclusive planning of urban water and sanitation was negotiated with officials from the *Cambodia Ministry of Public Works and Transport*. Siem Reap municipality, as a secondary city, was selected as the research location, as it was described as best equipped to benefit from the intention of the research based on existing programs and existing knowledge and capacity.

Table 11: Analysis One

Role	Definition	Actors
Clients	<i>The person or group of persons that caused the intervention to occur</i>	The primary authors of this paper in collaboration with officials from the <i>Ministry of Public Works and Transport, Siem Reap Provincial Department of Public Works and Transport. Siem Reap Municipal Administration, Siem Reap Water Supply Authority, and the Siem Reap Wastewater Treatment Plant Unit.</i>
Practitioners	<i>The person, or group of persons, conducting the investigation</i>	Sangkat and Village Chiefs, their deputies and committee members who participated in the transect walks identified issue owners in the community based on different roles and risk profiles and the research team (comprising the lead author of this paper, and three local research assistants).
Issue Owners	<i>The people regarded as being concerned about or affected by the situation and the outcome of the effort to improve it</i>	The in-depth interview and workshop participants who developed the purposeful models and participated in the workshops. A complete list of these issue owners is included in <i>Table 12</i> .

Consequently, meetings were arranged with different Institutions within Siem Reap, including the *Provincial Department of Public Works and Transport, the Municipal Administration, the Water Supply Authority, and the Wastewater Treatment Plant Unit*. The intentions of the research were discussed, along with the proposed research activities and an explicit reference to potential ethical implications. A formal agreement was reached, regarding the scope and intentions of the inquiry, and the proposed research activities, pending further negotiations with *practitioners* once a more specific research site was selected.

Following this agreement, grey literature, and local census information were used source data about existing water and sanitation service provision conditions to shortlist five potential research sites, where heterogeneous service profiles were identified at the scale of a village administration see [Ross et al. \(under review a\) \(National Institute of Statistics, 2023\)](#). *Transect walks* were planned for each of these sites; however, only three were conducted in practice, due to movement restrictions related to the COVID-19 pandemic.

For *Analysis One*, the transect walks aimed to, among other objectives, select an appropriate research site (i.e. a site consistent with heterogeneous supply and demand for urban water and sanitation services), and *practitioners* and *issue owners* likely to benefit from the research activities (see Analysis 2), as outlined in *Table 11* (Checkland & Poulter, 2010). During *Analysis One*, the structure of the problem was left deliberately open, enabling flexibility in defining the system and how different methods and research activities would be organised (Mobjörk, 2010).

6.3.1.2 Analysis Two (cultural feasibility)

Analysis Two was used as an ongoing prompt to reflect on the *cultural feasibility* of the action learning process, with particular attention paid to selecting the study site and *practitioners*, recruiting *issue owners*, and collaborating on the action research activities. This reflection acknowledges the importance of ensuring these activities appropriately reflected the broader social reality of the selected research site, and required focus and reflection on (i) formal and informal *roles* that societal actors played in the problematical situation and how this distinguished social positions; (ii) *norms* of behaviour; and (iii) the *values* by which the roles of the research team and local collaborators as *clients*, the *practitioners* and co-producers of knowledge, and the *issue owners* were judged (Checkland & Poulter 2010). These reflections were integral in navigating uncertainties when learning how to apply a soft systems intervention to this situation. One tangible output from *Analysis Two* was reaching formal agreements with relevant practitioners at the Sangkat and Village administrations in the two adjacent research sites that were selected. These agreements were explicit regarding the design of the intended research activities, and when, where, and how they were implemented, including the process by which *issue owners* would be engaged in the action research.

6.3.1.3 Transect walks

Analysis Two was facilitated by *transect walks* organised at three potential research sites. These activities were co-designed with Sangkat and Village officials and committee members who, as practitioners, were briefed on the intended aims and research activities and contributed to organising the latter. The transect walk had multiple aims, including (i) ground truthing data informing the shortlisting of possible research sites (ii) collectively observing and mapping the distribution of environmental and public health risks, with the support of an observation protocol (Campos et al., 2015; Narayanan et al., 2018); (iii) observing local *roles*, *norms*, and *values* and how they were relevant to the intended research activities (Checkland & Poulter, 2010); (iv) identifying *issue owners* as possible participants in these research activities; and (v) ultimately selecting the most appropriate research site for ongoing work.

The *walks* were conducted to facilitate accessing a cross-section of each village. A GPS device was used to map the route of the walk, geolocating significant features and where photos had been taken, clarifying administrative boundaries, and recording notes about risks identified from an observation protocol. Potential *issue owners* were identified via several approaches including (i) chance meetings in which possible *issue owners* approached *the practitioners*; (ii) recommendations and introductions by *practitioners*; (iii) *practitioners* approaching potential *issue owners* likely to have an interest in addressing risks identified from the observation protocol or otherwise. While consideration of power relations (see *Analysis Three*) had already shaped our intention to scope system boundaries at the geographical scale of a Village administration, the flexibility of this approach facilitated collaboration on the content included within the system boundaries of the inquiry. Contact information, demographic details, and location and roles within each study

site were recorded for a breadth of possible *issue owners* once consent to participate had been established. This information was used to organise later research activities upon finalising the study area selection, involving further deliberation regarding who and what was relevant to the inquiry.

6.3.1.4 Analysis Three (commodities of power)

Analysis Three was used as an ongoing prompt to critically reflect on the impact of *commodities of power* on decisions made about who and what was included within the system boundaries of the action-learning process (Checkland & Poulter, 2010). This deliberation became more significant following the selection of *Wat Svay* and *Kakranh Villages* as the study areas (see *Figure 15* and *Ross et al. (under review b)* for further details), where decisions were made about the selection of the study site and *practitioners*, recruitment of *issue owners*, and collaboration on the action research activities. For example, one *client* proposed a research site be selected, focusing primarily on an informal settlement with no access to formal water and sanitation services or direct interaction with planning frameworks. This suggestion prompted discussion among all clients, reconfirming the scope and intention of the research.

In particular, *Analysis Three* was integral to ensuring psychological safety and beneficence to *issue owners* when organising the collaborative interrogation of diverse individual and collective worldviews aligned with the ethics approval for the inquiry (Checkland & Poulter, 2010). Reflection by practitioners on the *commodities of power* available to different *societal actors* was a key criterion influencing (i) selection of possible *issue owners* interviewed by *practitioners*, (ii) prompts in the in-depth interviews used to construct individual mental models or root definitions of the worldview of each issue owner and how it represented an intention to improve the situation; (iii) curation of the root

definitions, representing the whole-of-system interview cohort as *purposeful activity models* by *practitioners*; and (iv) the facilitation of workshops used to interrogate these purposeful activity models as learning devices (Checkland & Poulter, 2010). *Analysis One, Two, and Three* were each important in informing the following research activities.



Figure 15: The study area in Wat Svay (yellow) and Kakranh (blue) villages, Siem Reap (Google Earth Pro, 2024)

6.3.2 Co-constructing rich pictures

While the *rich pictures* were constructed during a workshop informed by prior *in-depth interviews*, they are described earlier in this paper, as they represent a key artefact generated from an ongoing iterative process of finding out about the problematical *real-world* situation (Checkland & Poulter, 2010). These pictures represent the understanding of *issue owners* participating in a workshop on the 10th of April 2022 in a classroom of a local primary school situated close to the border of the two villages in the study area in *Wat Svay*. The aim of constructing the *rich picture* activity was to establish a collaborative model of the existing, without-project, problem situation, transforming a diverse range of individual *issue owner* perspectives into an integrated, whole-of-system perspective.

As an artefact, *rich pictures* can be used as a common frame of reference for real-world problem situations. They enable questions arising from a cohort of nine *purposeful activity models* described later in this paper about the *real-world* problematical situation to be reflected upon in a contextually meaningful way (see *Table 12*) (Checkland & Poulter, 2010). The rich pictures make the shared process of *finding out about the real-world problematical situation* recoverable for later use in interrogating this understanding. In total, 15 *issue owners* out of 32 the interviewed, participated in the co-construction of these rich pictures representing the diverse worldviews held regarding the system of interest contained within the study area. The criteria for selecting these *issue owners* are outlined later in this paper.

To facilitate this co-construction of the rich picture, we adopted a four-phase cycle similar to that recommended by Berg (2015). While it would have been possible to adopt many different approaches to this activity, this was selected as it offered a strategy by which full participation in co-constructing the picture could be ensured by accommodating potential differences in capacity. This process began with *facilitator instruction*, where all

workshop participants were provided guidance on constructing a rich picture. This included instructions on how to ensure the ideas of all issue owners were accommodated and connected as part of the drawing process. Issue owners were divided into three groups, supported and observed by a Khmer speaking facilitator and invited to briefly share and discuss their perspectives on problems related to urban sanitation in the study area.

Collaborative construction of the picture was triggered by inviting each group to identify three common problems for the drawing process to use as starting points. Beyond this instruction, the role of the facilitator was hands-off, answering questions and keeping time, but not intervening in the content of the picture.

The process was completed via an *external explanation* of the rich picture to the broader workshop to access comments on possible errors or omissions (Berg, 2015; Checkland & Poulter, 2010). In presenting the images of the rich pictures in *Figure 16*, it is important to reinforce that they should not be considered a static, or definitive, system map. Rather, they are a means of recovering the thinking in the workshop so it may be recovered and applied as a learning device in later structured discussions



The rich pictures identified a range of interacting relationships within the study area. *Municipal, Sangkat and Village authorities* oversee formal aspects of development in the study area but are less focused on informal development. *Newcomers* who raise land they purchase to build modern housing at ground level with fences and drainage, following regulations provided by authorities, in contrast to *households with vernacular housing*, who allow water to flow underneath buildings into rice fields. Water accumulates in these latter areas, which are more likely to have narrow roads and either lack drainage infrastructure or have informal open drains. *Solid waste collection* services do not access these areas, and households do not pay for them, leading to solid waste being burnt, buried, or transferred to open drains. Access to reticulated water is isolated to newer areas of the study area. Most *households* access contaminated groundwater, which needs to be treated for drinking. Many containment pits under houses are constructed or managed poorly, and during the wet season, they become blocked. Some households cannot afford to use pit emptying businesses and transfer septage or faecal waste to rice fields or open drains. Some low-lying areas of the study area smell bad and become unhygienic in the wet season.

Figure 16: Rich pictures

6.3.3 Making purposeful activity models

Purposeful activity models in SSM are a second key artefact used to organise learning about a problem situation. Making purposeful activities is a key component of an organised process of enquiry and learning about a system of interest. Models are constructed as devices for posing questions about the real-world situation from the perspective of *issue owners* intending to improve upon the existing situation (Checkland & Poulter, 2010). As with *rich pictures*, *purposeful activity models* act as artefacts, ensuring the integrity of SSM as a learning process by making it *recoverable*. Applying a structured process to this learning with consistent language that outlines what occurred and how conclusions were reached enables the learning to be reflected upon in later activities. This strategy is fit for purpose in messy, complex adaptive systems, where replicable results would not be expected to be reported (Checkland & Poulter, 2010).

Practitioners tasked with *organising the observation and understanding of the problem situation from different worldviews* (Ison, 2008) are required to balance learning that is culturally feasible (*Analysis 2*) with learning devices sufficient to envision a whole system and likely to provoke reflection and accommodate learning on how power is distributed and influences decisions within a system (*Analysis 3*). To increase the likelihood of beneficence for *issue owners*, this study aimed to curate models with the capacity to meet both of these criteria. That is, they should be able to gently reveal relatable assumptions and worldviews underlying latent forms of conflict within systems or the root causes of systemic problems. *Based on this rationale, issue owners* were sampled from the potential list generated during the transect walks. We aimed to reach a *saturation* of worldview-based models for the study population (Hennink & Kaiser, 2022), sweeping in as many partial *models* of how the real-world is perceived as possible until it was apparent that

it was unlikely that new or significantly different assumptions would be coded in new root definitions.

6.3.3.1 In-depth, semi-structured interviews

Observing the real-world problematic situation from different epistemological positions or worldviews was initially organised by conducting 32 individual in-depth semi-structured interviews with *issue owners*. The interviews were led iteratively by two *practitioners* on the research team who were not also *issue owners* (i.e., members of the Sangkat or Village administration) in Khmer. The interview was structured to co-produce individual *root definitions* comprising: (P) *What the issue owner would do to improve the situation?* (Q) *How the issue owner envisages achieving this?* and (R) *why?* (see [Checkland & Poulter, \(2010\)](#) for further details about root definitions). While in most cases, *issue owners* had previously consented to participate in the research, the first section of the interview revised the scope and objectives of the study, establishing a mutual understanding of key concepts that would be discussed.

Table 12: Summary of issue owners interviewed to co-construct root definitions using CATWOE

Residents									
Code	Age / Gender	Family	Tenure	Water supply configuration	Housing type	Faecal waste containment	Faecal waste transport	Priority problematical situation	Priority transformation
WS1-1	Male (mid-30s)	Large family (8 people)	10 years	Header tank (private well)	Medium quality wooden. Ground level.	Double pit (lined) to open drain	Pit emptying service (annually)	Flooding caused by solid waste disposal	Mitigate solid waste in public areas and flooding
WS2-1	Trans-gender (mid-40s)	Lives alone	6 years	Indoor storage (private well, intermittent)	Low to medium quality. Raised	Single pit (unlined)	Self-emptied into open drain	High cost, poor quality services	Mutual support for self-supplied services
WS3-1 (ID-Poor Status)*	Female (early-40s)	2 children	21 years	Indoor storage (private shared well)	Low quality Ground level	Single pit (unlined)	Pit emptying service & self-emptied	Sullage disposal Increased urban density	Finance to raise house level and access sewer
WS4-1	Male (early-50s)	Extended family (8 people)	50 years	Reticulated	High quality, Ground level.	Septic tank	Never emptied.	Illegal solid waste disposal	Inclusive sewer & drainage standards
WS4-2	Male (late 40s)	Large family (7 people)	20 years	Reticulated	High quality Ground level	Double pit (lined) to sewer	Pit emptying service (rarely)	Illegal solid waste disposal causing flooding.	Inclusive planning of water services.
WS5-1	Male (early-40s)	Extended family (14 people)	10 years	Header tank (private well)	Medium quality. Ground level.	Double pit (unlined)	Pit emptying service (once every 2 years)	Sullage disposal Increased urban density	Resolve conflicts with neighbours about sewer.
WS6-1	Male (late-40s)	Wife (2 children)	2 years	Header tank (private well)	Medium quality Ground level.	Double pit (lined) to open drain.	Never emptied.	No access to sewer	Inclusive standards for faecal waste containment
WS7-1	Female (early-60s)	Husband (2 children)	40 years	Indoor storage (private well)	Medium quality, wooden, raised	Single pit (unlined)	Never emptied.	Sullage disposal Increased urban density	Design containment options for low-income households

WS7-2 (ID Poor Status)*	Male (late-50s)	Wife & 2 children)	20 years	Indoor storage (private well)	Low quality, wooden, raised	Single pit (unlined)	Self-emptied into open drain	Not specified	Not specified
WS8-1	Female (late-30s)	Extended family	30 years	Indoor storage (private well)	High quality wooden, raised	Double pit (lined) to sewer	Pit emptying service (rarely)	Solid waste blocks sewers causing flooding	Provide universal waste collection and sewer services.
WS9-1	Male (late-30s)	Wife and daughter	5 years	Header tank (private well)	High quality housing.	Double pit (lined)	Pit emptying service (often)	Municipal solid waste causing local flooding	Develop sewer and drainage infrastructure
WS9-2 (ID Poor Status)*	Female (late-20s)	Husband & 4 children	3 years	Indoor storage (private shared well)	Low quality incremental housing	Double pit (unlined)	Self-emptied to open drain	Not specified	Not specified
WS9-3 (ID Poor Status)*	Female (mid-30s)	Extended family of 12 people	10 years	Indoor storage (private shared well)	Low quality incremental housing.	Single pit (unlined)	Never emptied	Pit overflows regularly in the wet season.	Save for new toilet and improved containment
KK1-1 (ID Poor Status)*	Female (early-70s)	Extended family of 10 people.	40+ years	Indoor storage (private shared well)	Lower quality wooden, raised	Single pit (unlined)	Pit emptying service (annually)	Unhygienic flooding of open drains	Prevent illegal dumping of solid waste.
KK1-2	Male (late-30s)	Wife & 2 children	4 years	Indoor storage (private shared well)	Medium quality Ground level.	Single pit (unlined)	Never been emptied	Solid waste disposal in vacant land near his house	Encourage leaders to resolve this issue
KK1-3	Male (early-30s)	Wife & 3 children	10 years	Indoor storage (private well, intermittent)	Medium quality Ground level.	Double pit (unlined)	Pit emptying service (bi-annually)	Wastewater accumulation around house	Flexible standards for drainage infrastructure.
KK2-1	Female (early-60s)	Extended family of 8 people	40 years	Indoor storage (private shared well)	Medium quality wooden house. Raised	Double pit (unlined)	Pit emptying service (bi-annually)	Newcomers stop wastewater drainage	New options for wastewater drainage.
KK2-2 (ID Poor Status)*	Male (early-60s)	Lives alone	5 years	Indoor storage (private well)	Low quality wooden house. Raised	Single pit (unlined)	Pit emptying service (rarely)	Impact of poor hygiene on health of the community.	More information about options for improving situation

KK2-2	Female (late-20s)	Extended family (11 people)	16 years	Indoor storage	Medium quality. Ground level.	Double pit (unlined)	Never been emptied	Wastewater accumulation around house	Understand how to reduce impact on other households
KK3-1 (ID Poor Status)*	Female (early-70s)	2 grand children	10 years	Outdoor jar (private shared well).	Low quality. Wooden, raised.	Single pit (unlined)	Pit emptying service (often)	Poor quality housing Unhygienic living conditions.	Mobilise support from networks to resolve problems
KK4-1	Female (mid-30s)	Husband and child	11 years	Header tank (private well).	Medium to high quality. Ground level	Double pit (lined)	Pit emptying service (annually)	Groundwater quality	Make reticulated water accessible
KK5-1	Female (early-20s)	Extended family (8 people).	10 years	Indoor storage (private well).	Medium quality intermittent housing	Single pit (unlined)	Self-empties to open canal	Flooding from open drain	Continue to improve families living situation
Service providers									
Code	Age / Gender	Role	Time in role	Water supply focus	Housing type focus	Faecal waste containment focus.	Faecal waste transport focus	Priority problematical situation	Priority transformation
WKA-1	Male (early-30s)	Property developer	8 years	Reticulated supply	New housing	Optimising cost of septic tanks	Sewer	Complex process to access state land for projects	Sustainable business model for housing development.
WKA-2	Female (early-30s)	Construction supervisor	1 year	Reticulated supply	New housing	Optimising cost of septic tanks	Sewer	Does not perceive any problems	Developers continue to with operations
WKA-3	Male (late-20s)	Pit emptying service provider	8 years	Self-supplied groundwater	Households with containment pits	Double and single pit	High demand in wet season	Single pit containment difficult to empty	Co-ordination by local authorities
WKA-4	Female (mid-30s)	Pit emptying service provider	Not specified	Self-supplied groundwater	Households with boreholes	Double and single pit	Single pit containment	Limited capacity to pay by low-income households	Subsidies for scheduled emptying services
WKA-5	Male (early-30s)	Well technician	30 years	Repairing bore holes and pumps.	Households with boreholes	Plumbing as a secondary service	Plumbing as a secondary service	Complex customers with issues that are not easy to service	To diversify his business to access more customers

Local authorities									
Code	Age / Gender	Role	Time in role	Water supply focus	Housing type focus	Faecal waste containment focus.	Faecal waste transport focus	Priority problematical situation	Priority transformation
WSA-1	Male (early-40s)	Sangkat Official	Not specified	Reticulated supply	Formal housing with a building permits	Septic tanks or double pit containment	Sewer	Regulations not applicable to-all households	Develop regulations that enable action for poor households
WSA-2	Female (late-30s)	Committee for Women and Children	18 years	Self-supplied groundwater	Low-quality housing	Single pit or double pit (unlined)	Unaffordable pit emptying services	No budget to support constituents	Provide support to low-income households
KKA-1	Male (early-50s)	Sangkat Official	Not specified	Self-supplied groundwater	Conflicts between new and old housing	Single pit or double pit (unlined)	Public sewer infrastructure on main roads	Difficult to regulate existing households	Develop regulations that enable action for poor households
KKA-2	Female (early-50s)	Village Official	30 years	Self-supplied groundwater	Conflicts between new and old housing	Single pit or double pit (unlined)	Unaffordable pit emptying services	Households cannot afford to pay for services	Seek support from donors to develop infrastructure
KKA-3	Male (late-50s)	Village committee member	35 years	Self-supplied groundwater	Medium quality housing.	Double pit (lined)	Pit emptying service (often)	Limited efforts to address problems locally.	Collaborate with the private sector

* **Note:** *ID Poor status* is a Khmer standard used to administer welfare to households.

Following this, the research team shared a range of prompts, including (i) hand-drawn diagrams of different household toilet and containment infrastructure configurations; (ii) enlarged, printed *GoogleMaps* depicting the specific zones of the study area in 2010 and 2020 to frame the context of rapid urbanisation and population growth; and (iii) hand-drawn avatars of a range of societal actors engaged in the supply and consumption of existing sanitation service models in the study area to engage each *issue owner* in open dialogue about the existing experience of urban sanitation services. These prompts were employed for around the first twenty minutes to establish a narrative about this problematical situation across each season, how this compared to other issue owners, as well as how the experience of the issue owner had changed over time.

The next section of the interview was aimed at structuring this narrative by co-constructing a mental model of the *root definition*, promoting reflection on all the key components of a *purposeful activity model*. In the language of SSM, this is known by the mnemonic CATWOE, as elaborated on in *Table 12* (Checkland & Poulter, 2010). The model is centred around a transformation (T) or a structured list of activities to improve a situation from a pure declared worldview (W), or the attitudes and values by which an individual perceives the real-world. Practitioners used semi-structured questions to guide *issue owners* towards an initial attempt at defining T and W before drawing attention to the other parts of the mnemonic to enrich the model by exploring how it might inter-relate systemically with the broader heterogeneous water and sanitation configuration.

The interview was finalised by clarifying and elaborating on the individual root definition ($P \rightarrow Q \rightarrow R$) by referring to handwritten notes taken by *research team* during the interview. This process was used to ensure that (P) *the intended objective of the root definition*; (Q) *the idealised model of activities interpreted as necessary to achieve this*

intention; and (R) *the criteria for efficacy, efficiency, and effectiveness*, accurately represented the worldview of the *issue owner* (Checkland & Poulter, 2010) (see examples provided in *Figure 17* and the full range of models in *Figure E1* in the Appendix. If additional relevant *issue owners* were identified during the interview, their details were requested to increase the likelihood that the evolving list of potential *issue owners* represented a whole-of-system perspective.

Immediately following each interview, the *research team* met to debrief about the process of co-constructing the root definition and its content. The aim was to establish whether the root definition recorded in the notes was coherent and consistent with each researcher's recollection of the process. Each iterative debrief concluded by confirming the details of the time and location of the interview with the next *issue owner* and reflecting on whether a saturation of the attitudes, values, and assumptions in each successive *root definition* had been reached. Consensus that *saturation* had occurred was reached after 32 individual *root definitions* had been co-constructed with a mix of *households, service providers, and local service authorities* (see *Table 12*). This number is comparable with the interviews required to reach *saturation* in reviews of other qualitative studies conducted for heterogeneous populations (Hennink & Kaiser, 2022). The hand-written notes were transcribed, coded to ensure anonymity, and saved on a secure server for later reference. Three detailed examples of how the interviews were used to facilitate structured reflections on these root definitions using CATWOE as a mental model are included in *Table 13*.

Table 13: Some examples of how structured reflection on root definitions was organised for three different issue owners in the study area using CATWOE as a mental model in the interviews (Checkland & Poulter 2010)

CATWOE model	Responses coded from interviews with three <i>issue owners</i> as examples		
	Property developers	Pit emptiers	ID poor households*
C (Customers): are the people who are the victims or beneficiaries of the transformation	The primary <i>beneficiaries</i> of this root definition are <i>property developers</i> , who are establishing a transformative business model that contributes to peri-urban development in Siem Reap. These benefits are not limited to providing <i>water and sanitation service outcomes</i> but also other economic benefits such as improved housing and transport, flood mitigation, and public safety and security. The success of the model is dependent on other beneficiaries who define the future needs of the municipality, such as <i>provincial, municipal, Sangkat, and village authorities</i> , as well as <i>newcomers</i> wishing to purchase new properties. Relationships between these beneficiaries enable the transformation to occur. Property developers perceived there to be no <i>victims</i> from this model and minimal negative impacts.	The primary <i>beneficiaries</i> of this root definition are <i>pit-emptying businesses</i> aiming to realise a more sustainable business model. Other beneficiaries include the <i>general public</i> , particularly those who value and can afford regular pit emptying services and have constructed functional, lined <i>double pit containment systems</i> . Potential victims are <i>lower-income households in peri-urban areas</i> with limited capacity to maintain hygienic containment via <i>unlined single-pit containment systems</i> . Dense faecal sludge contaminated with solid waste in systems increases the risk of collapse and is more difficult to service and fails at peak times during the wet season. Households unable to transition may bear higher costs and further marginalisation by this model.	The <i>primary beneficiaries</i> of this root definition are <i>ID-poor households</i> who may improve their living situation by lessening the impact of comparatively unsafe and unaffordable sanitation infrastructure and self-supplied services. In particular, ID Poor households may benefit directly from upgrading unlined single-pit containment systems that regularly overflow in the wet seasons. They may benefit indirectly from improving the situation where untreated wastewater accumulates in more marginal areas of the city where they reside with a lack of secure land tenure, exacerbating efforts to improve this situation. ID Poor residents do not seek to create <i>victims</i> by this model; rather, they improve living standards at the same time as mitigating impacts on the environment.
(Actors): are people who would do the purposeful activities that would make up the transformation	<i>Property developers</i> , as key actors, organise access to land for development, housing, and infrastructure construction and successfully transfer modern public infrastructure back to <i>local authorities</i> and hard title to <i>new residents</i> . This transformation relies upon actors establishing transparent relationships between <i>municipal authorities, utilities, and new homeowners</i> .	<i>Pit-emptiers</i> as key actors in the root definition engage with <i>village leaders</i> and <i>lower-income households</i> to use price signals to motivate desired behaviours to optimise the safe collection and transport of faecal sludge to a treatment plant at Sambour. The mental model relies on subsidies; however, the financing mechanism for these inputs is not clear. One possibility is to consider their	<i>ID Poor households</i> , as key actors in the root definition, mobilise a breadth of loosely connected secondary actors to improve their dignity, living conditions, and the impact of faecal sludge entering open drains or rice fields. They obtain co-ordinated, practical support from <i>family members, community networks and organisations, benevolent landowners, loans and saving groups, pit</i>

		role in the scheduled emptying of well-managed containment infrastructure.	<i>emptying businesses</i> , and <i>local officials</i> , who may or may not support the transformation.
T (Transformation): <i>is the purposeful activities structured with an intention to improve the problematical situation</i>	The transformation sees a replicable model emerge where faecal sludge and wastewater are separated from sullage and stormwater and treated appropriately. Impacts on human and environmental health are mitigated. The cost of ownership of the infrastructure is transferred to local authorities, which is recovered from new residents through tariffs. The city attracts increased migration to support economic development through investment in smart urban infrastructure.	The transformation sees <i>pit-emptying business</i> optimise their role in collecting and transporting faecal sludge within a broader heterogeneous water and sanitation configuration. The activities in the model recognise the value of their role to society through pricing that enables their business model to service customers at a viable profit. Infrastructure and behaviours at a household scale shift to address risks to the business model through practices such as scheduled emptying and public support for those who cannot afford these services.	The transformation <i>sees ID Poor households</i> realising tangible improvement in sanitation service outcomes, such as health and dignity, improving their life. They engage multiple actors in activities to access resources, information, and influence to access clean water and safer, more affordable and convenient means of containing and transporting faecal sludge. The transformation is iterative, enabling decisions to be made step-by-step to address uncertainties about the correct approach to improving the situation.
W (Worldview): <i>the attitudes and values that define the perspective in which an individual interprets the real-world</i>	The worldview adopted in the root definition of <i>property developers</i> is objective, technology-driven, optimised, and <i>modernist</i> , aligning with infrastructure planning outlined in <i>Smart City</i> policy and development priorities in Cambodia (Siem Reap Provincial Administration 2023). However, the governance of the transformation is influenced by a more <i>traditional</i> and <i>centralised</i> perspective to which actors such as property developers conform to ensure the success of the transformation.	The worldview adopted in the root definition of <i>pit-emptying businesses</i> is one of an economist seeking solutions to a problem where their societal role of providing city-wide services has not aligned with the capacity of lower-income residents to pay for these services (McGranahan 2002). Moreover, the benefits of managing the safe containment storage, and treatment of this waste are significant to society. Pit-emptying businesses are often placed in a situation where they want to provide services at lower cost but cannot.	The worldview adopted in the root definition of ID poor households is focused on <i>participation</i> . It suggests that existing urban sanitation planning frameworks are not responding effectively to some demands for service provision, resulting in obvious inequalities in service outcomes. This perspective is reflected in the activities in the <i>root definition</i> , where those with ID Poor status engage and mobilise a breadth of actors to support their needs for improved household infrastructure and services (McGranahan 2002).
O – Owners – <i>are people who hold commodities of power that stop the transformation from occurring</i>	Owners of this root definition include <i>local authorities</i> whose approval is pivotal to the business model's success regarding transferring the ownership of public infrastructure back to local authorities and the hard land title to those intending to purchase properties. Tacit approval from	Owners of the root definition are <i>Provincial and Municipal Authorities</i> who decide how the economic resources available to Siem Reap are budgeted. The economy of Siem Reap is driven by tourism, which aligns with prioritising modern sanitation services in the urban core. The economic benefits of	Owners of this root definition are diverse. All actors engaged by an <i>ID Poor household</i> play a partial role in supporting a transformation. For example, a pit emptier accepting that some toilets will be more challenging to empty while providing advice on more effective self-management as a coping

	<p>multiple authorities at different administrative levels is required. For example, organising the sub-division of land (2030 Municipal Land Use Plan.), construction permits (Sub Decree #86) and permission to release wastewater to the environment (Sub-Decree No. 235) are all strongly regulated and may cause the transformation to be blocked or delayed.</p>	<p>investing in enhancing the safe containment and transport of faecal sludge are less visible and considered a private expense. To an extent, lower-income households may be considered owners. The financial drivers to motivate shifts in practices and the adoption of improved containment systems may be deemed insufficient and thus fail to be effective.</p>	<p>strategy; or an owner or caretaker of unused land enabling ID Poor Households to reside informally; or an older women's network providing a loan; or a local official providing advance warning of risk regarding the living situation of the ID Poor residents. Owners, hold partial power to stop a transformation, which is limited to stopping their mutual activities from supporting the transformation.</p>
<p><i>E—Environmental constraints are things that are taken as given, external to a worldview, and accepted as placing real limits on a transformation</i></p>	<p>Environmental constraints, particularly stringent legal requirements for accessing hard title, limit the scope of the business model or transformation proposed by <i>property developers</i>. For example, for developments to be approved, they must provide a system for accessing sufficient quantity and quality drinking water and make provisions to treat and evacuate sewage water through a septic tank and a sub-terrain filtering system. Access to vacant land, where these requirements may be met in a way that is financially viable, is limiting and makes it challenging to develop models for existing housing. Regulations are designed to result in individual land titles, whereby independent responsibility for water supply and wastewater systems can be attributed. This stipulation clarifies responsibilities for property owners regarding the maintenance of new infrastructure. Yet, limits how effectively these stipulations can be applied to all households.</p>	<p>Environmental constraints such as urbanisation and increased population density affect how <i>pit-emptying businesses</i> interact with lower-income households, and limit strategies that have historically facilitated the removal of faecal waste from households to open drains or rice fields. Related flooding issues continue to affect the safe containment of faecal sludge in households, particularly in lower-lying areas downstream of the urban centre and within communities. Policy measures aimed at adapting household faecal waste containment and transport practices include the approval of building permits for new housing developments only. Financial constraints faced by many households will impede this model from being universally applied in Siem Reap. The capacity to pay for pit-emptying in peri-urban areas is limited, and there are no standards developed for existing containment pits, nor is there formal monitoring of how this household infrastructure functions. This situation makes planning strategies to optimise faecal waste and collection services in these areas challenging.</p>	<p>Environmental constraints arise for <i>ID Poor households</i> from activities that have improved wastewater management in the municipality overall. As urban density has increased, drainage infrastructure has not been made accessible to all, and inequalities have emerged. New housing developments raise the level of the land to mitigate flooding issues and facilitate connections to drainage infrastructure. This practice transfers these problems to lower-lying areas where households cannot afford to do the same. Stormwater, greywater, and septage have limited pathways to be transported away from living areas and accumulate. Households resort to practices such as disposing of greywater in pits designed for faecal sludge or transporting septage to open drains or rice fields manually in the wet season when poor quality housing can make it challenging to maintain hygienic living spaces. Greater population density also reduces the capacity of wastewater to leach into the ground, causing containment pits to overflow more frequently. Without reliable land tenure, these problems can be challenging to resolve.</p>

6.3.3.2 Transforming root definition into purposeful activity models

Co-constructing the *root definitions* led to a rich understanding of the diverse perspectives on the urban sanitation service delivery configuration in the study. However, not all root definitions were of consistent quality. Further, several root definitions presented similar worldviews and were not presented in a format equipped to structure practical learning activities. To respond to these, we transformed the root definitions into *purposeful activity models* as a learning device that might encourage a greater depth of insight from later *structured discussion*. Appropriately, this task was conducted by *practitioners* who were not also *issue owners* to ensure anonymity. The objective of this task was to organise *culturally feasible* observations (*Analysis 2*) that might also *gently disrupt, unsettle, or provoke new thinking* about the problematical situation at a local scale (*Analysis 3*).

To this end, it was important to ensure that the worldviews in the *purposeful activity models* were de-identified and could not be attributed to a particular person unless this was their intent. Further, to facilitate learning, the models needed to be equipped with root definitions generated in the interviews to structure meaningful discussions about the worldviews embodied within them. Nine of these conceptual, *purposeful activity models* were constructed from the 32 root definitions derived from the interviews. Three examples of these models are presented in *Figure 17*, with the complete set of models used to organise structured discussion about the real-world situation included in *Figure E1* in the Appendix.

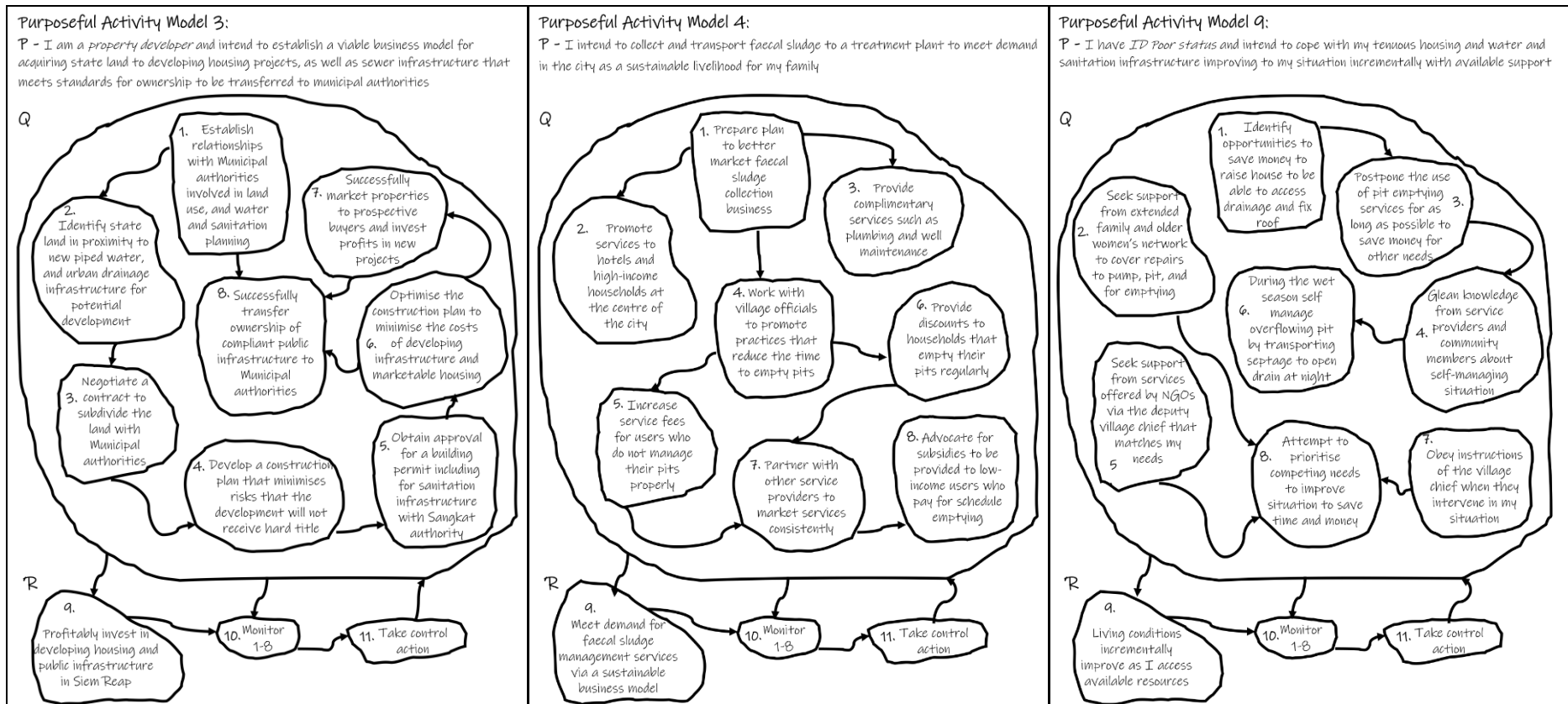


Figure 17: Examples of three purposeful activity models derived from root definitions co-constructed in the in-depth interviews

6.4 Using systems models to structure discussions about improving the situation

The root definitions (*Table 12*) and the *purposeful activity models* (*Figure 17* and *Table E1* in the Appendix) should not be viewed as tangible accounts of what each *issue owner* believes the real-world situation should be in practice. Instead, they express how the *real-world situation* was perceived from a single, idealised perspective at a particular point in time ([Checkland & Poulter, 2010](#)). The *purposeful activity models* are not intended to be applied or analysed directly. Instead, they are intended to be used conceptually in *thought experiments* as a source of questions about how the thinking arising in the model relates to the real-world, as represented by the rich pictures ([Checkland & Poulter, 2010](#)). Both models are used as learning devices that enable alternative worldviews to be *swept in* as part of a broader understanding of how a system of interest behaves.

This process involves organising a situation where *issue owners* with differing perspectives are curious enough to ask questions such as, *could this model work in real life?* And if so, *what would the implications be?* And so on ([Checkland & Poulter, 2010](#)). By asking such questions, individual *purposeful activity models* and the assumptions and values embodied in how individuals think and feel about an issue can be collectively interrogated to accommodate how others think and feel about the system of human activities. The learning process may be used to *transform* the purposeful activity models into a more desirable format that accommodates a broader group perspective and is more likely to be feasible. Iteratively sweeping in and interrogating additional perspectives in this way: (i) enhances the depth to which the real-world is understood, revealing options that are more likely to be relevant to the real-world problem situation; and (ii) prompts reflection on the criteria or reference system by which these options can be most meaningfully compared ([Checkland & Poulter, 2010](#); [Ulrich & Reynolds, 2010](#))

To illustrate these applications of purposive activity models, we outline two approaches where the *purposeful activity models* in *Figure E1* in the Appendix were used practically in a series of two workshops to structure this learning. To make the outcomes of the structured discussions in these workshops more tangible, we describe how the three *purposeful activity models* profiled in *Figure 17* were used as a *source of questions* about the messy real-world problematical situation and provide a summary of the outcomes of these discussions. The workshops included the same 15 *issue owners* out of 32 interviewed to produce the root definitions as the *rich picture* activity. Participants were selected on the basis of (i) obtaining a whole-of-system understanding of the diverse perspectives modelled within the study area, (ii) the extent to which the CATWOE mnemonic had enriched the *root definition* to provide a meaningful account of the *transformation* and the *worldview*; and (iii) ensuring that at least one *issue owner* represented each of the nine *purposeful activity models*.

6.4.1 Learning about desirable and feasible real-world options

The first approach was applied on the same day as the rich picture workshop and was *interpretive* in nature (Jackson, 2000). It was aimed at collectively structuring a discussion about the assumptions and values embodied within each purposive activity model. Each group from the rich picture activity was asked to interpret how they understood the transformative intention to improve the situation (T) and the worldview expressed (W) in three of the nine purposeful activity models. In particular, the groups were requested to reflect on those benefiting and being disadvantaged by the mental model (C), who might be involved in the implementation of the actors involved in the model, who may have the capacity and motivation to stop the transformation from occurring (O); and any constraints that might limit the feasibility of each model (Checkland & Poulter, 2010). This activity

provided a basis for developing a shared understanding of the purposeful activity model, independent of the original root definition. It also provided the basis for comparing the model to the rich picture the group had generated to pose questions about how the model might be situated in the real-world using the *rich picture* as a reference model (Checkland & Poulter, 2010).

Each group was asked to first consider any main contradictions between the purposive activity model and the rich picture; in particular, paying attention to contradictions that appear to be significant or a potential source of conflict, and discussing how these contradictions might be addressed in real life. Once a list of significant strategies for improving the situation was developed for each purposeful activity model, they were asked to consider from the group's perspective which were desirable, and which were feasible in the real-world. If disagreement emerged about any of these questions, the group was prompted to continue discussing each issue and attempt to come to a shared perspective. Through this approach, the individual activity model was transformed into a list of activities that are more likely to gain traction in the real-world (Checkland & Poulter, 2010). Key outcomes from this arising from this discussion for the three purposeful activity models presented in *Figure 17* are outlined in *Table 13*.

6.4.2 Boundary critique

The second approach was *emancipatory* in nature and was applied in a follow-up workshop on the 22nd of April 2022 (Jackson, 2000). It was used to generate critical questions about the real-world problematical situation as represented by the rich picture and an ideal vision of how the real-world situation ought to be, as represented by the *purposive activity models*. The source of questions about these two learning devices is a model of twelve CSH. These are otherwise known as boundary questions used in the process

of a *boundary critique*. Such questions (see Ulrich & Reynolds (2010)) are used to critically reflect on the role of the rich picture as a reference system for comparing different desirable and feasible options. The heuristics are used to focus on differences between the rich picture models of the real-world and the purposeful activity models as a concept of what the real-world ought to be. This approach provokes new thinking about the assumptions and beliefs adopted when co-constructing the rich picture. Because the *rich picture*, or any other model used as a reference system, is so critical to structuring discussions about which options are desirable and feasible, it is prudent to consider any latent tensions about how this model is defined and which components, actors, and interactions are included as relevant to these discussions.

In the workshop, the same groups applied the boundary questions to both models to consider differences in the judgements and assumptions made explicit about the problematical situation that exists in the real-world and those made when constructing the intended transformation of the *problem situation*. It prompted reflection on the scale of different intentions within each *purposeful activity model*, and whether they were conceptualised at a scale that might be effective in the broader context in which the problematical situation exists; how compelling the intention might be from this whole-of-system perspective; and whether the intention is ethically sound (Ulrich & Reynolds, 2010). Key outcomes arising from this discussion of the three purposeful activity models presented in *Figure 17* are outlined in *Table 13*.

Table 14: Example learning outcomes arising from the use of purposive activity models to pose questions of the problem situation

	Purposeful activity model 3	Purposeful activity model 4	Purposeful activity model 9
<p>Interpretive systems approach <i>Using the purposeful activity model to ask questions about the rich picture and identify and enhance desirable and feasible activities for improving these systems models</i></p>	<p>The purposeful activity model was described as having economic benefits to Siem Reap municipality overall. One key difference between the model and the real-world was that the model was not universally applicable and limited to areas where there was vacant land available for new housing. Further, design standards were only relevant for houses designed to be connected to the sewer and not relevant to many existing households. The <i>rich picture</i> defined downstream impacts from the model in areas where sewerage and drainage infrastructure was not available caused by new housing developments raising the level of land prior to construction. These impacts has resulted in conflicts between households in affected lower-lying areas of the study area, where there was less technical and financial support to resolve them. The workshop considered whether the model might be able to incorporate existing homes into a development project and that this would be desirable as the property developers had been able to use their knowledge the reduce the cost of infrastructure while still meeting regulatory standards. It was discussed that it might be difficult for this idea to become feasible due to the lack of standards for lower-quality housing and the lack of control developers would have over the design of existing households.</p>	<p>The purposeful activity model was described as most beneficial to households with higher quality containment infrastructure that could afford to have their pits serviced regularly. Key differences between the purposeful activity model and the real-world were that households with containment systems that were easier to empty were being transferred to the sewer and would require less visits by the pit-emptying businesses. This would mean that pit-emptiers would have more customers with single pit or poorly maintained double pit containment systems that were difficult to empty. The use of subsidies to encourage scheduled emptying was also a significant difference. The workshop discussed that it was unlikely that this would change the practices as this would still be expensive for households with poor quality containment systems. Increase in price would further encourage households to self-empty and dispose of faecal sludge in open drains and rice fields, while some households prefer to use septage as a fertiliser. The subsidies were said to be more desirable if they were provided to households to improve their containment infrastructure; however, the workshop believed that is was not feasible that authorities or organisations would support this idea financially.</p>	<p>The purposeful activity model was described by the workshop as only marginally valuable to <i>ID Poor households</i> noting that it was not significantly different to the rich picture except that many households in this situation are not as active as in the model. The workshop discussed that households in this situation may not try for a better situation than what is described in the model because they were uncertain about what might happen in the future. One difference in the real-world was that many people lived in a situation like this but did not have ID Poor status, and stayed only during the tourist season. Some people living in these situations had been relocated from houses that were along the riverside and mostly people that had stayed long-term lived on land owned by family members. To make this purposeful activity model more desirable, the workshop discussed that the Village Authority had a lot of knowledge about these these households and could provide more support to these households if they had more resources. Activities would also be more feasible if they were better co-ordinated, as often ID Poor Households were offered support by NGOs or community organisations that was at times different to what ID Poor households needed.</p>

	Purposeful activity model 3	Purposeful activity model 4	Purposeful activity model 9
<p>Emancipatory systems approach <i>Using CSH, or boundary critique to pose questions about how the reference system, or the without-project case for appraising desirable and feasible options, is defined</i></p>	<p>The workshop discussed that the <i>system objectives</i> of the <i>purposeful activity model</i> were well-aligned with the city development plan and regulations for developing standardised infrastructure. The business model was sustainable and supported by key institutions and newcomers wishing to purchase properties. However, it was considered that property developers ought to consider impacts on existing households and whether the model may be expanded to optimise the costs of connecting to the infrastructure established by developers. Existing regulations were irrelevant to large areas of the study area. While it was relatively simple to <i>govern</i> developments on greenfield sites, there was not an established strategy for how the containment and transport of faecal waste would be governed for existing households, especially lower-income households that are exempt from requirements to submit a building plan and blueprint for a septic system. Knowledge of potential improvements to <i>systems</i> is limited to formal planning because of this. The workshop identified that many of the broader benefits of the <i>purposive activity model</i> may not be realised by all residents for another 20 years and the model ought to consider some of the short-term impacts on lower income households and how they may adapt over this time to connect to planned infrastructure.</p>	<p>The workshop discussed that the <i>system objectives</i> of the <i>purposeful activity model</i> to improve the sustainability of faecal waste containment and transport were aligned with how the real-world <i>ought to</i> operate. However, standardising how pit-emptying businesses operate was not sufficient in itself. Support for lower income households to access functional containment infrastructure was also relevant, as was the capacity to dispose of grey water without causing conflicts with other households. These objectives were deprioritised in practice; however, as there is low capacity to pay for specific services to these households, there is also limited formal <i>governance</i> of these aspects. The role of pit-emptiers as skilled technicians that regulate household containment practices is informal and challenging to sustain. The workshop suggested that these practices ought to be formally monitored and regulated. Pricing may support regulation, and costs associated with upgrading household containment infrastructure, which are largely unknown, also need to be considered. Public utilities are responsible for connecting households to public sewer infrastructure and this also should be the case for faecal waste treatment plants. Responsibility for regulation household containment practices ought to involve pit-emptying businesses but be held by relevant authorities.</p>	<p>The workshop discussed that the <i>system objectives</i> of the <i>purposive activity model</i> ought to be more focused on the rights of households to access safe water and sanitation. The model was suggested to be focused on ID Poor households using the resources available to them to manage their own situation. This situation is largely consistent with conditions in the rich picture. In contrast, the structured discussion suggested that decisions about how the system was managed should take into account the need to ensure that all households in the study area benefited from urban sanitation services. In the rich picture, ID poor households are monitored and supported by the Commune Committee for Women and Children. However, this role extends to linking households with community organisation, has no budget, and minimal involvement in planning decisions. The workshop identified that there ought to be consideration of the impact of wastewater accumulation on the capacity of these households to contain faecal sludge when planning sewer and drainage projects in the Municipal and Sangkat budgets. Some in the workshop suggested pit-emptying businesses ought to be involved in monitoring how faecal waste is contained in households; however, others suggested this arrangement may disadvantage low-income households. Consensus was not reached on this concept.</p>

6.5 Discussion and conclusion

Planning for heterogeneous urban water and sanitation configurations is inherently complex, where interrelations between determinants of their behaviour are messy and unlikely to be perceived by all actors across a system in the same way. This messiness makes it challenging to structure functional or hard systems thinking approaches that define such configurations with a universal system objective and identify and deliberate about options that may fit contextually with any certainty. In this paper, we have demonstrated how SSM methodology may be used as an alternative action learning approach to organise the collaborative observation of these complex configurations from multiple perspectives and, as a result, learn how to better approach water and sanitation planning in such contexts. Central to the approach is the construction and application of systems as *learning devices* to structure discussions that assist *issue owners* (residents, service providers and local authorities) to understand their problematical situation holistically. This is part of an iterative process that increases the likelihood of action to resolve the situation.

The action learning process documented in this paper demonstrates how two types of models as learning devices were established to organise collaborative structured discussions about urban water and sanitation configurations. The first was intended to capture as much detail as possible about the real-world problem situation. This process brought 15 *issue owners* together representing diverse perspectives within the problem situation. These heterogeneous actors were otherwise unlikely to meaningfully engage with each other. Co-constructing *rich pictures* with this group transformed individual perspectives about the main components of the situation – how they are interrelated, relevant perspectives – and current and emerging issues affecting their interaction, into a common frame of reference. These *rich pictures* represent the first model type.

The second model type extends beyond what is possible in functional systems thinking approaches. These process involved developing *purposeful activity models* that embodied the assumptions, values, and beliefs underlying different perceptions of the real-world problematical situation in a format that was visual, recoverable, and intuitive. These second type of soft system models were key to organising the system of interest to be observed from multiple perspectives.

We demonstrated two complimentary and significant applications for these models in posing questions about the real-life situation in the structured discussions. Examples of the thinking that emerges from these applications was presented, not as recommendations, but instead as an iteration of an ongoing process. An *interpretive systems thinking approach* was used to collaboratively interrogate the objectives, activities, and measures of success for each purposeful activity model. *Issue owners* first engaged deeply with the assumptions and values of other issue owners in these systems, before being provided with an opportunity for their perspectives to be accommodated within the model to further enhance it. This process was shown to be effective for the collaborative definition of *system objectives, decision criteria*, and some possible *context specific interventions* for the study area. Moreover, an *emancipatory systems thinking approach* was used to gently trigger collaborative thinking and reflection about the ethical dimensions of these definitions. This thinking brought awareness to implicit judgements made when defining the system, making them more explicit in the rationale for how city-wide inclusive sanitation interventions are compared when planning urban water and sanitation service provision.

We encourage researchers and water and sanitation professionals (local authorities, planners, and engineers) to consider how constructing systems models as *learning devices* may enhance urban water and sanitation planning frameworks in LMICs. This research has

demonstrated the SSM is a flexible action research approach that may be applied to bring together *issue owners* to discuss issues in which there may be latent conflicts between perspectives. Moreover, it is possible to co-construct culturally feasible soft systems models with the potential to lead to tangibly addressing the root causes of inequalities in the planning of heterogeneous urban water and sanitation configurations. Future research should consider how the construction of soft systems models as learning devices may be integrated with functional systems thinking models to better support such planning.

Ethics statement

Ethical approval was granted by the University of Technology (ETH205222). All respondents were briefed about the study before providing written consent to participate. Additionally, all data has been anonymised to maintain confidentiality and prevent respondents from being identified.

CRedit author statement

Simon Ross: Conceptualisation, Methodology, Investigation, Formal Analysis Writing- Original draft preparation, Validation, Writing- Reviewing and Editing; **Simon Fane:** Conceptualisation, Supervision Writing- Reviewing and Editing; **Tim Foster:** Supervision Writing- Reviewing and Editing. **Sunday Yim:** Validation, Writing- Reviewing and Editing.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Part Three: Learning from the transdisciplinary case study
in Siem Reap Municipality to inform a comparative
economic analysis methodology and systemic urban
water and sanitation planning to improve the
problematical situation

Chapter Seven: Discussion and synthesis of a unified approach to the comparative economic analysis and systemic planning of heterogeneous urban water and sanitation service provision configurations

7.1 Overview

This chapter interprets and synthesises the findings from *Chapters Three to Six* of this thesis. It does so by extracting insights about planning approaches for urban water and sanitation services in heterogeneous contexts in low- and middle-income countries and discussing their implications for research and practice. Three interrelated aspects are considered: (i) what becomes visible to decision-makers and societal actors when *hard*, *soft*, and *critical* systems approaches are integrated in planning practice; (ii) how heterogeneous service provision configurations are more meaningfully represented within comparative economic analysis methodologies when complexity is made visible; and (iii) how a unified systemic thinking approach can inform learning-oriented planning that strengthens relational capacity to address persistent service outcome inequalities. These discussions interpret insights arising from applying the methods embedded in the transdisciplinary case study. They inform revisions to the integration concept for the systemic planning of heterogeneous urban water and sanitation configurations in LMICs proposed in *Section 2.4*.

The discussion is supported by the theoretical and methodological framework presented in *Chapter Two* and the scoping and systematic review of the least-cost comparative economic analysis and integrated resource planning principles applied to heterogeneous configurations in *Chapters Three and Four*. However, it is primarily shaped by the interpretation of the learning outcomes from applying the embedded methods of the transdisciplinary case study in *Chapters Five and Six*. Explicit responses to each research

question, together with a statement of the contributions, limitations, and implications arising from the discussion are then provided in *Chapter Eight*.

The literature supporting this thesis is engaged with in *Chapters Three to Six*, where comparative economic appraisal, residential end-use demand analysis and modelling, and soft and critical systems thinking approaches applied to urban water and sanitation planning are reviewed in detail. The strengths and limitations of applying these methodologies to heterogeneous urban contexts are discussed in the papers compiled in these chapters. *Chapter Seven* focuses on extracting and synthesising what was learned from integrating different systems thinking paradigms engaged with in these chapters to respond to identified gaps in the application of comparative economic analysis principles to these contexts to help synthesise a unified systemic planning approach.

The contribution of this thesis is therefore not to develop systems thinking approaches in isolation, but to use them to bring different ways of knowing about heterogeneous configurations, techno-economic, interpretive, and critical, together in planning practice. The discussion focuses on how this integration changes what can be known, compared, and actioned through urban water and sanitation planning. This rationale provides the basis for how learning emerging from the transdisciplinary case study is interpreted in the sections that follow

7.2 What was learned from integrating hard, soft, and critical systems approaches

Section 7.2 interprets the learning embedded in *Chapters Five and Six*. It explains how different systems thinking paradigms within each embedded study shaped what became visible when they were applied, and why the integration of these insights matters for learning-oriented planning. The discussion begins by examining the learning that emerged through the application and integration of *hard*, *soft*, and *critical* systems thinking

approaches within the transdisciplinary case study. The focus here is on interpreting what knowledge became visible when these approaches were applied together in practice. In line with each systems paradigm, the discussion considers how costs, epistemic uncertainty, and power relations associated with heterogeneous configurations were revealed and understood (Jaglin, 2014; Lawhon et al., 2017; Hutton, 2001; Daudey, 2018).

Across the case study, different forms of knowledge were co-produced, shared, and engaged with in ways that highlighted the distinct and complementary contributions of each systems thinking paradigm, as well as the limitations that became apparent when they were applied in isolation. This chapter interprets how integrating these approaches reframed the understanding of the problematical situation in the Siem Reap case study and uses this learning to revise the learning-oriented planning approach, i.e., the integration concept (see *Section 2.4*).

7.2.1 What each systems thinking approach revealed in practice

This subsection reflects on what was learned through applying and attempting to align hard, soft, and critical systems approaches within the transdisciplinary case study. It draws on insights from *Chapters Five and Six* to examine how different forms of knowledge were generated and engaged with, where integration was partial or uneven, and what these experiences reveal about knowledge co-production in heterogeneous urban water and sanitation planning contexts.

Each systems thinking paradigm surfaced different types of knowledge about the problematical situation. Further, the integration of this knowledge made aspects of service provision that are typically less visible when decision-making is shaped by narrow financial or infrastructure-led agendas accessible. For instance, when insights into how tangible and intangible costs of service provision are distributed; how power relations shape service

outcomes; and how epistemic uncertainty manifests and is managed. Interpreting these differences helps clarify how each approach contributes distinct yet partial insights into the problematical situation.

7.2.1.1 What became visible through a hard systems lens.

This subsection interprets what became visible when hard systems methods were applied to represent heterogeneous service configurations in practice, and where their limits became apparent. Hard systems thinking remains a dominant systems paradigm in water and sanitation planning. It is typically operationalised through quantitative models that represent system components and their relationships to support goal-oriented decision-making in response to uncertainty (Jackson, 2000; Ison, 2008; Reynolds & Holwell, 2010). In this inquiry, hard systems thinking played a central role in making the structure and functioning of heterogeneous service provision configurations visible.

The residential water end-use demand model presented in *Chapter Five* provided a quantitative representation of how water access, household practices, storage, and wastewater sinks were configured across the two case study villages (Ross et al., 2025). This modelling revealed that households with nominally similar access to water supply infrastructure experienced markedly different service outcomes. It was shown that this arose through variations in storage capacity, reliance on self-supply, coping practices, and wastewater sinks within households. These non-intuitive patterns are typically concealed when aggregated demand projections that assume homogeneous service outcome experiences are used to shape decision-making.

By disaggregating water demand and service outcome characteristics across socio-technical profiles, hard systems modelling increased certainty regarding how alternative interventions might influence system behaviour. It demonstrated the value of objective,

validated models that explicitly represent heterogeneity for informing discussions about what improvements may be desirable and feasible.

At the same time, the limitations of hard systems thinking became apparent. The end-use model's capacity to function as a meaningful boundary object depended heavily on contextual and interpretive knowledge generated through interviews and qualitative inquiry. Without this context, the model risked being interpreted through a single objectivist lens that could inadvertently reinforce infrastructure-led assumptions and obscure distributional impacts. In this sense, hard systems thinking was effective at revealing structural heterogeneity, but insufficient on its own to interrogate how service outcomes are experienced, justified, or prioritised within planning processes.

7.2.1.2 What became visible through soft systems perspectives.

This subsection examines how soft systems methods surfaced assumptions, values, and meanings that could not be accessed through hard systems modelling alone. Soft systems thinking is associated with *interpretivist approaches* and the use of *systems as learning devices*. It relaxes the assumption that *complex adaptive systems* can be objectively understood (Checkland & Poulter, 2010; Reynolds & Holwell, 2010). Instead, it emphasises engaging with multiple, often conflicting, interpretations of how a problematical situation might be improved.

In this inquiry, soft systems thinking made the values, assumptions, intentions, and worldviews through which different societal actors understood persistent water and sanitation service outcome inequalities visible. These insights were surfaced through the construction and comparison of *purposeful activity models* derived from in-depth interviews structured using CATWOE root definitions (Checkland & Poulter, 2010; Ross et al., [preprint]). Unlike the end-use model, these artefacts did not represent the real-world

heterogeneous configuration itself, but rather the mental models encompassing objectives, intended actions, and priorities for improving the situation.

When documented and compared, the purposeful activity models revealed diverse understandings of how responsibilities, risks, costs, and desirable outcomes were perceived by different societal actors. For instance, some models prioritised cost-efficient infrastructure led by utilities or municipal authorities, while others emphasised mitigating household-level impacts arising from different coping practices such as storage, self-supply, or engaging informal service providers.

These differences reflected conflicting aspirations and criteria for desirability and feasibility (Ross et al., [preprint]). They became visible in the case study through the structured comparison of the purposeful activity models (*Figure 17*) with the rich pictures (*Figure 16*) acting as a proxy boundary object. *Table 14* illustrates how contrasting assumptions about costs, responsibilities and roles could be used to accommodate diverse interpretations of desirable and feasible interventions, thereby prompting action to improve the situation.

One key insight is that this learning could not have been prompted through the residential end-use demand model alone. The *purposeful activity models* performed as epistemic objects, enabling participants to recognise gaps in their own understanding and engage reflexively with the perspectives of others. This learning was supported by the presence of a relatively stable reference point. Here, rich pictures, as a proxy for a fully developed residential end-use model. This acted to anchor structured learning within a shared representation of the heterogeneous configuration. Soft systems thinking was effective in prompting reflection because it did not seek to reduce uncertainty, rather it

made the assumptions and values of others within the configuration explicit, and open to being questioned.

7.2.1.3 What became visible through critical systems thinking.

This subsection reflects on what became visible when *critical systems heuristics* were applied in the workshops to *gently* interrogate boundary judgements, power relations and the persistence of inequitable service outcomes. *Critical systems thinking* extends interpretive systems approaches by explicitly examining how these aspects influence whose knowledge is legitimised and which interests are prioritised within complex adaptive systems (Jackson, 2000; Ulrich & Reynolds, 2010, 2020). It recognises that persistent inequalities may be actively reproduced if taken-for-granted assumptions about system boundaries and decision authority remain unexamined. In Cambodia, this sentiment has been reflected in critiques of normative planning frameworks and their tendency to marginalise certain groups, forms of knowledge, and service arrangements, even when equity is an explicit policy objective (e.g. WaterAid, 2015; Mosello & O'Leary, 2017; Grant & Willetts, 2019; Huggett, 2022; Kimbugwe et al., 2022; Rhodes-Dicker et al., 2024).

In this inquiry, critical systems thinking made how persistent service outcome inequalities were sustained not only by technical or financial constraints or divergent worldviews, but by normative boundary judgements embedded within existing planning institutions visible. These dynamics were surfaced through the application of *critical systems heuristics* as a means of interrogating each purposeful activity model in the third participatory workshop described in *Chapter Six* (Ross et al., [preprint]).

Those engaged in the workshop considered who benefited from existing service arrangements, who defined acceptable service standards, whose knowledge was treated as legitimate, and who bore the costs and risks of coping with inadequate services. This

process revealed why certain service configurations persisted despite being recognised as inequitable or socially unsustainable. Examples included the subsidisation of desludging services by marginal service providers, and household coping practices that contributed to the societal benefits of safe sanitation, yet remained outside formal planning boundaries (see *Table 14*) (Ross et al., [preprint])

Critical systems thinking thus reframed insights generated through *hard* and *soft systems* approaches by making power relations and institutional inertia visible. Rather than further characterising heterogeneity, it shifted attention toward interrogating why socially desirable and technically feasible options remained politically or institutionally constrained. This reframing was essential for extending planning beyond understanding complexity toward addressing the latent conflicts that sustain persistent inequalities.

7.2.2 What changed with the attempt to unify these paradigms?

This section interprets how bringing *hard*, *soft*, and *critical* systems approaches together within a unified integration concept altered how knowledge was produced. This shifted the interpretation of their function from methods applied in parallel, towards an integrated, learning-oriented planning framework. While *Section 7.2.1* examined which insights were revealed through the application of each systems thinking paradigm in practice, this section reflects on what changed when hard, soft, and critical systems thinking were intentionally unified. This reframing shifts the focus of inquiry toward how distinctions were drawn, how system boundaries were constructed, whose perspectives shaped decision-making, and why certain options either persisted or became deprioritised.

[Cabrera et al.'s \(2021\)](#) DSRP heuristic (*Distinctions, Systems, Relationships, and Perspectives*) was used as a meta-theoretical lens for this discussion. It is important to note that DSRP was not applied to prescribe how planning should occur, but as an interpretive

overarching lens for examining how epistemologically plural forms of knowledge were aligned in practice to contribute to *mutual and transformative learning* (Mitchell et al., 2015).

7.2.2.1 Distinctions

Making *Distinctions*, or *recognising what something is and is not*, was foundational to integrating insights across paradigms (Cabrera et al., 2008). Distinctions between service provision typologies, household infrastructures, wastewater sinks, and the roles of diverse actors were made explicit through the combined use of residential end-use demand modelling, rich pictures, interviews, household surveys and workshop discussions (Ross et al., 2025; [preprint]). These distinctions altered how the existing without-project situation was perceived. What had previously been treated as relatively uniform service provision model was reframed as multiple co-existing configurations producing heterogeneous service outcomes.

Notably, distinctions identified through the end-use model depended on qualitative insights to articulate how household experiences were shaped by coping strategies that imposed intangible costs on households. Making these distinctions visible was essential for enabling comparative economic analysis to account for distributional impacts. Without them, marginal experiences remained obscured within aggregated representations, limiting the inclusivity of planning decisions (Cabrera et al., 2015; Ross et al., 2024a).

7.2.2.2 Systems

The *Systems* pattern emphasised the definition of *part-whole relationships*, recognising the existence of subcomponents within interconnected wholes (Cabrera et al., 2008). In this inquiry, knowledge about such relationships, and how they influenced systemic behaviour, emerged through aligning quantitative, interpretive, and critical insights over time. A

definitive mapping of the heterogeneous configuration explored in the case study could not be achieved through any single method. Rather, system definition remained conditional and required iterative adaptation as new knowledge emerged (Ross et al., 2025; [preprint]). The integration of different systems paradigms in this case helped to reveal the contingent nature of system definition. Rather than being inherent or amenable to characterisation through a single persistent modelling approach, system stability depended on the ongoing negotiation of multiple part–whole relationships.

Conceptualising part-whole groupings as adaptive socio-technical configurations with dynamic relationships challenged pre-existing assumptions about how urban water and sanitation services are structured. One key reflection arising from this DSRP pattern was the need to establish a shared understanding as the basis for system definition and comparison. The implications for the case study arose from the necessity to organise the use of each system paradigm to manage these dynamics to meaningfully inform decisions across the configuration, rather than relying on a single persistent boundary object.

This pattern highlighted the socio-technical diversity of part-whole groupings across the heterogeneous configuration, and the instability of many of these relationships. An important methodological learning was that while the residential end-use model was initially intended to function as a boundary object, its stabilising role depended on ongoing interpretive and critical insights to remain effective. Without the epistemic certainty that a single, stable object might provide, new thinking about how different systems thinking paradigms could be brought together coherently within the transdisciplinary case study would be required.

7.2.2.3 Relationships

Closely related to the *Systems* pattern, the *Relationships* pattern prompted reflection on how interactions between infrastructure investments, household practices, and institutional arrangements shaped emergent outcomes for the system as a whole (Cabrera et al., 2008). In the case study, these relational dynamics became visible through the combined application of end-use demand analysis and soft systems methodology at a time in the real world context when formal water and sanitation infrastructure upgrades were being implemented unevenly across the two villages (Ross et al., 2025).

Interviews used to develop root definitions, together with the construction and comparison of purposeful activity models, revealed how planned service provision configurations interacted with existing household coping practices, tenure arrangements, and informal service relationships in ways that were not readily apparent to planners or utilities (see *Table 14*). Rather than revealing linear cause and effect relationships, these methods surfaced how infrastructure-led planning became entangled with existing socio-technical arrangements, shaping costs, risks, and coping strategies differently across households (Ross et al., [preprint]).

These interaction effects illustrate how service outcomes in heterogeneous urban configurations emerge from relationships between formal infrastructure decisions and informal, adaptive household practices, rather than from infrastructure investments alone. Making these relational dynamics visible was essential for understanding why rational interventions could produce uneven or unintended outcomes different parts of the configuration.

7.2.2.4 Perspectives

The *Perspectives* pattern prompted reflection on how integrating different systems thinking paradigms supported a less partial understanding of the problematical situation through learning across diverse ways of knowing (Cabrera et al., 2008). Perspectives modelled from different systems paradigms were intentionally integrated through comparison to prompt learning. When this occurred, the insights could be organised as prompts to structure collaborative action-oriented learning, as opposed to making insights visible through a specific systems approach.

For instance, in the transdisciplinary case study, this became evident in *Chapter Six*. The collaborative rich picture (as a proxy for the end-use model) contained the perspectives of all actors involved in its co-production about what exists in the real world without-project context. While less explicit, service provision could be differentiated, albeit qualitatively, by different socio-demographic groups and service provision typologies. These objective perspectives of what existed were compared with the worldviews represented in each *purposeful activity model*. This led to the aspirations and values supporting decisions to assume responsibility for costs, service outcomes, or applying coping practices in relation to this situation enabled such interpretive knowledge being questioned.

In practice, such knowledge is challenging to both access and interrogate, particularly from perspectives as diverse as property developers, desludging operators, low-income households, and others (see *Figure X; Appendix E*). When the knowledge from the different systems paradigms was brought together, it enabled these assumptions to be interrogated safely, within a recoverable artefact, prompting learning about what is desirable and feasible from a broader societal lens. The process transformed these *Perspectives* to become objects of collaborative learning when held in tension, rather than as asserted

competing preferences within a heterogeneous configuration aligned uncritically through existing power relations.

7.2.2.5 The unifying DRSP system

When the four systems thinking patterns, *Distinctions*, *Systems*, *Relationships*, and *Perspectives*, were brought together, they provided a pragmatic way of interpreting how epistemologically diverse forms of knowledge could be integrated in practice. The DSRP heuristic was used to reflect on how *hard*, *soft*, and *critical* systems approaches could be aligned within a learning-oriented systemic planning methodology. This alignment supported an understanding of how a mix of possible interventions might emerge from a complex, heterogeneous urban water and sanitation configuration, supported by a fit-for-purpose planning approach.

The *function* of the insights obtained through different systems thinking paradigms changed when they were unified. *Distinctions* revealed from the residential end-use survey model provided a structure by which competing cost perspectives could be projected to better represent the distributions within a more complete representation of the impacts of service provision. Component *part-whole relationships* that otherwise may have been invisible, or stable within a *Systems* definition were reframed as contingent and influenced by relational knowledge and latent conflicts that could produce uneven or unintended outcomes. The *Perspectives* pattern revealed that desirability and feasibility were criteria that required careful negotiation and critical engagement with inherent planning assumptions. Overall, these patterns provided a means of interrogating complex, epistemologically plural insights in ways that promote inclusive outcomes, while avoiding a reversion to one-size-fits-all simplifications (Cabrera et al., 2021).

The DSRP heuristic also supported reflection on how the *initial integration concept* was designed (see Section 2.4.2) and revised. That is, this involves leaning into where misalignments between intent and implementation emerged, and how the concept could be adapted to better support comparative economic analysis and the planning of inclusive urban water and sanitation interventions (Ross et al., 2024a, 2024b). These reflections inform *Section 7.3*, where the integration concept is revised based on learning experiments in *Chapters Five and Six*, and *Section 7.4*, where improvements are backcast from the evaluative criteria developed and validated in *Chapters Three and Four*

7.2.3 Positioning what was learned within the literature

This section situates the empirical learning from the case study within the broader literature on systems thinking applied to urban water and sanitation planning. It highlights how the unified use of systems thinking approaches extends their existing application in LMICs in isolation. Planning methodologies supported by these approaches have received increasing attention within WASH research and practice in LMICs over the past decade (Huston & Moriarty, 2018; Liddle & Fenner, 2017; Neely & Valcourt, 2024; Valcourt et al., 2020).

However, with few exceptions (see *Section 6.2*), this literature has largely focused on rural and peri-urban contexts, often applying systems concepts through generic *building block* approaches, external program evaluations, structured theories of change, and conceptual frameworks, such as *leverage points* (Grant & Willetts, 2019; Kimbugwe et al., 2022; Hollander et al., 2020; Wilkinson et al., 2021; Willetts et al., 2022). While these approaches can support practitioners, they are limited in their capacity to engage with the socio-technical heterogeneity and persistent inequalities characteristic of urban water and sanitation configurations (Lawhon et al., 2017; Ross et al., [preprint]).

In contrast, this transdisciplinary inquiry focuses explicitly on application to heterogeneous urban water planning contexts and the methodological challenge of integrating systems thinking paradigms within a unified planning framework. Applying systems thinking in this case was not used as an evaluative tool for planning. Instead, the research used the empirical application of *hard*, *soft*, and *critical systems* approaches to think through how they could be operationalised to support the resolution of gaps in the application of least-cost and integrated resource planning principles to this problematical situation (Ross et al, 2024a, 2024b).

In doing so, the study responds to a largely unexplored gap in the literature concerning how methodologically plural, participatory systems approaches can be used to address persistent service outcome inequalities in complex urban water and sanitation systems. This contribution aligns with emerging calls for more citywide inclusive approaches to service provision, while extending them through context specific, relational forms of systems thinking (Carrard et al., 2024).

7.2.4 What opportunities does this learning create?

This section interprets the implications of the integrated systems learning for future urban water and sanitation planning, focusing on how comparative economic analysis can better engage with heterogeneity, uncertainty, and inequality. Building on the DSRP-informed synthesis in *Sections 7.2.2 and 7.2.3*, this section highlights opportunities for urban water and sanitation planning in heterogeneous contexts. The case study demonstrates that integrating *hard*, *soft*, and *critical systems* approaches using the DSRP heuristic makes it possible to embrace complexity without reducing it to a single technical or institutional frame (Cabrera et al., 2021).

The learning generated through this inquiry points to three interrelated opportunities for systemic comparative economic analysis. First, it enables the deliberate integration of structured, quantitative representations of service provision with qualitative insights into lived experience, institutional norms, and power relations. Second, it supports planning as an iterative, learning-oriented process in which diverse societal actor perspectives are compared, reflected upon, and progressively integrated rather than aggregated. Third, it preserves sufficient methodological structure to support robust and transparent decision-making, while remaining flexible enough to accommodate epistemic uncertainty and emergent outcomes.

These opportunities inform both the revision of the initial integration concept (see Section 2.4.2) and the backcasting of a systemic comparative economic analysis methodology (see Section 2.3). In *Section 7.3*, they are assessed against the empirical experience of implementing the integration concept in Siem Reap. In *Section 7.4*, they are used to articulate how a revised methodology might better support inclusive, adaptive urban water and sanitation planning in complex, heterogeneous contexts.

7.3 What was learned from implementing the integration concept in practice

Building on Section 7.2, this section examines what was learned through implementing the integration concept within the transdisciplinary case study. It shows that making previously invisible costs, assumptions, and power relations explicit fundamentally changes how comparative economic analysis performs in heterogeneous contexts. This helps explain why such approaches often struggle to address persistent service outcome inequalities when applied in heterogeneous LMIC contexts (Ross et al., 2024b). The integration concept introduced in Section 2.4.2 was used to organise how diverse forms of knowledge were co-produced and brought together across the case study. While Section 7.2 focused on what

became visible when hard, soft, and critical systems approaches were applied together, this section reflects on how the integration concept itself performed when translated from design to practice.

The focus here is not on reinterpreting empirical findings, but on examining the implications of how different systems thinking approaches were sequenced, how knowledge artefacts functioned as boundary and epistemic objects, and how assumptions about knowledge integration shaped implementation in practice. Drawing on the embedded studies in *Chapters Five and Six*, this interpretation identifies where the initial integration concept aligned with its intent and where misalignments emerged. These insights are synthesised as responses to three opportunities for strengthening transdisciplinary integration and are taken forward in *Section 7.4*. They are used to backcast a revised integration concept and an improved systemic comparative economic analysis methodology.

7.3.1 Revisiting the initial integration concept and its original intent

The initial integration concept was first introduced and operationalised in *Chapter Two (Section 2.4.2; Figure 4)*. For clarity, it is reproduced here as *Figure 18* to support reflection on how the concept performed when implemented in practice. This concept was designed to organise epistemologically plural knowledge co-production within the transdisciplinary case study, guided by the three outcome spaces outlined in *Figure 1*. However, it was developed prior to the articulation of the theoretical framing and the publication of the papers compiled as *Chapters Three and Four (Ross et al., 2024a, 2024b)*. Thus, it was only partially informed by the conclusions that emerged from those studies.

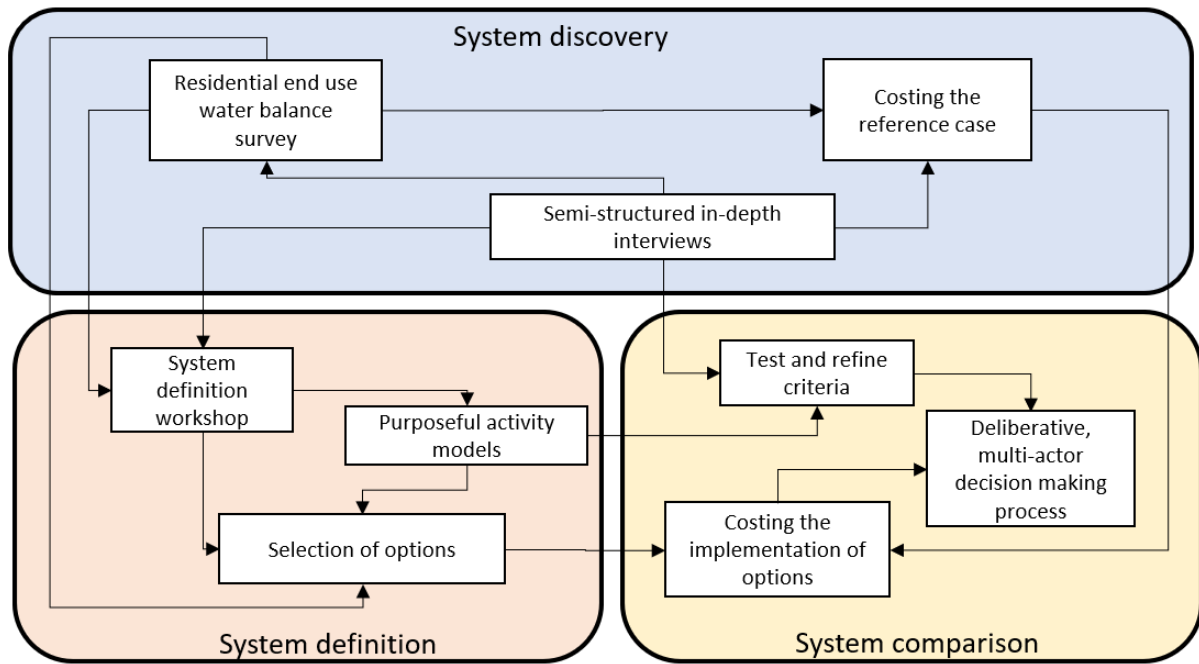


Figure 18: The initial integration concept

The concept was intended to be applied flexibly in response to emergent needs, while still providing a coherent structure for integrating boundary objects (the residential end-use model) and epistemic objects (the purposeful activity models) across three phases: (i) system discovery, (ii) system definition, and (iii) system comparison.

Table 15: Opportunities for transdisciplinary integration

Phase of the integration concept	Opportunity for transdisciplinary integration	How this was interpreted
System discovery	Bringing together structured and interpretive knowledge co-production	Challenges in unifying survey and interview results
System definition	Organising planning as an iterative, learning-oriented system	Implications of using rich pictures instead of end-use demand profiles as a boundary object
System comparison	Balancing flexible participation and robust decision-making	The role of a learning orientation in shifting how decisions are framed

Table 15 links these phases to three opportunities for strengthening transdisciplinary integration and provides the structure for the reflection that follows. To support this discussion, the three phases of the initial integration concept, as introduced in *Chapter Two*, are summarised below, providing a reference point for examining how the concept evolved in practice and where opportunities for strengthening integration emerged.

7.3.1.1 System discovery

The initial integration concept (see *Figure 18*) assumed that the residential end-use survey and in-depth interviews could jointly support the development of a costing model representing of the existing without-project case in the case study in Siem Reap. This assumption proved problematic in a heterogeneous context. The absence of a clear and consistent system definition, particularly at the household scale and for informal service provision, made it difficult to determine which cost data were relevant and how they could be collected systematically.

In practice, system discovery unfolded through the concurrent development of a household survey intended to define a without-project water balance (*Chapter Five*) (Ross et al., 2025), alongside in-depth, semi-structured interviews used to elicit individual root definitions and collect cost-related insights from diverse societal actors (*Chapter Six*) (Ross et al., [preprint])

While the survey was effective in generating sufficient end-use water demand data to establish a relatively stable and interpretable boundary object, its development was delayed by COVID-19 lockdowns, constraining the ability to systematically identify and collect relevant cost data (Ross et al., [preprint]). This demonstrated that a robust reference case could not be established in a purely qualitative way. Instead, this was dependent on first

validating the residential end-use survey as a shared boundary object upon which systematic costing could be built.

This experience revealed that the concurrent design assumed in the initial integration concept (see *Figure 18*) was insufficient to support the intended development of a cost model in a highly heterogeneous context, reinforcing the need to sequence inclusive system definition before detailed costing.

7.3.1.2 System definition

The second phase, *system definition*, was intended to integrate the outputs of *system discovery* into a shared systems model capable of supporting the scaling, costing, and comparison of intervention scenarios derived from the purposeful activity models. In the initial integration concept (see *Figure 18*), this phase assumed that the residential water end-use demand model would function as a stable boundary object, providing a structured quantitative point of reference against which the purposeful activity models could be interpreted and compared (Checkland & Poulter, 2010; Ross et al., [preprint]).

In practice, this assumption did not hold. Although the residential end-use model had strong potential as a boundary object, the bottom-up and highly heterogeneous nature of the demand data, combined with time constraints arising from COVID-19 disruptions, prevented its validation and effective use within collaborative workshops (Ross et al., 2025). As a result, the planned integration of the residential end-use water demand model and the purposeful activity models within participatory workshops was not conducted. Instead, the system definition phase pivoted towards the use of collaboratively constructed rich pictures as a proxy boundary object. These rich pictures enabled participants to visualise the real-world problematical situation and compare it directly with the purposeful activity models, supporting structured learning (Checkland & Poulter, 2010; Ross et al., [preprint]). However,

because a costed reference case had not been established during system discovery, the end-use model could not be used to project or compare the tangible costs associated with alternative interventions.

This experience revealed that, in a heterogeneous context, system definition cannot rely on the concurrent development of structured quantitative models and interpretive purposeful activity models. Without a validated and interpretable boundary object capable of supporting comparison of interventions at different scales, the approach was limited to qualitative, collaborative system definition. While this supported a reflexive learning orientation, it constrained the capacity to systematically compare tangible costs and forecast the impacts of heterogeneous configurations. This insight reinforces the decision in the revised integration concept presented later in this chapter (*Figure 19*) to deliberately sequence inclusive system definition prior to the development and validation of the end-use model as a boundary object (Cabrera et al., 2021; Midgley, 2003).

7.3.1.3 System comparison

The third phase, *system comparison*, was initially conceptualised as a deliberative, multi-actor assessment in which alternative intervention scenarios would be evaluated using co-created decision criteria. Because these scenarios were derived from the purposeful activity models, it was assumed that they would capture both tangible and intangible determinants of cost under a range of endogenous scenarios (e.g. Willetts et al., 2013). This phase relied on a validated residential end-use demand model functioning as a boundary object, alongside a set of refined purposeful activity models functioning as epistemic objects. It was assumed that these outputs from system discovery and system definition would together support the comparative assessment of costed scenarios against a clearly defined without-project reference case.

In practice, this assumption underestimated the time and methodological work required to integrate real-world knowledge into boundary and epistemic objects that were sufficiently robust to support comparison in a heterogeneous context. As discussed earlier, the absence of a validated system definition and a costed without-project case constrained the ability to quantify tangible costs consistently across scenarios. As a result, the system comparison workshops could not function as a deliberative decision-making exercise in the manner originally envisaged (Ross et al., [preprint]).

Instead, the workshops evolved into a more reflexive, learning-oriented process focused on interrogating the assumptions, values, and boundaries embedded within the purposeful activity models themselves. While this limited the capacity to compare the costs of alternative scenarios or define the impact on water demand, it enabled deeper insight into the intangible determinants of decision-making, including institutional inertia, contested responsibilities, and the lived experience of service outcome inequalities (Ross et al., [preprint]).

Importantly, this shift revealed why comparative economic analysis approaches that rely on well-defined reference cases and stable system boundaries often struggle to address persistent inequities in heterogeneous urban water and sanitation contexts. The difficulty of producing costed scenarios was not merely a technical limitation but reflected epistemic uncertainty regarding how the system should be defined, whose costs and benefits should be counted, and which perspectives were legitimised within planning processes (Ross et al., 2024a).

Despite these constraints, the system comparison phase played a critical role in reinforcing and validating evaluative criteria for systemic comparative economic analysis, particularly those concerned with epistemic uncertainty and boundary judgements. These

insights laid the foundations for *Wave Three* of the research, which shifted emphasis from the co-production of additional models towards critically examining how different forms of knowledge were integrated within the transdisciplinary case study. In doing so, the system comparison phase contributed directly to the revision of the integration concept and informed the backcasting of an enhanced comparative economic analysis methodology in *Section 7.4*.

7.3.2 What was learned in practice

While the three phases were implemented in alignment with the broad intent of the *initial integration concept*, their application was limited. A range of constraints were revealed, explaining why the context-specific comparative economic analysis methodologies reviewed in *Chapter Four* did not fully align with the evaluative criteria derived in *Chapter Three* (Ross et al., 2024a). Fortunately, insights from the attempted implementation of the integration concept also revealed opportunities for addressing these constraints (see *Table 14*).

7.3.2.1 Integrating structured and interpretive knowledge co-production

The first opportunity for improving transdisciplinary integration focuses on the system discovery phase of the integration concept. Specifically, it concerns the deliberate integration of (i) the residential water end-use demand analysis and resultant system models, functioning as a boundary object, and (ii) the plural root definitions and resultant purposeful activity models, functioning as epistemic objects. While these models were produced concurrently in the initial integration concept, this section reflects on whether sequencing these embedded methods differently may have enhanced the system of transdisciplinary integration.

Interpretation using the DSRP heuristic demonstrated that the residential end-use survey primarily contributed by making distinctions between different components of the heterogeneous configuration. Its flexible design enabled the capture of end-use data from non-standard household arrangements, such as diverse water access typologies, appliances, and wastewater sinks, that are rarely represented in conventional costing models (see *Chapter Five*) (Ross et al., 2025). As a result, the survey produced a richer representation of water end-use flows and revealed system components that are typically not visible within infrastructure-led planning frameworks.

However, as a boundary object, the survey alone could not capture how households and other issue owners, including informal service providers, experienced the costs associated with these flows, particularly intangible burdens faced by users with marginal access. These dimensions were accessed through in-depth, semi-structured interviews guided by the CATWOE mnemonic, which produced structured insights into why cost were perceived differently across the case study (see *Chapter Six*) (Ross et al., [preprint]). For example, marginal service users frequently described lost time, stress, and reliance on coping strategies as significant costs, yet these are aspects outside of the boundaries of planning frameworks.

Although both embedded methods contributed to the DSRP patterns, their integration into a unified costing model was constrained by the concurrent nature of data collection. While interviewees were provided with prompts such as maps and diagrams of common household configurations (see *Chapter Six*) (Ross et al., [preprint]), these did not support the systematic collection of cost data. In the absence of a stable, shared representation of the real-world context, cost-related insights remained fragmented and could not be consolidated into a robust without-project cost model.

A key insight from the case study is that the sequencing of knowledge co-production matters. Had the residential water end-use model been constructed and validated prior to the interviews, it could have provided a stable reference point for interviewees to situate their experiences within the broader heterogeneous service provision context, supporting more systematic articulation of both tangible and intangible costs. This sequencing would also have strengthened the grounding of root definitions and enhanced the value of the resultant purposeful activity models as epistemic objects within a comparative economic analysis methodology.

In future iterations of the integration concept, the system discovery phase could be restructured to sequence knowledge co-production more deliberately: first, by constructing and analysing the residential end-use survey to define the heterogeneous service provision configuration; second, by using this model to anchor subsequent in-depth interviews, enabling issue owners to articulate costs in relation to a shared reference point; and third, by iteratively refining both artefacts as new knowledge emerges. The earlier use of rich pictures as a complementary exploratory tool may further support this process by informing survey design and interview prompts. This opportunity is examined further in the next section.

7.3.2.2 Organising planning as an iterative, learning-oriented system

The second opportunity for improving transdisciplinary integration concerns the system definition phase. This phase was intended to operate as an iterative, learning-oriented process through which co-produced knowledge artefacts could be refined to support decisions about interventions in heterogeneous urban water and sanitation configurations.

Interpretation using the DSRP heuristic demonstrated that this phase is most relevant to the *Systems* pattern, which concerns how distinguishable elements are organised into

part–whole configurations. Purposeful activity models were intended to function as epistemic objects, supporting structured reflection on intentions, values, and assumptions (see *Chapter Six*) (Ross et al., [preprint]), while the residential end-use water demand model was intended to function as a boundary object, providing a shared quantitative reference point for comparing disaggregated impacts.

These artefacts were intended to support iterative learning cycles through which new system definitions could emerge and be refined over time. However, delays in data collection and development of the residential end-use model due to COVID-19 disruptions meant that rich pictures were used as proxy boundary objects instead. This shift revealed important limitations in how different knowledge artefacts support sustained transdisciplinary integration.

Rich pictures proved effective in enabling rapid, shared understanding of the problematical situation, particularly in surfacing diverse perspectives and system components. However, they function as context-specific, one-off representations rather than as stable models of the real-world configuration. As a result, the learning they supported could not be sustained or iteratively extended across different purposeful activity models or over time (Ross et al., [preprint]).

Using a DSRP interpretation, rich pictures supported distinctions and made perspectives visible, but they did not adequately represent evolving part–whole relationships or dynamic interactions, limiting their capacity to support ongoing iterative learning. Consequently, although the workshops supported reflection and learning within individual purposeful activity models, they did not generate cumulative or transferable insights about how changes in one part of the configuration would affect others. This constrained the

contribution of the system definition phase to knowledge production beyond the immediate workshop context.

In future iterations of the integration concept, greater attention should be given to the complementary roles of different knowledge artefacts. Rich pictures are well suited to early exploratory engagement, supporting shared orientation and problem definition, but they cannot substitute for structured quantitative models capable of representing interdependencies within dynamic configurations. This reinforces the need, identified in the first opportunity for integration, to prioritise and sequence the residential end-use water demand model earlier to provide a stable basis for refining epistemic objects such as purposeful activity models.

This limitation highlights the importance of integration concepts that support not only participatory learning, but also the accumulation and application of knowledge over time and across contexts, particularly in contexts where universal metering is not feasible. Ideally, a comparative economic analysis methodology would be supported by locally collected time-series data that continuously tests and refines assumptions about service provision. Existing urban water and sanitation planning frameworks in LMICs are often implemented as one-off exercises that produce static plans with external support. In contrast, a systemic comparative economic analysis approach lends itself to planning as an iterative, learning-oriented process capable of progressively improving the inclusiveness and performance of heterogeneous service provision configurations. This orientation could increase the likelihood of endogenous, societally beneficial outcomes.

7.3.2.3 Maintaining flexibility while supporting robust decisions

The third opportunity for improving transdisciplinary integration concerns the *system comparison* phase. This phase was originally designed as a deliberative, multi-actor process

in which desirable and feasible scenarios would be assessed using collaboratively defined decision criteria, reflecting both tangible and intangible determinants of cost (e.g., [Willets et al., 2013](#)). Comparison was intended to draw on the purposeful activity models as epistemic objects and the residential end-use demand model as a boundary object, with selected scenarios costed against a clearly defined real-world, without-project reference case in Siem Reap.

In practice, this phase could not be implemented as intended. Delays in establishing the residential end-use demand model, exacerbated but not solely caused by COVID-19 disruptions, meant that a costed without-project reference case was not available to support comparisons. More fundamentally, this reflected the difficulty of defining stable system parameters in a complex, heterogeneous service provision configuration. In such contexts, even the act of initial system definition is likely to be contested across perspectives.

Interpreted through the DSRP heuristic, the initial integration concept can be seen to have privileged *Distinctions* and *Relationships* by focusing on system components and their impacts on costs, service outcomes, and the distribution of impacts. However, in the absence of a stable quantitative boundary object, the system comparison workshops pivoted away from making decisions towards characterising diverse and contested perspectives. This shift was exemplified when *critical systems heuristics* were applied in *Chapter Six*, where the workshops were repurposed as a boundary critique to surface assumptions about institutional responsibility, sources of inertia, and exclusions that would not have been addressed through decision criteria ([Ross et al., \[preprint\]](#)).

This shift away from decision-making towards examining how decisions are framed suggests that the initial integration concept was not viable for comparative economic

analysis in this context. However, despite this, important insights could be accessed about the impact of epistemic uncertainty on urban water and sanitation planning frameworks. Instead of moving directly towards a decision-making process, comparing costed scenarios, the workshops revealed underlying, latent tensions: for example, how low-income households with self-supplied containment infrastructure paid for the full cost of service provision, and informal service providers were forced into decisions regarding the essential provision of services and ensuring their own wellbeing (see *Table 14* in *Chapter Six* for details) (Ross et al., [preprint]). These insights did not resolve the planning problem; however, they did help understand why the resolution of such issues persists, with the potential to prompt action to address such a situation. This is a valuable contribution to the planning process.

Viewed through the DSRP lens, the system comparison phase lacked the structure required to support transdisciplinary integration across the four patterns of systems thinking. Without the residential end-use balance model being complete, the focus on revealing diverse perspectives about the heterogeneous configuration could not be compared in a way that led directly to a decision. The *purposeful activity models* and *rich pictures* did not contain sufficient information to make clear *distinctions* about the impact on different elements of the system arising from the boundary critique. Further, the relationships between the system components could not be quantitatively defined to produce tangible evidence to support a robust decision.

This suggests that in a *revised integration concept*, there should be a shift towards sequencing reflection and decision-making in a way that first conducts a boundary critique. This revision would support participatory and collaborative learning to occur before iteratively defining objective boundary objects such as the residential end-use model to test

the feasibility of scenarios. Robust decisions in this conceptualisation would be best supported by processes that cycle between reflection and comparison, applying systems thinking approaches capable of supporting both processes.

This highlights a practical challenge for implementation. Existing planning frameworks used for LMICs still largely focus on decision-making as a one-off event rather than an ongoing adaptive process. In contrast, a revised planning framework supported by a *systemic comparative economic analysis methodology* requires ongoing monitoring to update knowledge about the demand for services and perspectives on how they should be improved. Embedding these insights into practice, thus, requires shifts in how institutions collect and share these data, supported by existing activities or establishing new processes. This outcome is necessary for supporting more robust decision-making in these contexts.

The discussion above of what was learned in practice demonstrates that strengthening transdisciplinary integration hinges on (i) sequencing structured and interpretive knowledge co-production, (ii) sustaining planning as an iterative learning system, and (iii) maintaining enough methodological structure to support robust decisions without foreclosing flexibility in the face of epistemic uncertainty. Section 7.4 takes these lessons forward by charting them against the evaluative criteria established in *Chapters Three and Four* (Ross et al., 2024a, 2024b), thereby backcasting a revised integration concept and an enhanced systemic comparative economic analysis methodology.

7.4 How the revised integration concept improves existing planning approaches

Building on *Sections 7.2 and 7.3*, *Section 7.4* applied backcasting to translate learning from the transdisciplinary case study into a revised integration concept and enhanced systemic comparative economic analysis methodology. It maps the three integration opportunities identified in *Section 7.3.2* against the evaluative criteria established in *Chapter*

Three and validated in *Chapter Four* (Ross et al., 2024a, 2024b). This analysis shows how previously invisible costs, assumptions, power relations, and epistemic uncertainty constrain comparative economic appraisal in practice in heterogeneous contexts.

Table 16 synthesises this analysis by mapping each evaluative criterion to (i) the relevant integration opportunity from *Section 7.3.2* (see *Table 15*), (ii) what was learned through implementation, and (iii) the implications for revising the integration concept and the comparative economic analysis methodology. Thus, it operationalises the backcasting approach described in *Section 2.2* and enables direct comparison with the practice gaps summarised in *Section 4.5.1*. *Figure 19* provides a consolidated reference for interpreting how the case study's contributions were distributed across the three phases of the revised integration concept: *system discovery*, *system definition*, and *system comparison*.

In this section the implications of the revised integration concept (see *Figure 19*) are interpreted for each phase of the systemic planning process. *Section 7.4.1* considers how system discovery sequences different systems thinking approaches, drawing on the need to understand the existing without-project case to frame the problematical situation in a way that includes diverse perspectives. *Section 7.4.2*, then considers how learning established during the *system discovery* phase should best be provided with the stability necessary for a *hard systems* boundary object to structure learning about *soft systems* epistemic objects. Finally, *Section 7.4.3* interprets how the *system comparison* phase of the revised integration concept supports structured, yet non-prescriptive trade-offs between different types of intervention scenarios that meaningfully account for the uncertainty of planning a complex heterogeneous configuration. This discussion frames how the revised concept supports improved alignment with the evaluative criteria for comparative economic analysis proposed in *Chapter Three* (Ross et al., 2024a).

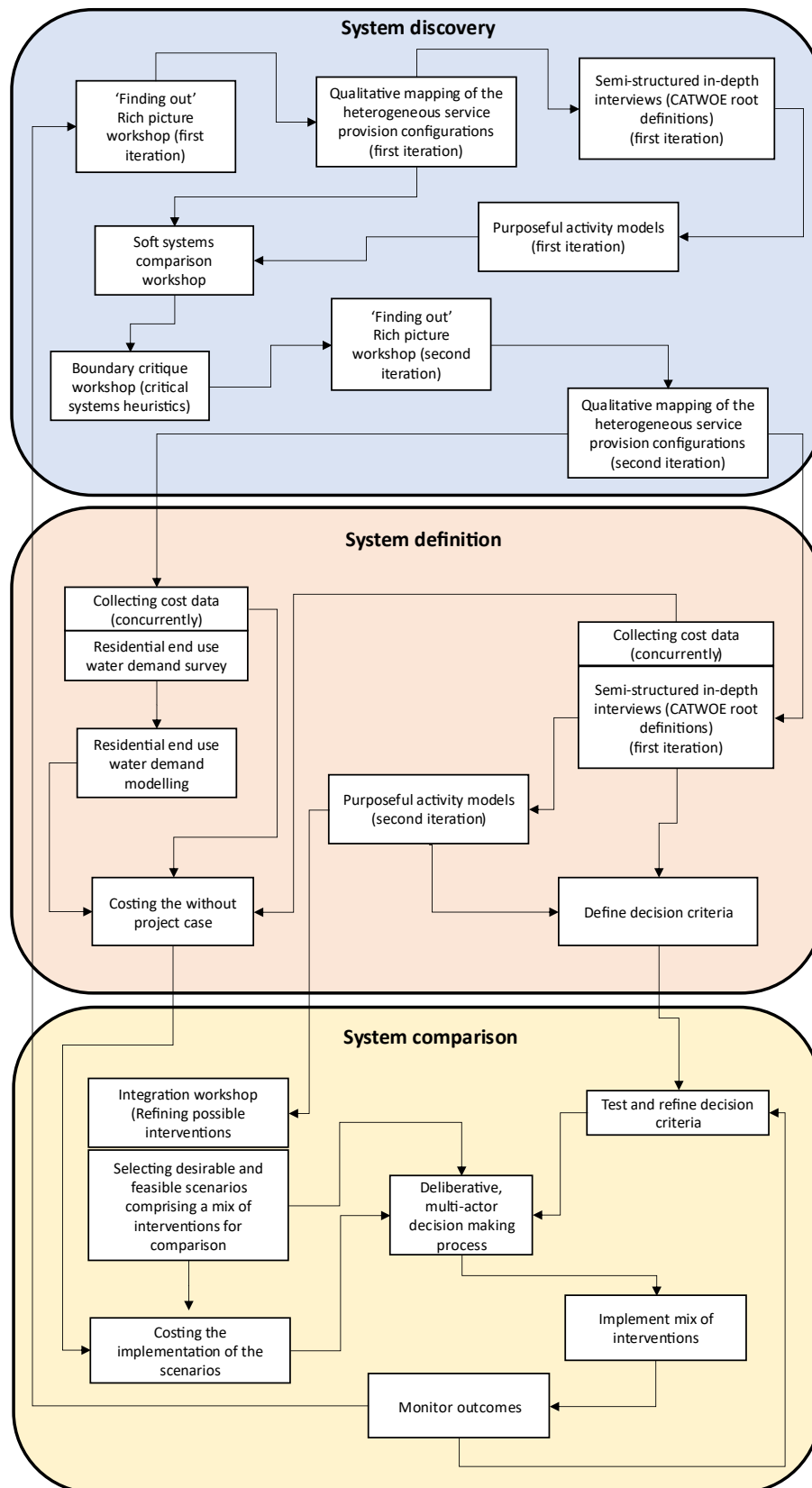


Figure 19: The revised integration concept for the inclusive and systemic planning of heterogeneous water and sanitation service provision

Table 16: The process of backcasting a comparative economic analysis methodology as informed by the revised integration concept (Figure 19) from the evaluative criteria established in Chapter Three (Ross et al., 2024a).

	Evaluative criteria	Integration opportunity	Insights or limitations from applying the integration concept	Implications for a revised comparative economic analysis methodology	Phase(s) impacted
Study design					
Research question					
1.1	<i>A research question is outlined that balances economic efficiency and equitable and sustainable outcomes, paying particular attention to marginalised groups.</i>	Balancing flexible participation and robust decision-making.	Diverse local perspectives were elicited through surveys, interviews, and workshops, but they could not be integrated into a cost model capable of representing disaggregated financial impacts on sub-groups experiencing service inequalities.	The revised integration concept sequences soft and critical systems approaches before system definition, ensuring diverse perspectives shape the framing of the research question and the boundaries of the without-project case.	<i>System discovery</i>
1.2	<i>A societal cost perspective is adopted, disaggregated by the cost perspectives of key societal actors and their subgroups.</i>	Organising planning as an iterative, learning-oriented system.	While the residential end-use demand survey enabled disaggregation of water demand profiles, cost perspectives elicited through interviews were not systematically integrated. A lack of clear system definition limited the structured collection of cost data across key societal actors and subgroups	The revised integration concept sequences qualitative system mapping and boundary critique prior to system definition, enabling the structured integration of disaggregated cost perspectives within a broader societal cost perspective.	<i>System definition</i>
The rationale for the comparison of alternatives					
2.1	<i>All alternative supply and demand-led interventions that might meet a defined service outcome are compared against the opportunity costs of forgoing the least-cost standard that would have emerged without a project.</i>	Organising planning as an iterative, learning-oriented system.	While diverse purposeful activity models were developed, they could not be compared against a complete, context-specific residential end-use demand and cost model. As a result, opportunity costs could not be assessed relative to a defined without-project standard.	The revised integration concept defines the without-project case through an iterative sequence, beginning with inclusive system discovery and followed by structured end-use demand and cost modelling in the system definition phase, enabling comparison of alternative interventions against a context-specific least-cost standard.	<i>System discovery and system definition</i>

2.2	<i>The without-project case and each alternative are critically defined within consistent system boundaries that are explicit about the people, time, and service dimensions included in an analysis and relevant to decision-makers.</i>	Balancing flexible participation and robust decision-making.	Consistent and explicit system boundaries were not established under the initial integration concept, as reliance on rich pictures did not provide a stable boundary object capable of supporting quantitative system comparison or forecasting of intervention impacts.	The revised integration concept establishes system boundaries through collaborative mapping and boundary critique in system discovery, producing a more stable system definition, which could be applied consistently during system comparison to support the structured and deliberative evaluation of alternative interventions.	<i>System discovery, system definition, and system comparison</i>
Economic analysis methodology					
3.1	<i>The economic analysis methodology comprises: (i) a comparable cost-effectiveness analysis; (ii) optimisation of each alternative; and (iii) end user(s), especially marginalised end users, making a final cost-benefit determination of the least-cost alternative based on broad sustainability criteria.</i>	Bringing together structured and interpretive knowledge co-production.	A complete economic analysis could not be undertaken under the initial integration concept, as a cost model was not developed. As a result, cost-effectiveness analysis, quantitative optimisation of alternatives, and end-user-led cost-benefit determination could not be implemented.	The revised integration concept consolidates the full economic analysis methodology across system discovery, system definition, and system comparison within a single, unified framework that disaggregates impacts on marginalised end users.	<i>System discovery, system definition, and system comparison</i>
Data collection					
Effectiveness data					
4.1	<i>Sources used to derive outcome measures are stated, and the study design is specific to the study context and system boundaries of the economic appraisal.</i>	There is no strong alignment with any of the opportunities for transdisciplinary integration	This criterion could not be applied under the initial integration concept because a cost model was not developed, and outcome measures were therefore not derived or compared.	This criterion was not applicable under the initial integration concept, as no cost model or defined outcome measures were developed. Had these artefacts been established, effectiveness data would have been derived from the residential end-use demand model and reported consistently with the defined system boundaries during system comparison.	<i>System comparison (informed by system discovery and system definition)</i>

4.2	<i>Details of the method of synthesis or meta-analysis of cost effectiveness data are given if based on an overview of studies, including a justification for its generalisability.</i>	Bringing together structured and interpretive knowledge co-production	This criterion was not applicable, as the case study was designed as an intrinsic, context-specific analysis and did not involve synthesis or meta-analysis of cost-effectiveness results across studies.	This criterion was not applicable, as the case study was designed as an intrinsic, context-specific case study rather than an overview or synthesis of multiple studies. Had comparative effectiveness data been generated, synthesis within the boundaries of analysis of the case study may be appropriate, but less so for a generalisable meta-analysis.	<i>System comparison</i>
Benefit valuation					
5.1	<i>A primary outcome measure is reported in units of total annualised costs per household or capita (TACH/TACC) and explicitly accounts for the costs and outcomes included in the measure.</i>	Organising planning as an iterative, learning-oriented system.	This criterion was not addressed under the initial integration concept, as a cost model was not developed and primary outcome measures such as TACH/TACC were therefore not established	This criterion was not applicable under the initial integration concept, as a cost model was not developed and primary outcome measures such as TACH or TACC could not be calculated. Had unit cost data and system boundaries been stabilised, these outcome measures would have been derived from the residential end-use demand and cost models to support structured system comparison.	<i>System comparison</i>
5.2	<i>If tangible and quantifiable benefits have been valued, the method adopted is relevant to the context for which the estimate is made.</i>	There is no strong alignment with any of the opportunities for transdisciplinary integration	This criterion was not explicitly addressed under the initial integration concept, as benefit valuation was not a focus of the case study methodology.	Where benefit valuation is applied, the revised integration concept emphasises alignment between valuation methods and the defined system boundaries; however, its applicability is limited in heterogeneous urban water and sanitation contexts.	<i>System definition</i>
5.3	<i>Intangible and unquantifiable benefits are reported separately in a format that enables their relevance when determined by users.</i>	Bringing together structured and interpretive knowledge co-production	Intangible costs were somewhat identified through interviews and purposeful activity models under the initial integration concept but could not be distinguished from tangible costs due to the absence of a structured cost model, limiting their use for a deliberative appraisal.	The revised integration concept distinguishes tangible and intangible costs by integrating structured cost models with interpretive insights from interviews, enabling users to consider intangible benefits explicitly during system comparison.	<i>System comparison</i>

Cost data					
6.1	<i>Quantities of resources are reported separately from unit costs and used to determine all relevant life cycle costs using average incremental costing.</i>	Organising planning as an iterative, learning-oriented system.	While quantities of water demand were estimated through the residential end-use survey, resource quantities and unit costs were not collected in a structured manner under the initial integration concept, preventing life-cycle costing or the application of average incremental costing.	The revised integration concept structures the collection of resource quantities and unit costs during system definition, enabling life-cycle costing using average incremental costing and their consistent application in system comparison.	<i>System definition and system comparison</i>
6.2	<i>Currency and price data are recorded, and details of adjustments for inflation or exchange rates are given.</i>	Organising planning as an iterative, learning-oriented system.	Cost data were recorded in either Khmer Riel or US Dollars, under the initial integration concept, but collection was not systematic and adjustments for inflation or exchange rates were not applied due to the absence of a cost model	The revised integration concept standardises the recording of currency, price year, and data sources during system definition, enabling consistent inflation and exchange-rate adjustments to support transparent system comparison.	<i>System definition and system comparison</i>
Modelling					
7.1	<i>A contextually relevant resource flow model is justified as the basis for estimating the economic costs over a consistent time horizon for a hybrid mixture of interventions, with any assumptions made explicit, recoverable, and testable.</i>	Organising planning as an iterative, learning-oriented system.	A contextually relevant residential end-use demand model was developed under the initial integration concept, but it was not integrated with a cost model or used to analyse hybrid intervention scenarios or long-term distributional impacts.	The revised integration concept aligns collaborative system discovery with structured system definition, enabling integration of resource flow, demand, and cost models to analyse hybrid interventions with explicit, testable assumptions over a defined time horizon	<i>System discovery and system definition</i>
Analysis and interpretation of results					
Adjust for the timing of benefits and costs.					
8.1	<i>The time horizon and discount rate(s) used in the analysis are stated and justified.</i>	Organising planning as a, learning-oriented system, and balancing flexible and robust decision-making.	A cost model was not developed under the initial integration concept, and the implications of selecting time horizons or applying discount rates could therefore not be examined or tested within resource flow or cost models.	The revised integration concept enables explicit consideration of time horizons and discount rates during system definition, allowing their implications to be explored and compared transparently during system comparison.	<i>System definition and system comparison</i>

Account for uncertainty					
9.1	<i>Details of statistical tests and confidence intervals are given for all stochastic data.</i>	There is no strong alignment with any of the opportunities	Statistical tests and confidence intervals were not applied under the initial integration concept; descriptive statistics were used, but uncertainty in key parameters could not be assessed quantitatively due to the absence of a cost model.	This criterion was not applicable under the initial integration concept, as the absence of a cost model and quantified outcome measures precluded the application of statistical tests or confidence intervals. Had such measures been established, uncertainty in key parameters would have been assessed to support transparent interpretation during system comparison.	System comparison
9.2	<i>Methods, such as sensitivity or scenario analysis, are described and justified to optimise how outcome measures may be interpreted by a range of societal actors when selecting a least-cost intervention.</i>	Organising planning as an iterative, learning-oriented system.	Sensitivity and scenario analysis were not undertaken under the initial integration concept, as a cost model was not developed and alternative scenarios could not be linked to quantifiable outcome measures.	The revised integration concept enables sensitivity and scenario analysis through the integration of structured cost and demand models with participatory system definition, supporting transparent interpretation of outcomes during system comparison.	System definition and system comparison
9.3	<i>Deliberative multi-stakeholder decision-making methods inclusive of marginal users that address epistemic uncertainty in the design of economic analysis and increase the likelihood that the root causes of gender and social inequity are addressed in an analysis are described and justified.</i>	Balancing flexible participation and robust decision-making.	Deliberative multi-stakeholder workshops were conducted under the initial integration concept, but epistemic uncertainties and the root causes of service outcome inequalities were not systematically embedded in the economic analysis, partly due to the sequencing of the end-use model and the absence of a cost model.	The revised integration concept embeds deliberative processes earlier through collaborative system mapping and boundary critique, enabling epistemic uncertainties and equity-related decision criteria to shape system definition and be carried forward into structured system comparison.	System discovery and system comparison

Present results transparently					
10.1	<i>Relevant, mutually exclusive alternatives optimised to meet the same service outcome are compared in incremental units of TACH/TACC against a cost effective, without-project standard.</i>	Organising planning as an iterative, learning-oriented system.	Under the initial integration concept, mutually exclusive alternatives could not be compared against a costed without-project standard in incremental units of TACH/TACC, as purposeful activity models were compared qualitatively using rich pictures rather than a costed resource flow model.	The revised integration concept enables incremental comparison and optimisation of mutually exclusive alternatives by establishing a costed residential end-use demand model as the without-project standard, supporting comparison in units of TACH/TACC during system comparison.	<i>System definition and system comparison</i>
10.2	<i>An aggregate primary outcome measure is also presented in disaggregated form for each stage of the sanitation service chain, life cycle cost component, and cost and subgroup perspective.</i>	Organising planning as an iterative, learning-oriented system.	Under the initial integration concept, outcome measures from the residential end-use demand model could be disaggregated by service chain stage, life cycle component, and user subgroup, but this disaggregation could not be extended to costs due to the absence of systematically collected unit cost and material quantity data.	The revised integration concept enables outcome measures to be reported and compared in disaggregated units of TACH or TACC by systematically linking collaborative system mapping with structured collection of unit cost and material quantity data across service chain stages and user subgroups.	<i>System discovery, system definition, and system comparison</i>
10.3	<i>A non-prescriptive conclusion is presented in response to the study question from the reported data accompanied by appropriate caveats, enabling societal actors, especially marginalised users, to interpret the study outcomes independently.</i>	Balancing flexible participation and robust decision-making.	Under the initial integration concept, deliberative workshops supported reflection on possible interventions, but the absence of a cost model and explicit outcome measures limited the ability of issue owners to interpret trade-offs independently, resulting in reliance on facilitation.	The revised integration concept supports non-prescriptive conclusions by linking deliberative processes with explicit outcome measures and decision criteria, enabling societal actors to interpret results independently while remaining aware of assumptions and caveats	<i>System comparison</i>

7.4.1 Implications for the system discovery phase

This section interprets how the *revised integration concept* (Figure 19) adapts the initial *system discovery* phase of systemic planning methodology (Figure YY). Table 16 demonstrates how and why *system discovery* is now intentionally structured as an iterative, learning-oriented phase that supports the development of an inclusive and context-relevant, without-project case. Rich pictures are used to qualitatively map a heterogeneous configuration, before they are compared with purposeful activity models to conduct a boundary critique at the outset of the methodology. This adaptation provides a means for interrogating assumptions that contribute to *persistent service outcomes* before they become implicitly embedded within end-use demand and costing models (Ross et al., 2024a, 2024b) and positions *system discovery* as a phase that establishes inclusion as a pre-condition for planning.

As illustrated in Figure 19, this results in *system discovery* becoming less linear and more capable of exploring complexity. It applies two linked iterations of a soft systems *finding out* process (Checkland & Poulter, 2010) that combine and compare rich pictures progressively to refine a system-wide characterisation of the heterogeneous configuration. A first rich picture workshop surfaces multiple experiences within heterogeneous service provision arrangements. These are consolidated through a qualitative mapping process, distinguishing between different typologies and inequalities in service outcomes. This surface understanding then informs semi-structured interviews used to elicit *CATWOE root definitions*, which are translated into a first iteration of purposeful activity models. These models are then used as learning devices, to collaboratively refine, and then gently interrogate them via boundary critique drawing on *critical systems heuristics* (Ulrich & Reynolds, 2010). Learning from these activities informs a second finding out process, leading

to the development of a more inclusive map of the heterogeneous configuration, resulting in system-wide experiences of service provision are represented to inform system definition.

The transdisciplinary case study in Siem Reap demonstrated that this adapted sequencing is necessary if the without-project baseline used to compare the costs and impacts of interventions in heterogeneous contexts is seen to credibly reflect the lived experiences of societal actors. As discussed in *Section 7.3*, applying the initial integration concept revealed limitations when the soft systems finding out process was applied concurrently with a household survey for collecting hard system end-use water demand and unit cost data. The unintended pivot to the rich pictures as a proxy boundary object revealed that soft systems modelling was a useful precursor to developing hard-systems representations of the without-project baseline. Such models require stability to act as a reliable boundary object, this system definitions require more concrete specification, particularly for the collection of unique, context specific unit cost data (Ross et al., 2024a, 2024b).

The sequencing of the revise integration concept applies collaborative systems mapping and boundary critique to facilitate inclusion in end-use demand analysis and cost modelling, rather than seeking input from diverse perspectives after modelling assumptions have already been locked in. This responds directly to *Criterion 2.1* in *Table 16*, which requires which requires modelling that support all possible interventions to be compared against a meaningful without-project case. This reference should be on that would have otherwise emerged, rather than an abstract or infrastructure-led representation. In heterogeneous configurations, such as the case study in Siem Reap, the without-project case is not singular, stable, or recoverable from a utility perspective alone. It comprises overlapping socio-

technical arrangements, informal practices, and differentiated access conditions within households that collectively shape how services are actually produced, accessed, and experienced (Ross et al., 2025). As illustrated in Figure 19, the revised integration concept positions *system discovery* as the phase in which these patterns become visible and are assembled into an iteratively refined into a heterogeneous without-project case that can be costed and compared in a way that embraces complexity.

This distinction matters because, as documented in *Section 4.5.1.3*, comparative economic analysis methodologies applied to urban water and sanitation planning in LMICs commonly rely on implicit baselines, with narrow system boundaries aligned to formal infrastructure and service provision models. When the heterogeneity of existing configurations is minimised in this way, the opportunity costs of standard interventions can be systematically misrepresented, obscuring how the costs and benefits of these services are distributed in practice (Ross et al., 2024b). By sequencing the integration concept in a way that embeds heterogeneous service provision models within the without-project reference, the opportunity costs associated with informal or self-supplied options can influence comparison and attain greater legitimacy. This increases the likelihood that least-cost economic analysis will be informed by contextually meaningful differences in service outcomes.

System discovery now arranges boundary critique in a way that decisions about what can be represented, costed, and valued in a comparative economic appraisal open to negotiation. This supports a response to both *Criterion 2.2* and *Criterion 9.3* of the evaluative criteria for comparative economic analysis (see *Table 16*) (Ross et al, 2024a, 2024b). It makes value judgements about who is included in the model, over what time frame, and for which service dimensions explicit at the outset of the methodology (Willettts

et al., 2010). This helps to address *epistemic uncertainty* in the collaborative design of the comparative economic appraisal, rather than being pre-determined by the structure of the hard systems demand and cost models, where what matters becomes difficult to interrogate. In contexts where persistent service inequalities are sustained in part by what is outside the boundary of analysis, this adaptation ensures opportunities for default technical or institutional arrangements to be deliberated on safely and openly.

In summary, the revised integration concept repositions *system discovery* as a phase in which a shared, system-wide understanding of existing heterogeneous configurations may be established in way that accounts for the socio-technical implications of persistent service inequalities. This is prompted by an explicit interrogation of boundary judgements to ensure that heterogeneous experiences of service outcomes become represented in a without-project case, and subsequent demand and cost models that define a systemic planning approach. In this way, comparative economic analysis is framed in a way that *equitable and sustainable outcomes that pay particular attention to marginalised groups*, are considered in a way that is balanced with questions of optimisation and efficiency, consistent with the intent of Criterion 1.1 (see Table 16). This provides the subsequent *system definition* phase a stronger social licence and more contextual relevant foundation for decision making.

7.4.2 Implications for the system definition phase

This section interprets how the *system definition* phase of the systemic planning approach is adapted by the revised integration concept (*Figure 19*). The limitations identified for this phase when experimenting with the integration concept (see *Table 16*) have been addressed through modifications made to the *system discovery* phase. The implications arising from these changes results in shifts in how heterogeneity may be effectively integrated into the structured definition of system boundaries, end-use demand

analysis, and cost modelling. In the revised concept, hard systems modelling in the *system definition* phase is better supported by interpretive and critical learning. The insights from this learning are stabilised within such models so they may be used to support meaningful comparisons of the costs of diverse, hybrid intervention scenarios. Thus, this phase consolidates the more inclusive and relational representation of the without-project case, by transforming it into a robust boundary object required for deliberative decision making in the *system comparison* phase.

Figure 19 makes the adaptation clear. A key output from the system discovery phase is the inclusive qualitative mapping of the heterogeneous urban water and sanitation configuration. This is used as a foundation for designing a context-relevant residential end-use demand surveys and a second iteration of semi-structured interviews to develop CATWOE root definitions that are better informed by the broader context of the problematical situation. As intended but not conducted effectively in the initial integration concept (see *Figure 18*), this data is collected concurrently, informed by a less partial understanding of how the system is comprised and the relationships that influence how it functions. This provides a more stable, but moderately flexible basis to guide the comprehensive collection of end-use demand and cost data. *System definition* is thus positioned as *system discovery* was in the initial integration concept. It brings *hard*, *soft*, and *critical* forms of knowledge co-production together to articulate the structure of a unified model representing the without-project situation.

Section 7.3 outlined why this was necessary for improving how the integration concept was applied to the Siem Reap case study. Under this concept, the collection of cost data was approached in an ad hoc way, focusing on what was technically available and most readily observable. This was due to a partial and messy understanding of the heterogeneous

configuration. Resolving this was essential to both methods embedded within the transdisciplinary case study, as instead of the approaches informing each other, they were conducted in a way that was less adaptive than planned. Knowledge co-produced by each study was not available in a format that facilitated integration due to the absence of a shared understanding of how the system might be defined. Because of this, the integration concept failed to bring together functionalist and interpretivist ways of knowing as a credible reference for comparison and systemic learning.

This limitation constrained the capacity to structure planning from a societal cost perspective, as considered best practice (*Criterion 1.2; Table 16*) for comparative economic analysis for heterogeneous configurations (Ross et al., 2024a). *Section 4.5.1.2* outlines how methodologies presented in the existing literature tend to reduce the complexity of comparative economic appraisal to a specific cohort or a very specific urban context, at the expense of being able to explore interactions arising from heterogeneous relationships with an urban environment. Studies that extend beyond formal infrastructure or institutions tend to depict informal services as homogenous, with intangible costs treated as marginal or outside the scope of an analysis, even where these system components contribute directly to societal outcomes (Ross et al., 2024b). In heterogeneous configurations, this can act to systematically misrepresent how the costs of service provision are distributed, limiting the understanding of how to address persistent inequalities in service outcomes.

A residential end-use demand survey that effectively disaggregates end-use water demand by service provision typology and user subgroup was established in the case study in Siem Reap (Ross et al., 2025). However, this could not be coupled with the collection of the unit cost data necessary to structure possible interventions arising from the purposeful activity models for comparison based on *average incremental costs* (see *Criterion 5.1* and

6.1; Table 16). In Sections 4.5.2.3 it is demonstrated that very few existing studies can claim the capacity to apply unit cost data to models that arise from heterogeneous urban configurations.

Section 4.5.2.8 suggests that it is common for such data to be either collected from utilities (which only has the capacity to partially cost a heterogeneous configuration), or to be inferred from generalised assumptions, or empirical results from other contexts (Ross et al., 2024b). The process in the revised integration concept, whereby system definition follows qualitative modelling, and a boundary critique has the capacity to help develop and exploit highly disaggregated end-use demand models (e.g. Ross et al., 2025) to help address this practice in cities of LMICs. Articulating, which water and wastewater flows and system components are most significant to the function of a heterogeneous configuration may help to prioritise efforts to collect cost data. In turn, this may contribute to costs models that more effectively represent existing without-project contexts in cities of LMICs, aligned with Criterion 7.1 (Table 16) and function as more inclusive and robust boundary objects.

The precision with which the *system definition* phase represents heterogeneous water and sanitation configurations is honed by adaptations to the *system discovery* phase. Exploring the context interpretively and critically is an important pre-requisite to establishing a more stable *hard systems* model to define such contexts. This process enables more meaningful comparisons through coupling disaggregated end-use demand models with context-specific knowledge that more accurately reflect how costs are incurred and experienced in practice. Such models stabilise comparisons between hybrid and informal service arrangements that extend, supplement, or operate alongside formal infrastructure systems in LMIC cities. Thus, the models are better able to function as robust boundary

objects to support deliberative decision making which is the focus of the *system comparison* phase discussed in *Section 7.4.3*.

7.4.3 Implications for the system comparison phase

This section interprets how the *system comparison* phase of the systemic planning approach is adapted by the *revised integration concept* (*Figure 19*). As summarised in *Table 16*, the most significant change is that system comparison is no longer treated as a one-off deliberative decision point that follows end-use and cost modelling. Instead, it is reorganised as an iterative and structured phase that supports ongoing comparison, learning, and adaptation as a heterogeneous urban water and sanitation configuration evolves over time.

In the revised concept, system comparison builds directly on the development of a context-specific, costed without-project case model during the *system definition* phase that acts a stabilised boundary object (see *Section 7.4.2*). This change addresses a key limitation observed in the initial integration concept in *Section 7.3*, where comparisons did not progress beyond qualitative deliberation, due to the absence of such an artefact. As the development of the costed without-project model is now sequenced ahead of *system comparison*, the revised concept provides a more effective basis for the transparent, incremental comparison of different intervention scenarios.

As illustrated in *Figure 19*, system comparison is now organised around a series of workshops that integrate knowledge from different systems paradigms. For example, possible intervention scenarios are improved through the collaborative use of *soft systems* methods. They are then projected incrementally in addition to the *hard systems*, costed without-project case, before being assessed using decision criteria informed by *critical systems heuristics*. To a varying extent, the learning artefacts produced by each systems

approach are flexible. The most stable is the end-use demand and cost models, enabling the forecasting and scaling of intervention scenarios. The possible interventions and decision criteria, informed by purposeful activity models, are less so.

This characteristic facilitates new perspectives to be swept into the planning process if adopted as an ongoing practice. Assumptions underlying new comparison are made visible to diverse societal actors, and recoverable through the co-production of learning devices. These artefacts support new systemic thinking to emerge, which may be revisited, to prompt a less partial and more inclusive understanding of the heterogeneous configuration. Awareness of the adaptive nature of the configuration through reflecting on the impacts of interventions as they are implemented and the development of new purposeful activity models can prompt new systemic thinking. This may be driven by *new purposeful activity models* being swept into the process representing the intentions of actors to improve the situation, as informed by this new knowledge.

This learning-oriented planning model supports deliberation that is structured yet non-prescriptive, and evolving, consistent with the requirements for planning for a complex adaptive heterogeneous configurations. It enables non-linear, non-intuitive, or emergent system behaviour to be accommodated. The costed without-project case, underpinned by the residential end-use demand analysis, enables hybrid intervention scenarios to be compared incrementally using outcome measures such as TACH or TACC (see *Criterion 10.1; Table 16*). Because these measures are derived from disaggregated demand and cost models, comparisons have the capacity to explicitly interpret how costs and benefits are distributed by any real world (hard systems) or purposeful (soft systems) interventions.

Possible future impacts can be deliberated across: (i) multiple sub-group perspectives; (ii) different part-whole groupings comprising service provision typologies at different

scales; and (iii) diverse systemic impacts at different stages of the life cycle of each interventions. Further, they may be aggregated for the heterogeneous configuration, as a whole, aligned with *Criterion 10.2 (Table 16)*. Such capacity is established through adaptations made that sequence qualitative mapping in the system *discovery phase* of the integration concept; and provide a more robust approach for collecting and modelling inclusive unit cost data in the *system definition* phase. These changes to the systemic planning approach bridge identified gaps in how effectively diverse participants may engage with directly with the results of existing comparative economic methodologies (see *Section 4.5.3.6 (Ross et al., 2024b)*). Conclusions may emerge from multiple cost perspectives informed by multiple criteria (*Criterion 10.3; Table 16*).

The revised *system comparison* phase (*Figure 19*) strengthens how uncertainty is accommodated within the comparative economic analysis in existing practice. This goes beyond the studies the fully meet the criteria of considering variability in water demand, costs, or physical systems parameters through sensitivity and scenario analysis (*Criterion 9.2; Table 16*). *Section 4.5.3.4* of this thesis (*Ross et al., 2024b*) demonstrates that to the extent that the literature on comparative economic analysis to urban water and sanitation planning in LMICs was reviewed, no existing study effectively accounts for *epistemic uncertainty*. That is, uncertainty that arises from boundary judgements, or assumptions about the limits of institutional responsibilities, or legitimacy of informal service arrangements and how this shapes persistent service outcome inequalities. Through this phase, Inherent assumptions that govern whose perspective are included in decision are made visible, recoverable, and contestable as intervention scenarios are assessed and refined (*Criterion 9.3; Table 16*).

The revised *system comparison* phase helps to position the systemic planning approach as akin to an investment in a local knowledge system, as opposed to a discrete analysis intended to inform mutually exclusive decision. The costed without-project case water demand model and soft systems artefacts may be considered assets that should be maintained and updated to support systemic learning. This learning orientation is valuable for supporting credible, adaptive decision-making in a complex and evolving problematical situation.

Recoverable soft and critical systems artefacts hold the assumptions, trade-offs, and value judgements embedded in comparisons in tension, and able to be revisited in future deliberative decisions. Hard systems end-use and cost models provide a stable, yet flexible structure capable of supporting robust and compelling decision-making. As a unified systemic model, the integration concept positioned comparative economic analysis as a living planning practice that supported persistent learning, negotiation, and adaptation, as a response to persistent service outcome inequalities.

7.4.4 How the overall revised integration concept builds on existing approaches

The revised integration concept enhances existing approaches to systemic urban water and sanitation planning supported by an enhanced comparative economic analysis methodology. The approach has been demonstrated to improve upon existing practice by more effectively responding to the evaluative criteria proposed in *Chapter Three* than the literature reviewed in *Chapter Four* (Ross et al., 2024a, 2024b) (see *Table 16*). Comparative economic analysis remains undervalued as a foundation for urban water and sanitation planning in LMICs (see *Section 1.2.3*). The discussion and synthesis of the revised integration concept in this chapter identifies significant empirical insights. This knowledge has been interpreted in this chapter through a discussion about the systems thinking paradigms

embedded within the transdisciplinary case study. The learning outcomes have been synthesised through adapting the integration concept in response to these insights.

The *system discovery* phase is strengthened by sequencing boundary critique and qualitative mapping as a means of exploring the problematical situations, ahead of attempting a more stable definition of the heterogeneous urban water and sanitation configuration. Scheduling these activities upfront enables diverse societal actors to collaboratively interrogate what should and should not be included within the decision-making process. By revealing the latent conflicts that make the situation complex, the relational factors that influence the how intervention scenarios are implemented in practice can be accommodated. This helps to embed planning in the local context, providing a foundation for an inclusive without-project definition, before it becomes stabilised within end-use water demand and cost modelling.

The *system definition* phase is reshaped because of the changes to *system discovery*. Thus, contextual and relational knowledge revealed in the first phase can be consolidated into more inclusive boundary objects that function more effectively as a shared frame of reference. Unit cost data that is more broadly relevant to diverse societal actors supports a disaggregated costing model that enables diverse societal actors to position themselves with the broader without-project heterogeneous configuration. This helps to stabilise comparisons of intervention scenarios arising from purposeful activity models drawn from diverse perspectives.

The system comparison phase is improved by reconceptualising comparative economic analysis as an ongoing, adaptive, deliberative process, rather than a linear decision. The revised concept supports iterative learning by balancing the need for comparisons that support robust decisions, at the same time as holding different perspectives in tension to

account for epistemic uncertainty. Planning is organised in a way that assumptions, trade-offs, and value judgements embodied in decisions recoverable so they can be revisited to influence ongoing planning cycles.

Overall, these adaptations improve comparative economic analysis for heterogeneous water and sanitation configurations in LMICs. They outline a methodology that supports a systemic planning approach that is inclusive, context-sensitive, and robust. The integration concept enables the costed, disaggregated, and deliberative comparison of both real world and aspirational intervention scenarios and supports decision-making as a legitimate ongoing, learning-oriented planning practice beyond a linear techno-economic evaluation.

7.5 Summary

Chapter Seven synthesises the findings from the transdisciplinary case study that have been presented in *Chapters Three to Six*. Overall, the chapter proposes and justifies a comparative economic analysis methodology for planning within heterogeneous urban water and sanitation service provision configurations. It then reflects on how a unified, systemic planning approach may inform inclusive and systemic planning for water and sanitation in practice.

First, this chapter revisited the methodological framing outlined in Chapter Two, guided by the *Transdisciplinary Outcome Spaces Framework* (Mitchell et al., 2015). This framing structured the research as three interdependent waves: (i) establishing evaluative criteria based on least-cost and integrated resource planning principles and assessing their application in existing practice; (ii) co-producing epistemologically diverse knowledge about a case study context in *Siem Reap, Cambodia*; and (iii) reflecting on how this knowledge was integrated to consider how a systemic comparative economic analysis methodology might improve urban water and sanitation planning in LMICs.

Section 7.2 contextualises the transdisciplinary integration that occurs in this thesis by reviewing four paradigms of systems thinking, hard, soft, critical, and a unified DSRP approach (Cabrera et al., 2021). This underpins a discussion of how these four paradigms contributed knowledge co-production in the case study, and the implications for a research approach that prioritises mutual learning to address the epistemic uncertainty that causes service outcome inequalities to persist in these contexts. In doing so, this section positions the case study in relation to previous work on urban water and sanitation planning in LMICs, defining its contribution to a methodologically plural unified systems approach to planning.

Section 7.3 is used to critically reflect on the implementation of the transdisciplinary case study methodology supported by an initial integration concept and what was learned from its application across three phases: system discovery, system definition, and system comparison. This reflection revealed three opportunities for strengthening transdisciplinary integration to improve comparative economic analysis methodologies and, as a result, inclusive and systemic urban water and sanitation planning. These were loosely aligned with each of these phases of the research and included: (i) focusing on how to sequence each type of knowledge co-production to improve how different ways of knowing are integrated in the methodology; (ii) considering how to organise planning as an iterative, learning-oriented system; and (iii) how to balance flexible participation in the planning process with robust decision-making. These opportunities provide practical insights into how knowledge integration unfolded in practice and form the empirical basis for the revised integration concept developed in *Section 7.4*.

Section 7.4 backcasts from the evaluative criteria established in *Chapter Three*, using empirical learning from the case study and the integration opportunities identified in *Section 7.3* to revise the initial integration concept and articulate an enhanced, systemic

comparative economic analysis methodology. The evaluative criteria established in Chapter Three are used to chart how insights from the case study can be used to improve the initial integration concept for a systemic planning approach. In doing so, it demonstrates the need to first apply participatory soft and critical systems tools to co-produce a contextual without-project case. This knowledge then provides the basis for systematically collecting unit cost data and developing a model capable of comparing and iteratively refining purposeful activity models, using the residential end-use demand model as a boundary object. These comparisons are then used to support a transparent decision-making process that balances tangible, costed outcomes with intangible social considerations.

Collectively, these refinements strengthen the comparative economic analysis, promoting inclusive deliberation, enhancing the legitimacy and interpretability of decisions, and creating a resilient foundation for iterative, adaptive urban water and sanitation planning. The synthesis presented in this chapter provides the interpretive foundation for articulating the contributions of the thesis. Chapter Eight builds on this foundation to explicitly answer the research questions, delineate the scope and limits of those contributions, and outline the practical, policy, and research implications arising from this work.

Chapter Eight: Conclusion

8.1 Overview

This chapter concludes the thesis by answering the research questions posed in *Chapter One* and articulating the research contributions. It builds on *Chapter Seven*, which synthesised and interpreted insights from the transdisciplinary case study, by explaining how those insights respond to each research question and why they matter for the theory and practice of urban water and sanitation planning in heterogeneous configurations in LMICs. *Section 8.2* answers each research question. *Section 8.3* articulates how these answers contribute to each outcome space. *Section 8.4* reflects on the tensions encountered in balancing contributions across these spaces within the scope of a doctoral thesis. *Section 8.5* outlines the implications for future research and practice, followed by a final reflection in *Section 8.6* to prompt ongoing systems thinking and practice in this space.

8.2 How the research questions have been responded to

This section answers each research question by stating what was found, how the knowledge was produced through the transdisciplinary case study methodology, and why it matters for planning heterogeneous urban water and sanitation configurations in LMICs. The findings are summarised by explaining how they were established through the studies presented in *Chapters Three to Six*, and through the discussion and synthesis of the revised integration concept guided by these component studies in *Chapter Seven*.

8.2.1 Research Questions 1a and 1b

Research Question 1a: What might a set of comprehensive least-cost, integrated resource planning principles for comparative economic costing of equitable and sustainable urban water and sanitation interventions look like?

Research Question 1b: In reference to the existing literature presenting comparative economic appraisals of urban water and sanitation interventions, what gaps exist in applying these principles, and how might they best be addressed?

Research Question 1 is answered by showing that for *comparative economic analysis* to be meaningfully applied to heterogeneous urban water and sanitation configurations in LMICs, it should be embedded within a transdisciplinary integration concept, sequencing *objective, interpretive, and critical* forms of co-produced knowledge.

The response to *Research Question 1a* considers what a comprehensive set of principles underpinning such an integration concept should include to move beyond current planning approaches in practice to account for how services are experienced from diverse perspectives within real-world heterogeneous contexts. The thesis shows that to achieve this, four main shifts in comparative economic analysis principles that underpin planning are required, including (i) the explicit adoption of a societal cost perspective, disaggregated by diverse subgroup perspectives, particularly those from the lens of those experiencing marginal access to water and sanitation services; (ii) the comparison of intervention scenarios against a context-specific without-project reference case that reflects the heterogeneity of existing service outcomes; (iii) the integration of knowledge about both the tangible and intangible costs and outcomes of service provision that integrates interpretive and critical knowledge, with quantitative cost modelling; and (iv) the collection of context-specific, incremental unit cost data that projects the disaggregated costs and outcomes of mixed formal, informal, and self-supplied service configurations over time. In this thesis, the need for these principles was evidenced by their synthesis through the

evaluative criteria developed in *Chapter Three* and operationalisation through the revised integration concept in *Chapter Seven*.

In contrast, *Research Question 1b* is answered by demonstrating that there are systemic gaps between these principles and the use of comparative economic analysis methodologies in practice, as indicated in the relevant existing literature reviewed in *Chapter Four*. Comparative economic appraisals are shown to typically: (i) adopt narrow boundaries of analysis aligned with the assets of utilities and municipal authorities, neglecting to integrate the heterogeneous, service-led perspectives of households or informal service providers; (ii) compare options against a do-nothing scenario, or implicit abstract models not supported by a contextual understanding of the heterogeneity of existing service provision arrangements; (iii) make boundary judgements that reduce and simplify institutional responsibility, underrepresent the significance of informal service provision, or aggregate diverse marginalised perspectives, failing to account for the epistemic uncertainty inherent in the design of a study; and (iv) inadequately apply context specific unit cost data and assumptions to model the long term relational and distributional impacts of heterogeneous service typologies. For the majority of the criteria, few studies were identified that applied the principle in full, with no study identified in the included cohort that fully operationalised the least-cost and integrated resource planning principles in the evaluation criteria for heterogeneous urban configurations in practice. This highlighted a need for methodological innovation.

In combination, these findings showed that existing comparative economic analysis tends to treat heterogeneity as a failure of planning, rather than recognising these heterogeneous configurations as a legitimate and prevailing model of service provision in LMIC cities. By proposing evaluative criteria that embody least-cost and integrated resource

planning principles and demonstrating where existing practice falls short, this thesis established the need for an approach capable of supporting inclusive, learning-oriented, and systemic planning. This response to *Research Question 1* contributed primarily to *Outcome Space One* to improve the problematical situation by bringing together fragmented disciplinary knowledge and reframing how it is understood. In turn, a secondary contribution to *Outcome Space 2* was made through the development of the evaluative criteria to support the integration of knowledge stocks and flows across different systems thinking paradigms. These contributions are further explained in Section 7.3.

8.2.2 Research Questions 2a and 2b

Research Question 2a: How might residential water end-use demand analysis characterise a heterogeneous without-project case for an urban water and sanitation configuration in Siem Reap to inform an inclusive planning approach?

Research Question 2b: How might a systems thinking approach identify possible desirable and feasible options for heterogeneous urban water and sanitation configurations in Siem Reap from diverse societal actor perspectives?

Research Question 1 identified the principles required for comparative economic analysis to be credible in heterogeneous contexts. Building on this work, *Research Question 2* considers how those principles can be operationalised through the co-production and integration of epistemologically plural knowledge in a real-world case study. The question is answered by demonstrating that heterogeneous urban water and sanitation configurations cannot be meaningfully compared unless the problematical situation is first made explicit, contested, and rendered comparable by relevant societal actors through the integration of this knowledge.

In response to *Research Question 2a*, the case study demonstrates that a bottom-up residential end-use water demand analysis can function as a robust boundary object for characterising a heterogeneous without-project situation. However, this is contingent on it being intentionally designed and conducted through a methodology that makes heterogeneity visible. The end-use analysis applied random stratified sampling and employed a flexible survey approach to ensure data could be collected in each sampled household. This resulted in a structured empirical representation of household water demand, disaggregated by household characteristics, appliances, service typologies, and wastewater sinks that exist in the real-world, without-project situation. The model established a stable, contextually relevant point of reference, which could be used to incrementally compare both pragmatic and purposeful intervention scenarios at different scales. This is evidenced in *Chapter Five*, where an end-use analysis for a case study in Siem Reap coherently characterises the heterogeneity of water demand for the without-project case. This model is shown to be suitable for use in a comparative economic analysis methodology.

The response to *Research Question 2b* explains how the residential end-use water demand model alone is not sufficient for defining all factors that should be compared to support equitable and sustainable outcomes. The use of *soft systems methodology* to ask questions of the heterogeneous configurations and support a boundary critique was also integral to this task. It supported the development of a structured approach to eliciting, comparing, and improving upon how diverse actors understood the problematical situation, where constraints were perceived, and which interventions might be considered desirable and feasible. *Purposeful activity models* and *critical systems heuristics* were applied as epistemic objects to structure deliberation in a way that held these perspectives in tension,

without reducing them to a singular institutional position. This finding is evidenced in *Chapter Six*, where soft and critical systems approaches are applied to surface contested interpretations of which interventions are desirable from diverse societal actor perspectives, before interrogating their feasibility and legitimacy within the heterogeneous configuration in Siem Reap from the same positions.

In combination, the answers to these questions show that the primary constraint to planning interventions in heterogeneous configurations is not a lack of data or participation in isolation, but the absence of a methodology capable of coherently integrating epistemologically diverse knowledge into a shared basis for comparison. By integrating bottom-up end-use demand modelling with soft and critical systems approaches, the case study demonstrates how heterogeneous configurations can be compared without reducing the complexity of how diverse perspectives interrelate with them.

Through experimenting with the integration of this knowledge, this thesis develops a planning approach that meaningfully compares heterogeneous configurations, without reducing the complexity of how diverse perspectives interrelate with them. This contributes to *Outcome Space Two* by strengthening how knowledge stocks and flows are applied across epistemological boundaries, to provide a foundation for more inclusive planning, as described in *Section 7.3*.

8.2.3 Research Question 3

Research Question 3: How might a systemic, learning-oriented approach to urban water and sanitation planning enhance the relational capacity of societal actors to address the inertia constraining equitable and sustainable water and sanitation service provision in Siem Reap, Cambodia, and other similar contexts?

Building on the methodological integration established in *Research Questions 1 and 2*, *Research Question 3* examines what changes when such an approach is enacted as a learning-oriented planning process. The question is answered by showing that organising comparative economic analysis as a local knowledge system strengthens the relational capacity of societal actors. This, in turn, helps address the inertia that constrains adaptive responses to persistent service outcome inequalities in heterogeneous configurations.

The transdisciplinary case study finds that relational capacity can be strengthened when planning is organised as a learning-oriented process that makes the assumptions, boundaries, and power relations within heterogeneous configurations visible, and provides structured opportunities for actors to interrogate their own worldview in response to perspectives of others. Mutual and transformative learning was evidenced through: (i) shifts in what those engaged in the collaborative workshops considered to be included within system boundaries, and therefore legitimately addressed in planning frameworks; (ii) increased recognition of how the roles and responsibilities of those in power shape which problems and possible solutions are deliberated; and (iii) how adaptations to the systems thinking approaches embedded within the transdisciplinary integration concept were sequenced in response to the intentions of actors within the configurations, particularly when the needs of marginalised actors were not being met.

This finding is established through conducting participatory modelling and workshops, and then interpreting them in *Chapter Six*, as well as the discussion and synthesis of what was made visible through these approaches in *Chapter Seven*. This is evidenced through the artefacts developed as part of each workshop (*rich pictures* and *purposeful activity models*) and the documentation of *soft systems* questioning and *critical systems* boundary critique. How the perspectives of those engaged in the workshops shifted when exposed to

competing perspectives was observable and the thinking that emerged is recoverable through this evidence. This learning is important as it shaped a more systemic understanding of the constraints producing persistent service outcome inequalities.

Chapter Seven reinforces why this finding matters by demonstrating how it informed revisions to the integration concept, linking improvements in relational capacity to the function of a local knowledge system and how it supports deliberation within the proposed systemic comparative economic analysis methodology. Making this connection explicit highlights how mutual and transformational learning can overcome political inertia to address persistent service outcome inequalities within a planning framework. Conflicting perspectives can be made visible, contestable, and revisable over time through diverse methods embedded within the design of a systemic, learning-oriented planning approach. Through this learning, adaptive decision-making that is better able to respond to persistent service outcome inequalities in complex and evolving urban contexts was enabled. The response to *Research Question 3* contributes directly to mutual and transformative learning (*Outcome Space Three*), while reinforcing how this methodology makes tangible improvements to the problematical situation (*Outcome Space One*) through contributing to knowledge stocks and flows (*Outcome Space Two*).

8.2.4 Overarching Research Question:

What planning approaches might be suitable for addressing persistent service outcome inequalities when planning interventions for heterogeneous urban water and sanitation service provision configurations in Siem Reap and other similar contexts?

Rather than introducing new findings, the response to the overarching research question synthesises how the answers to *Research Questions 1 to 3* interact when

integrated within a unified planning approach. The question is answered through demonstrating that this integration addresses the inertia that constrains how persistent service outcome inequalities are addressed within heterogeneous configurations. For instance, in the case study, an approach capable of embracing the complexity of deliberating diverse intervention scenarios in LMICs was developed and validated. The approach is shown to improve how effectively an integration concept could: (i) repurpose least-cost and integrated resource planning principles for heterogeneous configurations (see *Research Questions 1a and 1b*); (ii) integrate *hard*, *soft*, and *critical* systems methods to structure how knowledge is co-produced and related to other ways of knowing (see *Research Questions 2a and 2b*); and (iii) build deliberative and relational capacity to address inertia and inequality (see *Research Questions 3*). The approach, in turn, is able to respond more fully to the evaluative criteria for the comparative economic analysis of urban water and sanitation interventions in LMICs.

This integrated approach shows that diverse systems thinking approaches applied to comparative economic analysis make different types of knowledge visible. Further, this knowledge becomes systemic when organised to adaptively respond to the problem of persistent service outcomes through adaptive, learning-oriented planning. Backcasting the revised integration concept from the evaluative criteria developed in *Chapter Three* and validated in *Chapter Four* shows that this revised concept can improve how comparative economic appraisals in the LMIC literature are designed and evaluated. Moreover, the concept reframes comparative economic analysis as an adaptive local knowledge system that supports the inclusive deliberation of possible improvements to heterogeneous configurations. Diverse ways of knowing are organised in a way that is sufficiently structured

to enable comparison, while being flexible enough to prompt new systems thinking in response to emergent behaviours.

8.3 Contributions to each outcome space

The section outlines the contributions to each transdisciplinary outcome space guiding the thesis, as introduced in *Chapter Two* (Mitchell et al., 2015). Organising the contributions in this way makes explicit how the research has simultaneously: (i) contributed to reframing and improving the problematical situation of persistent water and sanitation service outcome inequalities; (ii) advanced knowledge stocks and flows through the transdisciplinary integrations of different systems thinking paradigms; and (iii) supported mutual and transformational learning among societal actors. This approach to framing the contributions ensures their coherence with the research design and synthesis of the results (as presented in *Chapter Seven*), reflecting the transdisciplinary intent of the thesis.

8.3.1 A tangible improvement in the problematical situation

As a result of this thesis, a heterogeneous urban water and sanitation service provision configuration in Siem Reap, representative of other LMIC contexts is perceived differently. To begin with, this situation was perceived as a failure to address the limitations of infrastructure-led planning. Now, a systemic planning approach has been conceptualised that perceives heterogeneous configurations as an object for systemic planning. This outcome represents a *tangible improvement in the problematical situation* as it shifts perspectives about what can legitimately be included and considered by a comparative economic analysis methodology.

This reframing is a significant contribution as it alters what is relevant, comparable, and valuable to consider as possible within urban water and sanitation planning approaches. This shift enables the inclusion of perspectives that are often marginalised or rendered

invisible in practice, including those of informal service providers, households reliant on self-supply, and other subgroups disproportionately affected by existing arrangements.

Positioning these worldviews, alongside institutional perspectives within an integrated local knowledge system enables the inherent assumptions and values that lead to service outcome inequalities to become more visible, contestable, and open to deliberation.

A related contribution to this outcome space is methodological. The repurposing of least-cost and integrated resource planning principles was pursued so they could be applied to this problematical situation. The intent was to both develop and operationalise a set of evaluative criteria for comparative economic analysis tailored specifically to heterogeneous urban configurations in LMICs. These criteria provide guidance on the definition of system boundaries and a contextual without-project situation, as well as how to compare mixed or hybrid options. The intervention scenarios compared directly respond to lived experiences of water and sanitation services and associated coping practices. The evaluative criteria were disseminated via two peer-reviewed publications (Ross et al., 2024a, 2024b) in a practitioner facing journal, increasing the potential influence on both applied research and practice.

8.3.2 Contributions to knowledge stocks and flows

This thesis demonstrates how comparative economic analysis can support a systemic planning approach for urban water and sanitation configurations. The approach functions as a purposefully structured local knowledge system that embeds different systems thinking approaches as part of a transdisciplinary integration concept. Within this concept, hard systems, residential end-use water demand and cost modelling, soft systems purposeful activity models, and critical systems heuristics are brought together to support a learning-oriented planning approach. This *contribution to knowledge stocks and flows* is prompted by

learning about possible improvements via comparison of objective and interpretive *ways of knowing* about the heterogeneous configuration in Siem Reap. Knowledge is co-produced and makes the ways that different perspectives are related within the configuration visible. This supports diverse societal actors to develop a less partial understanding of how the problematical situation might be resolved.

Other methodological *contributions to knowledge stocks and flows* also support this concept. *Chapter Five* presents one of the first explicit applications of residential end-use water demand analysis for the characterisation of a *heterogeneous* without-project situation within a LMIC case study. Employing a stratified sampling approach and a flexible survey methodology enabled the disaggregation of end-use water demand across different socio-demographic characteristics, water supply arrangements, household service typologies, and wastewater sinks. This resulted in a stable representation of existing heterogeneous water demand profiles, helping to explicitly define tangible aspects of the *without-project case* and embed it within a comparative economic analysis methodology. The resulting model enabled distinctions to be made about service outcomes that are typically obscured within aggregated demand models and provide an empirical basis for comparing both objective and purposeful intervention scenarios.

Chapter Six contributed a model by which soft and critical systems approaches may be embedded practically within a transdisciplinary case study methodology through collaborative workshops employing the interpretation of *purposeful activity modelling*, as well as a boundary critique. Different perspectives on how the problematical situation was perceived, how it might be improved, and what constraints are anticipated were transformed into recoverable epistemic objects. These artefacts enabled diverse viewpoints

to be held in tension within the workshops, without being collapsed into a singular institutional narrative.

When integrated with the more stable *end-use demand model*, they enabled diverse perceptions of how intangible impacts of the without-project situation interacted with tangible costs. Thus, these costs could be accounted for in collaborative deliberations about how each object represented what is feasible and desirable. This greatly extended the scope of what is possible to consider within a comparative economic analysis methodology. Further, this approach framed outcomes from deliberations as adaptive, and able to be revised in response to additional perspectives or emergent system outcomes.

The integration of each system thinking paradigm within a transdisciplinary case study methodology represents a broader conceptual contribution to *knowledge stocks and flows*. The integration concept demonstrates how these methodologies can be intentionally shaped to support learning and comparison in heterogeneous urban water and sanitation systems. The use of the DSRP heuristic (*Distinctions, Systems, Relationships, and Perspectives*) enables a meta-theoretical interpretation how knowledge integration and systemic learning occurs within a planning approach. Articulating this process strengthens the legitimacy of comparative economic analysis as a local knowledge system. This rationale makes the claim to be able to meaningfully engage with heterogeneity, epistemological plurality, and complexity more compelling. The dissemination of these contributions through a peer-reviewed publication (Ross et al., 2025), and the publication of this thesis, makes these theoretical and methodological contributions available to applied researchers and practitioners.

8.3.3 Mutual and transformational learning

As a result of this thesis, a conceptual framework for how a learning-oriented planning process can strengthen the relational capacity of societal actors has been empirically tested. It demonstrates the capacity to facilitate: (i) collaboration on the iterative improvement of intervention scenarios framed from diverse perspectives; (ii) deliberation on how to accommodate diverse needs within these scenarios; and (iii) greater awareness of power relations, and how advocacy may support more inclusive boundary judgements when planning heterogeneous urban water and sanitation configurations. In this way, the learning-oriented planning approach supports a contribution to *mutual and transformational learning*. Systems are used as *learning devices*, or artefacts that are purposefully embedded into the structure of a comparative economic analysis methodology, rather than learning resulting as an outcome of planning. This approach contributes towards an endogenous capacity to revise how problems are framed, roles and responsibilities are distributed, and interventions are adapted over time.

Evidence of this learning emerged through collaborative workshops conducted as part of the transdisciplinary case study (see Chapter Six) (Ross et al., [preprint]). These activities structured opportunities for issue owners to reflect on their own positions, and how they relate to others within the heterogeneous service configuration. *Mutual and transformational learning* were observable in the learning artefacts produced in the workshops and included: shifts in what societal actors described as legitimately included within formal planning frameworks; the surfacing of implicit assumptions that underpin existing arrangements; and stated intentions to negotiate power through actionable trade-offs.

As with *Outcome Space Two*, the broader contribution to *mutual and transformational learning* is conceptual. The integration concept demonstrates how relational capacity can be enhanced through the design of structured learning processes that bring together a stable representation of the problematical situation (*a boundary object*) with a learning prompt to promote new systemic thinking (*an epistemic object*). When applied to a comparative economic analysis methodology to support a systemic urban water and sanitation planning framework, learning becomes recoverable, with conflicting perspectives remaining visible, contestable, and revisable, as decisions evolve over time. Thus, decisions are negotiated via the accommodation of perspectives as opposed to consensus, which contributes to a softening of institutional inertia and a more adaptive outlook. This concept is underpinned by a further methodological contribution that captures and stabilises learning through the co-production of recoverable artefacts (i.e. rich pictures and purposeful activity models) as evidence in *Chapter Six* (Ross et al., [preprint]).

8.4 Tensions and limitations in contributing to each outcome space

While the limitations of the research design are discussed in *Chapter Two*, some tensions in contributing to each outcome space only became apparent once the transdisciplinary case study was conducted. This section clarifies the conditions under which the research questions have been addressed, and the extent to which the contributions articulated in *Sections 8.2* and *8.3* may be transferred to other contexts. These tensions are characteristic of transdisciplinary research conducted within the confines of a doctoral thesis, and have shaped how contributions have emerged, and are likely to continue to emerge, unevenly across the Transdisciplinary Outcome Spaces (Mitchell et al., 2015).

The contribution to improving the problematical situation focused primarily on reframing how heterogeneous urban water and sanitation configurations are understood

and evaluated, rather than on implementing or appraising fully costed intervention scenarios. While the evaluative criteria developed in Chapter Three and their incorporation into the revised integration concept provide a structured basis for more inclusive and systemic planning, their application within the Siem Reap case study was necessarily partial. The research influenced how the problematical situation may be perceived, assessed, and deliberated, but did not extend to modelling or projecting the impacts of alternative intervention pathways within the scope of this thesis.

The strongest contribution of the thesis was to the outcome space of *knowledge stocks and flows*. This contribution emerged through the integration of *hard, soft, and critical* systems thinking approaches within a transdisciplinary case study to co-produce diverse forms of knowledge about a heterogeneous water and sanitation configuration in Siem Reap (*Chapters Five and Six*). However, not all elements of the initial integration concept could be empirically tested as intended. Methodological adaptations, particularly those necessitated by COVID-related disruptions, meant that the integration concept was only partially enacted. For example, the absence of a fully developed end-use demand and cost model at the time of the workshops required the use of rich pictures as proxy boundary objects. While these adaptations informed important refinements to the integration concept, a larger interdisciplinary research team or multiple case applications may have enabled more comprehensive testing and earlier identification of potential issues.

The contribution to *mutual and transformational learning* is evidenced through the recoverable artefacts produced during collaborative workshops, which document shifts in how issue owners understood system boundaries, roles, and responsibilities within a heterogeneous service provision configuration. These artefacts demonstrate the capacity of the approach to structure learning that surfaces and interrogates assumptions sustaining

persistent service outcome inequalities. This contribution was necessarily the most context-specific, focusing on relational dynamics within a particular institutional and social setting. While elements of the learning process are transferable, exploring multiple cases or conducting a comparative study would be required to more fully demonstrate how durable and scalable this contribution was. While multiple workshop iterations were initially planned, time and access constraints meant that only one round was conducted, leaving some learning outcomes articulated in the revised integration concept emergent rather than fully demonstrated.

Overall, these tensions do not diminish the contributions claimed by the thesis. Rather, they reflect the dynamic, non-linear, and iterative nature of transdisciplinary research, in which learning, integration, and impact often unfold over extended timeframes. By making these tensions explicit, the thesis avoids over-claiming. Further, it demonstrates how a flexible, learning-oriented comparative economic analysis methodology can engage with the complexity of planning interventions in heterogeneous configurations and informs future research and practice beyond the scope of this doctoral study.

8.5 Implications and opportunities for future research

This thesis has demonstrated how a systemic, learning-oriented comparative economic analysis methodology can be applied to heterogeneous urban water and sanitation service provision configurations in low- and middle-income countries. Through a transdisciplinary case study in Siem Reap municipality, the research has shown how least-cost and integrated resource planning principles can be repurposed, how hard, soft, and critical systems approaches can be coherently integrated, and how systems comparison can function as a deliberative learning process rather than a purely technical appraisal exercise.

While these contributions have been established in depth within a single case, they also reveal clear opportunities for future research to extend, stabilise, and scale the methodology. Building on the tensions discussed in Section 8.4, this section identifies three priority directions for future research, each broadly aligned with one of the three Transdisciplinary Outcome Spaces.

8.5.1 Extending the application of the integration concept at scale

The evaluative criteria and revised integration concept developed in this thesis provide a structure for inclusive and systemic planning in heterogeneous urban water and sanitation contexts. Future research should focus on extending their application beyond a single intrinsic case study to explore how the methodology performs across different spatial and temporal scales, and different institutional settings.

In the Siem Reap context, this could involve expanding the residential end-use demand analysis and systematically collecting disaggregated unit cost data for a wider range of service configurations across the municipality. This would enable the full implementation of costed without-project and intervention scenarios, allowing the systems comparison phase to be repeated iteratively and over a longer planning horizon. Such work would deepen understanding of how deliberative comparison reshapes priorities over time, particularly in balancing cost-effectiveness, equity, and inclusion.

Applying the integration concept in cities of other LMICs, with similar experiences of socio-technical heterogeneity and institutional inertia, would further strengthen the legitimacy of the approach. Comparative applications across multiple LMIC contexts would help to clarify which aspects of the methodology are context-specific and which represent more generalisable planning principles, thereby strengthening its relevance for both applied research and practice.

8.5.2 Strengthening unified systems modelling and comparison

This thesis has demonstrated how systems comparison can be organised as a learning-oriented process that integrates boundary objects (such as disaggregated end-use demand models) and epistemic objects (such as purposeful activity models and boundary critiques). A key opportunity for future research lies in exploring the systems comparison phase in depth with the benefit of more detailed and stable boundary objects.

With a clearer system definition now established for the Siem Reap case through the work in *Chapter Five*, future work could focus on developing fully disaggregated cost models aligned with heterogeneous service typologies. This would enable more explicit exploration of how tangible costs, intangible impacts, and distributional impacts interact across different service typologies and possible interventions. Such modelling would allow the revised integration concept to be tested more rigorously as a comparative economic analysis methodology. This would extend the interpretation of the integration concept to reveal pragmatic implications, as opposed to being primarily a conceptual and deliberative decision-making process.

There would also be scope to experiment with more dynamic tools such as AI to integrate learning artefacts in real time or near-real time within planning workshops. Such modelling could enhance how efficiently the iterative comparison of intervention scenarios was processed, enabling issue owners to explore trade-offs, revise assumptions, and collaboratively adapt scenarios, without affecting the integrity of the systems approaches. This would strengthen how systems comparison could be used for learning-oriented planning, making the process more dynamic and iterative, while exploring a greater range of societal actor perspectives.

8.5.3 Supporting ongoing systemic, learning oriented planning practices

The collaborative soft systems modelling and critical systems boundary critique workshops documented in this thesis demonstrate how learning-oriented planning can enhance relational capacity and shift how societal actors understand their roles within heterogeneous service provision configurations. A key opportunity for future research is to examine how such learning translates into sustained changes to how the planning of heterogeneous configurations evolves over time.

Longitudinal research could be used to document how co-produced knowledge and learning artefacts influence decisions over time to shift institutional norms, and the types of intervention scenarios that are prioritised. Such research would help to understand how learning-oriented planning supported by the revised comparative economic analysis methodology contributes to transformations in the governance of urban water and sanitation services, beyond deliberation in a workshop.

A related opportunity, perhaps supporting this research, would be to develop practitioner-oriented resources to support the implementation of systemic comparative economic analysis in real-world planning contexts at the municipal scale. This could include action-oriented resources tailored to different audiences, such as municipal authorities, utilities, community-based organisations, and private service providers, or property developers. This could provide an opportunity to think through how effectively this approach could be applied at different scales within an urban environment, or how more discrete studies could be combined within a broader citywide framework.

8.6 A final reflection to prompt ongoing systems thinking

This chapter has synthesised the contributions of the thesis by reflecting on how the research questions and the transdisciplinary case study methodology responded to each of

the three Transdisciplinary Outcome Spaces. A central contribution has been the development of a revised comparative economic analysis methodology that supports more inclusive and systemic planning for heterogeneous urban water and sanitation configurations in LMICs. This approach is supported by evaluative criteria for least-cost comparative economic analysis, established with the purpose of addressing persistent service outcome inequalities within heterogeneous water and sanitation configurations in LMICs.

While these contributions respond effectively to the research questions posed at the outset of the inquiry, a number of limitations have also been acknowledged, particularly in relation to which aspects of the methodology could be empirically tested within the scope of this research, and which remain emergent within a flexible, systemic learning-oriented planning approach. By articulating these constraints, the thesis also identifies clear opportunities for future research that invite further iteration, adaptation, and application of the methodology in other contexts.

With this in mind, this thesis does not seek to provide a definitive answer to how interventions should be planned in complex, heterogeneous service provision configurations. Instead, it offers a foundation for continued action-oriented learning. The knowledge co-produced through this research is intended to prompt ongoing systems thinking, by enabling new distinctions to be made, *sweeping in* additional perspectives to continue to foster new systemic thinking. This work should continue to evolve through the engagement new actors, new contexts, and new questions that keep on redefining the boundaries of what inclusive, equitable, and sustainable urban water and sanitation planning can become.

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Appendix

Appendix A: Defining socio-technical diversity in urban WASH systems

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CONFERENCE POSTER

Defining socio-technical diversity in urban WASH systems

How can we better understand the heterogeneous contexts that systems of citywide inclusive sanitation will emerge from?



Simon Ross

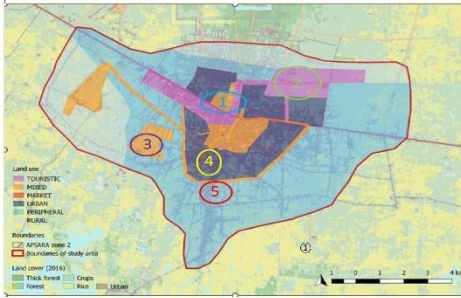
1 Emerging thinking about the planning of citywide inclusive sanitation

Citywide inclusive sanitation comprises diverse contexts and heterogeneous demands for services that drive mixed, incremental & adaptive responses with complex behaviours

<p>Citywide inclusive sanitation is focused on equitable outcomes. Everyone should benefit from mixtures of fit for purpose infrastructure configurations and service provision models that can facilitate the preferences of those who are vulnerable</p>	<p>A universal basic service level should not be assumed in low and middle income countries. Infrastructure(s) are multiple, layered and can often provide incomplete service outcomes, operating at different scales, with different intended outcomes.</p>	<p>Societal preferences for service outcomes are derived from multiple, diverse, individual trade offs about a service level that is affordable. Judgements vary with how water is sourced, available infrastructure, local constraints to service provision, and perceived priorities.</p>	<p>Mixtures of off-site, on-site, informal, and self-supplied sanitation systems emerge in relation to each other, as well as to other services such as water supply and urban drainage. Partial, decentralised efforts contribute significantly to improving marginal situations but are poorly understood.</p>	<p>Heterogeneity is not easily characterised within existing urban sanitation planning frameworks. Methods capable of adopting a broad societal perspective that can accommodate different localised demands are required.</p>
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2 The problem situation

- o Making decisions about the optimal mix of approaches applied in response to diverse contexts and demands is challenging for municipal authorities.
- o At present, citywide inclusive sanitation frameworks are conceptual and articulate why but not how diverse, appropriate systems might manifest.
- o Existing situation analyses used in urban sanitation planning perceive what is missing from a supply chain. This perspective is linear and is biased towards bridging historical gaps in the financial sustainability of supplying municipal services.
- o This misrepresents the breadth of the full mixture of approaches required to meet citywide demands. For instance, those that emerge in response to the diverse, incremental preferences of marginal users attempting to address immediate service constraints.



3 Approach

- To better understand the diversity of how water is demanded for urban sanitation services, and end-use survey was conducted with 98 out of 1630 households across two villages in Siem Reap in Cambodia (circles 4 & 5 above).
- A flexible, participatory method was used to compile an end use model disaggregating water demand for bathing, toilet flushing, washing clothes, dishwashing, cleaning, & potable water consumption.
- Violin plots representing how water demand is distributed at different scales for key end use components were interpreted to characterise the heterogeneous context in which mixtures of sanitation systems emerge.

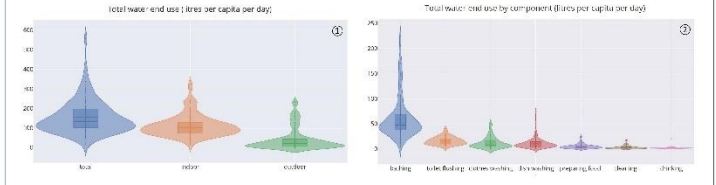


5 Implications for citywide inclusive sanitation planning

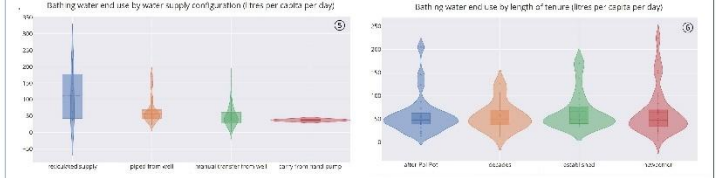
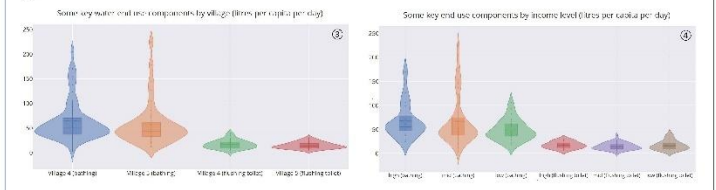
<p>Demands for sanitation are distributed across urban areas in low and middle income countries based on geographical, physical, technical socio-demographic determinants</p>	<p>Understanding the different ways water is demanded for service outcomes is critical knowledge for learning about the mixture of approaches needed to achieve citywide inclusive sanitation</p>	<p>Socially collecting granular end use data has been demonstrated to be an appropriate, alternative method to using smart meters in low- and middle-income countries</p>	<p>End use models derived from this data have been shown to be effective in describing the complexity of how heterogeneous demands for sanitation relate to each other.</p>	<p>Additional work is planned to incorporate end use modelling into a systemic citywide inclusive sanitation planning framework.</p>
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4 An demonstration of the utility of end use data in exploring heterogeneous demands

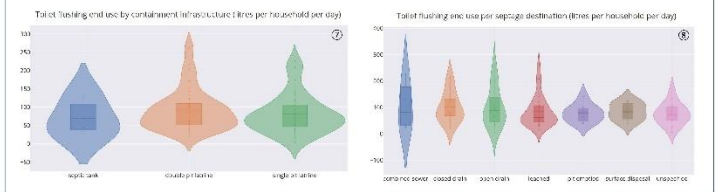
The end use model derived from the two adjacent villages in Siem Reap, Cambodia is represented in a series of violin plots that are disaggregated at increasingly granular scales. First, the total distribution of water end use, broken down into indoor and outdoor components (1), and different components of indoor end use (2) is presented.



Further disaggregating the distribution of demand by factors that are spatial (3) (by village or community); social (4) (by income level); technical (5) (by water supply configuration); or by perspective or worldview (6) (indicated in this case by historical length of tenure) is useful in understanding what is contextually appropriate for providing inclusive sanitation in different locations in the two villages. For example, it may be gleaned that where technical options are available (3), and household income (4) enables a reticulated or piped connection to a header tank (5); some users will prefer to use a shower for more convenient bathing. This might be especially true, where modern drainage presents few constraints for newcomers to dispose of sullage (greywater) in Village 4; but less likely in Village 5 where there is a higher proportion of households who prefer not to impede traditional drainage into rice fields with fences or buildings (6).



Unlike end uses that produce sullage, water demand for flushing toilets is more constrained irrespective of location (3) or income level (4) by limitations in household containment hardware (7) or the availability of public drainage infrastructure (8). Constraints in managing seepage solely through the use of on-site containment hardware, especially where only a single pit is present (7), leads to toilet flushing behaviours that use 20-30 fewer litres per household per day in the two study villages in Siem Reap, as compared to situations where off-site drainage is available (8).



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Figure A1: Poster presented at the Water and WASH Futures conference in February 2023

Appendix B: Least-cost economic evaluation of citywide inclusive sanitation interventions
in low- and middle-income countries

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CONFERENCE ABSTRACT

Least-cost economic evaluation of citywide inclusive sanitation interventions in low- and middle-income countries

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Abstract: In the 1980s, the World Bank applied '*theory of economic costing*' to derive an economic analysis methodology for the selection of sanitation alternatives, embedded within an influential sanitation planning framework. In practice, ambiguities about this framework persist. In response, a consensus-based evaluative criteria with demonstrated effectiveness in improving the quality of economic analysis studies of health interventions in British Medical Journal is considered. This framework is adapted to derive evaluative criteria for the economic analysis of sanitation interventions. These adapted criteria are then used as the basis for scoping the present literature and further iterate updated evaluative criteria for the least-cost economic analysis of *citywide inclusive sanitation*. The application of these criteria by is expected to improve the evidence base related to the cost effectiveness of urban sanitation interventions; and ultimately improve related planning and decision-support approaches.

Keywords: economic analysis; citywide inclusive sanitation; least cost planning

A methodology for the least-cost economic analysis of sanitation alternatives derived from '*theory of economic costing*' in the 1980s (Kalbermatten et al., 1982) is claimed to have revolutionised urban sanitation planning frameworks in low- and middle-income countries (LMICs) (Kennedy-Walker et al., 2014). Yet despite this putative influence, methodological uncertainty continues to limit how effectively economic analysis is applied to decisions about the selection of sanitation alternatives and optimal service levels in practice (Hutton & Chase, 2016). While evaluative criteria have had demonstrated success in improving the quality of economic analysis of health interventions (Drummond & Jefferson, 1996), these criteria are not fit-for-purpose for appraising studies on urban sanitation at the project scale, due to several theoretical and practical limitations (Hutton, 2001). A lack of evidence of the economic efficiency of *citywide inclusive sanitation* (CWIS) (Schrecongost et al., 2020) persists, with implications for the equitable distribution of the benefits of urban sanitation projects.

This study proposes evaluative criteria for least-cost economic analysis of CWIS. The methodology used to devise these criteria are outlined in Figure 1,1. First, criteria used to appraise studies of health interventions (Drummond & Jefferson, 1996) are interpreted for application to the least-cost methodology for the economic analysis of sanitation alternatives (Kalbermatten et al., 1982). Then literature aligned with a cost effectiveness analysis methodology for urban sanitation alternatives (Mitchell et al., 2007; Willetts et al., 2010; 2013) as well as emergent CWIS planning frameworks (Schrecongost et al., 2020) are scoped to further devise evaluative criteria for the economic analysis CWIS interventions. These criteria are presented in an abridged format in Table 1.1. The first evaluative criteria are best suited to a retrospective review of economic analysis studies comparing sanitation alternatives at the project scale in LMICs. Such a review is expected to develop insights into the methodological limitations in deriving generalisable evidence of the economic efficiency of sanitation alternatives, both within, and across different LMIC contexts. The second evaluative criteria encompass methodological advances that have since progressed how economic analysis may be applied to urban sanitation. It is best suited to informing the design of future economic analysis studies comparing interventions.

Key findings emerging from scoping these criteria include: (i) a need to adopt subgroup cost perspectives to better understand the systemic interactions between sewerage and non-sewerage sanitation alternatives, the relational determinants of service outcomes, and which sanitation alternatives best fit contextually; (ii) the importance of critically scoping economic analysis studies to ensure the system boundaries of an analysis represent an inclusive *without-project case* from which the broadest possible range of options can be compared; (iii) the utility of end-use, water balance models in enabling a flexible, integrated, aggregated and disaggregated analysis of water and sanitation outcome measures in conjunction with sanitation planning; and (iv) the need for planning methods that explicitly include a diversity of service users, and non-institutional service providers (including users who self-supply) in making a final cost-benefit determination when considering intangible aspects of decisions. A greater number of high-quality, context specific economic analysis studies, comparing urban sanitation alternatives responding to such prompts are vital if cost effective urban sanitation alternatives are to be selected in LMICs and then sustainably and equitably managed.

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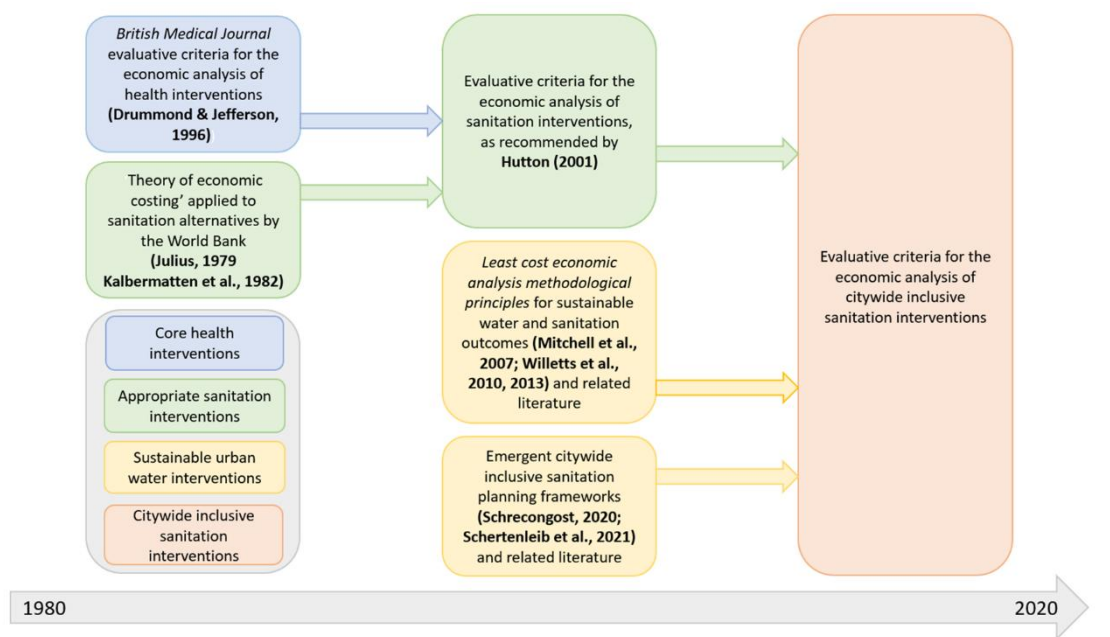


Figure B1: Scoping the evaluative criteria.

Table B1: Evaluative criteria for the economic analysis of urban sanitation interventions.

Evaluative criteria for the economic analysis of <i>appropriate sanitation alternatives</i> .	Evaluative criteria for the economic analysis of <i>citywide inclusive sanitation</i>
Study design: research question	
A research question is outlined that balances economic efficiency and equity outcomes. A societal cost perspective is adopted that is disaggregated key financial cost perspectives.	In addition, the study considers relevant subgroup cost perspectives
Study design: rationale for comparing alternatives	
The opportunity costs of alternative interventions are compared with a situation that would emerge <i>without a project</i> .	In addition, consistent system boundaries are defined to identify the costs and benefits included and excluded from an analysis for <i>people, time, and service</i> dimensions. A <i>service focus</i> is also applied to broaden the range of interventions considered for meeting service outcomes.
Study design: economic analysis methodology	
The economic analysis methodology used comprises three components (i) a comparable cost effectiveness analysis; (ii) optimisation of each alternative aligned with the objective of the analysis (iii) end user(s) making the final cost-benefit determination about each alternative	In addition, the economic analysis methodology optimises each alternative based on life cycle cost analysis. End user(s) make final cost-benefit determination accounting for broad sustainability criteria.
Data collection: effectiveness data	
The source(s) of effectiveness estimates are stated. If based on a single study, details of the study design and results are given. If based on multiple studies, the method of synthesis is given.	In addition, effectiveness data is sourced from within the system boundaries of the study context and is relevant to a diverse mix of options for meeting defined service outcomes.

Data collection: benefit valuation	
The primary outcome measure is a cost-effectiveness ratio. If benefits are valued, the method(s) used to do so are justified. Externalities are identified and reported. If a cost minimisation rule cannot be applied, they are included in a process of enabling service users to make a final cost-benefit determination.	In addition, if cost minimisation rule cannot be applied, externalities are identified and included in a process of enabling the least-cost alternative to accommodate all cost and subgroup perspectives.
Data collection: cost data	
Quantities of resources are reported separately from unit costs. Method(s) for estimating quantities and unit costs are described. A marginal or <i>average incremental cost</i> is determined based on population or water consumption (or demand) data. Shadow rates adjust market prices where appropriate. Currency and price data are recorded.	In addition, life cycle cost analysis is applied to estimate, structure, and sequence data about how the quantities of resources used by a project vary over the time horizon of a project.
Data collection: modelling	
Details of any model(s) used, and any key parameters on which it is based are provided and justified. Any assumptions used are made explicit and are relevant to the study context.	In addition, details of an integrated water balance model with the capacity to compare the discounted <i>average incremental cost</i> of the without-project case and each alternative over a
Analysis and interpretation of results: adjust for the timing of costs and benefits	
The time horizon of the analysis is sufficient to account for the project component with the longest asset life. Discount rate(s) applied are stated, and their selection is justified.	The same criterion is applied
Analysis and interpretation of results: allow for uncertainty	
Details of statistical tests and confidence intervals are given for stochastic data. The method of sensitivity analysis is given, with the choice of variables and the values for which they are varied stated.	In addition, of applied the method for scenario analysis is given, with the scenarios tested are stated and justified. Where qualitative data is presented to decision-makers, methods are applied to address real or perceived biases.
Analysis and interpretation of results: present results transparently	
Only relevant alternatives are compared. If data from other contexts are used, they are interpreted transparently. A cost-effectiveness ratio is reported as an aggregate outcome measure alongside disaggregated measures to the extent that is possible. Answer(s) to the research question are prompted to support conclusions to be derived from these results. Outcomes are not presented prescriptively, enabling users to interpret the reported outcomes independently. Appropriate caveats accompany conclusions to inform decision-makers about the limitations of the answer(s) informed by the study.	In addition, outcomes are presented in a format that enables an iterative multistakeholder deliberation on the reported outcomes. Particular attention to the participation of subgroups such as the poor, marginalised, women, and girls.

Appendix C: Evaluative criteria for least-cost economic analysis of citywide inclusive sanitation: a scoping review

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SUPPLEMENTARY MATERIAL

Table C1: Scoping evaluative criteria for the least-cost comparative economic appraisal of CWIS interventions

Criteria for health interventions	Chartered principles for appropriate sanitation interventions.	Chartered principles for citywide inclusive sanitation interventions
Study design		
Research question		
The research question is stated	[merged]A research question that balances economic efficiency and equity outcomes is stated (Squire & van der Tak 1975).	A research question is outlined that balances economic efficiency, equitable, and sustainable outcomes (Mitchell <i>et al.</i> 2007), paying particular attention to the needs of the poor, marginalised, women, and girls (Schrecongost <i>et al.</i> 2020)
The economic importance of the research question is stated		
The viewpoint(s) of the analysis are clearly stated and justified	A societal cost perspective disaggregated by the cost perspectives of key societal actors is adopted (Squire & van der Tak 1975)	Also, the disaggregated cost perspectives of relevant subgroups are included (Hutton 2001; Kohli-Lynch & Briggs 2019; Seymour <i>et al.</i> 2020)

The rationale for the comparison of alternatives		
The rationale for comparing alternative interventions is stated	In addition, the rationale enables the opportunity costs of forgoing the most cost-effective situation that would have emerged <i>without a project</i> (Sacristán <i>et al.</i> 2020) to be compared against alternative interventions (Drummond & Jefferson 1996; Julius 1979)	In addition, the without-project case is compared to all relevant supply and demand-led interventions for meeting a desired service outcome (Beecher 1996; Fane, Robinson & White 2003)
Each alternative compared is clearly described	The without-project case and each alternative are described in enough detail to enable decision-makers to interpret results (Drummond & Jefferson 1996)	Consistent system boundaries for people, time, and service dimensions are defined to identify the costs and benefits included and excluded from an analysis (Mitchell <i>et al.</i> 2007; Willetts <i>et al.</i> 2010)
Economic analysis methodology		
The economic evaluation method is described and justified for the research questions.	The economic analysis methodology comprises (i) a comparable cost-effectiveness analysis, (ii) an optimisation of each alternative, (iii) end user(s) making a final cost-benefit determination of the least-cost alternative (Julius 1979; Kalbermatten, Julius & Gunnerson 1982)	In addition, decision makers(s) make an inclusive cost-benefit, or cost effectiveness determination about the least-cost alternative balancing economic efficiency with needs of the poor, marginalised, women, and girls (Schrecongost <i>et al.</i> 2020) based on broad sustainability criteria (Willetts <i>et al.</i> 2013)
Data collection		
Effectiveness data		
The source(s) of effectiveness estimates are stated	[merged] Also, the source of effectiveness data and study design is specific to a least-cost <i>without-project standard</i> representing the most cost-effective existing intervention available (Kalbermatten, Julius & Gunnerson 1982; Sacristán <i>et al.</i> 2020)	In addition, the source of effectiveness data and the study design is specific to critically defined and consistently applied system boundaries (Willetts, Carrard, Retamal, Mitchell, <i>et al.</i> 2010)
Details of the study design and results of the effectiveness study are given (if based on a single study)		

Details of the method of synthesis or meta-analysis of estimates are given (if based on an overview of several studies)	In addition, a clear justification for the comparability effectiveness data is included (Daudey 2018; Drummond & Jefferson 1996)	In addition, the justification of how the effectiveness data is derived from within comparable system boundaries included (Sainati <i>et al.</i> 2020; Willetts, Carrard, Retamal, Mitchell, <i>et al.</i> 2010)
Benefit valuation		
The primary outcome measure of the economic appraisal is stated and compares costs and outcomes	In addition, the primary outcome measure is reported in units of total annualised costs per household (TACH) as a standard (Julius 1979)	In addition, the primary outcome measure includes all net, tangible and quantifiable direct and indirect costs and avoided costs (Beecher 1996; Fane, Robinson & White 2003; Mitchell <i>et al.</i> 2007) and is reported in units of total annualised costs, or NPV per household TACH, or per capita (TACC) (Sainati <i>et al.</i> 2020)
The method used to value benefits is stated, including details of the study population from which estimates are derived	If tangible and quantifiable benefits have been valued, the method is stated and justified for the study population. Shadow rates adjust market prices where appropriate (Julius 1979). Intangible benefits are not valued and reported separately (Kalbermatten, Julius & Gunnerson 1982)	Specifically, shadow rates are not used to adjust market prices for intangible and unquantifiable benefits (Hutton 2001, 2016)
Indirect benefits or externalities are reported separately	(merged] Intangible and unquantifiable benefits are included within the economic appraisal but reported separately in a format that enables users to determine their relevance (Julius 1979)	In addition, intangible indirect and unquantifiable benefits are negotiated from all relevant cost perspectives against deliberative sustainability criteria (Willetts <i>et al.</i> 2013), paying particular attention to the poor, marginalised, women, and girls (Schrecongost <i>et al.</i> 2020)
The relevance of productivity changes to the study question is discussed		

Cost data		
Quantities of resources are reported separately from unit costs, and the methods to estimate these variables are described	In addition, unit costs are defined in relation to an <i>average incremental cost</i> determined for a <i>without-project case</i> based on the number of households serviced (TACH) or a material flow (e.g., per volume consumed or volume treated). (Julius 1979; Kalbermatten, Julius & Gunnerson 1982; Squire & van der Tak 1975)	In addition, life cycle cost analysis (LCCA) is used to provide a detailed context-specific estimate of how unit cost data may be structured and sequenced over the time horizon of the study (Fonseca <i>et al.</i> 2011) in alignment with the <i>without-project</i> standard (Fane, Robinson & White 2003; Fonseca <i>et al.</i> 2011; Mitchell <i>et al.</i> 2007; Willetts <i>et al.</i> 2010)
Currency and price data are recorded, and details of adjustments for inflation or exchange rates are given	No changes based on this iteration	No changes based on this iteration
Modelling		
Details of any model(s) used are given, with the modelling approach and the key parameters justified	In addition, the assumptions for developing any model(s) are explicit and relevant to the study context (Julius 1979; Kalbermatten, Julius & Gunnerson 1980; Squire & van der Tak 1975)	In addition, end-use analysis is used to develop a disaggregated model of resource flows and costs model into the future. Assumptions about the systemic behaviour of a mixture of alternative service provision interventions are tested and made explicit (Mitchell <i>et al.</i> 2007; Retamal <i>et al.</i> 2011; Willetts, Carrard, Retamal, Mitchell, <i>et al.</i> 2010)
Analysis and interpretation of results		
Adjust for the timing of costs and benefits.		
The time horizon of costs and benefits is stated, and discount rate(s) are stated and justified. An explanation is given if costs are not discounted	In addition, the time horizon is selected based on the system component with the longest asset life	No changes based on this iteration

Account for uncertainty		
Details of statistical tests and confidence intervals are given for stochastic data	No changes based on this iteration	No changes based on this iteration
The sensitivity analysis method is given, and the choice of variables and the range over which they are varied is justified	No changes based on this iteration	In addition, where data have been modelled, a scenario analysis method is given with the assumptions used to justify the tested scenarios (Ilg et al. 2017)
		[new] The study design incorporates measures to address the epistemic uncertainty (Ilg et al. 2017) by designing knowledge about gender and social equity into decisions are stated and justified (ISF-UTS & SNV 2016 ; Schrecongost et al. 2020 ; Willettts et al. 2013)
Present results transparently		
Relevant alternatives are compared, and an incremental analysis is reported	The opportunities costs of mutually exclusive alternatives optimised towards the same objective are compared incrementally against the same <i>without-project</i> case or existing local cost-effective intervention in standard units of total annualised costs per household (TACH) (Julius 1979 ; Kalbermatten, Julius & Gunnerson 1982)	In addition, each alternative is compared within consistent system boundaries (Willettts, Carrard, Retamal, Mitchell, et al. 2010) and reported in units of TACH or total annualised cost per capita (TACC) (Sainati et al. 2020)
Significant outcomes are presented in an aggregated and disaggregated form	The primary outcome measure is disaggregated for each function or component of the sanitation service chain, as well as for capital and operating costs (Julius 1979 ; Kalbermatten, Julius & Gunnerson 1982)	In addition, the primary outcome measure is disaggregated for each component of the sanitation service chain, for each life cycle cost component, and different costs and subgroup perspectives, as appropriate

<p>An answer to the study question is given. Conclusions follow from the data reported and are accompanied by appropriate caveats</p>	<p>In addition, outcomes are not presented prescriptively, enabling decision makers to reach independent conclusions (Kalbermatten, Julius & Gunnerson 1980)</p>	<p>In addition, outcome measures are presented alongside contextual knowledge, enabling a deliberative, multistakeholder conclusion (Willetts <i>et al.</i> 2013) to be reached in response to broad sustainability criteria, accommodating the perspectives of the poor, marginalised, women, and girls (Schrecongost <i>et al.</i> 2020)</p>
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Note: Column 1 refers to the *Guidelines for authors and peer reviewers of economic submissions to the BMJ* (Drummond & Jefferson 1996) and related literature (Evers *et al.* 2005; Hutton 2001); Column 2 charts the literature related to the *theory of economic costing* presented by Julius (1979), the related methodology *Appropriate sanitation alternatives: a technical and economic appraisal* by (Kalbermatten *et al.* 1982), and related literature (Bradley & Raucher 1988; Feachem, Mara & Iwugo 1979; Kalbermatten *et al.* 1980; Kalbermatten *et al.* 1982; Kennedy 1964; Kulhlthau 1979; Mara 1996; Schumacher 1977; Squire & van der Tak 1975; Weiss 2006). Where necessary, the criteria for health interventions is further interpreted using the explanatory text in Drummond & Jefferson (1996) to provide clarity. In Column 3 charts the literature scoped literature related to the principles outlined in the publication *Costing for sustainable outcomes in urban water systems-a guidebook* (Mitchell *et al.* 2007) and the associated methodology *Cost-effectiveness analysis as a methodology to compare sanitation options in peri-urban Can Tho, Vietnam* (Carrard *et al.* 2010; Retamal *et al.* 2009; Retamal *et al.* 2011; Willetts, Carrard, Retamal, Mitchell, *et al.* 2010; Willetts, Carrard, Retamal, Nguyen, *et al.* 2010; Willetts *et al.* 2013). Additional literature was included in the review aligned with the process described in the methodology section.

Appendix D: Comparative economic analysis of urban sanitation interventions in low- and middle-income countries: a systematic review

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SUPPLEMENTARY MATERIAL

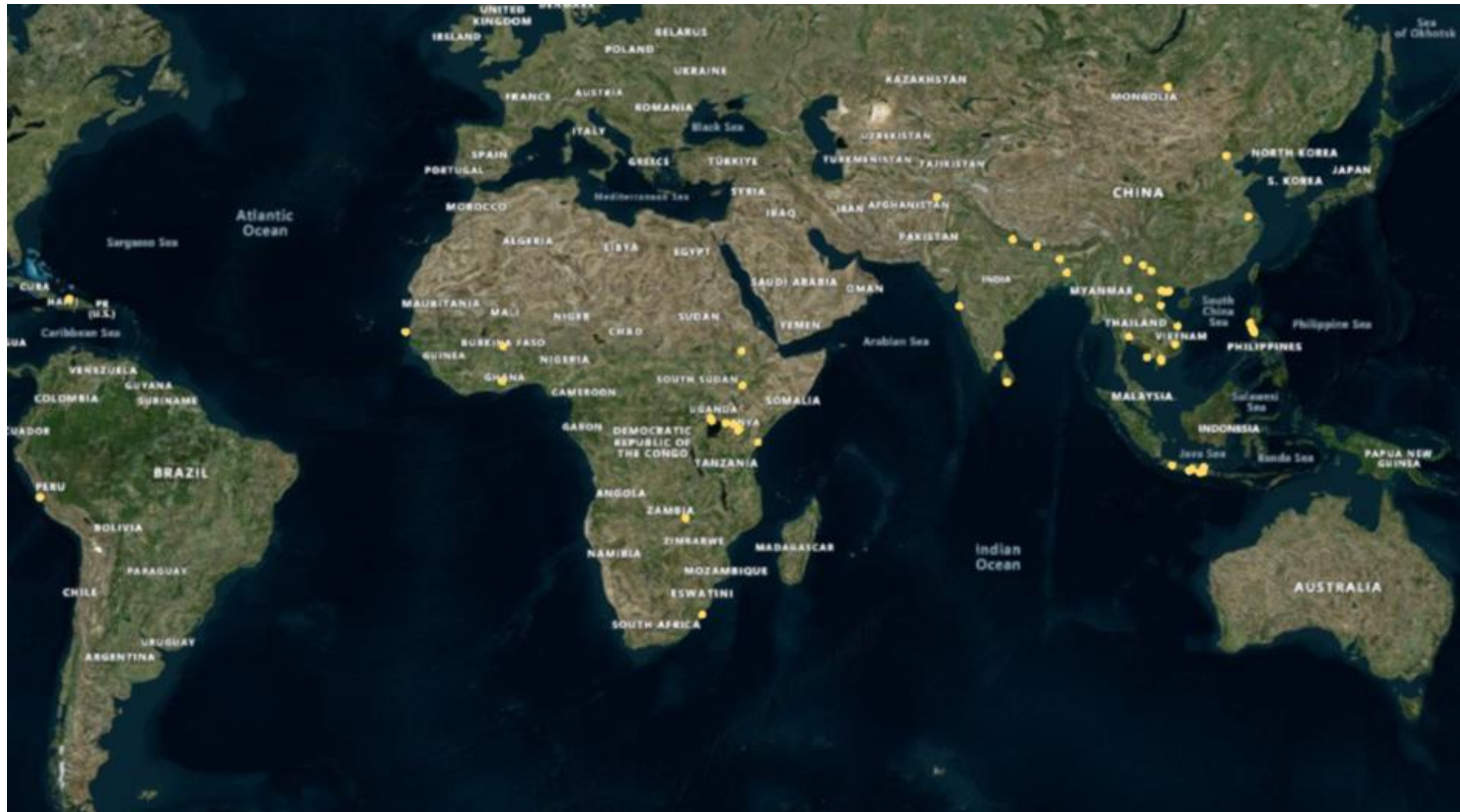


Figure D1: Location of studies included in the systematic review

Table D1: Interpretation of the evaluative criteria for citywide inclusive sanitation interventions (Ross et al., 2024a)

<i>Interpreted criteria</i> (Ross et al., forthcoming)		Abridged criteria	Fully applied	Mostly applied	Partially applied
Study design					
Research question					
1.1	<i>A research question is outlined that balances economic efficiency and equitable and sustainable outcomes, paying particular attention to marginalised groups.</i>	A research question is outlined that balances economic efficiency and equity outcomes	Presents a comprehensive economic analysis with an equity analysis, including the perspective of marginalised groups.	Present an economic analysis with narrowly defined societal benefits and an equity analysis	Presents an economic analysis without disaggregating different financial cost perspectives
1.2	<i>A societal cost perspective is adopted, disaggregated by the cost perspectives of key societal actors and their subgroups.</i>	A societal cost perspective is adopted and disaggregated by subgroup cost perspectives.	Present an economic analysis that conducts an equity analysis for multiple subgroup cost perspectives.	Presents an economic analysis for a single subgroup cost perspective or a financial analysis for multiple subgroup analyses.	Only presents a financial analysis for a single marginalised cost perspective.
The rationale for the comparison of alternatives					
2.1	<i>All alternative supply and demand-led interventions that might meet a defined service outcome are compared against the opportunity costs of forgoing the least-cost standard that would have emerged without a project.</i>	All potential options are compared against a least-cost without-project standard.	Study that forecasts a <i>least-cost</i> without-project standard into the future for comparison with a comprehensive range of options.	Studies that project an existing without-project standard against a partial range of options.	Studies project a without-project case, as opposed to a do-nothing scenario.

2.2	<i>The without-project case and each alternative are critically defined within consistent system boundaries that are explicit about the people, time, and service dimensions included in an analysis and relevant to decision-makers.</i>	Clear, consistent, and relevant system boundaries are applied.	Clear, consistent, and critically defined system boundaries are applied for a study's people, time, and service dimensions relevant to all decision-makers.	Clear and consistent system boundaries are defined for a study's people, time, and service dimensions.	Clear and consistent system boundaries are defined for some study dimensions.
3.1	<i>The economic analysis methodology comprises (i) a comparable cost-effectiveness analysis, (ii) optimisation of each alternative, and (iii) end user(s), especially marginalised end users, making a final cost-benefit determination of the least-cost alternative based on broad sustainability criteria.</i>	A comprehensive economic analysis methodology is adopted	The methodology comprises (i) a comparable cost-effectiveness analysis, (ii) optimisation of each alternative, and (iii) end user(s), especially marginalised end users, making a final cost-benefit determination based on broad sustainability criteria.	The methodology comprises (i) a comparable cost-effectiveness analysis, (ii) an optimisation of each alternative, (iii) end user(s), especially marginalised end users, make a final cost-benefit determination of the least-cost alternative	The methodology comprises (i) a comparable cost-effectiveness analysis and (ii) an optimisation of each alternative.
Data collection					
Effectiveness data					
4.1	<i>Sources used to derive outcome measures are stated, and the study design is specific to the study context and system boundaries of the economic appraisal.</i>	Sources of effectiveness data are specific to the study context	All sources used to determine effectiveness data are clearly defined and recoverable sources, with assumptions locally derived and justified.	Mostly clearly defined and recoverable sources are used to determine effectiveness data, with assumptions locally derived and justified.	Mostly clearly defined and recoverable sources are used to determine effectiveness data; however, some key measures or assumptions are derived from other contexts.

4.2	<i>Details of the method of synthesis or meta-analysis of cost-effectiveness data are given if based on an overview of studies, including a justification for its generalisability.</i>	A justification for comparisons of cost effectiveness across contexts is provided	If cost-effectiveness estimates are compared across contexts, a justified method of synthesis is provided	If a generalised comparison of cost-effectiveness estimates is attempted, a detailed justification and discussion of the limitations of the comparison are provided	If a generalised comparison of cost-effectiveness estimates is attempted, a discussion of the limitations of the comparison is attempted.
Benefit valuation					
5.1	<i>A primary outcome measure is reported in units of total annualised costs per household or capita (TACH/TACC) with an explicit account of the costs and outcomes included in the measure.</i>	Incremental unit costs in TACH/TACC are provided as a primary outcome measure.	Incremental unit costs in TACH/TACC are provided as a primary outcome measure compared to a least-cost standard projected over time.	Incremental unit costs in TACH/TACC are provided as a primary outcome measure, accounting for the costs and outcomes included in the measure.	Incremental unit costs are provided as a primary outcome measure, accounting for the costs and outcomes included in the measure.
5.2	<i>If tangible and quantifiable benefits have been valued, the method adopted is relevant to the context for which the estimate is made.</i>	Benefit valuation methods are described and justified for the study population.	Benefit valuation methods are described and justified for the study population.	Benefit valuation methods are described and justified from the perspective of the national economy.	Benefit valuation methods are described and justified by using generic data.
5.3	<i>Intangible and unquantifiable benefits are reported separately in a format that enables their relevance to be determined by users.</i>	Intangible benefits are reported separately and interpreted in the analysis.	Intangible benefits are reported explicitly and presented in a format that enables them to be interpreted by multiple actors.	Intangible benefits are reported explicitly and presented in a format that enables them to be discussed in the analysis.	Intangible benefits related are reported explicitly.
Cost data					
6.1	<i>Quantities of resources are reported separately from unit costs and used to determine all relevant life cycle costs using average incremental costing.</i>	Average incremental costing is used to structure life cycle costs over time.	Average incremental costing is used to distribute all relevant life cycle costs over the time horizon of analysis.	Average annualised costing is used to distribute all relevant life cycle costs over the time horizon of analysis.	Annualised capital and O+M costs are distributed over the time horizon of analysis.

6.2	<i>Currency and price data are recorded, and details of adjustments for inflation or exchange rates are given.</i>	Adjustments for inflation and currency conversion are made explicit.	Local currency and price data are recorded, and details of adjustments for inflation or exchange rates are given.	Local currency and price data are recorded, but details of some adjustments are not provided.	Currency and price data are recorded, but the details of adjustments are not provided.
Modelling					
7.1	<i>A contextually relevant resource flow model is described and justified as the basis for estimating the economic costs over the time horizon of analysis for a hybrid mixture of service provision interventions, with any assumptions applied made explicit, recoverable, and testable.</i>	Assumptions within the costing model are justified and contextually relevant.	A contextually relevant end-use analysis is used as a disaggregated basis for modelling resource flows for estimating economic costs over the time horizon of analysis for a hybrid mixture of service provision interventions, with any assumptions applied made explicit, recoverable, and testable.	A contextually relevant resource flow model is described and justified as the basis for estimating the economic costs over the time horizon of analysis for different service provision interventions, with any assumptions applied made explicit.	Any model(s) used to estimate financial costs over the time horizon of analysis and described and justified for different service provision interventions, with any assumptions applied made explicitly.
Analysis and interpretation of results					
Adjust for the timing of costs and benefits.					
8.1	<i>The time horizon and discount rate(s) used in the analysis are stated and justified.</i>	The time horizon and discount rate are stated and justified.	A time horizon defined for specific years and discount rate(s) is stated with a compelling justification.	A time horizon is defined for specific years, and discount rate(s) are stated without a clear justification.	Discount rates are provided, but the time horizon of the study is not made explicit.
Account for uncertainty					
9.1	<i>Details of statistical tests and confidence intervals are given for all stochastic data.</i>	Confidence intervals are presented for stochastic data.	Statistically significant confidence intervals are presented for all stochastic data collected within the study context.	Confidence intervals are presented for all stochastic data collected within the study context but are not statistically significant.	The confidence level in stochastic data is presented as a ballpark estimate.

9.2	<i>Methods, such as sensitivity or scenario analysis, are described and justified to optimise how outcome measures may be interpreted by a range of societal actors when selecting a least-cost intervention.</i>	Sensitivity and scenario analyses are used to enhance the use of modelled data.	Methods, such as a sensitivity or scenario analysis are described and justified to optimise how outcome measures may be comprehensively interpreted by all relevant societal actors when selecting a least-cost intervention.	Methods, such as a sensitivity or scenario analysis are described and justified to optimise how outcome measures may be interpreted by key institutional decision makers when selecting a least-cost intervention.	Methods, such as a sensitivity or scenario analysis, are described and justified but only clarify the relationship between a limited number of cost determinants
9.3	<i>Deliberative multi-stakeholder decision-making methods inclusive of marginal users that address epistemic uncertainty in the design of economic analysis and increase the likelihood that the root causes of gender and social inequity are addressed in an analysis are described and justified.</i>	Deliberative methods are used to allow for epistemic uncertainty.	Deliberative multi-stakeholder decision-making methods inclusive of marginal users that address epistemic uncertainty in the design of economic analysis and increase the likelihood that the root causes of gender and social inequity are addressed in an analysis are described and justified.	Deliberative multi-stakeholder decision-making methods that address epistemic uncertainty in the design of economic analysis and increase the likelihood that the root causes of gender and social inequity are addressed in an analysis are described and justified.	The limitations of the study concerning epistemic uncertainty in the design of an economic analysis are described.
Present results transparently					
10.1	<i>Relevant, mutually exclusive alternatives optimised to meet the same service outcome are compared in incremental units of TACH/TACC against a cost-effective, without-project standard.</i>	Reported outcome measures (TACH/TACC) align with the basis of comparison.	An incremental analysis in units of TACH/TACC is reported against a least-cost without-project standard.	An incremental analysis in units of TACH/TACC is reported	An analysis of comparable units is reported.

10.2	<i>An aggregate primary outcome measure is also presented in a disaggregated form for each stage of the sanitation service chain, life cycle cost component, and for each cost and subgroup perspective.</i>	Outcome measures are presented in an aggregated and disaggregated format.	An aggregate primary outcome measure is also reported in a disaggregated form for each stage of the sanitation service chain, life cycle cost component, and for each cost and subgroup perspective.	An aggregate primary outcome measure is reported in a partially disaggregated form.	An aggregate primary outcome measure is also reported.
10.3	<i>A non-prescriptive conclusion is presented in response to the study question from the reported data accompanied by appropriate caveats, enabling societal actors, especially marginalised users, to interpret the study outcomes independently.</i>	Conclusions arise from multiple cost perspectives informed by multiple criteria.	Conclusions are informed by multiple subgroup economic cost perspectives considering comprehensive social, economic, and environmental criteria.	Conclusions are informed by multiple economic cost perspectives considering broad social, economic, and/or environmental criteria.	Conclusions are informed by how costs are distributed from multiple financial cost perspectives.

Table D2: Detailed characterisation of the selected studies

Study & and location	Interventions compared & cost perspective(s)	Methodology & basis for comparison	Population & time horizon	Life cycle costs & service dimensions covered	Outcome measure(s)
Meddings et al. (2004) Kabul, Afghanistan	Latrine construction and rehabilitation program Societal cost perspective (disaggregated household & institutional (NGO) perspective)	Economic cost-utility analysis Case-control study providing a baseline of averted deaths	Sample of 1,863 (1238 case / 625 control) children in 5 out of 15 districts representing 400,000 people. Time horizon = 1 year	CapEx & ExpDS User interface and containment	Cost per death averted One-off costs

<p>City of Ulaanbaatar (2006) Ulaanbaatar, Mongolia</p>	<p>Basic hygiene improvement vs pit latrine</p> <p>Household financial cost perspective</p>	<p>Financial cost comparison.</p> <p>Incremental sanitation service ladder.</p>	<p>Single household representing Ger settlements</p> <p>Time horizon = non-specific</p>	<p>CapEx & OpEx</p> <p>User interface and containment</p>	<p>Cost per household</p> <p>Annualised costs</p>
<p>von Muench & Mayumbelo (2007) Lusaka, Zambia</p>	<p>VIP latrine vs UDDT</p> <p>Household and utility financial cost perspectives (not disaggregated)</p>	<p>Financial cost-effectiveness analysis</p> <p>Hypothetical do-nothing scenario.</p>	<p>Comparison for 30,000 low-income households in three districts was scaled to 1.23 million residents of Lusaka. Population not projected into the future.</p> <p>Time horizon = 10 years</p>	<p>CapEx & OpEx</p> <p>Partial user interface (UDDT latrines) containment, collection, transport, treatment, storage, and partial reuse.</p>	<p>TACC & 10-year financial NPV</p> <p>Annualised costs</p>
<p>Prihandrijanti et al. (2008)</p>	<p>Two low-cost, decentralised, off-site treatment alternatives vs a centralised, simplified sewer option</p> <p>Institutional economic cost perspective.</p>	<p>Economic cost-benefit analysis</p> <p>Do-nothing scenario.</p>	<p>Comparison for the population of Kalirungkut increasing from 35,000 to 50,000 people.</p> <p>Time horizon = 20 years</p>	<p>CapEx & OpEx</p> <p>Partial user interface and containment (communal ecosan facilities only); collection, transport, and treatment</p>	<p>Benefit-cost ratio & 20-year financial NPV</p> <p>Annualised costs</p>
<p>Kerstens et. al., (2009) Changzhou, China</p>	<p>Four future-oriented alternative resource-oriented sanitation scenarios</p> <p>Institutional financial cost perspective.</p>	<p>Financial cost-effectiveness analysis</p> <p>Hypothetical greenfield site (do nothing scenario).</p>	<p>Greenfield site is expected to have a population of 100,000 people within five years. Growth rate not specified.</p> <p>Time horizon = 30 years</p>	<p>CapEx & OpEx</p> <p>Transportation and treatment.</p>	<p>TACC & 20-year financial NPV</p> <p>Annualised costs</p>

<p>Schuen & Parkinson (2009) Kabala, Uganda; eThekwini, South Africa; & Ouagadougou, Burkina Faso</p>	<p>Ecosan (UDDT) option vs VIP latrines and centralised sewer.</p> <p>Household and project economic cost perspectives.</p>	<p>Financial and economic cost analysis</p> <p>Do-nothing scenario.</p>	<p>Kabale (83,000 people), eThekwini (425,0000), and Ouagadougou (930 households and 800 farmers) disaggregated by the service provision model. Population not projected into the future.</p> <p>Time horizon = 10 years.</p>	<p>CapEx, OpEx, ExpDS & ExpIDS, avoided waste management costs and volunteer labour, health costs, and benefits of reuse.</p> <p>User interface, containment, collection, transportation, treatment, and reuse.</p>	<p>10-year financial and economic NPV.</p> <p>Annualised costs</p>
<p>Willets et al. (2010); Retamal et al. (2011); Willets et a; (2013) Can Tho, Vietnam</p>	<p>Four hybrid (centralised and decentralised) configurations of infrastructure.</p> <p>Partial household, utility, developers, and government financial cost perspectives (non-disaggregated).</p>	<p>Financial cost-effectiveness analysis.</p> <p>Without-project cost (de jure policy standard)</p>	<p>Greenfield site expected to increase from 47,000 to 278,000 people</p> <p>Time horizon = 30-years</p>	<p>CapEx OpEx & CapManEx excluding costs that are consistent across options, or not possible to estimate.</p> <p>Partial user interface (UDDT latrines only), containment, collection, transportation, treatment and reuse.</p>	<p>30-year NPV; and levelized cost per volume (m³); and household (TACH)</p> <p>Average incremental costs</p>
<p>Hutton et al. (2014) 17 urban contexts in Cambodia, Indonesia, Laos PDR, the Philippines, Vietnam and China</p>	<p>Incremental infrastructure options relevant to each city.</p> <p>Societal (household, government, private sector) cost perspective</p>	<p>Economic cost-benefit, cost-utility, and cost-effectiveness analyses</p> <p>Incremental sanitation service ladder</p>	<p>A sample of between 80 and 300 households comprising at least 30 households per option was sampled for all 17 case studies.</p> <p>Time horizon = 20 - 25 years</p>	<p>CapEx, CoC, OpEx, ExpDS & ExpIDS</p> <p>Interventions included onsite and off-site options but did not consistently cover all elements of the sanitation service chain.</p>	<p>Ideal and actual benefit-cost ratios, financial and economic 20-year or 25-year NPVs, TACH and cost-utility measures of averted health costs per DALY, per case, and per death.</p> <p>Annualised costs</p>

<p>Dodane et.al., (2012) Dakar, Senegal</p>	<p>Sewer based vs faecal sludge management interventions within the same geographical area</p> <p>Partial household, private service provider, utility, and government financial cost perspectives.</p>	<p>Financial cost-effectiveness analysis</p> <p>Disaggregated do-nothing scenario</p>	<p>The Camberene area of Dakar has a population of ~ 500,000 people. [230,000 - sewer regime; 41,500 - FSM regime - 228,500 onsite] Populations not projected into the future</p> <p>Time horizon = 30 years.</p>	<p>CapEx & OpEx</p> <p>Containment, collection, transportation, treatment infrastructure, and reuse.</p>	<p>TACC</p> <p>Annualised costs</p>
<p>Mburu et. al., (2013) Juja, Kenya</p>	<p>Waste stabilisation pond vs a constructed wetland)</p> <p>Institutional financial cost perspective</p>	<p>Financial cost-effectiveness analysis.</p> <p>Do-nothing scenario.</p>	<p>Costs were determined for a population equivalent of 2700 for the WSP and 12 for the pilot constructed wetland.</p> <p>Time horizon = 20-years</p>	<p>CapEx & OpEx</p> <p>Treatment.</p>	<p>TACPE</p> <p>Annualised costs –</p>
<p>Peal and Georges (2013) Dhaka, Bangladesh</p>	<p>Four citywide hybrid sanitation service scenarios</p> <p>Institutional financial cost perspective with all costs attributed to households.</p>	<p>Financial cost-effectiveness analysis</p> <p>A without-project case was projected for population growth and financial flows.</p>	<p>Study population of 175,000 people and 30,400 households growing at a rate of 4% per annum. 12% of this population was low-income.</p> <p>Time horizon = 30-years.</p>	<p>CapEx, CapManEx & OpEx</p> <p>Collection, transport, and treatment.</p>	<p>30-year financial NPV and TMCH</p> <p>Annualised costs.</p>
<p>Tilmans et. al., (2015) Cap Haitien, Haiti</p>	<p>Public ecosan latrine model vs domestic container-based sanitation intervention.</p> <p>Institutional (NGO) financial cost perspective</p>	<p>Financial cost-effectiveness analysis</p> <p>Case-controlled experiment to determine the cost per volume of faeces.</p>	<p>Sample of 551 (275 case / 276 control) households representing 30 clusters with a population of 9,300 people.</p> <p>Time horizon = 13 weeks.</p>	<p>CapEx, CoC, OpEx, ExpDS & ExpIDS</p> <p>Containment, collection, and transportation.</p>	<p>Total cost per kg of faeces over 13 weeks.</p>

<p>Ketema et al., (2016) Arba Minch & Bahir Dar, Ethiopia</p>	<p>Four hypothetical hybrid urban sanitation interventions.</p> <p>Service provider (including self-supplier) cost perspective</p>	<p>Financial cost-effectiveness analysis</p> <p>Do-nothing scenario</p>	<p>A population equivalent and maximum daily water demand measure were used to define the population dimension of the analysis.</p> <p>No specific time horizon was defined.</p>	<p>CapEx & OpEx</p> <p>A range of component water supply and sanitation Interventions were considered, covering containment, collection, transport, and partial treatment that might form a more complete sanitation service provision configuration</p>	<p>25-year financial NPV</p> <p>Annualised costs.</p>
<p>Kennedy Walker et al., (2016) Lusaka, Zambia</p>	<p>Seven faecal sludge transportation and treatment configurations.</p> <p>Utility/community water trust cost perspective</p>	<p>Financial cost-effectiveness analysis</p> <p>Without-project scenario</p>	<p>A model is used to define the population for each alternative intervention based on an initial population, household size and growth rate –</p> <p>Time horizon = 25 years</p>	<p>CapEx & OpEx</p> <p>Transportation</p>	<p>TMCH and a 25-year financial NPV</p> <p>Average incremental costs</p>
<p>Ross et. al., (2016) Dhaka, Bangladesh</p>	<p>Four hypothetical low-cost off-site urban sanitation configurations.</p> <p>Multiple (household & institutional) cost perspectives</p>	<p>Economic cost-utility analysis and a financial cost-effectiveness analysis</p> <p>Simplified, hypothetical do-nothing scenario.</p>	<p>A population model for slum areas within the study is defined based on a representative survey of 720 households for the entire population of Dhaka.</p> <p>The time horizon is not stated explicitly but is 10 years.</p>	<p>CapEx, CapManEx & OpEx</p> <p>Containment, collection, transportation, and treatment.</p>	<p>Cost per death & illness & DALY averted, TACH</p> <p>Annualised costs</p>

<p>Jung et al., (2018) Alibag, India</p>	<p>Centralised wastewater management system vs modelled decentralised scenarios.</p> <p>Institutional financial cost perspective</p>	<p>Financial cost analysis</p> <p>Do-nothing scenario</p>	<p>A population projection for Alibag from 2011 (20,743 people) was disaggregated for a fixed and floating population to 2040 (35,900 fixed; 4,500 floating)</p> <p>Time horizon = 30-years</p>	<p>CapEx & OpEx</p> <p>Transportation and treatment.</p>	<p>30-year financial NPV</p> <p>Annualised costs</p>
<p>Shi et al. (2018) Beijing, China</p>	<p>Four urban resource-oriented public toilet interventions</p> <p>Institutional economic cost perspective</p>	<p>Economic cost analysis</p> <p>Chinese standard for the design of public toilets as a without-project scenario</p>	<p>A population of 780 women and 800 men were projected to use the toilet each day based on Chinese standards for urban public toilets.</p> <p>Time horizon = 20 years</p>	<p>CapEx, CoC, OpEx,</p> <p>Containment, collection, and transportation and treatment</p>	<p>20-year environmental NPV</p> <p>Annualised costs</p>
<p>McConville et al., (2019) Kampala, Uganda</p>	<p>Sewer based vs faecal sludge management interventions within the same geographical area</p> <p>Partial household, private service provider, utility, and government financial cost perspectives.</p>	<p>Optimised financial cost-effectiveness analysis.</p> <p>Disaggregated do-nothing scenario</p>	<p>Greater Kampala has a population of 3.2 million people. [41,000 - sewer regime; 1,100,000 - FSM regime – 2.06 million - onsite] population was not projected into the future</p> <p>Time horizon = 30-years</p>	<p>CapEx & OpEx</p> <p>Containment, collection, transportation, and reuse.</p>	<p>TACC</p> <p>Annualised costs</p>

<p>Furlong et. al., (2020) Pokhara, Nepal</p>	<p>Four hypothetical, hybrid urban sanitation configurations</p> <p>Institutional financial cost perspective.</p>	<p>Financial cost-effectiveness analysis.</p> <p>Financial without-project case</p>	<p>Nonthaburi has a population of 256,457 people and 129,597 households, of which 16,000 were sampled.</p> <p>Pokhara has a population of 454,372 people and 118,946 households, with a 2.2% growth rate), of which 50 households were sampled to contextualise the financial flow model.</p> <p>Time horizon = 30 years.</p>	<p>CapEx & OpEx</p> <p>Containment, collection, and transportation, treatment and reuse</p>	<p>30-year financial NPV</p> <p>Annualised costs</p>
<p>Manga et al., (2020) Soweto, South Africa</p>	<p>Three simplified sewer scenarios vs. two onsite sanitation options (VIP latrine and UDDT option)</p> <p>Institutional financial cost perspective with all costs attributed to households.</p>	<p>Financial and economic cost effectiveness analysis.</p> <p>Do nothing scenario.</p>	<p>A drainage basin of 12.9 ha and a population model of 517 households and 2,585 persons (200 persons/hectare was predicted to grow by 3% per annum to 1,057 households and 5,255 people (407 persons/hectare)</p> <p>Time horizon = 25 years.</p>	<p>CapEx, CoC, OpEx, ExpDS & ExpIDS</p> <p>User interface, containment, collection, transport, and treatment.</p>	<p>TACH, TACC, & 25-year economic NPV</p> <p>Average incremental costs</p>

<p>Delaire et. al., (2020) Kisumu, Nakuru, & Malindi, Kenya; Rangpur, Bangladesh; & Kumasi, Ghana</p>	<p>A range of interventions for meeting SDG 6.2 by 2030 by providing services to low-income households.</p> <p>Institutional financial cost perspective.</p>	<p>Financial cost analysis</p> <p>Financial without-project case</p>	<p>A population model disaggregated into general and low-income subgroups was developed in each of the five cities, with an initial population of 200,000 to 2 million people, or 35,000 to 500,000 households, projected to increase by a set population growth rate.</p> <p>Time horizon = 10 years.</p>	<p>CapEx, CapManEx, CoC & OpEx</p> <p>Household interface containment, collection, transportation, and treatment.</p>	<p>10-year economic NPV</p> <p>Annualised costs.</p>
<p>Carrard et. al., (2021) Balangoda, Sri Lanka</p>	<p>A single resource-oriented intervention representing an existing least-cost intervention</p> <p>Partial household local council financial cost perspectives</p>	<p>Financial cost-effectiveness analysis.</p> <p>Financial without-project case</p>	<p>Uncertainty about the serviced population led to multiple population projects being applied.</p> <p>Time horizon = 25 years</p> <p>Some costs were modelled based on retrospective data.</p>	<p>CapEx, CapManEx, CoC, OpEx, ExpDS</p> <p>Containment, collection, transportation, treatment, and reuse.</p>	<p>10-year financial NPV, and TACC</p> <p>Annualised costs.</p>

Appendix E: Using systems thinking to identify possible water and sanitation solutions for diverse urban needs in Siem Reap, Cambodia

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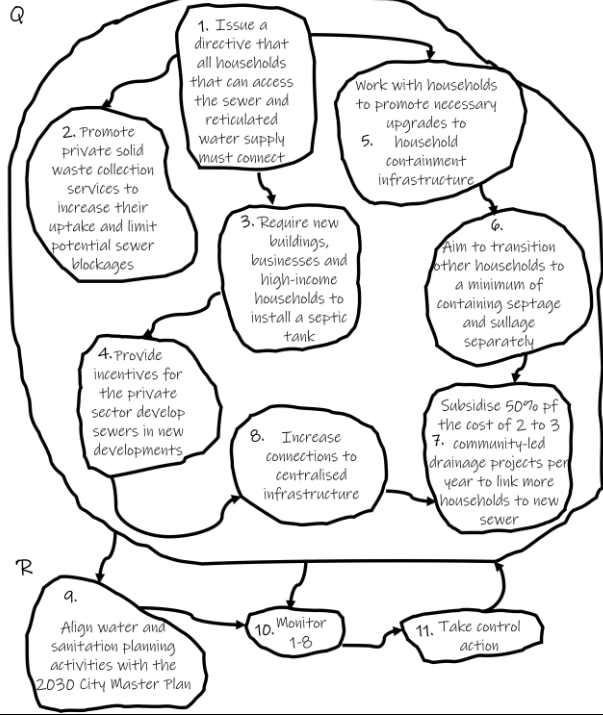
^b Ministry of Public Works and Transport, Street 598 Sangkat Chrang Chamres II, Khan Russey Keo, Phnom Penh, Cambodia, 12000

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SUPPLEMENTARY MATERIAL

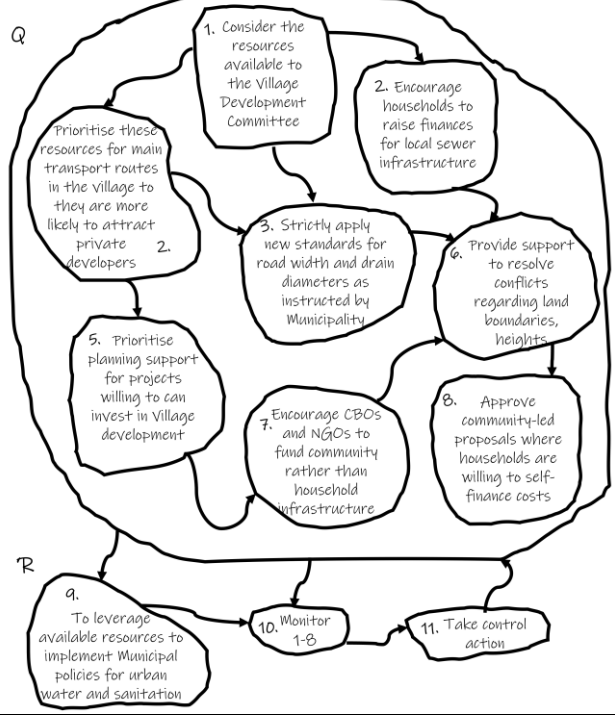
Purposeful Activity Model 1:

P - I am a local official in an area that has benefited from the development of road and sewer infrastructure from a large donor-financed project. I intend to transition households to connect to the new infrastructure.



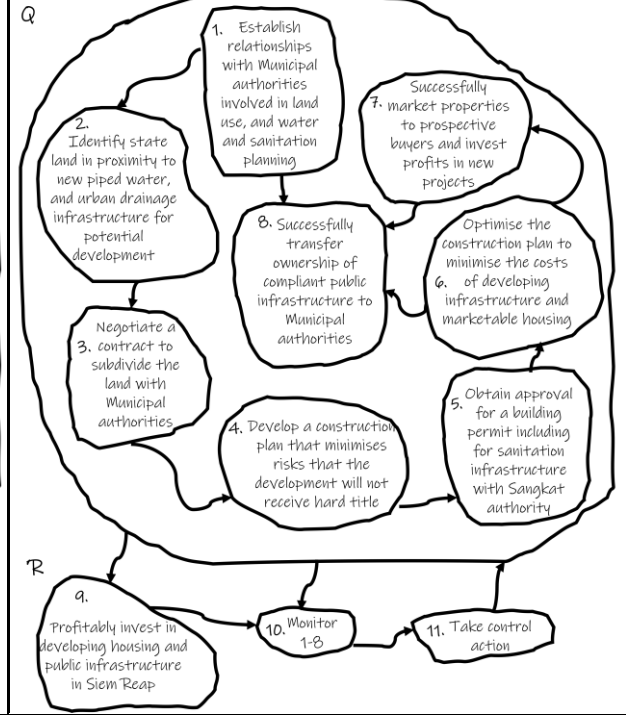
Purposeful Activity Model 2:

P - I am a local official with limited resources in an area that has not benefited from the large donor funded project. I intend to prioritise these resources to attract additional financing to maximise their benefits aligned with National policies



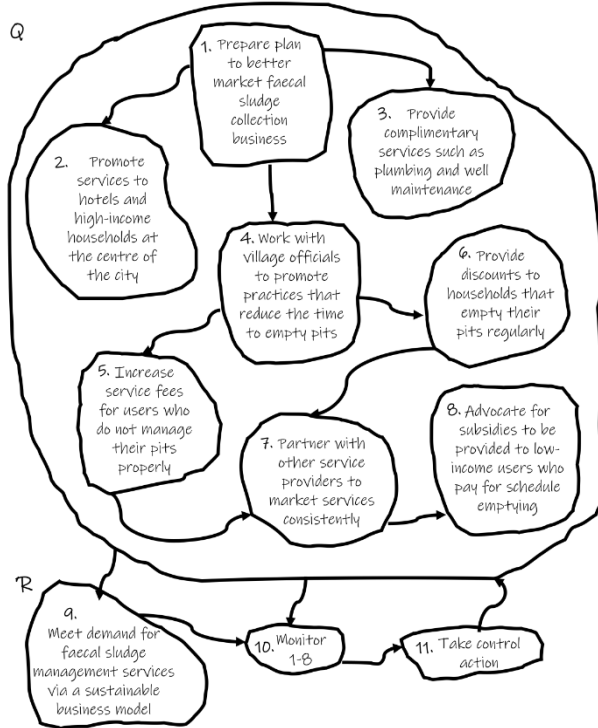
Purposeful Activity Model 3:

P - I am a property developer and intend to establish a viable business model for acquiring state land to developing housing projects, as well as sewer infrastructure that meets standards for ownership to be transferred to municipal authorities



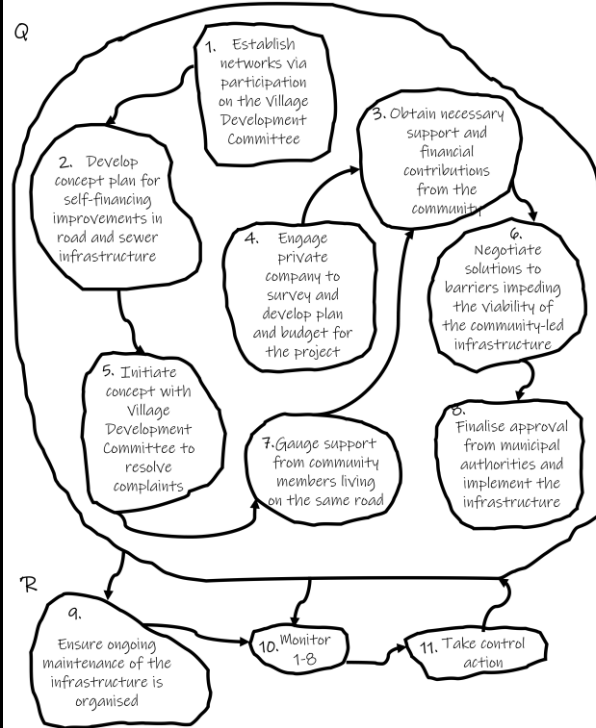
Purposeful Activity Model 4:

P - I intend to collect and transport faecal sludge to a treatment plant to meet demand in the city as a sustainable livelihood for my family



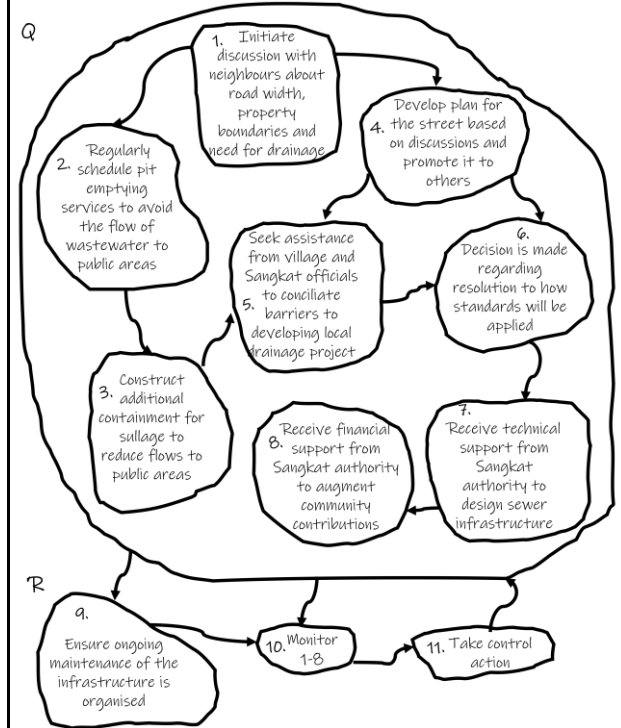
Purposeful Activity Model 5:

P - I intend to work as a community leader by collaborating with my neighbours, local officials, and the private sector to self-organise basic sewer services in my community



Purposeful Activity Model 6:

P - I live on a narrow road in an urbanising area and intend to resolve conflict over wastewater and stormwater drainage due to long-established informal planning areas and newly-established formal standards so we can improve the situation in our area



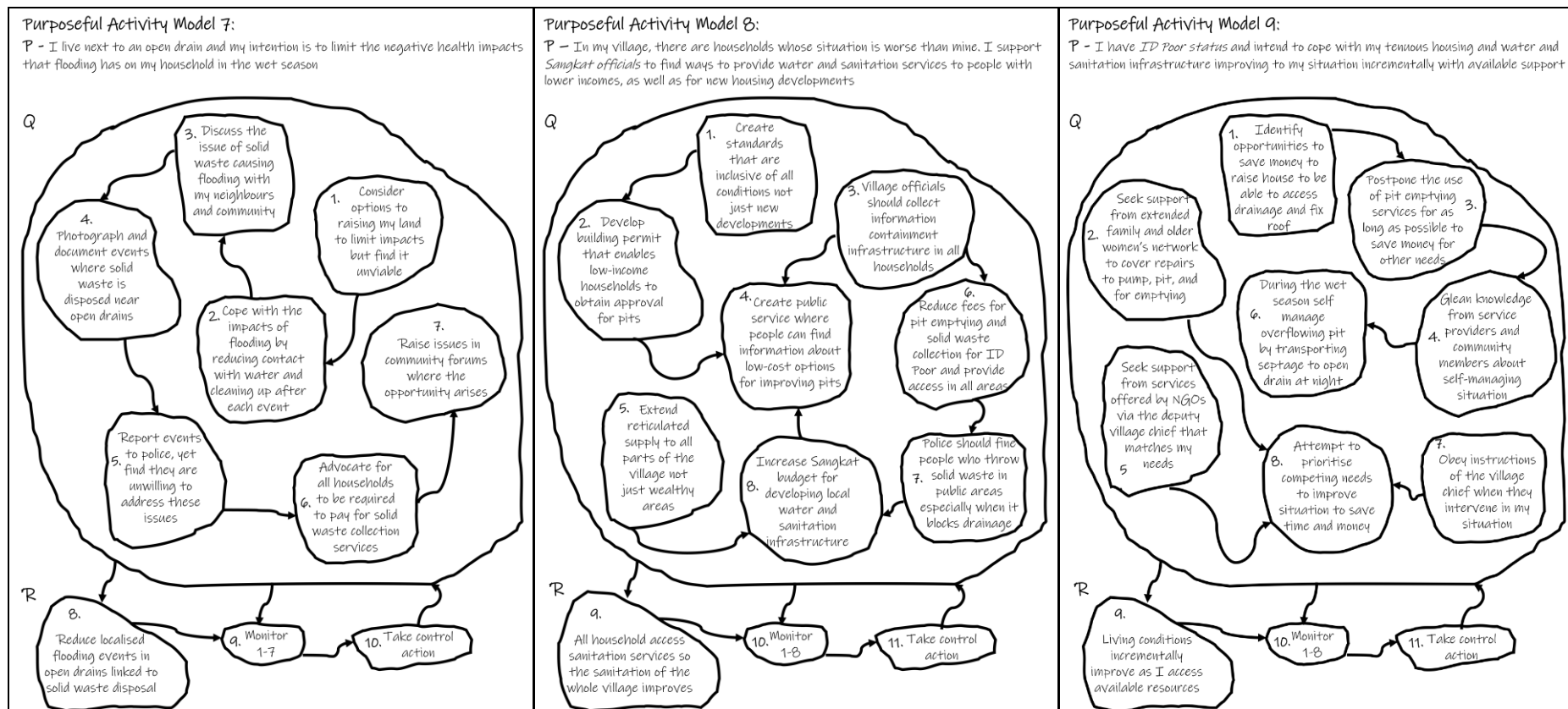


Figure E1: The full range of purposeful activity models used in the workshops

