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Urban water infrastructure: A critical review on climate change impacts and adaptation strategies

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ABSTRACT

Urban water infrastructure (UWI) plays a critical role in achieving sustainable development goals (SDGs) by providing safe drinking water, sanitation, and wastewater management, and contributing to sustainable cities. However, UWI faces significant challenges, including the high cost of failure in the face of devastating natural disasters increasingly caused by climate change. Many current infrastructures, built years ago, are not adapted to climatic changes, posing a threat to both UWI functions and the SDGs they support. To address these challenges, this study critically reviews recent research on UWI performance under climate change conditions, the impacts of climate change on long-term sustainability, and potential adaptation strategies. The present study suggests that incorporating the effects of climate change and sustainability criteria into UWI is essential. The results also reveal that severe flooding and water shortages are the most significant impacts of climate change on urban water infrastructure. Furthermore, the effects of other climate parameters, such as temperature rise due to the global warming phenomenon, should not be underestimated.

1. Introduction

Urban water infrastructure (UWI) encompasses a wide variety of elements and structures that serve numerous functions, including but not limited to water abstraction, water supply, water transfer, energy generation, water treatment, wastewater collection, wastewater treatment, and treated wastewater management, and flood defence systems (Alamdari and Hogue, 2022; Borgomeo et al., 2023). These components must work together as a complex yet integrated system to meet the needs of the current population and future generations (Behzadian and Kapelan, 2015). Effective WI is essential for ensuring a reliable supply of clean water for drinking, agriculture, and industrial processes. It facilitates the efficient transfer of water across regions, balancing areas of surplus and deficit (Kourtis and Tsihrintzis, 2021). Additionally, the integration of energy generation within UWI systems, such as through hydroelectric power, contributes to sustainable energy solutions (De Souza Dias et al., 2018). Water treatment and wastewater management are critical for maintaining public health and environmental quality. Treatment processes remove contaminants from drinking water,

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ensuring it is safe for consumption, while wastewater treatment and management systems process sewage and industrial effluents to prevent pollution and protect water bodies (Zouboulis and Tolkou, 2015).

Despite their significant roles, UWI must be resilient and adaptable to address challenges, particularly those posed by climate change (CC), population growth, and urbanisation (Nasr et al., 2020). The design and construction of UWI systems are highly complex, involving considerations such as geological, hydrological, hydraulic, structural, economic, political, and environmental factors, which are often uncertain (Fluixá-Sanmartín et al., 2018). However, among these factors, the resilience of UWI systems heavily depends on their ability to adapt and respond to climatic variables such as precipitation patterns, wind speeds, wind directions, and extreme temperatures, which are particularly challenging to predict, especially over the lifespan of these projects, which typically ranges from 20 to 100 years (Hughes et al., 2021).

Climatic variables, particularly changes in precipitation and temperature, are attributed to CC which refers to long-term shifts in average or extreme climatic conditions, notably temperature and precipitation (Girotto et al., 2024). The warming projections indicating a potential increase in global temperatures ranging from 1.8 to 3.7 °C by the end of this century expect severe adverse effects on global ecosystems and human settlements (Özerol et al., 2020). Specifically, it will lead to increased frequency and intensity of heatwaves, altering the distribution patterns and intensity of rainfalls, and accelerating the melting of glaciers and polar ice caps (Dasgupta et al., 2022). Furthermore, these climatic changes are likely to exacerbate the occurrence of natural disasters such as flash flooding, storm surges, hurricanes, and thunderstorms worldwide (Alamdari and Hogue, 2022).

In this context, the CC impacts on various aspects of human life and built systems remain uncertain, as different elements may react differently to these changes (Zolghadr-Asli et al., 2019). The effects of CC on UWI are particularly significant (See Table 1), because they are constantly exposed to these environmental conditions, with water being their primary load. Review papers, as shown in Table 1, have made significant efforts to map out these impacts, primarily focusing on how CC affects individual components of UWI. They mainly have focused on water abstraction systems and urban drainage systems. However, it seems that there is a need for more in-depth critical analysis to comprehensively understand how CC impacts should ideally be analysed across integrated components of UWI. This approach ensures that all sustainability perspectives are addressed in strategic planning for UWI components (Behzadian and Kapelan, 2015).

To address this, the present study aims to provide a comprehensive review of the potential impacts of CC on all major UWI components and present possible adaptation strategies both individually and collectively. The unique feature of this study is the critical analysis of all potential impacts, adaptation strategies, and recommendations for UWI in response to climatic risks in the literature. The results of this study can be used by designers, consultants, contractors, developers, decision-makers, policymakers, and researchers in the related fields to the topic, and works towards the climate action, which calls for a need to increase public awareness and institutional capacity on CC mitigation, adaptation, impact reduction, and early warning.

2. Research design and methodology

Seven search and screening strategies (S1-S7) were employed, as shown in Fig. 1. The preferred reporting items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and checklist were used to refine the selection of papers (Moher et al., 2009). These steps are outlined as follows:

Table 1
Recent papers on the impact of climate change on urban water infrastructures*.

Review scope	Main drivers	Main findings	Reference
Urban drainage systems	CC, AS	Describing precipitation patterns under CC is a challenging issue that affects drainage systems' design and operation.	Arnbjerg-Nielsen et al. (2013)
Urban drainage systems	CC, UI, AS	For making urban drainage systems sustainable, CC and urbanisation effects should be considered in their design.	Zhou (2014)
Hydropower plants	CC, AS	The rate of CC impact on hydropower potential depends on geographical location.	Sample et al. (2015)
Earthen flood defence infrastructure	CC	Although geotechnical failures rarely happen, CC has various effects on geotechnical infrastructure.	Vardon (2015)
Wastewater treatment plants	CC, AS	The impacts of CC can be classified into direct and indirect effects regarding water and infrastructure.	Zouboulis and Tolkou (2015)
Urban drainage systems	CC, UI, AS	Adaptation strategies should be carefully selected to adapt urban drainage systems against the combined impacts of CC and urbanisation.	Yazdanfar and Sharma (2015)
Hydropower plants	CC, AS	Hydroelectric dams can be employed to reduce the CC impacts.	De Souza Dias et al. (2018)
Dams	CC	Incorporating CC in dam's risk analysis has not been fully investigated.	Fluixá-Sanmartín et al. (2018)
Bridges	CC, AS	There are a broad range of CC effects that can affect both bridges and other infrastructures, and the associated adaptation strategies can be used for all of them.	Nasr et al. (2020)
Wastewater systems	CC, AS	The CC impacts can be categorized into three domains, including those related to water quality, flooding spills and odour, and infrastructural damages.	Hughes et al. (2021)
Urban drainage systems	CC, AS	Many items such as flood warning and forecasting systems, insurance-related measures, and public understanding have been regarded sufficiently in the literature.	Kourtis and Tsihrintzis (2021)

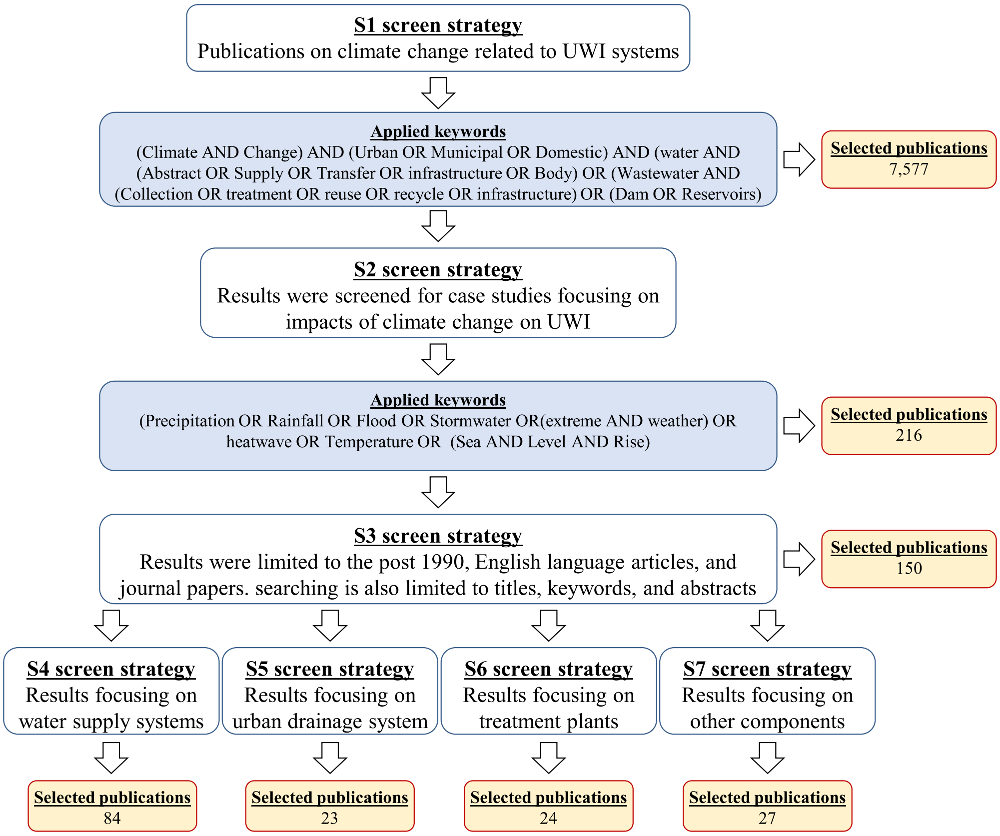

Fig. 1. Flowchart of screen strategies for selecting research works used in this study.

2.1. Search Strategy

The initial search strategy included keywords such as "climate change" and various components of UWI systems (see S1 applied keywords in Fig. 1). These keywords appeared in the bibliographic information (title, keywords, and abstract) and were related to study characteristics including research design and theories or models used, key findings such as main results, conclusions, implications, and methodological quality, including the strengths and limitations of the study (Higgins et al., 2023). Boolean operators (AND, OR, NOT) were used to combine the keywords effectively in the search query (Kumar and Thilagam, 2019). UWI components were also selected based on the classifications provided by Asano et al Verhagen and Visser (2007) and Hamil (2011). The search identified 7577 papers related to climate change and its connection to UWI in S1.

2.2. Screening Process

The initial results were refined to include only case studies that discussed the impact of climate change on UWI, resulting in 216 publications in S2. In this step, the demonstrated keywords from S2 shown in Fig. 1 are applied based on classifications provided by CRED (2024). This indicates that while many publications acknowledged climate change as a significant factor, they had no focus on its specific impacts on their research. The search was further narrowed to include studies published post-1990, coinciding with the first IPCC assessment report which investigates knowledge on climate change, its causes, potential impacts, and response options (IPCC, 2023). Older studies were excluded from the final database when more recent, comprehensive, and informative studies were available. Furthermore, selected case studies are limited to English language journal articles, peer-reviewed works, and focusing on titles, keywords, and abstracts. The papers were then fully screened, and the methodological quality of each article was assessed using the PRISMA checklist. By excluding those articles not meeting the quality standards, 150 articles were then selected in S3.

2.3. Coding Process

The selected papers were then labelled based on grounded theory (Hirschfeld and Hill, 2022), involving the identification of key concepts (open coding) and broader themes (axial coding) which were then integrated into a coherent narrative to address the purpose of the study (selective coding). These selected papers are classified into the four groups following the recommendations of UN-Water (2023): 84 papers on water supply systems (S4), 23 papers on urban drainage systems (S5), 24 papers on treatment plants (S6), and 27 papers on other components (S7). Each selected paper was finally synthesised using two methods of narrative approach to interpret the findings within the context of existing literature, and quantitative approach to combine similar studies for meta-analysis (Higgins et al., 2023).

2.4. Mapping UWI on UN sustainable development goals

Table 2 and Fig. 2 map various united nations sustainable development goals (UN SDGs) onto the UWI components and highlight relevant challenges to achieve SDGs. It can be observed that some are affected directly while some see indirect impacts. Nine SDGs can be mapped directly onto UWI components. SDG #2 (i.e., zero hunger) highlights the need for sustainable and productive agriculture that involves agricultural approaches and infrastructure. SDG #7 dictates affordable and clean energy that involves hydropower systems as a predominant source of energy generation in many countries. Reducing the hazards of climate-related extremes on the poor and vulnerable people can help end poverty, as stated in SDG #1, and can be achieved through flood mitigation infrastructures (dams, levees, and urban drainage systems). Pollution propagation and water quality are stated several times in various goals through different terms and conditions, which affect human health and ecosystem that depends on UWI – water quality can be controlled and is affected where it is stored (natural and artificial reservoirs), gathered (watersheds, urban areas, rainwater harvesting systems), or conveyed (irrigation canals, water distribution systems, drainage networks). Affordable, safe, and sufficient water resources must be provided to fulfil different targets, e.g., preserving water-related ecosystems. Some targets indicated the need for enhancing infrastructure and focused on urban life and cities. Other targets depend on informing societies, public and international collaboration, and performing research.

3. The impact of climate change on water infrastructures and adaptation strategies

Although the importance of UWI in achieving SDGs and providing basic city services is undeniable, reported failures suggest that the current practices are insufficient to protect infrastructures against environmental stressors such as CC (Mishra and Sadhu, 2022). The following sections will discuss the probable CC impacts on UWI and recommend strategies for climate adaptation.

Table 2
Linkage between UWI and the UN sustainable development goals.

SDG aspect	Challenges	Type of impact	References
SDG1: Poverty	Exacerbating poverty due to increased water scarcity and unequal access to basic water services	Direct	Shi et al. (2022)
SDG2: Hunger	Increased malnutrition and vulnerability to agricultural productivity due to lack of access to reliable water resources and crop loss from extreme weather events	Indirect	Vahedifard et al. (2018)
SDG3: Health	Health and well-being threats due to lack of access to safe water and sanitation and increased spread of vector-borne diseases related to flooding	Direct	Girotto et al. *(*2024)
SDG4: Education	Physical loss of educational centres due to extreme weather events	Indirect	Martoredjo and Benny (2023)
SDG5: Equality	Increased unpaid labour for women and girls in providing daily water needs or disposing of wastewater	Indirect	Reddy (2008)
SDG6: Water and sanitation	Decreased equitable access to clean, safe, and affordable water and safely- managed sanitation, leading to decreased water quality and ecosystem threats	Direct	Kimbrough (2019)
SDG7: Energy	Decreased efficiency or lack of access to sufficient hydropower or offshore wind electricity, leading to economic and physical damage to energy infrastructures, especially for local and decentralized renewable energy facilities	Direct	Farfan and Breyer (2018)
SDG8: Economic	Threatening water-related economic growth and productivity due to lack of water and wastewater infrastructure and components	Indirect	Jevrejeva et al. (2018)
SDG9: Industry	Obstacles to develop or upgrade resilience and sustainable water infrastructures and industries	Direct	Grigg (2019)
SDG10: Inequality	Facilitating unsafe migration and social exclusion due to inappropriate water infrastructure access	Indirect	Bakhtiari et al. (2024)
SDG11: Cities and communities	Increased inadequate and unsafe basic water services, leading to increased deaths or affected population related to water-related disasters and decreased access to open and green public spaces disrupted by extreme events	Direct	Ferdowsi et al. (2022b)
SDG12: Consumption	Obstacles to efficient use of natural water resources due to water scarcity, flood damages, and inappropriate wastewater management	Indirect	Dikanski et al. (2018)
SDG13: Climate	Decreased resilience and capacity to climate-related events and disasters	Direct	Genivar (2011)
SDG14: Aquatic life	Increased marine pollution near cities and threats to coastal ecosystems	Direct	Cerco and Noel (2016)
SDG15: Plants and animals	Threatening of freshwater ecosystems and their services due to increased risk of droughts and floods	Direct	Auestad et al. (2018)
SDG16: Peace and justice	Increased risk of local, national, or international water climatic conflicts, especially in water allocation, flood management, and wastewater transmission	Indirect	Vairavamoorthy et al. (2008)
SDG17: Partnership	Decreased chance of resource mobilisation, capacity, data monitoring, and multi-stakeholder partnership building to improve sustainability worldwide	Indirect	Bakhtiari et al. (2023)

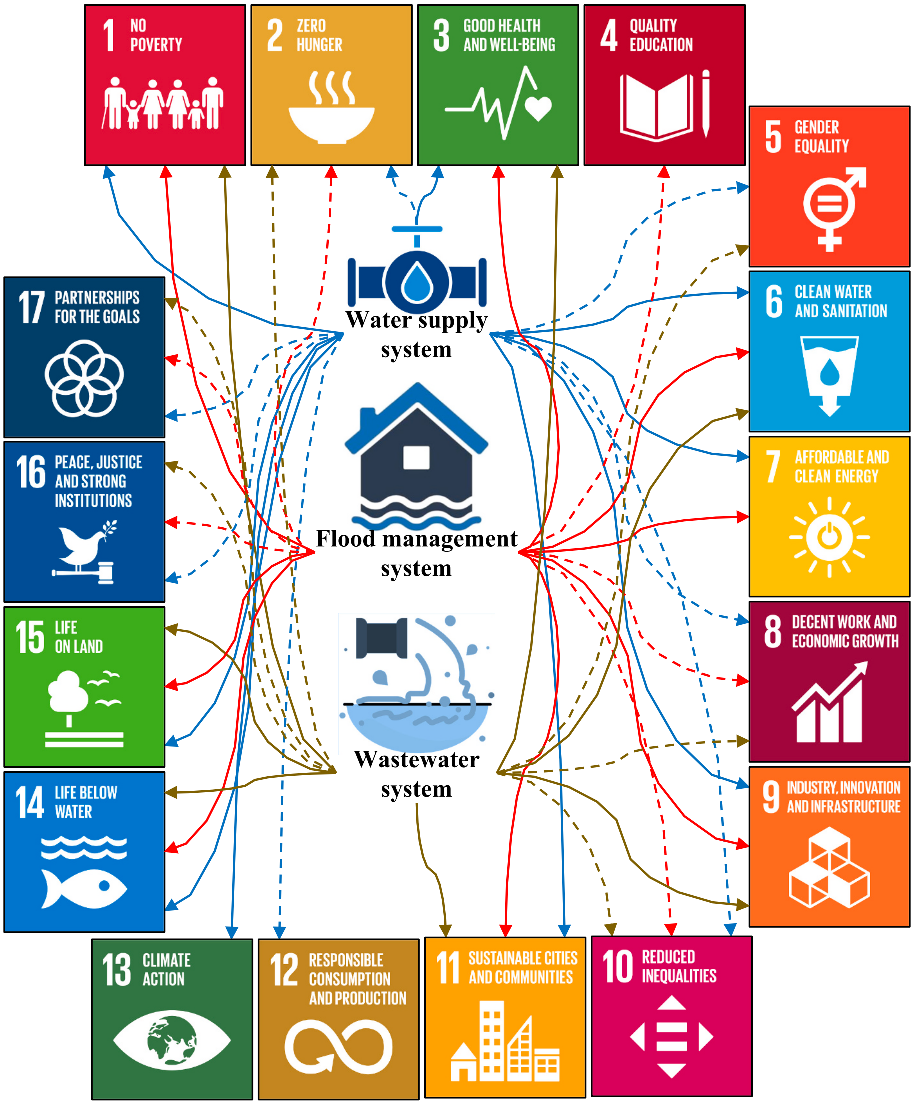

Fig. 2. Breakdown of UWI and the UN SDGs (the figure structure was inspired by Piadeh et al. (2024) and content was inspired by references documented in Table 2).

3.1. Water supply systems

3.1.1. Urban dams, reservoirs, and main water bodies

Dams have different types/functions and consist of many ancillary structures and elements. Among all common types of dams, embankment dams built with erodible materials can be more prone to CC impacts (Atkins, 2013). However, these dams are the most popular types (i.e., 85–90 % of all dams are among this category) due to technical and economic reasons (Novak et al., 2007).

Design flood is one of the most important parameters in dam design, that is calculated according to hydrological studies. Probable maximum flood (PMF) is an important mandatory approach to determine design flood, with a return period of at least 100,000 years (Transportation, 2004). Noticeably, the PMF estimated by different hydrologists using the same data can have a ± 15 % difference, which highlights the uncertainty in the design flood calculation. Probable maximum precipitation (PMP) is the most important parameter in the calculation of PMF, which traditionally neglects the CC effects (Clavet-Gaumont et al., 2017). Recent works have attempted to incorporate climate models into PMP calculation (Rouhani and Leconte, 2016). CC can affect dams' capacity and operation (Ehsani et al., 2017). Table 3 reviews the potential effects of precipitation/temperature increase as a result of CC, and adaptation strategies to mitigate CC impacts are summarised in Fig. 3.

During flooding, releasing valuable winter-derived runoff seems inevitable to safeguard the dam body against dam failure. Therefore, the flood control capacity of reservoirs by discharging excess water should be provided, and optimal reservoir policies can be employed. In addition, optimisation methods can be combined with simulation models (Che and Mays, 2017) not only to mitigate

Table 3
Major impacts of climate change on dams.

CC feature	Impact	Reference
Increased precipitation	Higher soil erosion rates and consequently an increase of sediment load to dam reservoir, which can result in less capacity for floodwater trapping and or less effectiveness of flood mitigation	Chen et al. (2020)
	Less capacity for water supply as a result of increased sediment load	Cerco and Noel (2016)
	Less expected dam service life	JHCSEE (2002)
	More expenses for water treatment	Ustaoğlu and Tepe (2019)
	More problems for the operation of lower intakes and spillways	JHCSEE (2002)
	Increasing overtopping probability and dam breach	Temple and Hanson (2005)
	Limiting the recreational use of the reservoir	JHCSEE (2002)
Increased temperature	Water quality deterioration	Azadi et al. (2019)
	Increase in treatment costs; threatening aquatic ecosystems; increased evaporation (causing water supply and water quality problems); causing dam surface cracks	Ghaemian (2006)
	Jeopardising tourists' and workers' health	Kovats and Hajat (2007)
	Causing snow melting and contributing to more flood formation during spring season	

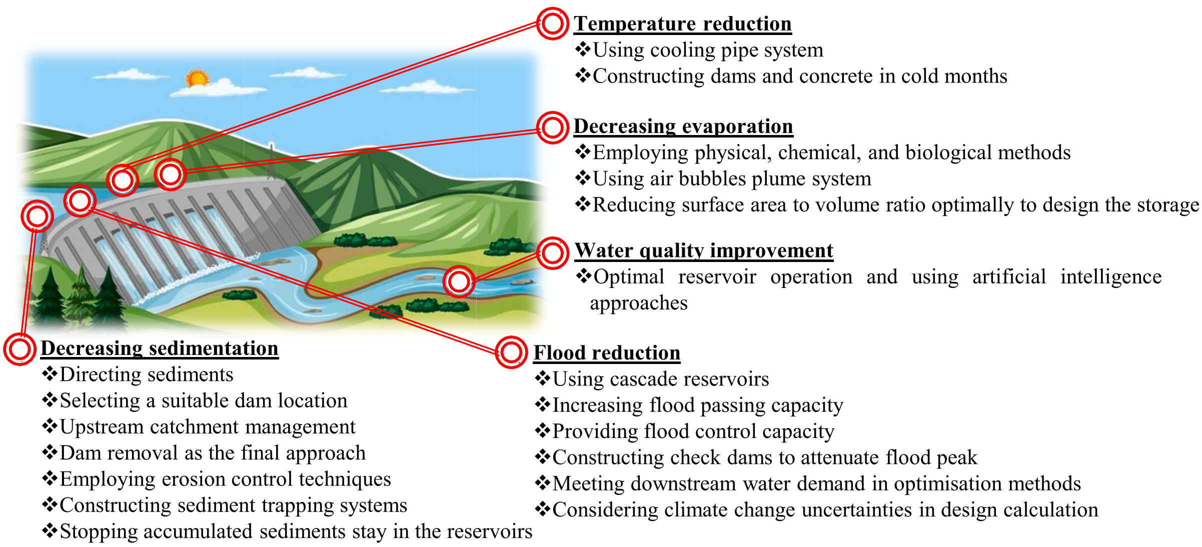

Fig. 3. Main climate change adaptation strategies used for dams and reservoirs (Inspired by Temple and Hanson (2005); Cerco and Noel (2016); Chen et al. (2020); Ustaoğlu and Tepe (2019); Azadi et al. (2019)).

flood damages but also to meet downstream water demands. Using cascade system is proposed in Fig. 3 to mitigate flood risk, which can be considered if a single reservoir is unable to provide enough capacity to maintain floodwater. Cascade reservoirs must work together (Zhou et al., 2018) as a hybrid flood-protection system. Flood- passing capacity of dams can be increased by facilitating existing dams with more spillways or with higher-capacity spillways, and by constructing check dams to attenuate flood peaks (Yazdi et al., 2018).

The frequency of intense rain events can increase in changing climate conditions, which results in higher soil erosion rates and consequently increase of sediment loads to the dam reservoir. The current rate of annual water loss due to sedimentation is estimated to be approximately 0.5 % to 1 % of total dams' storage capacity while this rate is exacerbated under CC conditions (JHCSEE, 2002) that can be mitigated by the measures listed in Fig. 3. In case of an increase in sediment rate, one of the following strategies may be followed: stopping sediments entering the reservoir (or reduce their amount) by constructing sediment trapping systems, e.g., check dams (Al-Janabi et al., 2020), employing erosion control techniques (Sumi et al., 2004), by catchment management, as a preventive method (Johansson and Sellberg, 2006) such as increasing managed vegetation cover (Szalińska et al., 2020) at the upstream basin, stopping the sediments accumulating in the reservoir by flushing through spillway (Khatsuria, 2004), regular hydraulic dredging (Castro and Mantilla, 2021), and dry excavation (Kantoush et al., 2010); directing sediments through sediment bypass (like Asahi Dam sediment bypass system in Japan, as an example), off-stream reservoirs, sediment sluicing systems, or venting of turbid density flows (Sumi et al., 2004); dam removal may be taken as the final approach to release accumulated sediment of reservoirs and selecting a suitable dam location can reduce the probability of sedimentation-related problems. However, the CC can lead to the reduction of sediment load in some regions or under some emission scenarios (Bussi et al., 2014) through precipitation reduction and temperature increase. It should also be noted that sediment rate is more susceptible to runoff impacts and land cover than increased precipitation due to the CC and hence vegetation cover and soil characteristics can remedy sediment load (Lu et al., 2013).

The conditions of climatic parameters such as air temperature, wind patterns, and precipitation have a significant effect on natural and artificial reservoirs' thermal structure, chemical status, phytoplankton growth, sediment load, and nutrient levels, which finally affect water quality (Firoozi et al., 2020). Therefore, the CC can result in altering climatic variables (e.g., air temperatures and consequently surface and bottom water temperatures in the reservoirs) and consequently the reduction of water quality (Azadi et al., 2019). This can also threaten aquatic ecosystems, and all living creatures, as well as an increase in treatment costs. This may also result in future biological changes and the condition of freshwater ecosystems (Gerten and Adrian, 2000). As stated in Fig. 3, optimal reservoir operation, specifically using artificial intelligence approaches, can alleviate water-quality-related problems (Aalami et al., 2018). However, as recently well reported by Bartlett and Dedekorkut-Howes (2023), the investigation of CC impacts on water quality was mainly neglected, and most attention was paid to water quantity in the literature.

Concrete is extensively used in dam construction that highlights the significance of the cement hydration reaction in this process. During operation, surface cracks often develop in gravity dams due to tensile stresses caused by temperature gradients near the surface. In the case of arch dams, downstream cracks are primarily attributed to thermal loads, more so than to other factors such as self-weight and hydrostatic pressure (Sheibany and Ghaemian, 2006). Consequently, implementing protective methods to regulate temperature and prevent cracking is essential for the longevity of dams (Wang et al., 2018). Although research on temperature control and crack prevention has been ongoing since the 1930s, the CC has also exacerbated these temperature-based impacts.

Evaporation due to temperature increase in a changing climate may affect water quantity and quality. Evaporation increases water salt content, which makes the potable water become saline, brackish, briny, and then bitter as well as water supply reduction (Bąbel and Schreiber, 2014). Evaporation can significantly decrease water levels – approximately 25 % of the water used in agriculture, industry, and households evaporates worldwide (Haghighi et al., 2018). Up to 40 % of some storage bodies in Australia is lost due to annual evaporation (Craig et al., 2007). A variety of physical, chemical, and biological approaches have been proposed in the literature to address reservoir evaporation issues (Schmidt et al., 2020). These measures can also be effective in mitigating increased evaporation resulting from the CC. Physical techniques mainly include continuous and modular covers in the shape of floating or suspended (fixed) objects over the water surface as well as air bubble plume systems by injecting air bubbles into water (Yao et al., 2010). Examining multiple elements (shade balls, shade cloth, aqua caps) and materials (foam, polystyrene, wax, MDF sheets) shows that physical techniques can reduce evaporation up to 95 % (Youssef and Khodzinskaya, 2019). Note that water footprint and other unintended consequences (Konar and Marston, 2020) should be considered in advance of using any physical solution (Haghighi et al., 2018). Solar photovoltaic cover is another physical method that has recently attracted a lot of attention (Farfan and Breyer, 2018). Chemical and biological methods have been less efficient than physical techniques. In addition, employing supplementary techniques, e.g., windbreaks such as embankments and trees, can reduce wind velocity and evaporation rate while this method is more suitable for small reservoirs (Helfer et al., 2010). The effect of tree roots on potential seepage should be also considered (Schmidt et al., 2020). Reducing surface to volume ratio can be proposed as a general tip for designing the storage to reduce the evaporation loss rate (Watts, 2005; Schmidt et al., 2020).

As the design of the spillway is based on PMP and PMF or, in general, input flow to dams, increased flood due to the CC impacts could greatly impact the spillway design and safety (Ferdowsi et al., 2020). Recent research has attempted to consider the CC effect for identifying design floods (Rouhani and Leconte, 2020). However, employing adaptation strategies to mitigate current spillways against the CC is vital. The first step may entail recalculating design floods for the constructed spillways. If the design flood is insufficient for future conditions, some measures can be applied. A new spillway can also be built to supply additional water-passing capacity. The discharge capacity of the spillway is directly related to its crest length and hence, one problem with constructing a longer spillway, with greater discharge capacity, might be space limitation (Ferdowsi et al., 2019). Since valley width is almost a constant parameter, the construction of a longer spillway might not be possible in all cases. Labyrinth and piano-key spillways are the nonlinear types of spillways that could have longer crest in a specified width, compared to linear spillways, and consequently have higher discharge capacity. In some cases, a fuse gate can be proposed as an emergency spillway on existing dams that normally uses an erodible embankment (Khatsuria, 2004).

Hydro-mechanical elements can experience more pressure or even failure under CC conditions when there are more demands in case of population growth or a warm climate. CC can increase sediment content in the water conduit. Sediments could cause abrasion and erosion of these devices and large floating debris could block them and consequently cause more risks, particularly in flood mitigation systems (Paxson et al., 2016). Correct maneuvering of these elements can also be a function of temperature. They may endure additional stresses or even deformations when exposed to high/low temperatures. Blockage or malfunctioning might be the outcome of these stressors (Fluixá-Sanmartín et al., 2018). Removing suspended loads from water conduits can reduce damage to the hydro-mechanical equipment. Using resistant materials can reduce the concerns of deformation and abrasion in these tools to some extent, as well.

3.1.2. *Energy generation*

Hydropower plants are disputed as a source of generating renewable energy because they contribute to reducing carbon emissions, although in some studies only small-size hydropower plants are considered as a source of renewable energy (Brożyna et al., 2019) and large ones are excluded from renewable energy sources due to their harmful impact on the environment (Auestad et al., 2018). Regardless of the aforementioned issues, they are the main sources of electricity generation in some countries such as Canada, Norway, Paraguay, Brazil, and Austria (De Souza Dias et al., 2018). Their importance and great contribution to supply energy necessitates outlining the possible impacts of CC on their performance and conditions. Probable impacts of climate variables on hydropower systems are reviewed in Table 4. As can be seen in this table, a reduction in precipitation as well as an increase in temperature can cause several problems for hydropower generation and can prevent plant operation.

Hydropower plants are classified based on their characteristics into two main types, including run-of-river and reservoir. Table 5 compares the positive and negative features of run-of-river and reservoir plants in response to the CC. The information in Tables 4 and 5 can be used by planners and decision-makers to select the appropriate type and capacity of future hydropower plants for the location of interest. Run-of-river hydropower systems are more environmentally friendly and preferred to reservoir hydropower (Hidrovo et al., 2017); however, they are more vulnerable to climatic changes. Therefore, future works need to focus on site selection for run-of-river plants. This may lead to avoiding their construction in watersheds vulnerable to streamflow reduction and focusing on rivers with more discharge. Table 5 shows that a reservoir hydropower plant has also its inherent pros and cons; for example, it is less vulnerable to streamflow changes, particularly when the CC can reduce summer streamflow and increase winter streamflow.

Strategies provided under the dams section (e.g., methods for reducing evaporation from the water surface, floating debris, and sediment load reduction) can be used to make hydropower plants to be more climate-adapted. Installing two sizes of turbines (large and small) for efficiency increase in a changing climate was also proposed in the literature – small turbines can be used for summer flow (when there is less discharge) while larger ones are used in winter (when there is high discharge), which entails additional costs (Sample et al., 2015). Employing an optimal operation policy and rules; runoff prediction under the CC, considering future climate risks in plants' management; facilitating plants' infrastructure for future CC-related changes; modernising plants' infrastructure; land-use management to decrease erosion; vegetation growth control; flow regulation measures considering seasonal flow regimes; along with considering performance criteria, including reliability, resiliency, and vulnerability could also help to mitigate CC effects.

3.1.3. Water distribution system

Water distribution system (WDS) is a combination of various hydraulic and hydro-mechanical elements such as tanks, pipes, pumps, valves, etc., which is considered one of the most important urban infrastructures with a key role in living standards and health. An increase in water demand due to a warming climate, population growth, urbanisation, and industrialisation can affect the performance of a WDS that is already subjected to aging and hence is unprepared to withstand more pressure. Water demand management includes different techniques and simply means using limited supplies efficiently without reducing serviceability levels to the consumers (Vairavamoorthy et al., 2008). Decreasing demand, which is referred in Fig. 4, to mitigate the CC impacts on WDS can include employing demand management techniques (based on local conditions and decision-making scenarios) including intermittent water supply (Li et al., 2020), water metering (Boyle et al., 2013), wastewater reuse (Madungwe and Sakuringwa, 2007), water pricing (Reddy, 2008), employing water-saving devices (Shi et al., 2022), institutional development, public awareness and educational campaigns (Dziegielewski, 2003), and water loss reduction (e.g., pipe-network leakage minimisation) (Vairavamoorthy et al., 2008).

Increased temperature can affect biological reactions and may lead to evaporation, dissolution, complexation, solubilisation, and degradation and consequently affects rates of chlorine decay and nitrification (Kimbrough, 2019). All these can threaten public health. Constant monitoring of water quality and employing treatment techniques such as adding chlorine and flushing stale water (Kimbrough, 2019) can mitigate these issues.

Apart from water quantity and quality issues, the CC, by reducing groundwater levels and increasing soil consolidation, can result in land subsidence and jeopardise the integrity of water distribution systems (and other underground pipe infrastructures) (Wols et al., 2014). Land subsidence is now a major problem for countries with water scarcity and those that have severely depleted their underground water supplies (Mahmoudpour et al., 2016). To predict, estimate, and model land subsidence, the use of machine learning (ML) techniques and remote sensing (RS) products have recently been suggested in the literature (Azarakhsh et al., 2022). A combination of ML and RS can be used for planning land use and land cover changes, groundwater management, and agricultural subjects such as crop cover. A general solution to increase the water level of aquifers is diverting floods to recharge groundwater artificially

Table 4
Major impacts of climate change on hydropower plants.

CC feature	Impact	Reference
Increased precipitation	- Increased sediment loads due to flooding and soil erosion (depending on catchment characteristics like vegetation cover) that decreases reservoir storage capacity, river discharge, and hurts the blades for increased river flow	Zhang et al. (2019)
	- Increased power generation depending on plant capacity	De Souza Dias et al. (2018)
	- Increased risk of dam failure in case of flooding	Lumbroso et al. (2015)
Decreased precipitation	- Decreased river flow and reservoir volume that can decrease water availability for energy generation and other downstream demands	De Souza Dias et al. (2018)
	- Reduced water level in the reservoir (below minimum operating water level) that forms vortices and can prevent plant operation	Sarkardeh (2017)
	- Making inefficient, dirtier, and expensive the cities and areas that depend on hydropower	Mukheibir (2013)
Increased temperature	- Increased evaporation rate that may reduce water volume and decrease energy generation	Lumbroso et al. (2015)
	- More river flows in winter and less in summer due to ice thaws	Mukheibir (2013)
	- Increased other demands, for instance agriculture, that may reduce water availability for energy production	Sample et al. (2015)
	- Making flow regime unstable	De Souza Dias et al. (2018)

Table 5
Comparison of run-of-river and reservoir hydropower plants under climate change*.

Type	Negative features	Positive features
Run-of-river	- More vulnerable to ephemeral streams due to lack of enough water storage during drought - Be damaged or stop functioning because of increased floating debris (logs, etc.) and sediment load due to floods - Vulnerable to increased temperature as it can cause ice melting, increase winter flow, and reduce summer discharge of rivers - Turbine vulnerability to unexpected and irregular discharges	- Cost-effective strategy to generate energy Considering the CC More Environmentally-friendly
Reservoir	- Vulnerable to water loss from reservoir surface through evaporation due to increased temperature - Forming vortices due to the drop in reservoir height as a result of decreased precipitation and increased temperature, causing many problems, including hydraulic losses at the intake entrance, entering floating debris, and reducing turbine performance	- Less dependent on seasonal streamflow changes

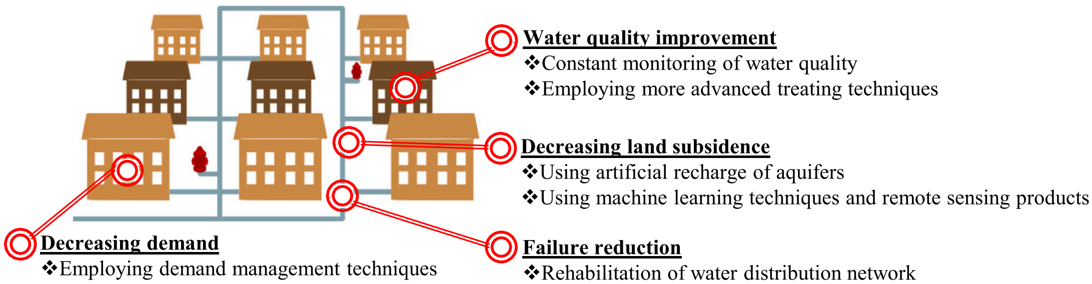

Fig. 4. Main climate change adaptation strategies used for a water distribution system (Inspired by Boyle et al ., (2013); Mahmoudpour et al. (2016); Kimbrough (2019); Li et al. (2020); Şen (2021); Azarakhsh et al. (2022)).

(Şen, 2021).

3.2. Urban drainage system

The CC and urbanisation influence flooding in urban areas that affect the performance of urban drainage systems. In particular, the CC challenges the capacity of current systems by increasing runoff and causing more frequent floods. Urbanisation also causes urban areas to become larger and denser and increases their imperviousness (Kang et al., 2016), and consequently, the flooding risk and its consequences. These issues may affect both the quantity and quality of water. Table 6 gives the CC-related problems for urban drainage systems. Previous studies have shown that urban drainage systems cannot deal with the effects of the CC and urbanisation that necessitate needing for adaptation measures (Ferdowsi and Behzadian, 2024). One approach recommended in the literature for urban drainage systems is adding design criteria that consider the effects of the CC, urbanisation, and population growth (Kourtis and Tsihrintzis, 2021). Using pervious concrete is also a physical method that can manage urban runoff and flood, which with recent advances, can also reduce water pollution (Azad et al., 2020). Attenuating additional water using green roofs and topographic modifications are other methods that are recommended in the literature (Zhou, 2014). However, a more complete list of flood mitigation adaptation strategies and source control of flood water is provided in the general recommendation section of the current study. In addition, early warning systems and real-time flood forecasting are under soft engineering methods that can alleviate the negative impacts of the CC (Piadeh et al., 2022).

Table 6
Major impacts of climate change on urban drainage systems.

CC feature	Impact	Reference
Increased precipitation	- An increased risk to overburden urban drainage networks, which can threaten public health, shutdown public transportation systems, increase flood damages (increase property damage and fatalities), and result in untreated wastewater (or sewage) discharged into receiving water bodies such as rivers, lakes or sea	Kourtis and Tsihrintzis (2021)
	- Increased damages and related costs	Willems et al. (2012)
	- An increase in water that spills from flooding manholes	Nie et al. (2009)
	- An increase in number of flooded nodes	Hoppe (2008)
	- Increased quality-related problems	Yazdanfar and Sharma (2015)
Temperature variations	- Affecting soil water content and consequently runoff generation	Berggren et al. (2014)
Sea-level rise	- An increase in urban runoff, flooding, and their consequences	Huong and Pathirana (2013)

Culverts, as widely used infrastructures for cross-drainage, play an important role in transportation systems in urban areas. Culverts suffer from the same problems of bridges under the CC. Bridge adaptation strategies in a changing climate can also be considered for culverts with spans longer than 6 m (Genivar Inc., 2011). While they may pass major floods, they might not accommodate future CC under land use variations (Blanc, 2013). In other words, the existing culverts may have insufficient capacity for future increases in flow rates due to the CC impacts (Bastos et al., 2020). Identifying climate-prone culverts is the primary step before employing adaptation strategies that has been neglected by researchers and the authorities. To improve the conditions of the existing and future culverts in perspective of the CC, some recommendations are proposed in Fig. 5, such as structural measures (e.g., using armour stones and gabion baskets) to decrease erosion (Genivar Inc., 2011), shortening the length of a culvert as much as possible, as in long culverts, the chance of trapping debris is higher, and their removal is more difficult; reducing the risk of trapping floating debris and becoming blocked by constructing culvert cross section without bends, steps, or other changes (Blanc, 2013); taking into account that small culverts are more susceptible to blockage (EA, 2009); constructing a single culvert with larger size instead of constructing some barrel culverts (if multiple-culvert design is needed, one of them should be built larger to reduce blockage risk and let large debris pass); replacing the existing incapable culverts by ones having enough discharge capacity (Bastos et al., 2020). If replacing a culvert is not feasible, retrofitting measures should be considered to enhance its performance. One approach involves applying resin or other materials to the inner lining of the culvert, which can reduce surface roughness and, consequently, increase the culvert's discharge capacity. The construction of appurtenant elements for flood mitigation can also be beneficial (Cochran, 2009). Another set of strategies includes hydraulic-based approaches, such as implementing a self-cleaning system. This system is designed to redirect flow and sediment towards the central zone of the culvert, thereby reducing the likelihood of blockages and improving overall culvert efficiency (Muste and Xu, 2017). Considering that culverts with free-surface flow are less likely to trap large debris compared to those with full-pipe flow, it's advisable to avoid using inverted siphon culverts. These are particularly prone to blockages due to debris accumulation during low flow conditions (EA, 2009; Blanc, 2013). Furthermore, the location of culverts is critical; areas prone to sedimentation or subject to morphological changes, such as the apex of active meanders, should be avoided to reduce the risk of blockage and ensure efficient water conveyance (Blanc, 2013).

3.3. Water and wastewater treatment plants

Undoubtedly, water and wastewater treatment plants/facilities are an intrinsic part of societies, which have had great contributions in enhancing public health, reducing mortality rates and disease outbreaks, and environmental contamination (Hughes et al., 2021). It appears that the CC would be one of the primary problems threatening the urban wastewater treatment systems (Zouboulis and Tolkou, 2015). However, the investigations in the literature that have been focused on this concern are limited (Abdulla and Farahat, 2020) and it is needed to consider in the CC assessments (Hyde-Smith et al., 2022). Treatment plants are under pressure to purify more water when there is less water available, considering population growth and CC impacts on temperature and precipitation.

A deep evaluation can show that all parts of the treatment networks could be influenced by the CC. Some of the important CC imposed-difficulties are mentioned in Table 7, for both treatment plants and their conveyance systems. In summary, the probable CC impacts on a treatment network can be divided into some categories including damages to structures and elements, problems caused by flooding, water quality problems, cost-related issues, and capacity and serviceability of the treatment plant.

For adapting treatment plants against the CC, it is essential to enhance the knowledge of decision-makers and government authorities on the climate-related impacts which could arrange regulations and design standards for adaptations of the water treatment infrastructures (Hughes et al., 2021). It should be noted that the more treatment plants work, the more they emit greenhouse gasses (Singh and Tiwari, 2019). Therefore, another important factor in the operation and design of treatment plants is the energy-water nexus. In other words, it is crucial to know how much energy is needed to produce drinking water and treat wastewater and how much water is needed to produce the energy used by water utilities, considering the diversified energy sources.

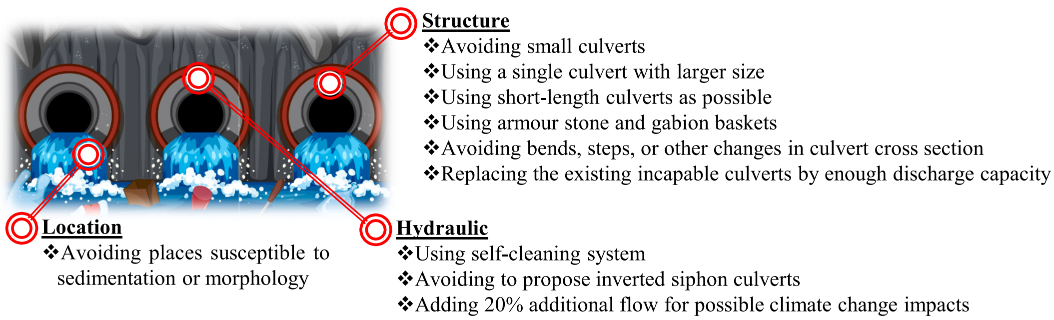

Fig. 5. Main climate change adaptation strategies used for culverts (inspired by Hoppe (2008); Nie et al. (2009); Willems et al. (2012); Yazdanfar and Sharma (2015); Kourtis and Tsihrintzis (2021)).

Table 7
Major impacts of climate change on a treatment plant*.

CC feature	Impact
Increased precipitation	- Decreased water quality - Increased untreated wastewater - Increased costs and reduced efficiency - Heavy precipitation can be compounded with overflows of sewage and consequently cause environmental and drinking water pollution, increased overflows, breakages, and flooding probability in pumping stations, intrusion of pollutants in treatment systems, percolation of sewer water into groundwater, rising sediments rate in water collection networks, and surcharging of manholes - Causing more inflows that need repeated bypasses - Increased possibility of power outage
Increased temperature	- Decreased water quality - Increased odour - Performance variations - Increased risk of blockage as a result of user action changes in conditions of hot weather
Decreased precipitation	- Corrosion, blockage, and siltation in combination with high-temperature
Sea-level rise	Floating of pipes caused by an increase in the level of groundwater; cracking; corrosion; reduced capacity and loss of function as a result of groundwater intrusion; erosion; inundation

* : Data is collected from Berggren et al. (2007), Singh and Tiwari (2019), Reznik et al. (2020), Hughes et al. (2021)

3.4. Other UWI components

The CC is one of the main issues exacerbating the threats of bridges crossing over rivers (Markogiannaki, 2019). The majority of bridges built in the past have been designed without the CC impacts. This includes one-fifth of the US bridges built more than half a century ago, and over 300,000 railway bridges across Europe, with more than 35 % built over 100 years ago (Vagnoli et al., 2018). When designing a bridge across a river, traditional flood risk assessment methods have no consideration of the CC impacts. This can result in significant underestimations, especially if CC causes increased floods. The CC accounts for a significant vulnerability in bridges by changing the frequency and intensity of floods. Precisely, 52 % of the failures of US bridges have been due to hydraulics failure (e.g., flood and scour) (Khandel and Soliman, 2019). Scouring is the most important reason behind bridge failures worldwide (Dikanski et al., 2018). It was reported that bridge scour might rise between 5 % and 50 % in the United Kingdom by the 2080s (DEFRA, 2012). Table 8 categorises the climate-related threats to bridges.

The design of levees and dykes, as hydraulic structures for protecting drylands against flooding, is based on the flood rate and water level. Hence, future floods due to the CC may have a water level higher than the conditions that levees have been designed for. Recent research (Jasim et al., 2017) showed that extreme precipitations under the CC could raise the probability of levees failure up to 12 %. In addition, the stability of soil slopes can be significantly affected by temperature fluctuation (Robinson and Vahedifard, 2016). Many regions have suffered from drought, which has various effects on levees' (structural) condition. Recent investigations, based on Table 9, show that each climate variable can have some potential effects on levees. These items can ultimately change the integrity of levees. Briefly, future changes in climatic parameters increase the failure probability of levees and show that using historical records leads to an underestimated design strategy (Vahedifard et al., 2020). Failure can happen under different modes, including uplift, overtopping, slope instability, piping, sliding, (internal) erosion, grass cover erosion, and landslides.

A protected and safe means of designing for earthen embankments against external changes, such as the CC impacts, may consist of different measures. According to Fig. 6, these measures can be classified into two groups related to an increase in drought events (and temperature) and increased flooding or water level. In case of droughts, moisture content and propagation of cracks should be probed (Illés and Nagy, 2022). Flood protection embankments should be constructed from appropriate materials to reduce the probability of

Table 8
Major impacts of climate change on bridges.

CC feature	Impact	Reference
Increased precipitation	- An increase in scouring; increased material degradation; increased pavements damages	Nasr et al. (2020)
	- More landslides; imposing additional hydro-static loads on abutments and retaining walls	Komori et al. (2018)
	- An increase in the number of floods and water-level	Jevrejeva et al. (2018)
	- Increased pavements damages	Toll et al. (2012)
	- An increase in risk of collapse settlement; decreased stability of side slopes	Nasr et al. (2021)
	- An increase in soil liquefaction possibility	Nasr et al. (2020)
Increased temperature	- Imposing higher thermal stresses; an increase in wildfire possibilities that threatens steel bridges	Kerr et al. (2018)
	- Increased material degradation; increased pavements damages	Meyer (2008)
	- An increase in scouring rate due to snow melting; more landslides; decreased stability of side slopes	Toll et al. (2012)
	- Losing force of pre-stressing (for pre-stressed bridges)	Bell (2008)
	- An increase in number of floods and water-level	Nasr et al. (2021)
Decreased precipitation	- An increase in consolidation settlement probability	Toll et al. (2012)
	- A decrease in buoyancy forces that over-stresses the pile foundations	Toll et al. (2012)
	- An increase in bio-degradation of wooden piles	Kumar and Imam (2013)
Increased fog	- An increase in the probability of collision of ships and cars with bridge piers	Nasr et al. (2021)

Table 9
Major impacts of climate change on levees.

The CC feature	Impact	
Increased precipitation	Higher probability of failure, extreme soil erosion, flooding, hydro-mechanical failure, mass wasting, soil suction reduction, loss in soil quality, instability due to water table change, shear strength reduction	Vardon (2015) Jasim et al. (2017),
Increased temperature	Increased soil drying, suction, desiccation, shrinkage, land subsidence, reduced strength of arctic soils, cracks on dyke pavements	Illés and Nagy (2022)
Decreased precipitation	Soil desiccation, soil shrinkage, reduction of vegetation/soil erosion, difficult to compact for new dykes i.e., cost is increased, causing cracks, increased permeability	Chen et al. (2017) Sencier and Jayaratne (2017)
Sea-level and wave-height rise	Increase the probability of failure (piping, overtopping, erosion, coastal landslides), bank soil erosion, coastal flooding and damaging the coastal buildings on dykes in the vicinity of the seafront	Vahedifard et al. (2018)

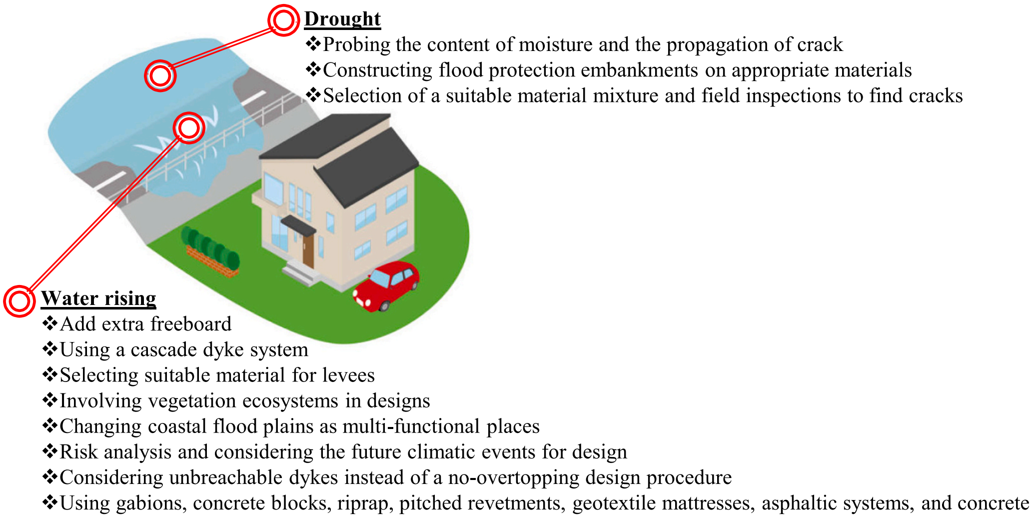

Fig. 6. Main climate change adaptation strategies for levees (Inspired by Vardon (2015); Jasim et al. (2017); Vahedifard et al. (2018); Illés and Nagy (2022)).

forming thick pavement fissures (Illés and Nagy, 2022), and the selection of a suitable material mixture and field inspections to find cracks (Vahedifard et al., 2016) should be performed. The proposed strategies in the literature concerning water level and flooding can be proposed as follows:

Changing coastal floodplains as multi-functional places that serve social and environmental demands such as tourism, recreation and fishing (Verhagen and Visser, 2007); using vegetation (van Wesenbeeck et al., 2017; Vardon, 2015) i.e., involving ecosystems in designs; considering unbreachable dykes instead of a no-overtopping design procedure (Verhagen, 2007); using gabions, concrete blocks, riprap, pitched revetments, geotextile mattresses, asphaltic systems, and concrete (Verhagen and Visser, 2007) to protect a dyke body; using a cascade dyke system can be a better option to preserve the area behind a dyke (Nehlsen et al., 2007); adding extra freeboard, i.e., rising dyke height while determining the amount of rising is challenging and entails uncertainty (Nehlsen et al., 2007); selecting suitable materials for levees could increase the safety (Vahedifard et al., 2016), which should be according to the geographical zone (Pk et al., 2018); fully-submerged vegetation is more effective for wave attenuation (growing weeds for bank erosion protection and wave overtopping prevention, for example, is a highly successful and cost-effective way of adaptation (van Wesenbeeck et al., 2017); risk analysis and considering the future (extreme) climatic events for current levee design (Jasim and Vahedifard, 2017).

4. General recommendations

In the previous sections, the adaptation strategies for each UWI component were reviewed. However, some general approaches can be generally used to mitigate the CC impacts on UWI as presented in Table 10. Importantly, Burian et al. (2013) stated that in adapting UWI to CC, the interconnection of UWI with other systems such as energy should be considered. It is recommended that the mitigation strategies not only should benefit UWI conditions but also should create other opportunities such as new jobs, help biodiversity, tourism, recreation, and public health. In Table 11, the natural systems acting as UWI are shown can cause less environmental impact and help to reach a sustainable future.

Table 10
General climate change adaptation strategies for water infrastructures.

Category	Adaptation strategies	Reference
Nature-based solutions	- Constructing wetlands and parks to flood mitigation, water purification, wildlife conservation, and for recreational purposes	Liquete et al. (2016)
	- Using plants to reduce sediment load and wave attenuation	Halide et al. (2004)
	- Providing technical and financial support to showcase the importance of natural systems and ecosystem services	Grigg (2019)
	- Taking advantage of beaches, dunes, saltmarshes, mangroves, sea grasses, coral and oyster reefs for dealing with sea level rise problem; using green roofs, bio-retention systems, soakaways and infiltration basins, pervious pavements, swales, detention basins, retention ponds, and wetlands	Pontee et al. (2016)
Soft computing and numerical modelling	- ML, evolutionary (single- and multi-objective) optimization, data mining, agent-based Modelling, game theory, multi-attribute decision-making	Ferdowsi et al. (2022a, 2023)
	- Using RS and IoT-based appliance	Xiaocong et al. (2015)
	- Avoiding measures that may inevitably increase risks, such as relying on outdated flood risk mapping	Van Abs (2016)
	- Digital twins	Callcut et al. (2021)
	- Real-time flood prediction modelling	Piadeh et al. (2023a, 2023b)
Material	- Using concrete (and pre-cast concrete) due to its advantages in comparison to other materials, especially steel (i.e., higher durability under ambient conditions, longer life spans, its resistance against corrosion and damages caused by debris, cost-effective, becoming stronger over time, more hydraulic efficiency, environmentally safe, and is a preferable material at sites with overtopping risks	Bartlett (2012)
Non-structural	- Improving runoff prediction systems	Grigg (2019)
	- Using real-time monitoring and early warning systems	Piadeh et al. (2022)
	- Watershed and landscape management (or source control methods), including reducing flow and sediment through different methods like soil conservation and land-use changes, and an increase in storage capacity of floodplains, polders, and washlands, considering precautionary approaches, including evacuation of floodplains and susceptible areas to floods	Kundzewicz (2002)
	- Periodic inspection	Genivar Inc (2011)
	- Periodically updating design codes and standards according to local and global CC; passing laws and regulations to implement CC-related guidelines	Connor et al. (2013)
	- Responsibilities between water authorities, governments, and private and public services should be clear, particularly in water crises and emergencies, providing sufficient and valid data	Sitzenfrei et al. (2013)
Education and public communities	- Institutional development; public awareness regarding floods	Vairavamoorthy et al. (2008)
	- Changing the behaviour of consumers through educating and informing them	Hunt and Shahab (2021)

Table 11
Natural urban water infrastructures.

Objective	Water infrastructure	Description
Water production	Watershed	Watersheds drain water into a water body that is at a lower elevation, categorized based on size, shape, etc.
Water storage	Lake and ponds	Lakes are water bodies that are surrounded by land – ponds are usually smaller and shallower than lakes.
Water production and storage	Aquifer	Aquifers are underground reservoirs, which store water that seeps into the ground from the earth surface.
Flood-water harvesting	Floodplain	Floodplains store storm water, precipitation, and sediments, which reduces flood risk.
Water conveyance	Riverine network	River networks include waterways with different sources that carry water, sediment and flow debris, nutrients, etc.
Water treatment	Wetland	Wetlands protect wildlife, mitigate floods, and contribute to treating water.
	Riparian zone	Riparian as areas between streams and lands that remove sediments and nutrients, reduce flow velocity, and stabilise riverbanks.
Erosion and flood control	Tree and vegetation cover	Trees and plants, through their roots, trunks, and leaves, control erosion, protect shorelines, decrease waves, increase permeability, reduce flood risk, and provide other benefits.

5. Conclusions

This paper critically reviewed the effects of the CC on UWI components and explored potential measures to mitigate these effects. It can be expected that by implementing appropriate adaptation strategies, future harm to human lives and financial resources could be minimised, thereby contributing to the more attainable realisation of the UN SDG. It is crucial that strategic planning for new UWI developments incorporates sustainability criteria aligned with the UN SDGs to ensure that the impacts of CC on each UWI component are analysed and effectively managed. Variations in climate variables such as increased precipitation and temperatures, as well as decreased precipitation, significantly influence UWI. However, the effects of temperature changes due to CC are generally less significant compared to precipitation alterations. Adaptation measures for UWI may involve structural changes and non-structural approaches, including real-time flood forecasting and early warning systems.

While this research analysed numerous WI components, it did not explore the effects of CC on inland navigation systems, as well as offshore and onshore structures, including ports. These areas merit further investigation in future studies. A comprehensive analysis is also needed to assess the potential extent of problems for each WI component. Such an analysis would help quantify the financial and human losses resulting from the failure of each component. Furthermore, examining the impact under various CC scenarios could provide valuable insights into the consequences of both the most optimistic and pessimistic outcomes.

CRediT authorship contribution statement

Ahmad Ferdowsi: Writing – original draft, Methodology, Investigation, Conceptualization. **Farzad Piadeh:** Writing – review & editing, Writing – original draft, Visualization. **Kourosh Behzadian:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Sayed-Farhad Mousavi:** Writing – review & editing. **Mohammad Ehteram:** Writing – review & editing.

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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