# A mini-review on the impacts of climate change on wastewater reclamation and reuse

Phuong Tram Vo[1], Huu Hao Ngo[1*], Wenshan Guo[1], John L. Zhou[1], Phuoc Dan Nguyen[2], Andrzej Listowski[3], Xiaochang C. Wang[4]

[1]Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia

[2]Faculty of Environment, Ho Chi Minh City University of Technology, 268 Ly Thuong Kiet, District 10, Ho Chi Minh City, Viet Nam

[3]Sydney Olympic Park Authority, 7 Figtree Drive, Sydney, NSW 2127, Australia

[4]Key Lab of Northwest Water Resources, Environment and Ecology, Ministry of Education, Xi'an University of Architecture and Technology, Xi'an 710055, China

* Correspondence author. Tel: +61 2 9514 2745; Fax: + 61 2 9514 2633.

*Email address:* h.ngo@uts.edu.au

**Abstract**

To tackle current water insecurity concerns, wastewater reclamation and reuse has appeared as a promising candidate to conserve the valuable fresh water sources whilst increasing the efficiency of material utilization. The climate change, nevertheless, poses both opportunities and threats to the wastewater reclamation industry. Whereas it elevates the social perception on water-related issues and fosters an emerging water-reuse market, the climate change simultaneously presents adverse impacts on the water reclamation scheme, either directly or indirectly. These effects were studied fragmentally in separate realms. Hence, this paper aims to link these studies for providing a thorough understanding about the consequences of the climate change on the wastewater reclamation and reuse. It initially summarizes contemporary treatment processes and their reuse purposes before carrying out a systematic analysis of available findings.

**Key words -** Climate change, impacts, wastewater reclamation and reuse, opportunities

## 1 Introduction

Climate change is no longer a scientific fiction. It has been convinced by an enormous amount of publications from various disciplines since 1960s when technological advances allowed researchers to monitor the transformation of $CO_2$ in the atmosphere and predicted the changes of global temperature by computer models (Isobe, 2013; Moss et al., 2010; Parry et al., 2007; Seinfeld and Pandis, 2006; Vittoz et al., 2013). Despite of skepticisms from the anti-climate change movement, Intergovernmental Panel on Climate Change reconfirmed the phenomenon by its long-term observation through representative indicators such as temperature, greenhouse gases (GHGs) concentrations, extreme events, sea level changes and hydrological cycle (IPCC, 2013).

As United Nations Water (2012) expressed, water is the fundamental medium that transfers the effects of climate change to the ecology and human beings. This has led to an ultimate concern over the water sector in the medium confidence stand of strongly fluctuated precipitation *(more precipitation in medium and high latitudes, less in subtropical countries),* increased Global Mean Surface Temperature *(average surface temperature in the period of 2016-2035 will be +0.3-0.7 $^{o}$C higher than that of 1880-1950)*, sea level rise *(+0.2-0.6 m by 2100)* and extreme weather situations *(stronger cyclones in North Pacific, Indian Ocean and Southwest Pacific, more prolonged droughts, heavy rainfall and flooding in certain areas)* (IPCC, 2013; World Bank, 2009). Water security has been consequently violated through changing patterns of the hydrological cycle, water availability, water demand and water quality (World Bank, 2009).

To tackle this issue, one of the promising trends adopted under the thirst of precious freshwater resources is wastewater reuse. It has been considered as an essential part of Sustainable Water Management Scheme (Marlow et al., 2013). The last three decades have indeed experienced a rising attention on wastewater reclamation and reuse in various parts of the world (National Water Commission, 2011; Sa-nguanduan and Nititvattananon, 2011). The research themes were very diverse, ranging from its applications and advantages (Guest et al., 2009); treatment technologies and operational issues (de Koning et al., 2008; Venkatesan et al., 2011); economics of water reuse (Daniels and Porter, 2012; Listowski et al., 2013; Molinos-Senante et al., 2011) to its impacts on the environment, public health and safety (Peterson et al., 2011; Rose, 2007; Zhang et al., 2011) as well as social reactions of end-users (Hartley, 2006; Po et al., 2003; Russell and Hampton, 2006).

Water reclamation often refers to the treatment of storm-water, industrial wastewater and municipal wastewater for beneficial reuse (National Research Council, 2012). Its technical infrastructure basically comprises of transmission pipes, treatment facilities and distribution structures. Whilst the use of treated wastewater often bears larger financial, technical, and managerial challenges than conventional water sources, wastewater can be exploited at different levels for diverse end-use purposes (Chen et al., 2013). The degrees of treatment regarding to common methods were simplified and presented in Table 1. Raw or primarily processed wastewater was used for agricultural purposes in developing countries with arid or semi-arid climate such as Ghana, Bolivia and Mexico, regardless environmental degradations it may cause (Bernard et al., 2003; Landa-Cansigno et al., 2013; Zabalaga et al., 2007). This type of service should be banned for future use because its costs would exceed the benefits (World Bank, 2010). Fortunately, the highest fraction of reclaimed water came from the secondary treatment where organic compounds, suspended solids, and pathogens were substantially partially removed (National Research Council, 2012). It could be utilized for agricultural irrigation, landscaping, civil non-potable purposes, cooling or other industrial applications (Buhrmann et al., 1999; Carr et al., 2011; Gori et al., 2003; Lazarova and Savoye, 2003). However, nutrients, predominantly nitrogen and phosphorus, which can cause eutrophication while being discharged to the environment might not be removed in the conventional secondary treatment. These nutrients were commonly treated by chemical or advanced biological treatment in the tertiary treatment (Metcalf & Eddy et al., 2002). Therefore, more stringent requirements on nutrient removal would be requested for the environmentally sensitive areas. Thanks to the scientific innovations in membrane and nanotechnology, tertiary treatment techniques allowed refurbished wastewater to be used in advanced practices such as groundwater recharge of potable aquifer (Scottsdale Water Campus, the USA), surface water reservoir augmentation (Permian Basin, Colorado River Municipal Water District, Texas, the USA) and water supply (Cloudcroft Village, New Mexico, the USA) with more favorable economic value (National Research Council, 2012). Plentiful water reclamation projects have proven the economic efficiency between the expenditure on investment and profits in return (Nasiri et al., 2013).

Table 1 - Types of reuse appropriate for increasing levels of treatment (adapted from US EPA (2012)

| | | | | |
|---|---|---|---|---|
| | Increasing Levels of Treatment → | | | |
| Treatment level | Primary | Secondary | Tertiary | Advanced |
| Processes | Sedimentation | Biological oxidation | Chemical coagulation, biological or chemical nutrient removal, filtration, and disinfection | Activated carbon, reverse osmosis, advanced oxidation processes, soil aquifer treatment |
| End Use | No uses recommended | Surface irrigation of orchards and vineyards | Landscape and golf course irrigation | Indirect potable reuse including groundwater recharge of potable aquifer and surface water reservoir augmentation and potable reuse |
| | | Non-food crop irrigation | Toilet flushing | |
| | | Restricted landscape impoundments | Vehicle washing | |
| | | Groundwater recharge of non-potable aquifer | Food crop irrigation | |
| | | Wetlands, wildlife habitat, stream augmentation | Unrestricted recreational impoundment | |
| | | Industrial cooling processes | Industrial systems | |
| Human Exposure | Increasing Acceptable Levels of Human Exposure → | | | |
| Cost | Increasing Levels of Cost → | | | |

However, even with numerous studies carried out in this field, just a few papers observed the influence of the climate change on the reuse schemes. Thus, the paper conducts a systematic analysis of available findings to feature the influence of climate change factors such as temperature, rainfall regime and extreme events on water reclamation and reuse.

## 2 Opportunities of Wastewater Reclamation and Reuse

### *2.1 Social Perception*

The most critical factor determining the sustainability of the reclamation scheme is not lying on the technology itself but rather on public acceptance (Marks and Zadoroznyj, 2005). Despite the exploration of public attitude towards water reuse was only originated 20 years later than its first application, there was a substantial amount of studies evolved. However, this section does not aim to review the factors influencing public perceptions of water reuse, which was done extensively in Po et al. (2003. Instead, it observes how public perception about wastewater reclamation has been changed due to the influence of climate change. The available literatures were accordingly categorized into three groups with reference to different circumstances. The first category dealt with general public opinions on climate change and reclaimed water, not assigned to any specific reuse scheme. The second category examined public consultation with people towards a forthcoming water reclamation project while the third reviewed the satisfaction of those who already experienced the actual use of treated wastewater.

For the first category, political and public perception on climate change was considerably elevated. Independent surveys carried out to investigate awareness of different groups revealed positive results. For instance, over 78 % of local residents in Switzerland "perceived long-term changes in precipitation and/or temperature" and experienced its effects on the urban drainage and wastewater system in recent years (Veronesi et al., 2014). At the decision-making and expert level, the figure was much higher with 91 % of respondents in Florida Keys believing "climate change is real and impacts are felt today" (Mozumder et al., 2011).

There is a strong correlation between a willingness-to-pay (WTP) for tackling the impacts and the perception of risks or personal experiences associated with climate change (Veronesi et al., 2014). Stronger risk perception usually resulted in higher WTP. As people suffered a prolonged drought in Bendigo, Victoria (Australia), they were willing to pay an average amount of A$7.66 /kL[1] for recycled water delivered to their homes, compared to A$1.33 /kL of potable mains water charge in water use restrictions at the same time (Hurlimann, 2009). Interestingly, Canadian and Australian studies on the WTP for using reclaimed water in toilet flushing to avoid the water restriction exposed a noteworthy contradiction. While the level of acceptance in Canada is lower than the figure of Australia (80 % and 95 %, respectively), its WTP is substantially higher ($150 compared to $121 per year)[2] (Dupont, 2013). Therefore, besides perception of the climate change, there are other factors that influenced the WTP such as personal experience, income, preferences, age and knowledge (Dolnicar et al., 2011).

The secondary category related to upcoming projects. The ratio of people willing to use recycled water for non-potable purposes, not surprisingly, overweighed those for drinking purposes (Buyukkamacia and Alkan, 2013; Radcliffe, 2010). A greater support of reclaimed wastewater for agriculture, public utilities and low-contact purposes was well recognized (Boyer et al., 2012) whereas most of objections fell into projects with human close-contact such as California's Bay Area Water Recycling Program, Los Angeles East Valley Water Reclamation Project (the US) and Toowoomba (Australia) (Po et al., 2003). The public objections for indirect and direct potable uses mainly come from the lack of trust in public authorizes, health and environmental concerns (Dupont, 2013). Nonetheless, it seemed that public reluctance towards drinking purified treated wastewater was less serious than previously. A survey done by San Diego County Water Authority presented that the rate of people who strongly supported the use of reclaimed water for drinking dramatically shifted up from 12 % to 34 % whilst its strong opposition dropped from 45 % to 11 % between 2004 and 2011 (US EPA, 2012).

The last category aimed to assess the satisfactory level of real users. The results were harmony with the category two but the acceptance level of users was moderately uplifted. The enthusiasm of end-users towards recycled water was significantly improved as the projects had been properly implemented (Hurlimann, 2008). Medium- and low-contact purposes such as firefighting, landscaping, irrigation and toilet flushing attracted 85-96 % support from surveyed Israeli (Friedler et al., 2006). Another study for 5-year implementation of water reclamation for indoor uses at Mawson Lakes (Australia) provided more optimistic results when 94 % of interviewees were pleased with their recycled water. Contingent value of reclaimed water in this case increased from A$0.46 /kL in 2004, to A$0.49 /kL in 2005

[1] Surveyed in January 2009
[2] Value converted to value in 2005 for comparison

and A$0.89 /kL in 2007 (Hurlimann, 2008). Three most common advantages cited in reusing wastewater at the household scale were cost-saving (71 %), positive outcomes on the environment (36 %) and saving potable water (34 %) (Friedler et al., 2006).

The fact is that the success of advocating a wastewater reuse scheme depends greatly on the adopted communicative strategy and transparency of information (Dolnicar et al., 2011). Promoting a voluntary spirit (bottom-up) where people familiarized themselves with recycled water would result in a higher support than applying compulsory measures (top-down) did (Dolnicar et al., 2011). Hurlimann (2011) believed that as long as people involved their senses with reclaimed water, they tended to accept of recycled water for close to personal use. Trust on water authorities to ensure water quality and quantity was proportionally increased. These factors were proved effectively in Monterey County Water Recycling Project (California, the USA), when it spent more than 20 years of planning before its actual launch in 1998 (Po et al., 2003). Besides providing facts and figures from 5-year health research and 2-year food safety investigation (technology), supplying safe and reliable water source (environment) whilst creating a fair market (economic), this project focused on empowering local people by an intensive public involvement program (society). Therefore, a water reclamation project must utilize the mass media and larger communities for communicating scientific information about its benefits and risks to maximize the public understanding on water reuse (Marks and Zadoroznyj, 2005).

### *2.2 Water-reuse Market*

As 2030 Water Research Group (2009) predicted, with the current rate of water exploitation, the global annual water requirements in 2030 would be 6,900 billion $m^3$, exceeding more than 64 % of total accessible and reliable water source (4,200 billion $m^3$). Climate change was believed to worsen the situation (2030 Water Research Group, 2009). Therefore, the necessity of finding alternate resources like purified wastewater is seriously perceived by the governments. The increased perception on benefits of reclaimed water by both decision-makers and the public (as previously discussed) is an invaluable premise for development of the water-reuse market. As a consequence, the water-reuse market is experiencing favorable conditions from current policies.

First, national targets for wastewater reuse have been clearly regulated in the official documents. Specific goals for water reuse in different countries were set for different periods of time (Table 2). Taking Israel as an example, this semi-desert country in Middle East was the pioneer when it established the goal for recycling all of its domestic wastewater in the late 1980s (Friedler, 2001). At this moment, it is among leading countries in the world, in term of the effluent recycling ratio, with nearly 90 % of wastewater reclaimed (Rejwan, 2011). The country with highest wastewater reuse ratio is Cyprus with 100% of its treated wastewater is exploited for agriculture and urban amenities (55-60 %) (European Commission, 2013a; Mediterranean Wastewater Reuse Working Group, 2007).

In general, there are no official goals for the USA and Europe, with regards to wastewater reuse target. For both areas, the total rate of wastewater reuse was quite low, only taking account of 2-3 % of treated wastewater (European Commission, 2013b; Futran, 2013). However, the promises of wastewater reuse attracted the attention of the European Commission (EC) when it has currently implemented a project to promote the reuse of treated wastewater by 2015 (European Commission, 2013b).

Table 2. National targets for water reuse of selected countries

| Country | Recorded practice of wastewater reuse | Year | National target for wastewater reuse | Year | Reference papers |
|---|---|---|---|---|---|
| Australia | 16.8 % | 2009-2010 | 30 % | 2015 | Marsden Jacob Associates (2012) |
| China | 10-15 % (northern cities) | 2011 | 20-25 % (northern cities) | 2025 | Dow Water & Process Solutions (2011) |
| | 5-10 % (southern cities) | 2011 | 10-15 % (southern cities) | 2025 | |
| Cyprus | 100% | 2007 | - | - | Mediterranean Wastewater Reuse Working Group (2007) |
| Israel | 84 % | 2011 | 100 % | 2020 | Rejwan (2011) Futran (2013) |
| Mexico | 40.6 % | 2009 | 100 % | 2030 | National Water Commission of Mexico (2010) |
| Saudi Arabia | 30 % of municipal wastewater | 2010 | 50 % | 2015 | Al-Saud (2013) |
| | | | 100 % | 2030 | |
| | 10 % of industrial wastewater | 2010 | 40 % | 2015 | |
| | | | 80 % | 2030 | |

Moreover, the last decade indeed experienced a growth in the official guidelines for water reuse. As reported in Global Water Intelligence GWI (2010), 28 countries, predominantly developed countries, had established wastewater reuse standards and regulations. European Commission also developed a proposal to establish its common standards for all members to ensure the public health security, environmental protection as well as removing obstacles for agricultural products irrigated by treated effluent by 2015 (European Commission, 2013b). Developing countries, normally accompanied with water-constrained conditions, tried to adapt gradually the World Health Organization (WHO) guidelines (2006) for more flexible approaches. Although the United States did not set up the national target for effluent reuse, pioneering states adopted the regulations for mandatory connection to reclaimed water systems where it was available, such as California and Florida and some cities as Yelm (Washington), Cary (North Carolina) and Westminster (Maryland) (US EPA, 2012). This created advantageous conditions for future investments in water reuse industry.

Furthermore, playing ground in the water supply sector is more open to private companies. This sector was formerly seen as a monopoly of governmental organizations in most countries (National Water Commission, 2011), yet there was a tendency of socializing the water supply industry to share the financial burden of the Governments (2030 Water Research Group, 2009; National Research Council, 2012). Even though key actors of the total cycle water management were still local water authorities, private sectors could participate in the process by delivering professional service packages as in Public – Private Partnerships (PPPs) models (Szyplinska, 2012).

Finally, the monetary mechanisms for water reuse projects have been modified to attract the investors' interests (Szyplinska, 2012). The reclaimed water was perceived as a part of total urban water management and received similar subsidy like other water services (US EPA, 2012). For instance, in Australia, nearly half of $1.6 billion Water Smart Australia program (2008) by Australian Government Water Fund has contributed to water recycling projects (Radcliffe, 2010).

Thanks to the above factors, the water reuse market is very promising as GWI stated "the current trend of the global water market is mainly to expand water reuse capacity" (Szyplinska, 2012). Whereas the global municipal wastewater flow-rate was estimated about 680-960 million $m^3$ per day, only a small fraction (4 %), equivalent to 32 million $m^3$) was reclaimed in 2010 (GWI, 2010). With an increasing demand on resource saving, the quantity of recycled wastewater was expected to jump to 55 million $m^3$ in 2015 (Szyplinska, 2012).

Presently, the largest water-consuming sector is agriculture which made up 65 % of the global water demand (2030 Water Research Group, 2009). The same pattern was repeated in the water reclamation chart (World Bank, 2010). In fact, about one tenth of global crops was irrigated with sewage; unfortunately, in which only 10 % was properly treated (World Bank, 2010). Although treated wastewater could supplement necessary nutrients for plants, an important issue must be considered is the existence of emerging pollutants such as phthalates, polychlorobiphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), pharmaceutical compounds, personal care products, etc (Peterson et al., 2011). Since the compounds may enter the food chain through bioaccumulation and biomagnification, the utilization of reclaimed water should follow proper standards (Peterson et al., 2011). With more stringent regulations on the quality of irrigated water, the market of effluent reclamation for agriculture would be encouraging (Mekala et al., 2008; Yi et al., 2011).

It was anticipated that the water reclamation would shift from the dominant agricultural reuse to more advanced purposes in the near future (US EPA, 2012). Regions with expected high growth of advanced water reuse included USA, China, Saudi Arab, Australia, Spain, and Mexico (Table 3). The market revenue in advanced water reuse was supposed to escalate 19.5 % per year between 2009 and 2016 (GWI, 2010). Some industrial sectors already prepared plans for their reuse targets to maximize their profits through water and energy savings. The water reuse market, coupled with desalination, for water-critical industries (such as power generation, petroleum, petrochemical, food and beverage, pulp and paper, and microelectronics) was expected to gain the average growth rate of 11.4 % from 2012 to 2017 and achieved 12 billion USD by 2025 (GWI, 2012a). In another research, the revenue sale of supporting materials - membrane and membrane bioreactor (MBR) - for the water reuse was projected to gain a strong growth by 4 times to $3.44 billion in 2018 (GWI, 2012b).

Table 3. Projected reuse capacity in selected countries, 2009-2016 (adapted from GWI, 2010)

| Country | Additional advanced use capacity (Million $m^3$/d) |
|---|---|
| USA | 10.7 |
| China | 5.9 |
| Saudi Arab | 3.5 |
| Australia | 2.5 |
| Spain | 2.1 |
| Mexico | 2.1 |
| United Arab Emirates | 1.9 |
| Oman | 1.6 |
| India | 1.2 |
| Algeria | 1.1 |

The number of projects relating to direct potable reuse (DPR) and planned indirect potable reuse (IPR) is increasing, thanks to the successful demonstration cases on purified treated wastewater in Namibia, USA, and Singapore (Chen et al., 2013). In an attempt to bridge the gap between water supply and demands, the Governments are more enthusiastic to support these projects, as in case of IPR in Bangalore (India), Wulpen (Belgium) and Langford (UK) (US EPA, 2012). With lower marginal costs and more public acceptance, these projects tend to be more attractive to investors.

Another promising domain was on-site wastewater reuse for buildings and commercial complexes. These small-scale services did account for a small portion of water reuse market but the trend continued to grow constantly (Godfreya et al., 2009). One of the most common drivers was the environmental certification Leadership in Energy and Environmental Design (LEED). Water conservation was often included in the planning and design phase of new buildings to ensure the environmental-friendliness. Furthermore, opportunities for the market were benefited from the regulatory obligations (rather than voluntary actions) of installing the wastewater recycling or rainwater harvesting facilities for new buildings with large gross floor areas as in New Zealand and Japan (Rygaard et al., 2009). Representative cases could be referenced to the installation of MBR in a business complex building in Tokyo (Japan) in 2007 (IWA, 2013) or the black-water plant incorporated in Blight Street building (Sydney, Australia) in 2011 (Green Building Council of Australia, 2013).

# 3 Impacts of the Climate Change on Wastewater Reclamation and Reuse

Risks of the climate change on the water reuse industry can be classified into two groups – direct and indirect impacts. Direct impacts are defined as the influence of climatic factors on the technological performance, whereas indirect impacts are mainly involved with management and operation activities.

## *3.1 Direct Impacts of the Climatic Factors*

### *3.1.1 Temperature*

Influence of alternated air temperature by the climate change on wastewater reuse process was hardly studied. Only a few exceptions were found. Most of them occurred in high-latitude countries where winter-related practices were examined. Sustained high temperature in the winter with snow on the ground increased the influent flow-rate which exceeded the pumping capacity and put the pumping stations at a high risk, as in the case of Town of Prescott’s Sanitary Sewage System (GENIVAR, 2011).

In fact, temperature is one of the control factors of the treatment process (Metcalf & Eddy et al., 2002). Although wastewater generally has a buffer capacity to tolerate a mild fluctuated thermal array, temperature exceeding or below the optimal range will affect biological processes, especially with temperature-sensitive nitrifying bacteria (Eckenfelder and Wesley, 2000). The representative illustration was the Bekkelaget wastewater treatment plant (WWTP) (Olso, Norway). For the cold weather as in Norway, a minimum of 12 $^{o}$C was strictly set for wastewater temperature to ensure at least 70 % removal of nitrogen, or 15 $^{o}$C for optimal operation (Sallanko and Pekkala, 2008). To assess the impacts of altered air temperature on the efficiency of wastewater treatment, Plósz et al. (2009) conducted an extensive analysis of 6-year continuous data on meteorological indicators and treatment performance figures. They found that higher winter temperatures had a positive correlation with an increase in the number of melting points. As a result, stronger and colder influx generated from melting points significantly reduced temperatures of wastewater influent. The sudden drop in the wastewater temperature to below 10 $^{o}$C then greatly inhibited the nitrifying micro-organisms when the nitrogen removal was reduced with the rate of 6 % per 1 $^{o}$C decline (Plósz et al., 2009). They also noticed the thermal variation in the influent and mixed liquor in the secondary clarifiers weakened the separation capacity. The situation was even worse if the flow-rate of wastewater increased.

For temperate regions, little attention has been paid for the increase in the ambient temperature as it was commonly admitted that warmer climate would accelerate the reaction kinetics (Metcalf & Eddy et al., 2002) thus reduce the energy requirements. However, the warmer temperature was reported to create favorable conditions for corrosion of raw wastewater pipelines with the formation of hydrogen sulphide (KWL, 2008). In addition, it increased fermentation of solids in the sludge thickeners, which caused odor issues (KWL, 2008).

#### *3.1.2 Precipitation*

One of the most common impacts of climate change over the wastewater reclamation is the increase of rainfall intensity. Although some cities applied separated sewerage networks, most of urban areas still employed their aging combined systems to convey both municipal wastewater and storm-water together, even in the Europe and North America regions. These systems were very sensitive to rainfall intensity (Kessler, 2011; NACWA, 2009). The intensified rainfall regime may increase the sewage flow in the conveyance system by infiltration through cracks, improperly-constructed manholes or even direct inflow (O'Neill, 2010). Sewerage overloading scenarios with regards to climate change provisions were predominantly studied via hydraulic models (Mark et al., 2008; Semadeni-Davies et al., 2008).

Moreover, heavy rain affected the performance of wastewater treatment processes by increasing the pollutant concentrations, floatable materials and sediments in grit tanks or primary settling tanks at the beginning of the storm event. It was resulted from "first flush effect" as stormwater washed off roadway debris and sediments into the combined sewage system. More frequent cleaning of bar screens and grit chambers was required. Meanwhile, the wastewater characteristics changed considerably when wastewater was diluted with rain water and contaminated by toxic chemicals in roadway sediments (Samrania et al., 2004). Alternated influent constituents in turn modified the following biological processes such as activated sludge, nitrification/ denitrification or formation of sludge flocs (Wilen et al., 2006). Additionally, the quality of primary clarifier effluent was deteriorated due to a reduced hydraulic retention time (Schütze et al., 2002). The phenomenon was illustrated by a longitudinal study of Dommel WWTP (Eindhove, Holland) by Langeveld et al. (2013). After a long dry period (38 days), the heavy rainfall suddenly occurred. It immediately reduced the concentration of activated sludge in aeration tanks from 3 g/L to 1.5 g/L whilst surged the sludge loading from 0.05 kg BOD/kg MLSS (mixed liquor suspended solids) tenfold to 0.5 kg BOD/kg MLSS. The high organic loading rate accompanied with high nitrate concentration caused denitrification in the secondary clarifiers and created a gel-like scum layers on the surface. It took approximately 2 weeks to remove the scum layers and 5 weeks for the recovery of SVI (sludge volume index) to the designated value (100 mg/L).

### *3.1.3 Sea Level Rise and Severe Conditions*

Since most of wastewater collection networks were gravitational, treatment and reuse plants often located at the low-lying areas or in the coastal zone. The risks accompanied to sea level rise comprised of inundation, flooding, storm surges, erosion and salt water intrusion (Parry et al., 2007). Friedrich and Kretzinger (2012) carried out a model to estimate the vulnerability of wastewater infrastructure of coastal cities to sea level rise in South Africa, based on its size, connectivity and underground components. In addition, sea level rise can impact directly to the quality of recycled water by raising the salinity concentration (Howe et al., 2005).

Together with sea level rise, the severity of flooding, hurricanes, storms, cyclones and thunders was expected to be stronger under the impacts of climate change (Parry et al., 2007). The combination of warmer temperature, decreased variation between polar and equatorial temperature as well as increased humidity was expected to magnify the intensity of extreme events (Riebeek, 2005). The statistical numbers of natural catastrophes grew substantially from 1980 to 2013, especially in the period 2006-2013 with an average of 790 events per year (Münchener Rückversicherungs-Gesellschaft, 2014).

Catastrophic events can destruct partly or the whole wastewater reclamation scheme. The typical impacts were physical damages such as (i) destruction of treatment facilities, pump stations and sewer mains; (ii) interruption of treatment processes by disrupting the energy supply or spilling hazardous chemicals into the system; and (iii) shut-down of the plants or discharge of sewage to the surrounding environment (Moyer, 2007). Sandy (2012) and Colorado catastrophes (2013) were representative cases for these impacts. In September 2013, a storm hit the state of Colorado (the US). The wastewater treatment system was shut down, which left about 170-290 million gallons of raw and partially treated wastewater on the environment (The Denver Post, 2013). Just a year earlier, the Sandy Hurricane alone (2012) cost nearly $2 billion dollars to repair the damages on sewage treatment plants in New York and further $2.7 billion dollars for building up the resilient system (Kenward et al., 2013).

### *3.2 Indirect Impacts*

#### *3.2.1 Water Use Control*

Under the efforts to adapt to the climate change, water reduction programs were introduced (National Water Commission, 2011). On the one hand, it was good for the resource conservation. On the other hand, the volume of wastewater discharge to the transmission systems was proportionally decreased, but not the contaminant loading. As such, the strength of the wastewater increased and accelerated the corrosion rate of the conveyance system (Larsen, 2011). Furthermore, its amplified viscosity required more frequent cleaning services for the sewerage (O'Neill, 2010).

Ablin and Kinshella (2004) provided a good example of the influence of water restriction and warmer temperature on the occurrence of anaerobic sewers. The unlined concrete sewer system in Phoenix city experienced many advantageous conditions for the formation of hydrogen sulfide, including warm temperature, long retention time, and lack of metals due to source control program. The concrete was deteriorated unevenly by crown corrosion, springline corrosion and invert corrosion. It was suggested to use nitrate to prevention the existence of hydrogen sulfide, but then, its negative effect was a higher demand of nitrogen removal in the following treatment system (Larsen, 2011).

### *3.2.2 Green House Gas (GHGs) Emission*

Whereas the water reuse aimed to offset the climate change's impacts, the treatment itself still emitted the GHGs (Hardisty et al., 2013). The generation of GHGs in the treatment process has been underestimated for a long time when $CO_2$ production was presumably negligible because of its biogenic Carbon origin in the wastewater stream (Bani Shahabadi et al., 2009). This assumption did not reflect the facts that nearly 20 % of Carbon in wastewater originated from fossil fuel and energy consumption was also a GHGs emitter (Rodriguez-Garcia et al., 2012). Indeed, there were two sources of GHGs from a wastewater reclamation plant. While onsite GHGs ($CO_2$, $CH_4$ and $N_2O$) related to wastewater and sludge treatment activities, offsite GHGs ($CO_2$ and $CH_4$) came from energy demands, chemical production and transportation (Bani Shahabadi et al., 2009). Wastewater treatment and reclamation was blamed for an average of 56 % of GHGs emission in the water industry, as studied by Sweetapple et al. (2014. Subsequently, the "global warming potential" (GWP), a common measure of the total energy that a gas absorbs over a particular period of time (usually 100 years) in comparison to $CO_2$ (Solomon et al., 2007), was used as an indicator for assessing the impacts of GHGs emission from wastewater reclamation treatment plants.

Bani Shahabadi et al. (2009), along with other authors, made early efforts to quantify both onsite and offsite GHGs (only for $CO_2$ and $CH_4$) for various secondary treatment schemes with nutrient removal. Aerobic, anaerobic and hybrid treatment processes were examined in different scenarios of energy recovery and nutrient removal. According to their investigation, the energy retrieval from biogas could substitute power for the whole plant without further generating GHG emission. Regardless of energy recovery scenarios, hybrid and anaerobic treatment produced more GHGs ($CO_2$ and $CH_4$) than aerobic treatment did, mostly due to chemical consumption (methanol and alkalinity). This result was somewhat contradictory with previous findings (Cakir and Stenstrom, 2005), because of different process control parameters, perspectives on material consumption and consideration of $N_2O$ emission. Another study done by Chen et al. (2011) found the GHG generation rate of constructed wetland was only a quarter of that of cyclic activated sludge system for the same volume of municipal wastewater influent. These studies frequently applied mathematical models to estimate the quantity of GHGs. However, accuracy of the calculations was mysterious as different presumptions had been made to control the simulation. Indeed, determination of the sources and sinks of GHGs through the whole reclamation process was extremely complicated, since it depended on numerous variables such as (i) influent characteristics, (ii) treatment technology and equipment, (iii) operational and system control, (iv) effluent standard, and (v) reuse application and locations.

Following the Kyoto Protocol (1997) and Doha Amendment (2012), signatory countries set more stringent targets for GHGs reduction. As Bani Shahabadi et al. (2010) predicted, GHGs emission potential was likely to become a major parameter for selecting treatment technology. Wastewater reclamation was though confronting with a huge constraint amongst keeping low GHGs emission, ensuring a proper quality of treated water whilst retaining an economic efficiency. Despite the fact developed countries preferred to shift the treated wastewater towards a higher standard of organic compounds and nutrients to ensure the environmental safety; on-site GHGs emissions from the treatment process as well as off-site GHGs from energy input were substantially higher (Fine and Hadas, 2012).

In addition, nitrogen removal moderately intensified GHG generation rate (Bani Shahabadi et al., 2009) owing to high GWP of $N_2O$ (GWP = 298), an immediate product of nitrification. The important factors influencing the increase of $N_2O$ were (i) low dissolved oxygen (DO) concentration in nitrification, (ii) higher nitrate concentration in nitrification/ denitrification process, and (iii) low COD/N ratio (Kampschreur et al., 2009). $N_2O$ was believed to contribute for more than 90% of total GWP in the treatment (Préndez and Lara-González, 2008). Bellucci (2011) discovered a consistent $N_2O$ exhaustion rate (85 %) from aeration basins in three wastewater reclamation plants in Chicago. Townsend-Small et al. (2011) showed that $N_2O$ emission in nitrogen elimination in the wastewater reclamation plant in Southern California was tripled in comparison with a conventional treatment plant for COD (chemical oxygen demand) removal only. For the widespread reuse of treated wastewater for irrigation purposes, treatment process with nutrient removal appeared to be costly and extravagant. Townsend-Small et al. (2011) suggested the wastewater reclamation with nutrient removal should be exploited for advanced purposes such as indirect potable reuse, rather than agricultural irrigation.

Water reclamation plants must adopt green technology to reduce its GHGs through treatment process selection, process optimization and plant management in a near future (Radcliffe, 2010). The green technologies did not only imply to the treatment process itself, but covered innovations in equipment (EPA, 2013), process control (Préndez and Lara-González, 2008), as well as energy and resource recovery (Fine and Hadas, 2012; Liu et al., 2013). Prior to implementation of any measures, GHGs of the plant must be audited through a comprehensive life cycle assessment (LCA) from the influent till the end-use of treated wastewater and sludge (Rodriguez-Garcia et al., 2012; Sweetapple et al., 2014). A representative case study was Gippsland Water Factory project which won The Gold Banksia Environmental Award (2011) for incorporation of sustainability principles in the early stage of process design (pragmatic improvements in membrane bioreactors and independent power sources from its biogas).

In terms of treatment technology, Fine and Hadas (2012) promoted the application of anaerobic treatment technology to preserve nitrogen in the effluent whilst optimizing biogas and sludge production. Biogas recovery and wastewater-nutrient utilization would reduce 23-55% of the total GHGs emission (Fine and Hadas, 2012; Mo and Zhang, 2012). This result harmonizes with the conclusions from Bani Shahabadi et al. (2010). Sharma et al. (2012) recommended the use of $H_2O_2$/UV for disinfection following their investigation of $CO_2$ emission rates for $H_2O_2$/UV, $O_3$/UV, $TiO_2$ and $O_3$ (0.20; 5.54; 6.38 and 10.74 kg$CO_2$/kL, respectively). From the practical perspective, EPA (2013) listed numerous best practices being adopted to reduce the GHG emission, for example upgrading energy-efficient devices (Lake Bradford Road Water Reclamation Facility, Tallahassee, Florida), automatic control, especially with aeration regime (Kent County Department of Public Works, Delaware; Narragansett Bay Commission's Bucking Point Wastewater Treatment Facility, Rhode Island; Oxnard Wastewater Treatment Plant, California), combined with biogas recovery and co-generation (Struthers Water Pollution Control Facility, Ohio; The Clearwater Cogeneration Wastewater Treatment Plant, California).

### *3.2.3 Adaptation Measures*

The climate change urged significant responses from all countries to find proper adaptation strategies for remediating its negative effects. The conventional impacts and adaptation strategies are shown in Table 4. Basically, adaptation measures included but not limited to installation and operation of new systems, upgrading old ones, installation of protective structures around the treatment and reuse sites (NACWA, 2009). In NACWA's report (2009), the adaptation measures were grouped into four categories, with regards to influential factors. The higher precipitation regime required green infrastructure measures to reduce the run-off rate before entering the combined sewerage systems as well as rapid-response treatment technologies. Likewise, green infrastructure could help to eliminate the increased temperature. Another measure could be used in this case was mechanical cooling. To tackle increased sea level, sea protection walls would be built to reduce the risk of flooding to

WWTP and key infrastructure components. Finally, the reuse of wastewater required a new distribution system. Huge challenges have been encountered from these measures.

Table 4. Typical impacts and projected adaptation strategies for wastewater treatment and reuse (modified from NACWA (2009)

| Factors | Adaptation strategies |
|---|---|
| Changes in precipitation quantity and timing | • Reduce infiltration and inflow into sewers, flow diversion<br>• Green infrastructure to manage site run-off<br>• Rapid treatment |
| Changes in maximum temperature and other environmental variables | • Wetland treatment<br>• Riparian restoration<br>• Mechanical cooling<br>• Evaporative cooling<br>• Blending with cooler waste streams |
| Increased sea level<br>Increased flood events | • Installing levees and sea walls around WWTP and key infrastructures<br>• Hardening sewer collection systems to reduce infiltration |
| Collaboration between supplied water and wastewater | • A new distribution infrastructure |

The first issue was replacement of old systems or installation of new systems. Most of the countries had inadequate and insufficient systems for handling wastewater collection and treatment. Despite the fact that more than 80 % of wastewater was treated in high-income countries (Baum et al., 2013), a majority of their sewage systems was installed 30-50 years ago or even more (Willems, 2013). These systems were approaching their useful life (O'Neill, 2010), and rather old to cope with the new intensified rainfall regime (Mailhot and Duchesne, 2010). They need to be re-installed, repaired or replaced for the demand of climate change adaptation. The situation was more pessimistic in developing countries where the rates of connection to sewage collection networks were extremely negligible (Baum et al., 2013). In higher-middle income countries, the collecting rate was improved (53%), but only a third of collected municipal wastewater was treated (Baum et al., 2013).

The probability and severity of ultimate situations would definitely decide the cost of adaptation. This was reflected in the study of National Association of Clean Water Agencies (2009) where total cost for the adaptation program for the US was projected about 123-252 billion USD to 2050, excluding societal costs associated with disruptions to water and wastewater services. In a smaller scale as in New York, a rough estimation revealed that $315 million USD would be used for preventing the WWTP's damage cost (City of New York, 2013). Therefore, the adaptation cost towards climate change was too expensive and somehow infeasible for many countries where the fear of starvation overwhelmed any environmental stress.

The second challenge was determination of meteorological design parameters. In the past practices, meteorological data used for designing these systems were assumed to be static over their life cycle. The reality proved the contradiction when the climatic factors were not stable but changed faster under the shade of climate change (O'Neill, 2010). Revisions in intensity–duration– frequency (IDF) statistics and design storms have been proposed in the US, Canada, Belgium, Norway and Sweden (Mailhot and Duchesne, 2010; O'Neill, 2010; Willems, 2013). Although all of them agreed that the return of designated storm was shortened, the recurrence interval was not somewhat agreed. While O'Neill (2010) predicted that the recurrence interval should be shortened by 20-40 % for 100-year event, Willems (2013) expected a higher rate at 50% for the return period of 5-20 years. The differences may refer back to the applied climatic scenarios and models.

Last but not least, a controversial issue over a resilient reclamation project was the uncertainty of trend predictions (Major et al., 2011). Three common factors that contributed to the uncertainty were: (1) long projection period, (2) insufficient data to forecast future climate scenarios, and (3) sophistication of the model (Hughes et al., 2010; Mailhot and Duchesne, 2010; O'Neill, 2010). It definitely hindered efforts of scientists to persuade the decision-makers to judge on such type of project.

## 4 Conclusion

In this paper, a wide range of documents has been analyzed to provide a synthetic outlook on the impacts of climate change on wastewater reclamation and reuse. Under the influence of climate change, alternate water source like recycling water should be viewed as a necessity, not an option. Indeed, the opportunities and threats posed by the climate change for the water reclamation industry were interwoven.

While the climate change provided a prosperous market with higher willingness on the use of reclaimed water, it challenged treatment processes by imposing various pressures on the technical performance of the plants through direct factors such as changing rainfall regime, temperature and extreme events. To date, these impacts have hardly been studied thoroughly where only few studies reported the influence of the climatic factors on the treatment and reuse performance. This could be partly explained by the lack of meteorological and performance data over a long period of time. As a result, limited adaptation measures have been proposed for tackling impacts of climate change on the operation of the treatment and reuse. Likewise, the investigation on indirect impacts is rather negligible. Three emerging topics, including water use control, GHGs emission and adaptation measures, were addressed in this paper.

From this review study, some prospective topics are recommended for future research on:

- Influence of the combination of fluctuated climatic factors on the reuse schemes;
- Multi-criteria assessment of wastewater reuse schemes with regards to life cycle inventories;
- Auditing the GHGs emission from wastewater treatment and reuse plants and the offset capacity of GHGs generation from reuse activities.

**Acknowledgments**

The authors acknowledge Sustainable Water Program - Wastewater treatment and Reuse Technologies, Centre for Technology in Water and Wastewater (CTWW), School of Civil and Environmental Engineering, University of Technology, Sydney (UTS) and UTS – Vietnam International Education Development Scholarship.

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