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Research article

Climate change impact and adaptation assessment for road drainage systems

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ABSTRACT

Climate change exhibits a clear trend of escalating frequency and intensity of extreme weather events, posing heightened risks to drainage systems along the existing road networks. However, very few studies to date have investigated the consequences of projected future changes in rainfall on main road drainage and the resulting risk of road flooding. The work presented in this paper builds on the limited research by introducing a probabilistic model for assessing the impact of climate change on road drainage systems, incorporating climate uncertainty and drainage system variation. The probabilistic scenario-based model and associated framework offer a practical and innovative method for estimating the impact of short-duration storms under future climates for 2071–2100, in the absence of fine-resolution spatio-temporal data. The model also facilitates the assessment of the effectiveness of a climate adaptation strategy. An illustrative case-study of a road drainage system located in the south of Ireland is presented. It was found that the probability of road flooding during intense rainfall is projected to surpass the current acceptable limits set by Irish standards. Assessment of a proactive climate adaptation strategy implemented in 2015 indicated it may need to be adjusted to further reduce climate change impacts and optimise adaptation costs.

1. Introduction

Climate change represents an urgent and irreversible threat to human societies, with increasing atmospheric greenhouse gas concentrations driving changes to all aspects of the climate system, especially increasing the frequency and intensity of extreme weather events (Allen, 2018; Othman et al., 2023). These observed climate changes are likely to lead to an increased risk of flooding, catastrophic storms, intense droughts, and rising sea levels (Abbass et al., 2022). Existing aging infrastructures are alarmingly vulnerable to these risks (AghaKouchak et al., 2020), and such hazards can have considerable effects on both society and the economy, leading to possible consequences such as physical damage to infrastructures and disrupted operations (Krogstrup and Oman, 2019; Diffenbaugh and Burke, 2019). Building climate-resilient infrastructure, as well as adapting existing structures, will help to reduce both direct and indirect costs of disruption (Michael and Berenice, 2018). In this context, international and national governing bodies have issued warnings about the imperative need to strengthen inundation control and flooding management in preparation for the future, as climate change is expected to pose significant challenges to the transport and drainage networks during extreme weather conditions (Steinhausen et al., 2022).

The implementation of effective climate adaptation strategies is required to tackle the escalating risks linked to climate change for flooding and other hazards (Cinner et al., 2018). This approach is being progressively adopted on a global scale, with the development of tools to incorporate adaptation into crucial policy domains, including regional frameworks, legislation, and standards (IPCC Climate Change, 2021). These efforts aim to consider the impact of climate change on systems and facilitate the shift towards climate-resilient societies and economies by the year 2050. Successful implementation of climate change adaptation, however, does require a thorough understanding of the projected

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nature and scale of the impacts of climate change on infrastructure networks. However, conducting this research for road drainage systems as part of future flooding management poses significant challenges for four reasons: (1) Investigating the performance of drainage systems during extreme rainfall events presents technical difficulties involving intricate hydraulic and hydrologic dynamics (H. Wang et al., 2022; Kamali et al., 2022); (2) The available meteorological data for specific locations, particularly for storms with short durations, is sparse (Fowler et al., 2021); (3) There is a scarcity of standardized climate projections at sufficiently resolutions in both temporal and spatial domains at the national and international levels (O'Brien and Nolan, 2023); (4) In addition to drainage system variability, there is significant uncertainty associated with climate projections (Wu et al., 2022). These challenges create difficulties for managers responsible for road drainage systems when attempting to accurately assess the impacts of climate change, and thus ascertain if adaptation is required, and if so, what adaptation is appropriate.

This paper introduces a probabilistic framework to evaluate the impacts of climate change on main road drainage systems. Examination of the effectiveness of climate adaptation strategies is also considered within this framework. Herein, main roads refer to the primary transportation routes in a given country, including motorways, dual carriageways, and important single-lane roads, which are typically located in non-urban areas and managed by government organizations. A crucial aspect of the proposed framework is its development within a probabilistic context. The Monte Carlo (MC) simulation method is utilised as a part of the assessment process to account for the effects of uncertainty in climate projections and drainage system variability, thus providing a comprehensive and robust evaluation of the impacts on the system. Several studies (e.g., Hu et al., 2023; Xu et al., 2020; O'Brien and Nolan, 2023; Wu et al., 2022) have demonstrated that the uncertainty associated with climate projections and hydrological models significantly influences the simulation outputs. Recognizing and incorporating these uncertainties are paramount to ensure the reliability of design solutions (Dong et al., 2017). Despite the widespread agreement that probabilistic methods are the most appropriate tools for quantifying climate risks to infrastructure (Stewart and Deng, 2015; Ryan et al., 2016; Aven, 2016; Watkiss et al., 2014; Bastidas-Arteaga and Stewart, 2019), studies applying these approaches in the context of main road drainage systems are very limited (Al-Ghadi et al., 2020).

To date, many studies have explored the influence of climate change on urban drainage systems (Zhang et al., 2021; Balistrocchi and Grossi, 2020; Raimondi et al., 2023). Far less research has however been conducted to examine the climate change impact on main road drainage systems (Al-Ghadi et al., 2020), which tend to run through mostly suburban and rural areas. This is an important gap in the literature given the significance of main road drainage networks worldwide (i.e. there are more than 5000 km of national primary and secondary road networks in Ireland (TII, 2023), in Australia, national highways span more than 14,500 km, with estimated drainage systems construction costs of approximately $ 470,000 per km (ACO Pty Ltd, 2023)). When considering the literature which does examine the impacts of climate change on main road flooding, it is noteworthy that the majority of these studies utilise qualitative and quantitative deterministic approaches (Kalantari and Folkeson, 2013; Wang et al., 2019; Pedrozo-Acuña et al., 2017). This is a noteworthy gap in the context of the importance of uncertainty considerations for climate impacts discussed above. Only Jiménez-U et al. (2022) utilised a fully-quantitative risk-based approach (i.e. probabilistic analysis) to examine the climate change impacts on main road drainage systems. This study addressed the uncertainty associated with the generation of precipitation for various future time periods (e.g., 2011–2040, 2041–2070, and 2071–2100) through stochastic autoregressive moving average (ARMA) models. However, the authors did not model the performance of drainage system probabilistically to capture the associated variability/uncertainty, nor did they assess potential climate change adaptation.

This paper aims to further advance the state of the art in the existing literature by considering both the climate change impacts and adaptation effectiveness for main road drainage systems through probabilistic modelling of both current and future climates, and the drainage system itself. The following section introduces a three-step risk-based framework for evaluating the impact of climate change on main road drainage systems using the most up-to-date climate projections. The proposed probabilistic framework is applied within the Irish context, examining the climate change impacts on main road drainage systems located in County Cork, in the south of Ireland. In the 'Assessment Methodology' Section, the study provides comprehensive details on how the probabilistic approach is implemented, followed by the analysis of climate change impact and examination of the effectiveness of a climate adaptation strategy in the 'Results and Discussions' Section.

2. General framework

The general framework for probabilistic risk-based assessment of the road drainage systems considering climate change is presented in Fig. 1. The first step involves assessing the hazard component. This begins with the identification of key hazards, which are selected based on past experiences of extreme events, stakeholder input, and relevant literature. For main road drainage systems, the climate hazard arises from extreme weather events, specifically intense rainfall events or storms with short durations. Once the hazard of concern has been identified, the next step is to model the existing hazard and project how it will evolve as a result of climate change (Jones, 2001) (Step 1: Fig. 1).

Since climate change is usually defined relative to a climatological baseline (see Fig. 1), it is necessary to define the baseline period as the reference point for the future projected climate (Ongoma et al., 2018). Typically, a baseline period is selected because good rainfall data for that period is available from various sources including meteorological observatories, reanalysis (a combination of observed and model-simulated data), Regional Climate Model simulations, and stochastic weather generators (Pörtner et al., 2022). In cases where meteorological records for extreme rainfall events with short durations are not publicly available, they can often be obtained directly from governmental agencies. Using the collected data, the likelihood of a specific amount of rainfall for various durations can be evaluated through statistical analysis. This assessment leads to the creation of rainfall Depth-Duration-Frequency (DDF) tables, which depict the relationship between rainfall depth and duration for a given return period. To create intense rainfall events with short durations, several methods have been developed based on the DDF relations, for example, the City of Los Angeles method (Hicks, 1944), the Chicago Hydrograph Method (Keifer and Chu, 1957), Alternating Blocks Method (Chow et al., 1988) and the block rainfall applied in New York (Watt and Marsalek, 2013). These generated storms are then used as the hazard input for subsequent probabilistic numerical modelling to represent the hazard corresponding to the baseline period (Step 1: Fig. 1).

Standardized climate projections are generally obtained through the detrending, bias-correcting, and further downscaling of the ensemble raw output of Regional Climate Models (RCMs), considering a number of climate scenarios under CMIP5 or CMIP6 (IPCC Climate Change, 2021). For this study, this information for Ireland was obtained from the Translate project (Met Éireann, 2023) via O'Brien and Nolan (2023), with both RCP 4.5 and RCP 8.5 considered as future scenarios (i.e., medium and worst-case) for quantitative risk analysis, as is common practice in climate change impacts and adaptation studies (Sabóia et al., 2017). Uncertainty is intrinsic to the climate projections, and if not adequately considered, has the potential to hinder effective climate action (Franzke et al., 2015). The quantitative risk-based method proposed in this study provides a means of incorporating uncertainty through probabilistic modelling using MC simulation. This approach enables the representation of projected changes in future storms and drainage system parameters as probabilistic distributions. This study

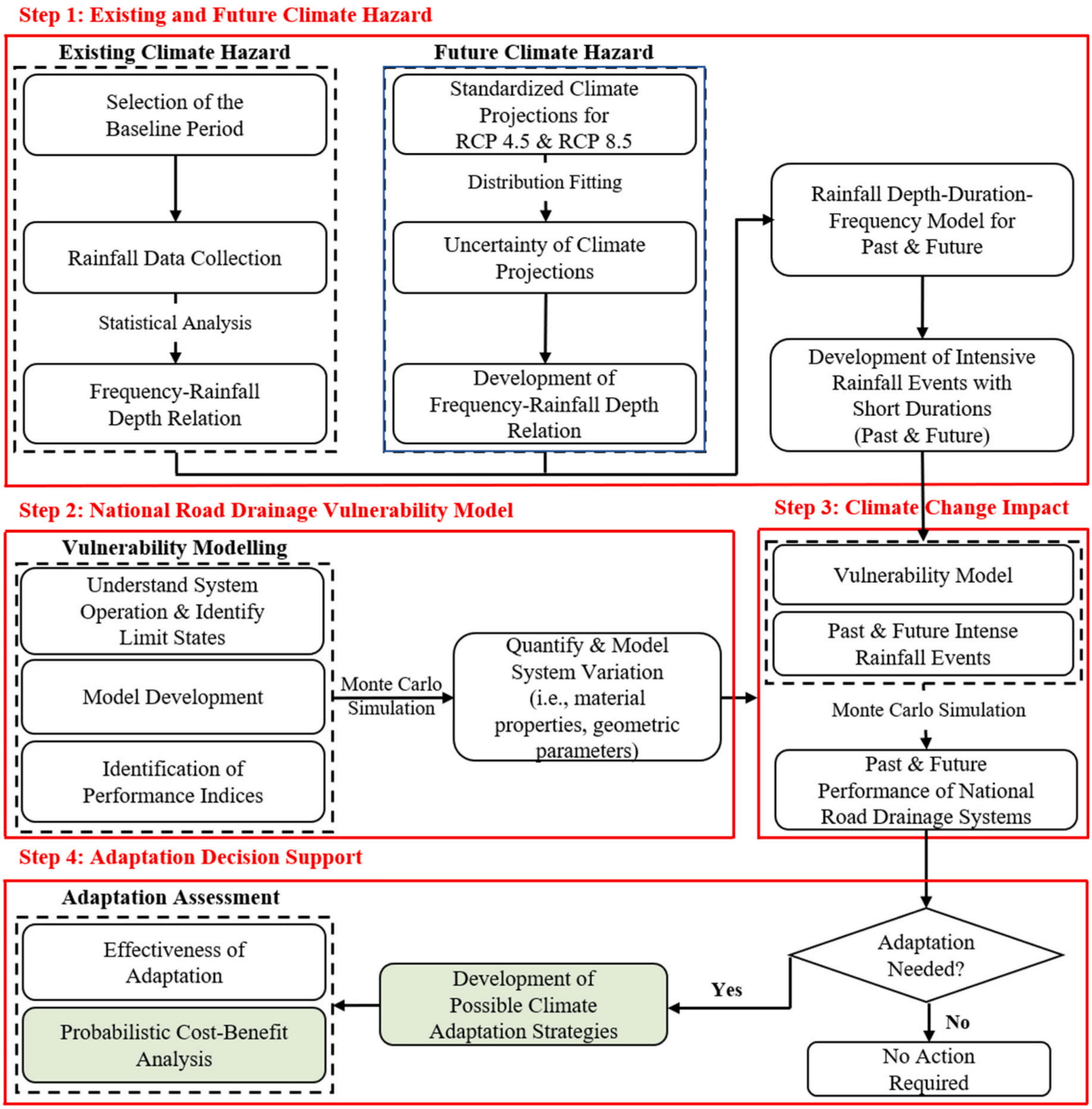

Fig. 1. Framework for probabilistic risk-based assessment of the main road drainage systems considering climate change.

introduces a practical and innovative way to estimate future high-resolution spatio-temporal precipitation projections with short durations from daily projections and past observation data at sub-daily or sub-hourly resolutions, e.g., future projections for storm events with 15 min duration. By studying the relationship between available historical precipitation data (i.e., metric) for various durations and assuming this relationship remains unchanged in the future, predicted DDF relations under future climates can be developed. (Step 1: Fig. 1).

Before commencing the vulnerability analysis, it is essential to establish a comprehensive understanding of how the drainage systems operate and identify potential climate-related weaknesses (Binesh et al., 2016). In the case of road drainage systems, the fluid flow within the system exhibits time-varying characteristics, and a wide range of conditions can occur during rainfall events (Tuohy et al., 2018; Wood and Heitzman, 1983). Various possible limit states, (i.e., failure states), are determined accordingly. Having established an understanding of the potential weakness in the drainage system, the next step involves developing a vulnerability model of the system. This model incorporates variables that may impact the system's performance, such as material properties, and geometric parameters. The most appropriate tool for this task is numerical modelling using commercial or open-source software (e.g., SWMM (Rossman, 2010), MIKE software, PCSWMM (Paule-Mercado et al., 2017)). The modelling process involves three steps: understanding system operation and identification of limit states, model development, and identification of performance indicators (Step 2: Fig. 1).

Having developed a vulnerability model, this can be integrated with the existing and future hazard models to quantify the climate change impact based on the performance of the drainage systems. This allows for a clear determination of whether climate adaptation measures are necessary (Step 3: Fig. 1). If the impact is significant for the research region, an investigation into climate adaptation strategies is warranted. Accordingly, the risk models can be extended to include a probabilistic cost-benefit analysis of climate adaptation strategies to assess their effectiveness (Ryan and Stewart, 2017, 2020). This analysis considers climate projection uncertainty and system variation, and utilises well accepted economic assessment metrics that system managers, owners, and researchers across disciplines can relate to, such as, net present values (NPVs) and benefit-to-cost ratios (BCRs) of adaptation strategies (Ryan et al., 2021). This approach can provide valuable insights into the economic viability and effectiveness of various adaptation strategies, guiding decision-makers in making informed choices to ensure the long-term sustainability and climate resilience of the drainage systems (Step 4: Fig. 1). The illustrative example in the following sections focuses on Irish road drainage systems and showcases hazard and vulnerability modelling to determine the projected impacts of climate change. The effectiveness of the current climate adaptation strategy proposed by TII standards in reducing the impacts of climate change is also examined. Future work through collaboration with industry partners in Ireland on costs will expand the research detailed in this paper to include probabilistic cost-benefit analysis for the assessment of climate adaptation strategies. The future work component of the framework is shown with a green background in Fig. 1.

3. Assessment Methodology

As an island nation susceptible to the effects of climate change, Ireland is likely to experience shifts in its climate that align with regional and global patterns. Notably, there is a predicted rise in the frequency of future extreme rainfall events (Allen, 2018). This increase could result in a higher occurrence of drainage system failures and lead to localized flooding on road surfaces. In this section, the proposed general framework is applied to study the likely climate change impact on main road drainage systems located in County Cork in the south of Ireland. The assessment was carried out under intense rainfall events characterized by short durations for both historical and future scenarios (i.e., RCP 4.5 and RCP 8.5). As mentioned previously, the MC simulation method is utilised as a part of the assessment process to account for the uncertainty in climate projections and drainage system variability. This approach is adopted based on the realistic and robust assumption of statistical independence between the generated climate hazards and simulated drainage systems. Similarly, varied parameters due to construction tolerances within the vulnerability drainage model, such as subcatchment Manning coefficient, depression storage depth, pipe roughness, and diameter, exhibits complete randomness without discernible correlations or dependencies. Thus, the assumption of statistical independence among variables for the entire simulation is unlikely to introduce significant bias into the results and is feasible in this case. For the development of future rainfall hyetographs under RCP 4.5 and RCP 8.5, a novel means for estimating extreme rainfall events with short durations is put forward based on the validated assumption that the linear relationships between rainfall metrics (i.e. relationship between r30in 24 and r4in15, r5in30 etc.) remain unchanged from the past to the future. This development was required as rainfall projections may lack the necessary sub-daily and sub-hourly temporal resolutions (i.e. detrended, bias-corrected and downscaled) in Ireland to capture intense rainfall events for a specific location, given the high computational demand of downscaling Global Climate Models (GCMs).

In Ireland, the standards for the design of national road and associated drainage system is operated, maintained, and improved by TII. Due to the future risks associated with climate change, in 2015 TII incorporated a 20% increase in the design rainfall intensities for the drainage systems along the main roads throughout the country as a climate change adaptation measure (TII, 2015b). Since there was a lack of insight into projected changes in extreme rainfall and the subsequent effects on drainage systems in Ireland at that time, the 20% adaptation strategy thus had to be selected without robust research or evidence base. As a result, it remains unclear whether the adaptation is adequate to handle future intense storms or if it is overly conservative, leading to unnecessary expenditure. This challenge, commonly faced by industry, of whether to take climate action given uncertainties around strategy effectiveness, future climate, etc., formed the context for this case study.

3.1. *Climate hazards: existing and future intense rainfall events*

3.1.1. *Existing climate hazard*

As mentioned above, the existing climate hazard in this case refers to the intense rainfall events with short durations in the historical scenario. Industry collaboration identified these short-duration storms as the key limit state i.e. events that result in flooding of the drainage system. To generate the existing hazard for short-duration storms, it is necessary to gather sufficient and valid rainfall data from meteorological stations. A minimum of 30 years of continuous rainfall records is required to establish stable and reliable statistical characteristics of storms (Di Baldassarre et al., 2006). For this study, the baseline period from 1976 to 2005 was chosen because fine-resolution gridded rainfall observations along with multiple model simulations and station data are available for this timeframe. Rainfall data from the Inishcarra Meteorological Station are utilised as the primary data source, specifically nine metrics representing 'peak over threshold' (POT) values, as indicated in Table 1. Since the number of observed events for the given metrics was limited and sporadic, non-parametric methods were not applicable for data analysis. Thus, a standard 'parametric' distribution was assumed, and the parameters of the distribution were determined iteratively to achieve the best fit for the data. Specifically, the numbers of intense rainfall events (measured by r4in15, r5in30, etc.) were assumed to follow Generalized Extreme Value distributions (characterized by three parameters, i.e., μ, σ, ξ). The POT exceedance values (i.e., rainfall depths above a certain threshold) were assumed to follow Generalized Pareto (GP) distributions based on the best-fit principle, which formally involves three parameters to be determined. However, in practice, this reduces to two parameters since one parameter represents the threshold itself (Castillo and Hadi, 1997). Based on the derived GP distribution, the frequency-rainfall depth relations for nine metrics were developed and summarized in the DDF table as shown in Table 2 for the baseline period with six return periods, i.e., 5-year, 10-year, 20-year, 30-year, 50-year, and 100-year.

Having developed the DDF table, it can be consolidated as the Sherman formula (Eq. (1)) (Sherman, 1931; Moré, 2006) using the Marquart method (Ranganathan, 2004). In the Sherman formula, i denotes rainfall intensity, mm/h; t represents rainfall duration, h; T stands for the return period, year; while K, m, n, *and* b are fitting parameters.

$$i = \frac{KT^m}{(t+b)^n} \qquad \text{Eq 1}$$

Given Eq. (1), the 'Alternating Blocks Method', an evolution of the 'Chicago Hydrograph Method', was utilised to construct rainfall hyetographs (Chow et al., 1988). In the literature (Li et al., 2013), intense rainfall events typically last from 1 h to 3 h. Therefore, storms with a duration of 2 h were generated to represent rainfall intensity and retain process details. Further information about the 'Alternating Blocks Method' can be found in Fig. 2, and the resulting examples of intensive rainfall events with a 2-h duration for the historical period are illustrated in Fig. 7 using solid lines which have been validated through comparison with the rainfall hyetographs obtained from the Office of Public Works (OPW) Flood Studies Update (FSU) Programme portal.

Table 1
Rainfall metrics and their meanings.

Metrics	Meaning
r4in15	rainfall depth over 4 mm for any 15 min
r5in30	rainfall depth over 5 mm for any 30 min
r6in1h	rainfall depth over 6 mm for any 1 h
r10in2h	rainfall depth over 10 mm for any 2 h
r12.5in3h	rainfall depth over 12.5 mm for any 3 h
r15in4h	rainfall depth over 15 mm for any 4 h
r20in6h	rainfall depth over 20 mm for any 6 h
r25in12 h	rainfall depth over 25 mm for any 12 h
r30in24 h	rainfall depth over 30 mm for any 24 h

Table 2
Rainfall Depth-Duration-Frequency relation for the historical period (1976–2005).

Metric	Return Period, year					
	5	10	20	30	50	100
	Rainfall Depth, mm					
r4in15	6.55	8.86	12.63	15.86	21.49	33.23
r5in30	8.30	11.17	15.99	20.22	27.76	43.93
r6in1h	12.07	16.94	24.98	31.93	44.17	69.96
r10in2h	13.52	16.78	22.41	27.44	36.55	56.53
r12.5in3h	16.11	19.92	26.29	31.84	41.67	62.61
r15in4h	18.16	21.92	28.19	33.63	43.25	63.64
r20in6h	21.57	25.12	30.86	35.73	44.17	61.60
r25in12 h	25.22	30.33	38.35	45.01	56.32	79.10
r30in24 h	–	35.37	44.02	51.35	64.03	90.15

3.1.2. Projected future climate hazard

This study uses RCMs from Nolan and Flanagan (2021) and the EURO-CORDEX project which were detrended, bias-corrected, and further downscaled onto a common 1-km grid over Ireland to provide the standard climate projections (O'Brien and Nolan, 2023). The rainfall projections generated from the fine-resolution RCMs across Ireland served as the data source to develop the DDF relation for future climates of the period from 2071 to 2100. Projected daily precipitation was generated and compared with field-mean values of historical grid observations for the baseline period. In Fig. 3, the occurrence frequency *vs.* daily rainfall depth relation for two different RCPs (i.e., RCP 4.5 and RCP 8.5) is presented, showing ensembles of 27 and 35 simulation results, respectively. These curves display statistically stable relationships for rainfall depths up to 70 mm. For the historical data, daily rainfall of 10 mm has a return period of about 30 days, while daily rainfall of 70 mm corresponds to a return period of about 90,000 days, or approx. 250 years. Fig. 3 shows a clear separation between the ensemble of projected distributions and the historical distributions at large rainfall depths, for both RCP scenarios. From the above curves, the change in daily rainfall from the past to the future can be easily represented through the 'frequency ratio' variable, which is calculated by comparing the daily rainfall occurrence frequency between past and future:

$$Frequency\ ratio = \frac{Daily\ rainfall\ occurrence\ frequency\ for\ the\ future}{Daily\ rainfall\ occurrence\ frequency\ for\ the\ past} \quad \text{Eq 2}$$

Using the obtained frequency ratio, the change in the occurrence frequency-rainfall depth relation was estimated for the daily metric (i.e., r30in24) under the future climate scenarios (Fig. 4). To establish the complete DDF relation for the future, which is required to examine the impact of short duration rainfall events, the change in occurrence frequency-rainfall depth relation for the other eight metrics, such as r4in15, r6in30 etc., must also be estimated. However, it was not feasible to apply the above method to all other metrics, which involved adapting the relationship from the past to the future using the frequency ratio, as detrended, bias-corrected, and further downscaled precipitation projections at sub-daily and sub-hourly temporal resolutions in Ireland were not available. Indeed, this is the case for many other countries given the high computational demands associated with developing downscaled climate projections. Importantly however, past research identified a potential linear relationship between the rainfall depth values observed in sub-daily metrics and those in daily metric as both are subject to the same Clausius-Clapeyron scaling with respect to temperature (Arnbjerg-Nielsen, 2012; Larsen et al., 2009; Pérez Bello et al., 2021; Förster and Thiele, 2020; Westra et al., 2014). This relationship can be

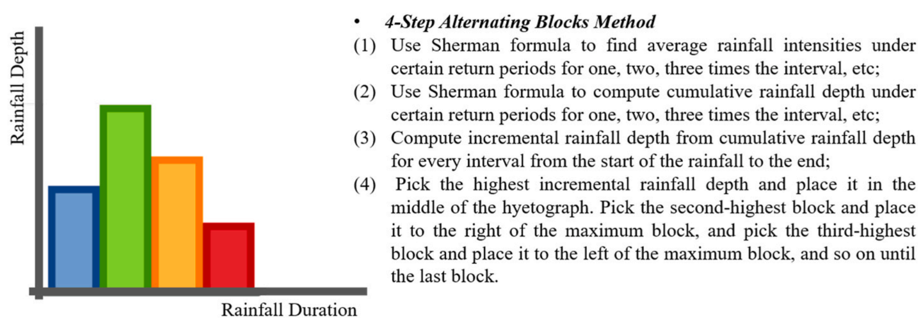

Fig. 2. Schematic illustration of the Alternating Blocks Method.

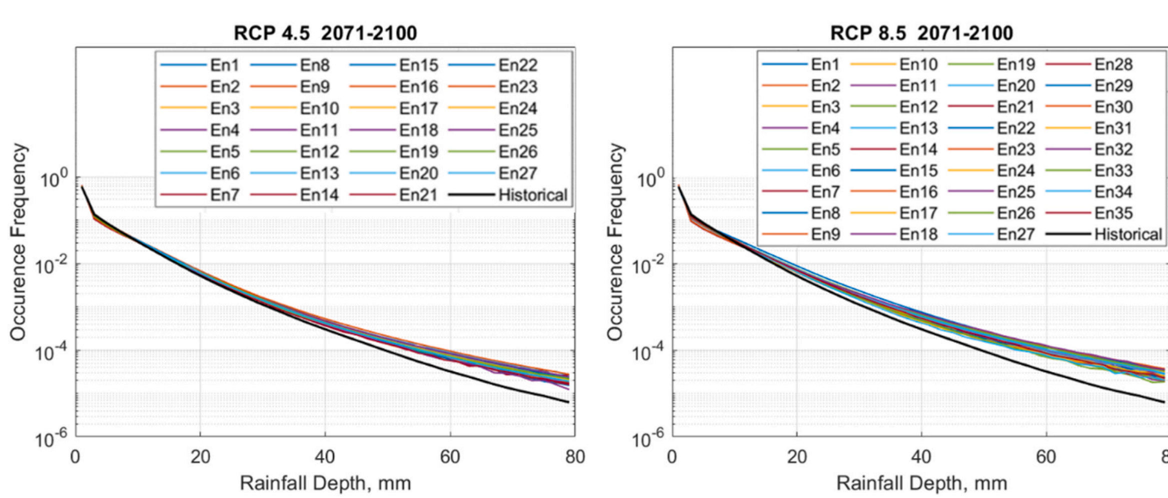

Fig. 3. Climate projections of the occurrence frequency-daily rainfall depth relation (Note: 'EnXX' refers to the ensemble members under the RCP 4.5 and RCP 8.5 emission scenarios from the GCMs of Nolan and Flanagan (2021) and the EURO-CORDEX project).

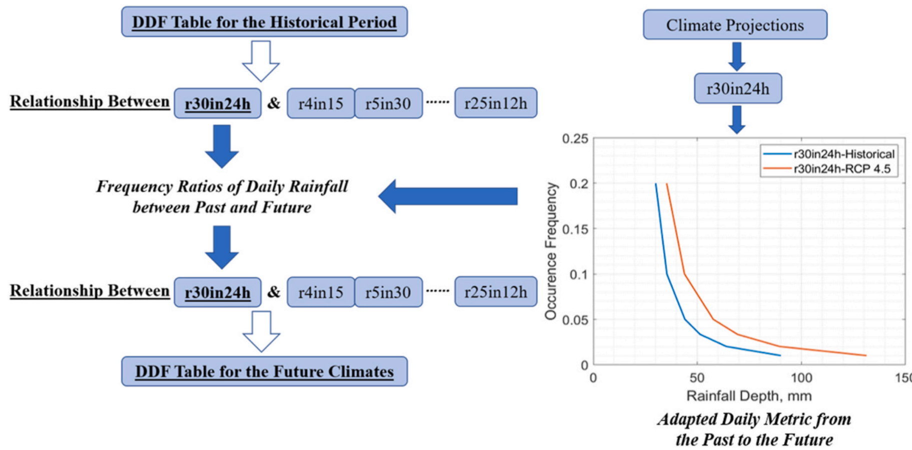

Fig. 4. Adapted daily metric from the past to the future working as the bridge to predict future DDF relations.

established by analyzing the historical rainfall records collected from meteorological stations during the baseline period. With this relationship, it is possible to estimate changes in all the metrics by adapting the occurrence frequency-rainfall depth relation based on the daily metric, according to the assumption that the relationships between metrics remain unchanged from the past to the future.

This assumption was verified, to some extent at least, by studying the relationships between the paired values of rainfall depth observed in sub-daily metrics (i.e. 'r12.5in3h', 'r20in6h', and 'r25in12 h') and daily metric (i.e. 'r30in24 h') under future climates (see Fig. 5). This analysis was made feasible by the availability of future projections every 3 h from 5 members of the Nolan and Flanagan (2021) ensemble, which constitutes a subset of the larger ensembles depicted in Fig. 3. In Figs. 5 and 6, for each point on the x-axis, the y-value of each curve shows the rainfall amount with the same return period (or occurrence frequency) for each of the metrics shown. The linear nature of the curves in Figs. 5 and 6 underscores that the 'shape' parameter of the GP distributions remains unchanged across the different climate models, and between the climate projections and the historical records. The differences in the slope of each curve reflect the different values of the "scale" parameter of the GP distributions for each metric. All analyses support the basic assumption of this work, that while the number distribution of the various POT

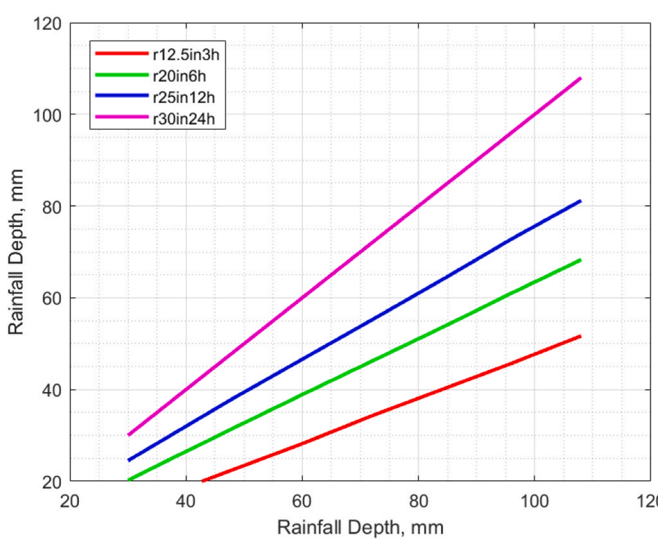

Fig. 5. Validation of the linear relationship between daily and sub-daily rainfall metrics under the future RCP 8.5 scenario during 2071–2100. For each point on the x-axis, the y-value of each curve has the same return period or occurrence frequency as the 'r30in24 h' metric.

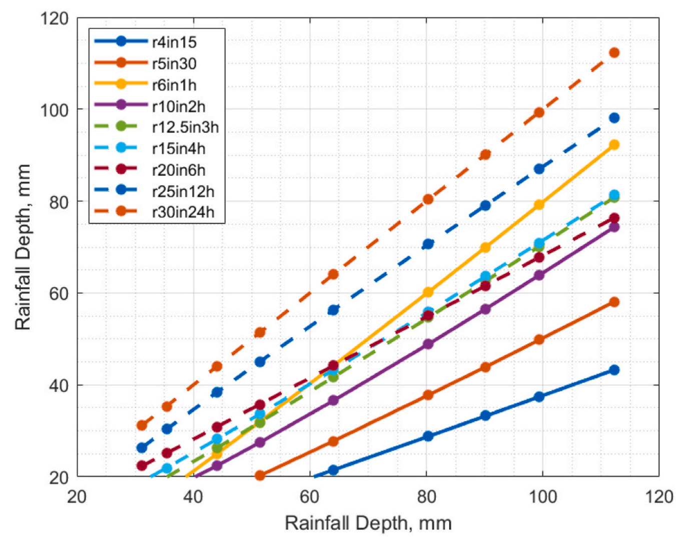

Fig. 6. Linear relation between the sub-daily metric and daily metric based on the historical rainfall records. (As in Fig. 6, for each point on the x-axis, the y-value of each curve has the same return period or occurrence frequency as the r30in24 h metric.).

events may change in future climates, the exceedance distribution (as modelled by the GP distribution) will not. Any extra events that may occur should simply fill out the histogram that is fit by the same GP distribution.

The rainfall depths of various metrics were treated as random variables and specific parameters were used to estimate the relationship between the paired values of sub-daily and daily metrics based on historical data. The study confirmed the highly linear relationships for all the metrics of the Inishcarra rainfall records, as depicted in Fig. 6. These relationships enabled the characterization of rainfall depth for other metrics (i.e., the dependent variables), as simple linear functions of the daily metric 'r30in24 h' (i.e., the independent variable). Consequently, adjustments could be made to the relationship between occurrence frequency and rainfall depth for all the metrics under future climates, allowing the derivation of future DDF relations. The procedure in Fig. 2, outlined in the previous section, was then applied to generate future intense rainfall events with short durations (i.e., 2-h) under RCP 4.5 and RCP 8.5. The dashed lines displayed in Fig. 7 represent the resulting intensive rainfall events with 2-h durations under RCP 4.5. The plot demonstrates the impact of climate change on rainfall intensity, revealing that, for example, the historical 50-year storm is comparable

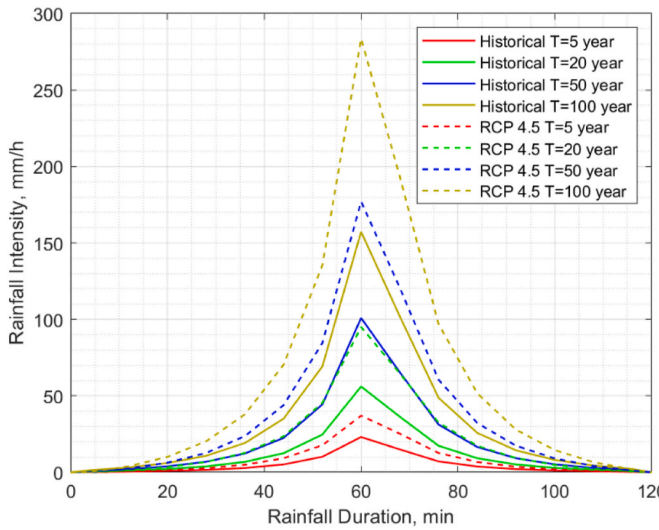

Fig. 7. Intensive rainfall events with 2-h duration and various return periods for historical scenarios and RCP 4.5.

to the RCP 4.5 20-year storm due to the projected changing climatic conditions.

As discussed, it is crucial to incorporate uncertainty while representing projected climate change. To achieve this, the distribution characteristics of the computed frequency ratios across the full climate projection ensemble were examined using Matlab. Through this analysis, it was determined that the Generalized Extreme Value (GEV) distribution best represented the variation of frequency ratios for future scenarios, as illustrated in Fig. 8. The uncertainty in climate projections was thus incorporated utilising GEV distribution to generate samples of frequency ratios through MC Simulation. These frequency ratios were then employed to modify the occurrence frequency-rainfall depth relation for the historical metric to account for the variation of future climates. It is important to observe that there is 100% surety that future climates will increase the likelihood of short-duration intense rainfall events.

3.2. Road drainage system

The drainage design for main roads in Ireland adheres to the standards and guidelines established by TII (TII, 2015a; TII, 2015b). In this study, an idealist yet illustrative drainage system was developed after close collaboration and consultation with TII, and the engineering design consultancy Arup. The drainage system is designed for a length of road section extending 1.2 km in County Cork. The road under consideration is 8.0-m-wide, with a 7.0-m-wide carriageway and two 0.5-m-wide hard strips, and runs on a 1% gradient embankment before transitioning to a 0.5% gradient cutting (DoT, 2022). The catchment along the road has an impermeable footprint area of approximately 1.055 ha and the average annual rainfall depth for the site is about 1230 mm based on observations of the meteorological station (Met Éireann, 2023). The soil type is classified as Type 4, with a soil index of 0.45, as determined by the Flood Studies Report (TII, 2015b). The designed drainage systems consist of a pipe network, manholes, and an attenuation pond with outfall structures at the terminal. A sketch of the system is presented in Fig. 9.

According to standards, the pipe network should be designed for rainfall events with a 5-year return period without occurrence of flooding, while for the pond, a 100-year return period with 300 mm freeboard on the top is required (TII, 2014). For the drainage system, pipes were designed to facilitate the transfer of rainwater collected from the road surface after rainfall (Bray, 2021). Specifically, the flow inside the pipes was calculated using the 'Modified Rational Method', and the pipe was sized following the 'Colebrook-White Equation' (Kellagher, 1981). The primary function of manholes is to provide access for maintenance and work as junction boxes for the connection of vertical drop inlets and pipelines (Nemerow et al., 2009). The attenuation pond stores runoff volumes, which is necessary for limiting the discharge from roads in Ireland to receiving watercourses (TII, 2015a). The required storage volume of the pond is determined by comparing the development and greenfield runoff rate of the catchments subjected to rainfall events with various durations and return periods (TII, 2015a). In this study, the drainage system was designed with and without the 20% climate adaptation factor to facilitate the assessment of the climate adaptation strategy implemented by TII standards in 2015 (i.e., efficiency & effectiveness).

3.3. Road drainage vulnerability model

The development of a vulnerability model is the most challenging part of the analysis as it involves developing representative numerical models for physical entities and integrating associated uncertainties. In this study, the vulnerability model of the road drainage system was developed using Storm Water Management Model (SWMM), an open-source public software developed by the United States Environmental Protection Agency for planning, analysis, and design for drainage systems (Rossman, 2010). Since SWMM is a deterministic program, code was developed to create a probabilistic model incorporating the

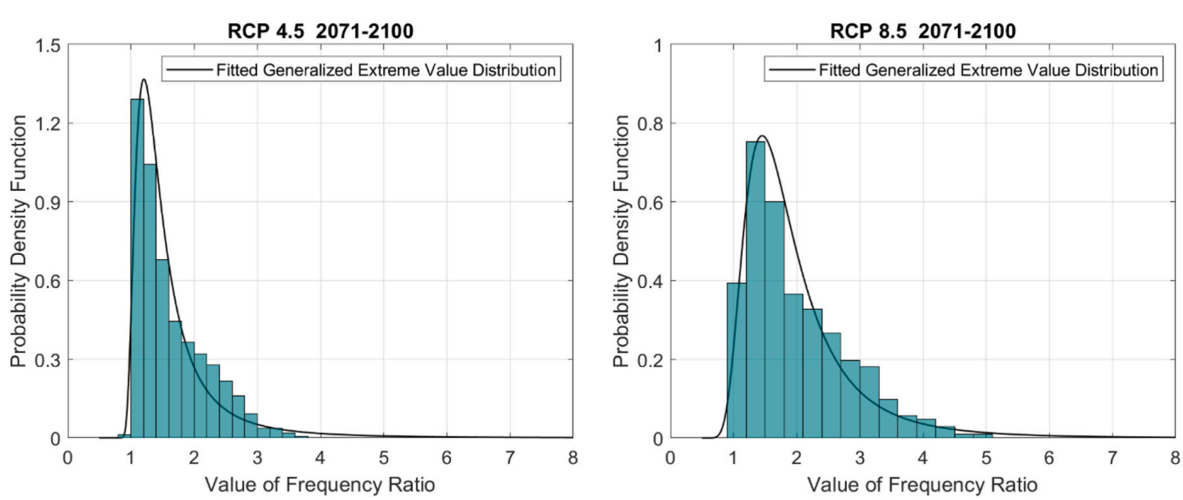

Fig. 8. The best-fit distribution (GEV) for frequency ratios of daily rainfall between historical and future climates.

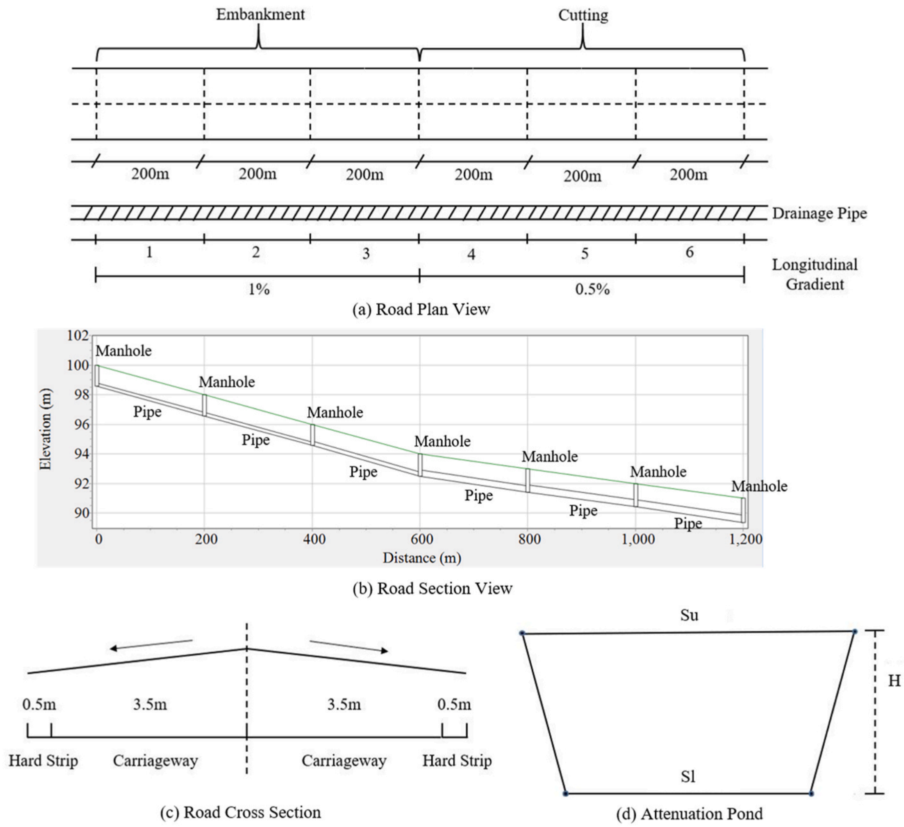

Fig. 9. Skematic of the drainage system (Su = the upper surface area of the pond; Sl = the lower surface area of the pond; H = the height of the pond).

uncertainty and variability associated with the drainage system performance during extreme short-duration rainfall events.

The established vulnerability model of the drainage system is shown in Fig. 10. S1–S6, J1-J7, and C1–C8 represent sub-catchments, manholes, and pipe networks of the system, respectively. Sto 1 refers to the attenuation pond with outfall structures including an orifice (Orifice 1) and a weir (Weir 1). In the developed model, the system variation was considered by incorporating probabilistic parameter distributions as listed in Table 3. Although tolerances for road construction do influence the geometry of the road, the variation of road geometry will not change the design of the alongside drainage systems due to the tolerance limitations required by Irish local government. Based on the functional insights into the system during storm events provided by the standard managers and designers (TII and Arup), two limit states were identified as follows: (i) the overflow of manholes to the road surface and (ii) the exceedance of the allowable pond level permitted under Irish standards.

4. Results and Discussions

This section presents the impact of climate change on main road drainage systems and the effectiveness of the climate adaptation strategy adopted in Irish standards in 2015, through examination of three performance indicators: a) system inflow, b) probability of road flooding, and c) maximum capacity usage of the attenuation pond over storm duration. The impact of climate change on drainage networks constructed prior to implementation of the 2015 climate adaptation strategy are first presented in Section 4.1 below. Section 4.2 examines the effectiveness of the 2015 adaptation strategy in mitigating these impacts.

4.1. Climate change impact

Figs. 11–14 illustrate the results for system inflow, probability of road flooding, maximum flooding rate, and maximum usage of pond over the storm duration under historical and future climates. In Fig. 11, it can be seen that the system inflow is the highest under RCP 8.5, followed by RCP 4.5, and the lowest for the historical period. The results show an increase in rainfall volume under intense rainfall events for future climates of approximately 37% for RCP 4.5 and 55% for RCP 8.5 b y 2071–2100, when compared with the historical period. This percentage increase is quite consistent across the return periods. The projected increased inflow will result in higher demands on the drainage system to transmit rainwater during rainfall events. It is also clear from Fig. 11 that the predictions of inflow volume for future climates exhibit increased variability with return period, however, historical inflows exhibit small uncertainty. This is driven by climate change uncertainty,

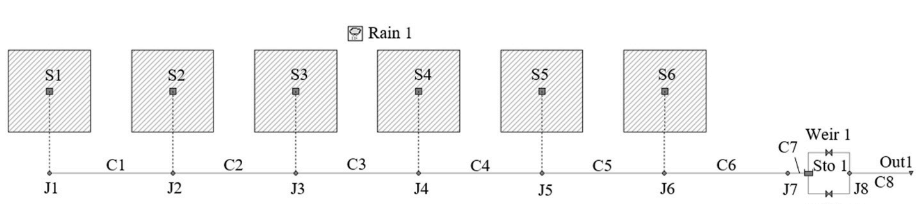

Fig. 10. Vulnerability model of the drainage system.

Table 3
Statistical parameters for the vulnerability model.

Variable	Distribution	Range			Source
Manning Coefficient for Subcatchment	Uniform	[0.011,0.013]			McCuen et al. (1996)
Pipe Roughness	Uniform	[0.011,0.017]			(ASCE, 1982)
Depression Storage Depth (mm)	Uniform	[1.27,2.54]			(ASCE, 1992)
Pond Top Area (Su, m^2) Pond Bottom Area (Sl, m^2)	Deterministic	With a 20% allowance factor, Su:1878.7 S l:1011.4 Without a 20% allowance factor, Su:1535.8 S l:764.4 (see Fig. 9 (d))			(TII, 2015a)
Pond Height (m)	Deterministic	1.628 (see Fig. 9 (d))			(TII, 2015a)
Pipe Diameter (mm)	Normal	Drainage System	Mean	COV	(TII, 2015a; Duan et al. (2016)
		With a 20% allowance factor	225; 375; 450	0.05	
		Without a 20% allowance factor	225; 300; 375; 450; 525	0.05	

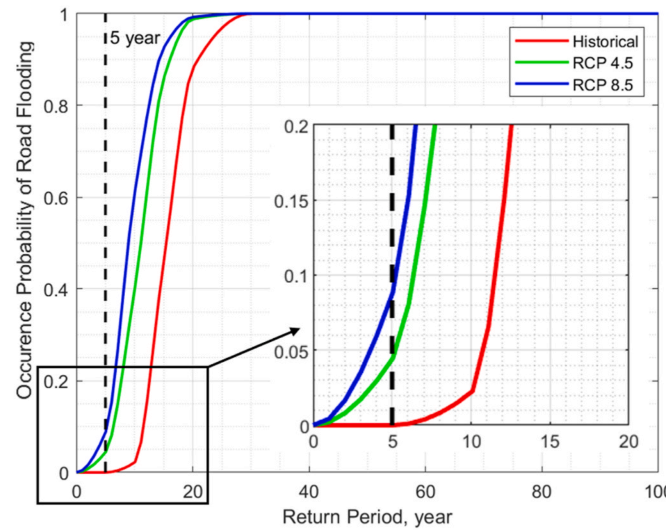

Fig. 12. Flooding failure probability of the pipe network under storms of historical and future climates for 2071-2100.

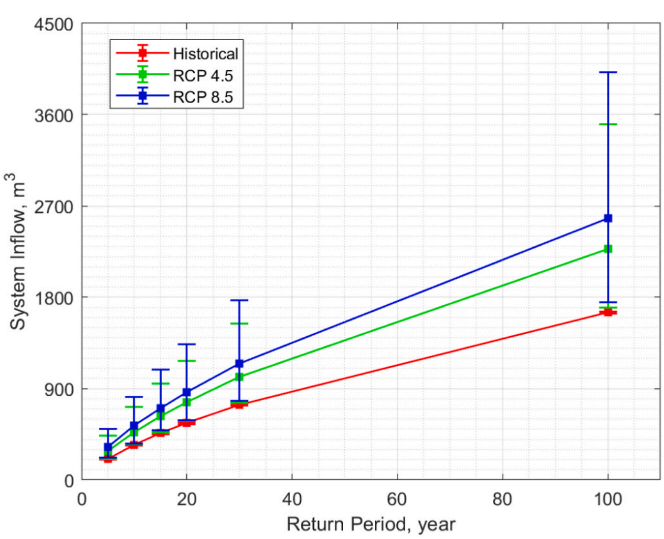

Fig. 11. System inflow under storms of historical and future climates for 2071–2100 (mean value, 5th and 95th percentile shown).

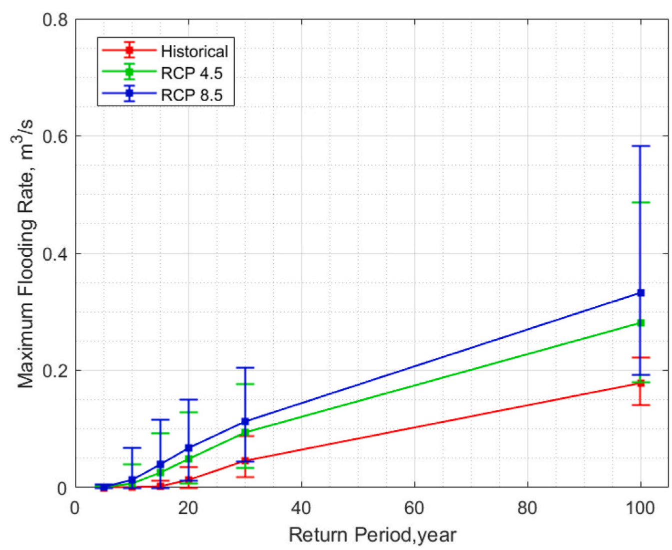

Fig. 13. Maximum flooding rate of road drainage systems under historical and future climates for 2071–2100 (mean value, 5th and 95th percentile shown).

which results from the increase of ensemble divergence with rainfall depth (see Fig. 3).

Examining Fig. 12, it is clear that both RCP 4.5 and RCP 8.5 climate scenarios result in increase in the probability of pipe surcharge, and subsequent road flooding, reflected in the trend of maximum flooding rate as shown in Fig. 13. As previously mentioned, the design return period for pipes in the Irish standards is 5-year without occurrence of flooding (TII, 2015b). From the plot, it can be seen that the likelihood of pipe overflow and road flooding goes from 0% at the 5-year return period under the historical scenario, to 4.4% under RCP 4.5 and 8.7% under RCP 8.5, respectively. Similarly, for intense rainfall events with a 20-year return period, the probability of road flooding increases by 10.8% under RCP 4.5 and 11.2% under RCP 8.5. These are significant increases when considered in the context of flooding implications, which include flooding rate increasing from 0 at the 5-year return period under the historical scenario, to 9.5E-4 m^3/s under RCP 4.5 and 12.6E-4 m^3/s under RCP 8.5, resulting in higher likelihood of impassable roads and traffic accidents (Diakakis et al., 2020; Halpin and Newell, 2022). Thus, there is a clear need to adopt the climate adaptation strategies for the pipe network.

In Fig. 14, the permissible maximum utilisation of pond capacity over the storm duration (i.e. failure limit state), following the Irish standard's specifications without considering the allowance factor for climate change, is normalized as 1.0. It is noted that this limit state level is 300 mm below the top surface of the pond (i.e. the pond overflow level shown as the upper boundary with the value of 1.23), as TII standards require a 300 mm freeboard to be maintained at all times (TII, 2015b). Fig. 14 shows that across all three climate scenarios, both the predicted mean and the 95th percentile do not exceed the allowable pond usage, i. e. the design limit state is not reached. Fig. 15 shows the probability of exceedance of this limit state for various storm return periods. While the probability of exceedance is zero across all return periods for the historic climate, RCP 4.5 and RCP 8.5 result in non-zero values, ranging from 1 in 1000 (0.1% probability) to 1 in 100 (1% probability) for storm return periods from 100 to 200 years. The probability of pond overflow (i.e., the upper boundary in Fig. 14) was found to be zero across all climate

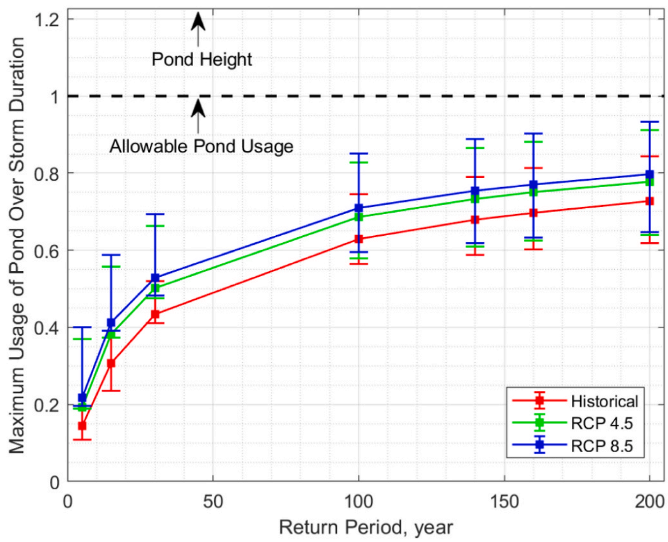

Fig. 14. Maximum usage of pond capacity over storm duration under historical and future climates for 2071–2100 (mean value, 5th and 95th percentile shown).

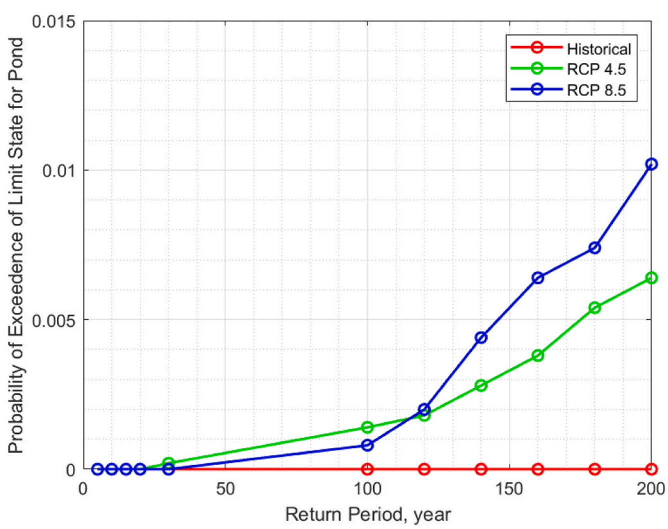

Fig. 15. Occurrence probability of limit state exceedance for pond (i.e. allowable pond usage exceedance).

scenarios. This result reflects the conservatism in the design standards, which was likely implemented given the potential for environmental damage resulting from pond overflow. However, it is noted the level of pond usage under future climates shows an obvious increase, with a 5%–32% increase under RCP 4.5 and a 7%–48% increase under RCP 8.5, depending on the return period. Thus, there is a noteworthy reduction in the reserve capacity of the pond under these short-duration storms as a result of climate change. Future work will examine the potential for climate change impacts considering storms with longer durations, which may have a higher probability of exceeding the pond limit state.

4.2. *Effectiveness of climate adaptation*

The results in the previous section indicate there is significant potential for climate change to impact the safe operation of road drainage systems in Ireland. As previously mentioned, TII implemented a climate adaptation strategy in their standards since 2015, whereby a 20% increase in the design rainfall intensity is applied. Thus, networks constructed after 2015 have increased climate resilience. This study assesses the effectiveness of the climate adaptation strategy for the first time through a comparison of the road drainage system with and without the adaptation strategy applied under the RCP 4.5 and RCP 8.5 scenarios for 2071–2100.

Results of the failure probability of pipes, maximum flooding rate and maximum usage of the pond over storm duration are shown in Figss. 16–18. As described in the previous section, without adaptation at the 5-year return period, the probability of pipe surcharge and resulting road flooding goes from 0% for historical, to 4.4% for RCP 4.5 and 8.7% for RCP 8.5. With adaptation applied, the probability of flooding failure under RCP 4.5 reduces to 1.3%, while the corresponding failure for RCP 8.5 reduces to 1.9% (Fig. 16). As mentioned in the previous section, maximum flooding rates without adaptation went from 0 for historical to 9.5E-4 m^3/s under RCP 4.5 and 12.6E-4 m^3/s under RCP 8.5. Application of the adaptation strategy reduced these 5-year flooding rates to 4.2E-4 m^3/s (55% reduction vs no adaptation) and 4.0 E−4 m^3/s (68% reduction vs no adaptation) (Fig. 17). Thus, although the climate adaptation strategy significantly reduces climate change impact (~70% reduction), it is not fully effective in mitigating the flooding probability to zero at the design return period and avoiding flooding on the road surface as required by Irish standards. This can be seen in Fig. 16 by comparing the red line to the dashed blue and green lines at the 5-year return period in the magnified tile. The adaptation is almost fully effective at the 20-year return period, reducing the probability of failure to below historical levels for RCP 4.5 and close to historical levels for RCP 8.5. However, given the standards focusing on the 5-year design return period, the analysis indicates a more aggressive adaptation strategy may be required for pipe design.

On the other hand, as shown in Section 4.1, without adaptation the pond has a low probability of exceedance of the design limit state at the 100-year storm period for RCP 4.5 and RCP 8.5, and zero probability of overflow for 2-h storms up to the 200-year return period. This initially indicates that the implementation of climate adaptation strategy to the pond may be overly conservative, especially given that overflow over the top of the pond does not occur until the water level rises 300 mm above the design limit specified by standards. As can be seen in Fig. 18, the climate adaptation strategy performs as expected at lower return periods, reducing pond usage. However, at larger return periods (e.g., 200 years), the pond reserve capacity actually reduces due to the implementation of the adaptation strategy. This is due to the following: When the return period of storms is lower, the system inflow is relatively small. Consequently, there is very little road flooding and most collected

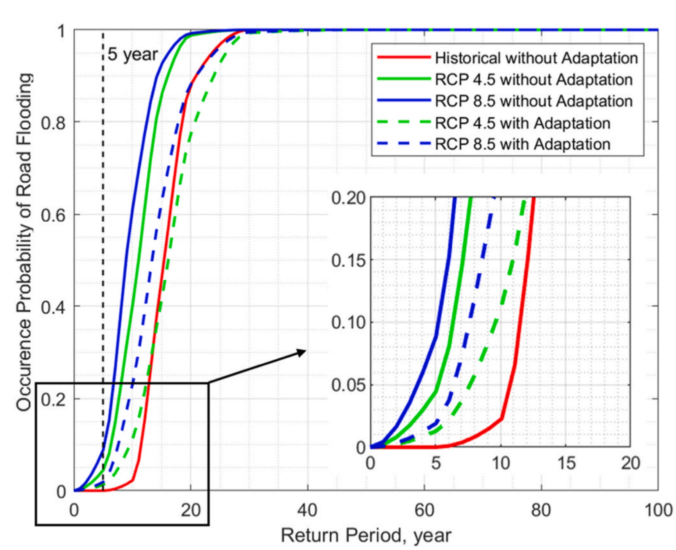

Fig. 16. Flooding failure probability of pipes for drainage system with and without adaptation.

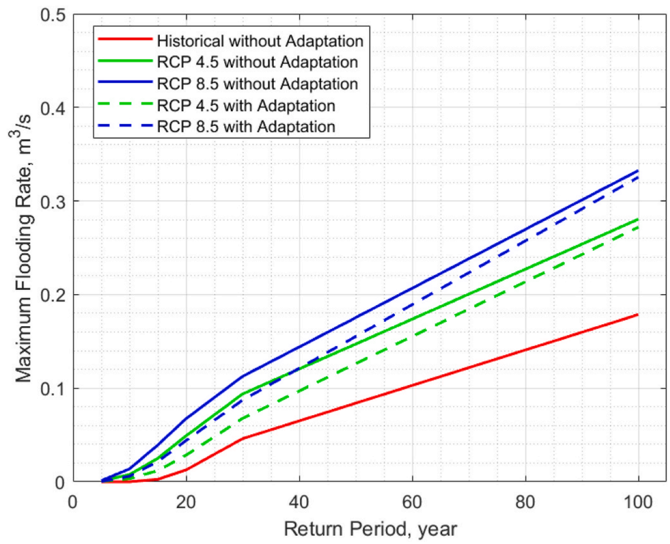

Fig. 17. Maximum flooding rate of road drainage systems with and without adaptation under historical and future climates for 2071–2100 (mean value).

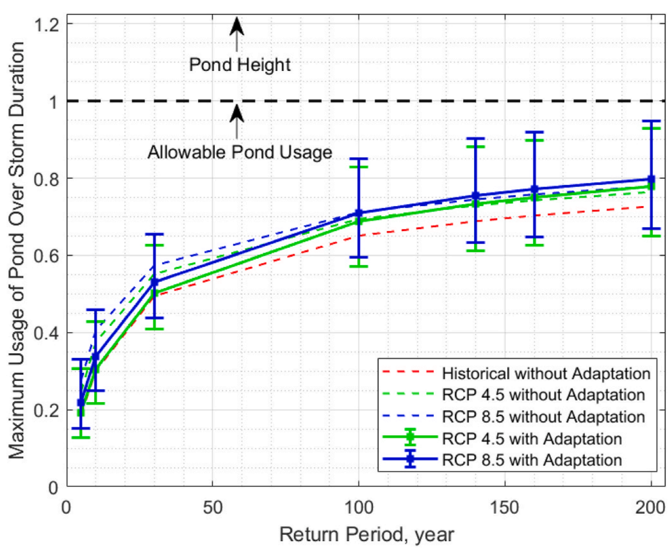

Fig. 18. Maximum usage of pond capacity for drainage system with and without adaptation (mean value, 5th and 95th percentile shown).

rainwater is efficiently transmitted through the pipe network to the pond. The pond size without the adaptation strategy is smaller and thus exhibits a higher maximum usage compared to adapted (larger) ponds. Conversely, when the return period of storms is high, e.g., 200-year, a significant amount of road flooding occurs, especially for the non-adapted system, which has smaller pipes. The adapted system with its larger pipes conveys more water to the pond than the non-adapted system, resulting in reduced road flooding but greater usage (i.e., reduced reserve capacity) for the pond with adaptation. An analysis was also conducted to examine the system performance with the 20% adaptation factor applied to the pipes only, and not to the pond. The probability of exceedance for the limit state of the pond in this scenario was approximately 5% for RCP 4.5 and 10% for RCP 8.5. This represents a significant increase over the drainage system without pond or pipes adapted, which as discussed in Section 4.1, had a limit state exceedance probability of 0.1%. This highlights the need for the systems-based approach for adaptation strategy planning, considering the pipes and the pond together i.e. if adaptation is applied to the pipes, some adaptation is also required for the pond to handle extra volumes of water conveyed by the larger pipes. Overall, the analysis indicates that the 2015 TII adaptation strategy needs to be revised somewhat. However, further research is required before this action is taken, e.g., to examine the influence of different storm durations and the effect of various values of climate adaptation factors.

5. Conclusion

The probabilistic methodology developed in this paper enables the evaluation of climate change impacts on main road drainage systems and the assessment of the effectiveness of climate adaptation strategies. The uncertainty arising from both climate change projections and road drainage system variation were incorporated into the framework. The approach also proposes a practical and innovative way to estimate short-duration storms under future climates in the absence of climate projections of fine spatio-temporal resolution. The representative case study developed indicates that climate change is expected to have significant impacts on the main road drainage in Ireland. This case-study considered both the drainage pipe network and the attenuation pond. The analysis of the pipe network indicates that projected climate change will result in the probability of road flooding during intense rainfall events surpassing the acceptable limits set by Irish standards for both the RCP 4.5 and RCP 8.5 scenarios. This could lead to societal consequences such as road closures and damage, and the potential increase in road traffic accidents. When modelling the pond, it was found that projected climate change resulted in a significant reduction in the pond reserve capacity, and the likelihood of exceedance of the design limit state at the 100-year design return period went from 0% for the historical analysis, to approximately 0.1% for future climates. These probabilities are low and the likelihood of pond overflow remained zero for all scenarios examined, reflecting the somewhat conservative nature of the attenuation pond design.

The case-study also included the assessment of a climate adaptation strategy adopted in Ireland in 2015, whereby the design rainfall intensity for road drainage system was increased by 20%. The analysis indicated that while the climate adaptation strategy did reduce impacts, it was not fully successful in mitigating the impacts of climate change on pipe flooding. For the attenuation pond, the implementation of adaptation strategy for both pond and pipes actually resulted in a reduction of pond reserve capacity during higher return periods. This was due to the use of larger pipes in the adapted system, which conveyed more water to the larger adapted pond, with resulting reduction in pond reserve capacity and road flooding. This emphasizes the importance of considering different climate adaptation effect factors for various components within the road drainage systems during the design stage due to the systems-based nature of road drainage between the components. Overall, the analysis indicated that the 2015 TII climate adaptation strategy needs to be revised somewhat. However, before recommending any standard alterations, further research considering various storm durations, and the effectiveness and cost-benefit of various adaptation strategies needs to be conducted.

CRediT authorship contribution statement

Jingyu Wang: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Enda O'Brien:** Writing – review & editing, Data curation, Investigation. **Paul Holloway:** Writing – review & editing. **Paul Nolan:** Writing – review & editing, Resources, Project administration. **Mark G. Stewart:** Writing – review & editing. **Paraic C. Ryan:** Conceptualization, Methodology, Investigation, Supervision, Writing – review & editing, Funding acquisition.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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