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Hydro-Environmental Research on Climate Change Adaptation of Water Infrastructure in the Mediterranean Region

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Abstract: Water Infrastructure (WI) incorporating water supply, wastewater, and stormwater systems is vulnerable to Climate Change (CC) impacts that can disrupt their functionality; thus, WI needs to be adapted to CC. In 2021 the European Commission (EC) released the technical guidelines on "Climate-proofing Infrastructure" that include mitigation and adaptation strategies; these guidelines and the relevant guides that followed, focus mainly on CC aspects without examining sufficiently the engineering features of WI that are described mainly in the relevant hydro-environment research; this research is vast and includes various terminologies and methods for all aspects of CC adaptation. The adaptation procedure of WI to CC can be significantly improved when this research is known to guidelines' developers. To facilitate this knowledge transfer, we performed a review on the hydro-environmental research that we present in this paper as follows: firstly, we introduce and typologize the climate hazards for WI systems and identify the most important of them in the Mediterranean Region that we classify into seven groups; then, we classify the hydro-environmental research into five categories that is based on the EC guidelines, present the main aspects for each of these categories, discuss the future research, and finally we summarize the conclusions.

Keywords: climate change adaptation; water infrastructure; climate proofing; climate risk and vulnerability assessment

1. Introduction

Infrastructure embraces a wide array of elements including structures, networking frameworks, and an assortment of constructed systems and assets [1]. European Critical Infrastructure (ECI) [2] is defined as "an asset, system or part thereof located on EU territory, which is essential for the maintenance of vital societal functions, health, safety, security, economic or wellbeing of people, and the disruption or destruction of which would have a significant impact on at least two Member States, as result of the failure to maintain those functions. The Critical Entities Resilience Directive (CER) of the European Union [3] presents a comprehensive approach aiming to reduce their vulnerabilities and strengthen their physical resilience for the provision of vital services on which the livelihoods of EU citizens and the proper functioning of the internal market depend. Water Infrastructure (WI) that incorporates water supply, wastewater, and stormwater systems is one of the most significant sectors of the critical infrastructure, because it provides essential services to our communities and plays a vital role in maintaining our health and safety by preventing flooding and keeping our water courses clean. Resilient WI is considered as mandatory for the health and well-being of modern societies [4]; it is directly linked to the Sustainable Development Goals (SDGs) adopted by the United Nations General Assembly in 2015, which include "ensuring healthy lives and promoting well-being for all at all ages" (SDG3), "ensuring availability and sustainable management of water and sanitation for all"

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(SDG6), and "building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation"(SDG9).

Water Infrastructure is vulnerable to climate hazards that can disrupt their functionality [5]. Following the IPCC categorization [6] and the typology proposed by Stamou [7,8], the general categories and types of climate hazards for WI systems are shown in Table 1. Table 1 depicts that there are five categories of hazards: Heat & Cold (HC), Wet & Dry (WD), Wind & Air (WA), Coastal (C) and Snow & Ice (SI). Based on the EU Taxonomy [9] these hazards are related to (1) temperature, (2) water, (3) solid mass, and (4) wind and chronic or acute. As expected, the types of chronic hazards are represented by mean values of the corresponding hydro-meteorological variables, while acute hazards by their extremes. For example, the categories of chronic hazards of Heat & Cold (HC), Wet & Dry (WD), Wind (W) and Coastal (C) are represented by the corresponding mean values of air temperature (HC1), precipitation (WD1), wind speed (W1), and relative sea level (C1), while the corresponding quantities of extreme hazards are (1) extreme heat (HC2) or cold spells and frost (HC3), (2) heavy precipitation (WD2) and flooding (WD3) or drought (WD6), (3) severe windstorm - maximum wind speed (W2), and coastal flooding (C2). The mean values of chronic hazards can be daily, monthly, seasonally, or annually average.

Table 1. Categories and types of climate hazards for WI systems.

Category of hazard based on IPCC [6]	Symbol	Type of hazard
Heat & Cold (HC)	HC1	Mean air temperature (increase)
	HC2	Extreme heat- Heat waves
	HC3	Cold spells and frost
Wet & Dry (WD)	WD1	Mean precipitation (decrease)
	WD2	Extreme precipitation
	WD3	Flooding (fluvial and pluvial)
	WD4	Aridity
	WD5	Drought
	WD6	Wildfires
	WD7	Soil erosion
	WD8	Landslide (incl. mudflows)
	WD9	Land subsidence
	WD10	Water temperature
Wind & Air (WA)	WA1	Mean wind speed (increase)
	WA2	Extreme winds
	WA3	Air quality (change)
Coastal (C)	C1	Relative (mean) sea level (rise)
	C2	Coastal flooding
	C3	Coastal erosion
	C4	Saline intrusion
	C5	Sea water temperature (& marine heat waves)
	C6	Sea water quality (incl. salinity and acidity)
Snow & ice (SI)	SI1	Snow and land ice
	SI2	Avalanche

Based on the literature, the most important climate hazards for WI systems in the Mediterranean region can be categorized into the following seven groups:

1. Mean air temperature increase (HC1) [10,11], and extreme heat - heat waves (HC2) [12].
2. Mean precipitation decrease (WD1), aridity (WD4) and droughts (WD5) [11,13–17].
3. Extreme precipitation (WD2) and flooding (WD3) [11,18,19].
4. Wildfires (WD6) [20–22].

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5. Soil degradation, such as erosion (WD7) and landslides (WD8) [14].
6. Extreme winds (WA2), including medicanes and sandstorms [14,23].
7. Coastal hazards, including sea level rise (C1) [11,14,23,24], coastal flooding (C2) and erosion (C3) [25].

Due to Climate Change (CC), the above-mentioned climate hazards are expected to intensify in Europe and in the Mediterranean region during the 21st century [26]. According to the IPPC's fact sheet for Europe [27]: (1) the current 1.1°C warmer world is already affecting natural and human systems in Europe, (2) impacts of compound hazards of warming and precipitation have become more frequent and (3) largely negative impacts are projected for southern regions. IPPC [28] identified the following four key risks for Europe, with most becoming more severe at 2°C Global Warming Levels (GWL) compared with 1.5°C GWL in scenarios with low to medium adaptation: (1) mortality and morbidity of people and changes in ecosystems due to heat, (2) heat and drought stress on crops, (3) water scarcity, and (4) flooding and sea level rise. Very recently, EEA [29] performed a European climate risk assessment and reported: (1) Europe is the fastest-warming continent in the world; extreme heat, once relatively rare, is becoming more frequent, and (2) precipitation patterns are changing; downpours and other precipitation extremes are increasing in severity, and recent years have seen catastrophic floods in various regions, while at the same time, southern Europe can expect considerable declines in overall rainfall and more severe droughts. Moreover, EEA [29] identified and assessed 36 major climate risks with potentially severe consequences across Europe and grouped them into five broad clusters: (1) ecosystems, (2) food, (3) health, (4) infrastructure, and (5) economy and finance.

Climate change effects are expected to intensify in the Mediterranean region during the 21st century [26]. Projected climate patterns indicate a rise in both air and ocean temperatures, surpassing the global mean, with an emphasis on a notable increase in heatwave occurrences. By the end of this century, land temperatures are expected to warm by an average of 0.9 to 5.6 °C, in comparison to the latter two decades. Recent observations and modelling highlighted the Eastern Mediterranean as an important CC hotspot. A more analytical description of the expected behavior of the above-mentioned seven groups of climate hazards is as follows:

8. Mean air and sea temperature (HC1) and their extremes (HC2 and HC3). These are likely to continue to increase more than the global average; heat waves on land (HC2) and in the sea will intensify in duration and peak temperatures [30]. The Mediterranean region is warming 20% faster than the global average, while water temperature is expected to rise by between 1.8°C and 3.5°C by 2100 with hotspots in Spain and in in the Eastern Mediterranean [26]. With the ongoing warming of the global climate, the marine hot spells (HC3) are expected to continue increasing and marine cold spells to decrease in frequency, intensity and duration over the coming decades [31]. Furthermore, the frequency and intensity of marine cold spells declined globally over the last four decades, with no exception in the Mediterranean Sea [32].
9. Mean precipitation decrease (WD1), aridity (WD4) and droughts (WD5). Mean precipitation will likely decrease in most Mediterranean areas by 4–22% [30]. An increase of 2°C to 4°C would reduce precipitation by up to 30% in Southern Europe [26]. Droughts (WD6) are projected to become more severe, more frequent, and longer under moderate emission scenarios, and strongly enhanced under severe emission scenarios [30]. Drier conditions (WD4) are to be expected in the future along a wide zone in southern Europe, including Spain, Italy, Bulgaria, Greece and Turkey, as well as in Northern Africa, towards the end of the century [33].
10. Extreme precipitation (WD2) and flooding (WD3). Heavy precipitation (WD2) and rainfall extremes will likely increase in the northern part of the region potentially accompanied by an increase of flash floods [30].
11. Wildfires (WD6). The frequency of heat-induced fire-weather is projected to increase by 14-30% by the end of the century (2071–2100) suggesting that the frequency and extent of large wildfires (WD9) will increase throughout the Mediterranean Basin [34]. Increasing heat waves, combined with drought and land use change, reduce fuel moisture, thereby increasing fire risk, extending the duration of fire seasons and increasing the likelihood of large, severe fires [35–38].

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12. Soil degradation (WD7) and landslides (WD8). The Mediterranean region has been identified as particularly vulnerable to soil degradation [39]; it has the overall highest erosion rates within the EU [40], the lowest levels of soil organic matter [41] and severe salinization problems [42]. The observed and expected decrease in mean precipitation (WD1) due to CC is accompanied by an increase of extreme precipitation (WD2), flooding (WD3) and subsequently increased erosivity [43]. In tropical and sub-tropical regions, the on-site impacts of soil erosion dominate, and are manifested in very high rates of soil loss, in some cases exceeding 100 t ha^{-1} yr^{-1} [44,45], while in temperate regions, the off-site costs of soil erosion are often a greater concern; for example, siltation of dams and ponds, downslope damage to property, roads and other infrastructure [46].
13. Extreme winds (WA2). Mid-latitude cyclones and medicanes are projected to decrease in frequency, but medicane intensity will likely increase [30].
14. Coastal hazards. The mean sea level (C1) has risen by 6 cm over the past 20 years; this trend is likely to accelerate (with regional differences) by the global rate of 43 to 84 cm until 2100, but possibly more than 1 m in the case of further ice-sheet destabilization in Antarctica [26]. Sea level rise already impacts extreme coastal waters around the Mediterranean and it is projected to increase the risk of coastal flooding (C2), erosion (C3) and saline intrusion (C4) [30]. Coastal flood risks (C2) will increase in low-lying areas along 37% of the Mediterranean coastline [30]. The duration and intensity of marine heat waves are projected to continue increasing in the future [47]. Acidification (C6) is projected to continue [48], with a pH decrease of up to -0.46 in a high emission scenario Salinity is projected to increase from +0.48 to +0.89 psu by the end of the century [49].

Currently, in most of the European countries, the design, construction, operation and regulatory standards of WI systems typically do not account for CC impacts. In 2021 the European Commission (EC), aiming at fostering the development of resilient, climate-proof infrastructure released the Technical Guidelines on “Climate-proofing Infrastructure” for the period 2021-2027 [1]. These guidelines incorporate both CC mitigation and adaptation strategies and mainstream climate considerations in future investment and development. The EC Technical Guidelines, as well as the relevant guides for WI that have been recently published [50–53] are based on the relevant EC official documents and IPCC’s reports [28].

They are systematic and practical focusing mainly and in detail on aspects related to climate hazards without examining at the required detail the engineering aspects of the WI regarding climate adaptation, which are based mainly on the relevant hydro-environment research performed in Universities and Research Institutes, unless these are part of the official EU or of national documents [50]. This research is vast and includes a variety of terminologies and methods for practically all aspects of CC adaptation by specialized researchers and experienced engineers; thus, the adaptation procedure of WI to CC can be significantly improved and be more effective when this research is known to the scientists developing these guidelines and thus to the decision makers. To facilitate this knowledge transfer, we performed a review on the hydro-environmental research that we typologized and present [7,8] in this paper. The present work is structured into four main sections. Section 1 provides the introduction that includes the identification of the most important climate hazards on WI in the Mediterranean Region, which are classified into seven groups. Section 2 presents the grouping of the hydro-environmental research into five categories, and indicative impacts of the seven groups of climate hazards on WI. Section 3 deals with the presentation of the hydro-environmental research of the five categories and the corresponding research areas with indicative cases. Section 4 includes the discussion and proposals for future research and section 5 offers a summary of the key conclusions drawn from this research.

2. Materials and Methods

2.1. Methodology

The typologized categories and areas of hydro-environmental research, which correspond to the five steps of the adaptation procedure of infrastructure to CC and are consistent with the EC Technical Guidelines, are shown in Table 2 [54].

According to this typology, the hydro-environment research is classified into the following five categories, which are based on the EC guidelines and correspond to the five steps of the adaptation procedure of WI to CC

Table 2. Categories and areas of hydro-environmental research [7].

Categories	Research areas
I Description of Water Infrastructure	(a) Identification of the main components of the WI and selection of their time scale, (b) identification of the potential hazards for each WI component, and (c) selection of the corresponding climate indicators for each hazard.
II Climate Change Assessment	(a) Selection of climate change scenarios, and (b) estimation of the values of indicators for each climate scenario.
III Vulnerability Assessment	(a) Sensitivity analysis, (b) exposure analysis, (c) adaptive capacity analysis, and (d) vulnerability analysis.
IV Risk Assessment	(a) Likelihood analysis, (b) impact analysis, and (c) risk analysis.
V Assessment of Adaptation Measures	(a) Identification of the adaptation options, (b) their appraisal, and (c) their integration into the design and the operation of the WI system.

2.2. Indicative Impacts of Climate Hazards on Water Infrastructure

In section 1 we have identified based on the literature the most important climate hazards on WI systems that were categorized into seven groups. To illustrate this identification, indicative possible impacts of these groups of hazards on WI systems are presented in Table 3. For specific WI systems, an estimation of possible impacts for all potential hazards and all components of the WI system (see section 3.1.1) is often required.

Table 3. Indicative possible impacts for WI systems for the seven groups of climate hazards.

Groups of climate hazards	Indicative possible impacts of climate hazards on WI systems
Mean air temperature increase (HC1) & extreme heat (HC2)	Increased water demand [55]; damage to concrete structures, such as channels; expansion of metal elements, such as valves [56,57]; faster biochemical reactions in wastewater transport systems, pumping stations and treatment units; increased production of odors; increased quantities of sludge in wastewater treatment plants (WWTPs) [23]; deterioration of effluent quality due to increased aeration needs in WWTPs [58,59]; stronger density currents in secondary settling tanks [60]; increased air-conditioning requirements in buildings [61]; damage to energy networks [62]; increased vegetation in reservoirs and dams resulting in increased evapotranspiration, increased reduction in reservoir capacity and blocking of spillways; enhanced growth of algae, microbes, parasites, and invasive species in fresh water; increased siltation in small reservoirs [56,63].
Heavy precipitation (WD2) & flooding (WD3)	Increased production of erosion deposits intensifying siltation of water reservoirs [56,63]; increased frequency of sewer overflows due to increased extreme rainfalls [18,64–67]; increased quantities of suspended matter and debris causing cracks on pipes, sewer blocking, clogging and breakage [68] and sewer overflows [69,70]; flooding and pollution of receiving waters increasing exposure risks of residents to wastewater-borne pathogens [18,64–67]; inundation and pollution of treatment units and buildings of WWTPs [61]; reduced hydraulic retention times in wastewater treatment units; increased concentrations of suspended matter and debris; blocking of inlet and outlet structures; increased odor emissions in wastewater treatment units; levee and embankment failures; increased overflows and increased blockages and breakages [23]; increased risk for overtopping of dams and deterioration of water quality in reservoirs [56]; increased turbidity and nutrient

	loadings in reservoirs due to rain events [71]; disruption of access roads to support safety and operations [72].
Mean precipitation decrease (WD1), aridity (WD2) & drought (WD5)	Increased pollutant concentrations in transportation networks and treatment processes in WWTPs due to lower flowrates; increased sedimentation of suspended matter and increased corrosion, blockage, increased emission of odors [23]; lower river flows reducing the ability to abstract from and discharge to the environment [56]; reduced water volumes, increased concentration of pollutants, lower water quality in reservoirs, reduced yields, increased demand for water for irrigation and environmental uses [56]; damage to energy networks due to land subsidence [62].
Wildfires (WD6)	Increased amounts of sediment, nutrients and other constituents discharged to streams and reservoirs after a wildfire [73]; electricity failure and damages in units of WWTPs and energy networks [74]; damages to transportation infrastructure [75]; increased surface water contamination after wildfires including the impact of fire retardants [76,77].
Soil erosion (WD7) & landslides (WD8)	Reduction of reservoir capacity and deterioration of its water quality due to increased sediment quantities [78]; increased risk for landslide-induced surge development that is one of the main causes for dam overtopping [79]; increased concentrations of suspended solids that reduce the effectiveness of disinfection systems [80]; damages to energy networks [62].
Sea level rise (C1), coastal flooding (C2) erosion (C3) & saline intrusion (C4)	Saltwater intrusion and inundation due to increased coastal water table; acceleration of the corrosion of concrete and steel constructions [81–83] and [84]; increased inland groundwater table leading to ground water infiltration into sewers through cracks in old sewer pipes [85]; deterioration of networks by salt water [80]; floating of pipes due to increased groundwater level; flooding, inundation and damage to infrastructure [23]; damage to energy networks [62]; increased temperature, combined with increased salinity and humidity, accelerates deterioration on concrete structures, such as bridges and roads [75].

3. Presentation of the Hydro-Environmental Research

3.1. Research on the Description of Water Infrastructure

3.1.1. Components of the Water Infrastructure and Their Time Scales

Every WI system consists of a series of components, such as pipes, pumps, tanks and buildings. In the adaptation procedure to CC, a WI system needs to be broken into components; then, (i) the CC impacts on each component are determined, and (ii) the vulnerable components whose risk is high are identified, so that proper adaptation measures are proposed to reduce this risk. The determination of the components of WI systems is a practical and technological task that should be systematic and typological; it is usually performed by professional engineers-experts, who design, construct and operate specific WI system in cooperation with researchers specialized in these systems.

Currently, there is no standard procedure to determine the components of a WI system. Moreover, due to the technological nature of this task, the relevant publications are very limited and usually in the form of roadmaps [86], guidelines [1], and guides [50–53]. The World Bank [86] created a structured road map for WI systems, in which it is stated that the first step on the path to resilient design is to determine the appropriate unit of analysis, referred to here as the "component." The component to be made resilient may be a water treatment plant or perhaps a part of the distribution network. World Bank–financed projects typically include multiple components, and these units of analysis need to be identified in advance and standardized aiming at the assessment of quickly how vulnerable the components under scrutiny are to climate change or natural disasters. Furthermore, the Cybersecurity and Infrastructure Security Agency (CISA) of USA has established a water infrastructure taxonomy [87] and identified more than fifty WI assets including protective elements [87]. Jaspers [50] in its very systematic sensitivity analysis for water and wastewater projects proposed the following general components for the four key themes of used in the sensitivity analysis (see section 3.3):

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- Inputs, such as water sources, river or groundwater abstractions, treatment chemicals and human resources.
- Assets, such as supply pumps, water supply network, water intakes, discharge outlets, WWTPs, sewerage network, water storage and distribution network, combined sewer systems and outlets, control systems, existing network of pipes, pumps, tanks, and any other element required for the operation of the proposed project.
- Processes, such as pumping and supply from sources, water treatment and controls, clean treated water storage, water distribution and wastewater treatment.
- Outputs, such as clean drinking water, sustainable water supplies, treated effluent, waste products, sewage sludge.
- Interdependencies, such as power supply, access roads.

Regarding the time scale of a WI project, it is usually assumed to be equal to its Design Working Life (DWL); according to Eurocodes, DWL is defined as "the period for which the structure shall be used with anticipated maintenance but without major repair" [88]. The scale of WI systems, which can be different for its various components, is usually of the order of 100 years and determines the CC scenarios that need to be considered in the vulnerability and risk assessments.

3.1.2. Indicators for Water Infrastructure

A literature survey was performed on climate indicators for WI that revealed the following: (1) there exists a significant number of research works in the literature on indicators that are related to WI, (2) the number of works on indicators for specific WI projects is very limited, and (3) the most common climate hazards examined in these research works are: mean air temperature increase (HC1), extreme heat - heat waves (HC2), mean precipitation decrease (WD1), extreme precipitation (WD2), flooding (WD3), aridity (WD4) and drought (WD5). Table 3 summarizes the indicators, which are commonly used in water resources management (mainly agriculture/irrigation), water supply, stormwater and wastewater projects, and the corresponding references, in which these indicators are defined by specialized organizations, such as IPCC [89], WMO [90] and ETCCDI [91].

Table 3. Indicative climate indicators for Water Infrastructure projects and corresponding references.

Climate Hazard	Climate Indicator/Units	Water resources management projects	Water supply projects	Storm-water projects	Waste-water projects
Mean air temperature increase (HC1) & extreme heat (HC2)	Temperature: annual average; intra annual variance; annual mean; seasonal mean; monthly maximum, average, minimum (°C)	[92]	[92]	[92]	[10,92,93]
	Monthly maximum value of daily maximum temperature; monthly minimum value of daily maximum temperature (°C)	[94]			
	Number of events per year with 3, 5 or 7 consecutive days with temperature between two values, e.g. 38 and 41°C, or greater than a value, e.g. 38°C			[95]	[95]
	Number of days per year with temperature greater than a value, e.g. 38°C			[95]	[95]
	Warm spell duration index (days)	[96]			
Mean precipitation decrease	Simple precipitation intensity index (mm/d)	[97–101]	[102,103]	[102,103]	[102,103]
	Consecutive dry days	[92,98–101,104,105]	[102,105]	[101,102]	[102]
	Aridity actual/ Aridity index	[92]		[106]	

(WD1), aridity (WD4) and droughts (WD5)	Standardized Precipitation Index (SPI). SPI-3 for 3 months or SPI-6 for 6 months.	[105,107,108]	[105,109–112]	[105,109–112]	[111,112]
	Duration of meteorological droughts based on SPI-3 (months)	[92]	[113]		
	Magnitude of meteorological droughts based on SPI-3	[92,105]	[105]		
	Standardized Streamflow Index (months)	[104]	[114]		
	Standardized Runoff Index (SRI) (months)	[105]	[105,110,115]		
	Low Flow (LF) index (m^3/s or days)	[105]	[105]		
	Standardized Precipitation Evapotranspiration Index (SPEI) (months)	[107]	[111]	[111]	[111]
	Palmer drought severity index (months)		[110]		
	Duration of soil moisture droughts (months)	[92]			
	Duration of short- and long-term hydrological droughts; based on SRI (months)	[105]	[105,113]		
Extreme precipitation (WD2) and flooding (WD3).	Annual total precipitation (mm) in wet days (daily precipitation ≥ 1 mm)	[98,99,104]			
	Annual total precipitation (mm) in very wet days (> 95th percentile)	[99]	[116]	[116]	[116]
	Annual total precipitation (mm) in extremely wet days (> 99th percentile)	[92,99]			
	Contribution to total precipitation from very wet days (%)	[97,98,100]	[103]	[103]	[103]
	Contribution to total precipitation from extremely wet days (%)	[98]	[103]	[103]	[103]
	Number of wet days (daily precipitation ≥ 1 mm)	[100,101]		[101]	
	Number of very wet days (> 95th percentile)		[117]	[93,106,117]	[93,117]
	Number of extremely wet days (> 99th percentile)	[92]			
	Maximum number of consecutive wet days (daily precipitation ≥ 1 mm)	[98–101]	[102]	[102]	[102]
	Maximum consecutive 5-days (or 1 day) precipitation (mm)	[92,97,99,101]	[102,103,116]	[102,103,116]	[102,103,116]
	Number of heavy precipitation days	[97,98,101,104]		[118]	[118]
	Number of very heavy precipitation days	[98–101]	[102]	[102]	[102]
	River Flood Index using runoff; daily river flow for T=100 years (m^3/s)	[92]		[92]	

3.2. Research on Climate Change Impact Assessment

Climate change assessment is critical to understanding the potential impacts on WI, particularly in regions like the Mediterranean, where climate variability is expected to intensify; see section 1. Research in this domain has evolved to incorporate a variety of methodologies, each aiming at providing a comprehensive understanding of how CC will affect WI systems. Climate change assessment involves the use of climate models that serve as the foundation for predicting future climate conditions. These models, including General Circulation Models (GCMs) or Earth System Models (ESMs) and Regional Climate Models (RCMs), are integral to simulating temperature, precipitation, and other climatic variables at different spatial and temporal scales.

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Climate change impact assessment studies have increasingly focused on downscaling these models to regional scales to better capture localized impacts. This is particularly important for the local nature of the exposure unit under study, i.e. the WI systems, where microclimatic variations can significantly influence water availability and quality. For instance, Lionello and Scarascia [119] have emphasized the need for high-resolution RCMs to accurately project future climate scenarios in the Mediterranean region; these models are often coupled with hydrological models to assess the potential impacts on water resources, such as river flows, groundwater recharges, and reservoir levels. This integration is crucial for understanding the full extent of CC impacts on WI, as highlighted by the research works of Arnell and Delaney [120], who demonstrated the significant influence of changing precipitation patterns on water supply systems in the UK, and Koutroulis et al. [15], who examined the future impacts of altered precipitation patterns on water resources in Crete, revealing severe declines in water availability under various climate scenarios.

Case studies from the Mediterranean region emphasize the importance of localized assessments in developing effective adaptation strategies for WI systems. For instance, Nogherotto et al. [121] used integrated climate-hydrological modeling in the Po River Basin to inform flood protection infrastructure. Similarly, Rocha et al. [122] examined the impact of CC on reservoirs in southern Portugal, revealing potential water quality issues that could compromise their effectiveness. In Turkey, Gorguner and Kavvas [123] highlighted how CC could lead to significant water storage challenges in reservoirs, especially during peak irrigation seasons. Ertürk et al. [124] focused on the vulnerability of groundwater-dependent infrastructure in the Köyceğiz-Dalyan Watershed, where reduced groundwater recharge could undermine water supply systems. Additionally, Pool et al. [125] explored the transition from flood to drip irrigation in Spain, illustrating how infrastructure adaptation can mitigate climate impacts though trade-offs, such as reduced groundwater recharge.

Despite significant progress in understanding the impacts of CC on water resources and related WI, it is essential to approach the results with caution. Future climate projections and their implications are inherently subject to uncertainty, which arises at various stages of the modelling process. These uncertainties can stem from the initial climate models themselves, the downscaling techniques used to apply global models to regional scales, and the assumptions made during the integration of these models with hydrological and infrastructure simulations. In addition the CC scenarios injected in the simulations are also a source of uncertainty [126].

The assessment of CC impacts on WI involves a multidisciplinary approach that integrates climate modeling, hydrological analysis, and risk assessment. The ongoing challenge is to refine these methodologies to reduce uncertainties and improve the reliability of predictions, thereby enabling more effective planning and management of water infrastructure in the face of CC; see section 4.

3.2.1. Selection of Climate Change Scenarios

The selection of CC scenarios is a crucial step in assessing the potential impacts of CC on WI. Climate scenarios are projections of future climate conditions based on different assumptions about greenhouse gas (GHG) emissions, socio-economic developments, and land-use changes. These scenarios are essential for understanding the range of possible future climates and for planning appropriate adaptation measures.

One of the most used frameworks for climate scenario development is the Representative Concentration Pathways (RCPs), which represent different levels of radiative forcing by the end of the century. The RCPs, developed by the Intergovernmental Panel on Climate Change (IPCC), include pathways such as RCP2.6 that assumes strong mitigation efforts leading to low GHG concentrations, and RCP8.5 that represents a high-emission scenario with little to no mitigation [127]. These pathways are instrumental in projecting future changes in temperature, precipitation, sea level, and extreme weather events.

The selection of appropriate RCPs for WI adaptation to CC in the Mediterranean region requires careful consideration of several factors. Firstly, it is important to select scenarios that cover a wide range of potential future conditions, from the most optimistic to the most pessimistic outcomes; this ensures that infrastructure planning is resilient under various future climates. Additionally, the

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selected scenarios must be relevant to the specific vulnerabilities of the Mediterranean region, where changes in precipitation patterns, increasing temperatures, and rising sea levels are expected to pose significant challenges [128]; see also section 1. For example, Furlan et al. [129] utilized RCP8.5 to assess the potential impacts of extreme sea level events on coastal infrastructure in Italy and highlighted the severe risks associated with high-emission scenarios. In contrast, Koutroulis et al. [15] demonstrated the potential benefits of lower-emission scenarios, such as RCP2.6, in reducing the risks associated with droughts and heatwaves in East Mediterranean islands.

The process of scenario selection is not without challenges. One of the main difficulties lies in balancing the need for detailed, high-resolution projections with the practical constraints of applying these outputs in impact assessments. Furthermore, the inherent uncertainty in long-term climate projections makes it difficult to predict specific outcomes with high confidence. As such, the use of multiple scenarios, along with sensitivity analyses, is often recommended to capture the range of possible futures and to inform robust decision-making [130,131].

The selection of CC scenarios is a fundamental aspect of climate impact assessments for WI. By choosing scenarios that reflect a range of possible futures and that are tailored to the specific climatic conditions of the study region, researchers and planners can better anticipate the challenges ahead and develop more resilient WI systems.

3.2.2. Estimation of the Values of Climate Change Indicators

The estimation of CC indicators is a critical step in assessing the potential impacts of CC on WI. These indicators, which include variables such as temperature, precipitation, sea level rise, and extreme weather events, provide the quantitative basis for understanding how CC might affect water resources and infrastructure. To estimate these indicators, researchers and practitioners typically rely on outputs from climate models, which simulate future climate conditions under different scenarios. For example, mean annual temperature and precipitation changes are commonly derived from GCMs and RCMs, which provide projections at various spatial and temporal scales. These models are particularly useful in capturing the large-scale patterns of CC, but they are often downscaled to regional levels to improve the accuracy of local impact assessments [132,133].

The process of downscaling is crucial for WI assessments, where local climate conditions can differ significantly from the broader patterns predicted by global or regional models. Statistical downscaling techniques, such as bias correction and empirical-statistical modeling, are often employed to refine model outputs, making them more applicable to specific geographic areas [134].

Once the climate model outputs are refined, the next step is to translate these outputs into relevant indicators for WI. This involves calculating specific metrics, such as the number of extreme heat days, changes in the frequency and intensity of heavy rainfall events, and the projected sea level rise. Indicative climate indicators for WI projects are shown in Table 10 (section 3.1.2). These indicators are then used in vulnerability and risk assessments (section 3.3) to evaluate the potential impacts on different components of WI systems, such as reservoirs, WWTPs, and distribution networks. The estimation of climate indicators also involves dealing with uncertainties. Climate models are inherently uncertain due to limitations in data, model structure, and the unpredictable nature of climate systems. To address these uncertainties, researchers often use ensemble approaches, combining the outputs of multiple models to create a range of possible outcomes.

The estimation of CC indicators is a vital part of assessing the impacts of CC on WI. By using advanced climate models and downscaling techniques, researchers can produce reliable estimates of how key climate variables are likely to change.

3.3. Research on Vulnerability Assessment of Water Infrastructure

3.3.1. Definitions and Initial Comments

The vulnerability of a WI system to a climate hazard can be defined as the predisposition of the WI to be adversely affected by this climate hazard considering its capacity to adapt [135]. Typically, vulnerability assessment combines the analyses of sensitivity, exposure and adaptive capacity (see also Table 2). The sensitivity of a WI system to a climate hazard can be defined as the degree to which

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the WI and its components are affected by this climate hazard, while the exposure of a WI system to a climate hazard can be defined as the degree to which the WI is exposed to this climate hazard due to its location [136]. In other words, the sensitivity of a WI system depends on the characteristics of its components regardless of its geographical location, while its exposure depends mainly on its location. Thus, in the sensitivity analysis, the components of the WI project that are sensitive to potential climate hazards are identified, while in the exposure analysis it is estimated how exposed is the WI system to each climate hazard by comparing the values of the corresponding hazard's indicators under current and future climate conditions (see section 3.2.2). The adaptive capacity can be defined as the ability of a WI system to foresee, prepare for, respond to, and recover from CC impacts [137]. The adaptive capacity refers to CC impacts on the WI system (see section 3.2) and it is mainly linked to and influence its sensitivity analysis; thus, usually, it is included in the sensitivity analysis or performed alongside or after the sensitivity analysis [61]. It is noted that there are similarities between the sensitivity and exposure analysis in the vulnerability assessment and the corresponding impacts and likelihood analysis in risk assessment; see section 3.4.

3.3.2. Methodologies for Vulnerability Assessment

There are a significant number of research works on the vulnerability of WI that are generally applied at a large scale of a city or a country [54]. In most research works, the sensitivity analysis of a WI system is based on the scoring (of the sensitivity) of its general characteristics or the characteristics of its components, while the exposure analysis is typically performed quantitatively via the comparison of the values of exposure indicators for the current and future climate conditions; see section 3.1.2 [1,117]. According to EC [1] "the assignment of sensitivity scores to project types is best carried out by technical experts, i.e. engineers and other specialists with good knowledge of the project", moreover, JASPERS [50] states that "the sensitivity analysis is best carried out by technical experts in the field of the project component under assessment".

In the literature, the sensitivity characteristics of a WI system can be encountered by various names, such as themes [1], dimensions [117] or key infrastructure sectors [138]; Table 4 depicts indicative evaluation criteria of sensitivity analysis. Moreover, it is noted that there are differences in the definition of sensitivity among various researchers and thus in its assessment; in some of the research works, the sensitivity analysis seems to be virtually the same as the impact analysis. To realize this difference, indicative evaluation criteria used in the impact analysis are shown in Table 5; these can also be encountered by various names, such as impact criteria [139], risk areas [1], impact areas [61], impacts [140], and consequences [141]. For reasons of consistency and to avoid any misinterpretations, the themes proposed by EC[1] can be used in the sensitivity analysis, which can be considered practically as a preliminary impact analysis of CC impacts on the components of the WI.

Table 4. Indicative evaluation criteria of sensitivity analysis.

Themes [1]	**Dimensions** [117]
On-site assets and processes.	Physical dimension.
Inputs, such as water and energy.	Economic dimension.
Outputs, such as products and services.	Social dimension.
Access and transport links, even if outside the direct control of the project.	Environmental dimension.

Table 5. Indicative evaluation criteria of impact analysis.

Impact criteria [139]	**Risk areas** [1]	**Impact areas** [61]	**Impacts** [140]	**Consequences** [141]

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Public effects. Economic effects. Environmental effects. Political effects. Psychological effects on the population.	Asset damage - engineering and operational. Safety and health. Environmental. Social. Financial. Reputation.	Physical impacts on buildings, i.e. structural damage. Effects on the health and safety of those using the buildings. Financial impacts, encompassing both the cost of damages and the depreciation of property value. Impacts on heritage, including the loss of cultural significance. Environmental impacts. Impacts on reputation.	Casualties. Economic and financial perspectives. Environmental losses. Impacts on reputation. Societal impacts.	Physical harm. Injury. Death. Loss. Damage to property or revenue. Loss of reputation and credibility.

Similarly, the adaptive capacity analysis may involve the use of criteria that are usually called "key elements", which are critical to a WI system's ability to adapt [136,137]; these are: (1) economic resources, (2) technology, (3) information and skills, (4) infrastructure, (5) institutions, and (6) equity. Koutroulis et al. [113] assessed the sensitivity and the adaptive capacity of European freshwater availability using indicators, after defining the sensitivity of water availability and stress in CC as the responsiveness of the socioeconomic system to the related climate induced hazards. The indicators for sensitivity were: (1) population density, (2) irrigated agriculture, and (3) sectorial water demand, and for the adaptive capacity were: (1) economic resources available to adapt, (2) law enforcement, (3) human capital, (4) level of natural freshwater storage capacity (capacity of aquifers and inland water bodies), and (5) level of artificial freshwater storage capacity (capacity of dams).

The outcomes of the sensitivity and exposure analysis are usually presented in tabular (or matrix) form; then, they are combined to produce the vulnerability matrix; see for example Stamou et al. [54].

The definition of scales and scores of the evaluation criteria, i.e. the theme's scores in the sensitivity analysis and the indicators' nominal values or thresholds in the exposure analysis, is one of the most important procedures of the climate adaptation procedure, since it determines to a significant degree the climate hazards that can be significant for a WI system. Despite its importance, the number of relevant research or practical/engineering works is very small and in most of these works the nominal values and scores reported are not adequately justified, but it is simply stated that this task is performed for sensitivity themes by technical experts in the field of the project component under assessment [1], and for exposure indicators by expert elicitation [50]. There are only a few research works published on sensitivity scales and scores for critical infrastructure that have been used by various researchers, such as Forzieri et al. [138] and JASPERS [50]. Forzieri et al. [138] constructed a sensitivity matrix based on a survey of experts, in which the channels through which the CC impacts are transmitted to the infrastructure were explained based on a literature survey; Table 6 presents a part of this sensitivity matrix adjusted by Stamou et al. [54] for WI. Indicative sensitivity scores and evaluation criteria for water supply or wastewater projects and an indicative sensitivity assessment for the components of a water supply project, are shown in Tables 7 and 8, respectively [50,51]. Likewise, the number of research works on the exposure scales (or scores) is also very small. Table 9 depicts indicative exposure indicators and their scores for water supply or wastewater projects proposed by JASPERS [50,51], Table 10 shows a classification of drought based on the indicators SPI [142] and SPEI [143], while thresholds for the Aridity Index (AI) and the rainfall amount can be found in Ashaolu and Iroye [144] and Barde et al. [145], respectively. The sensitivity and exposure scales proposed by JASPERS [50,51] can probably be used in CC assessments; however, there is no published document available explaining the scaling procedure.

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Table 6. Sensitivity matrix for WI based on Forzieri et al. [138] and adapted by Stamou et al. [54].

Water Infrastructure	Drought (WD6)	River floods (WD3)	Coastal floods (C2)	Windstorms (W2)	Wildfires (WD9)	Heat waves (HC2)
Hydropower plants.	High	Medium	Medium	Low	Low	Low
Inland waterways.	High	High	High	Medium	Low	Low
Water & wastewater treatment.	Medium	High	High	Medium	Medium	Medium

Table 7. Sensitivity scores and evaluation criteria for water supply or wastewater projects [50].

Quantitative score Numerical score	High 3	Medium 2	Low 1	No 0
Impact on assets and processes, inputs, outputs and transport links.	Significant	Slight	No or insignificant	No on any component
Shutdown duration of the wastewater system or water supply.	>2 days	1-2 days	<24 hours	-
Pollution incident.	-	Affects non-residential properties.	Minor affecting collection system.	-
Impact on water quality.	-	Medium	Minor	-
Potential of failure that results in the exceedance of design levels or capacity, breach of flood defenses or can no longer perform to the required standard.	Yes, for the instantaneous failure or exceedance of the flood risk management system.	Yes, for the gradual degradation of the flood risk management system.	No (or very low potential).	No impact on the ability to manage the infrastructure -business as usual.

Table 8. Sensitivity assessment for the components of a water supply project [50].

Category of hazard (IPCC)	Climate Hazards	Input Ground Water Aquifer (Water Source)	Assets and Processes Water treatment plant and treatment processes	Outputs Quantity and quality of water supplied	Global score
Heat & Cold (HC)	Annual / seasonal / monthly average (air) temperature (HC1)	1 Possible degradation of raw water quality through increased turbidity.	2 Impact on efficiency of treatment processes.	1 Possible impact on quality of treated water.	2
	Extreme temperature occurrences, including heat waves (HC2)	0 No impact on groundwater sources (see drought for secondary effects of heat waves on water resources)	2 Possible increase in the concentration of pollutants on the influence with effect on the treatment process.	1 Additional demand for water during heatwaves.	2

Table 9. Exposure indicators and their scores for water supply or wastewater projects [51].

Climate hazard	Exposure indicator Score	High 3	Medium 2	Low 1	No 0	Units 0

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Annual / seasonal / monthly average (air) temperature (HC1)	Annual average air temperature increase compared 1981-2010 average	>4	2-4	<2	0	°C
Extreme temperature occurrences, including heat waves (HC2)	Human health heat waves per year	>20	5-20	<5	0	days
Cold spells (HC3)	Number per year, or 1 with duration > 6 days	>4 >6	2-4 >1	1	0	-
Freeze-thaw damage (HC3)	Frost days per year	>90	30-90	<30	0	days
Annual / Seasonal Monthly average rainfall (WD1)	% change in any average / seasonal / monthly rainfall total	>25	10-25	<10	0	%
Extreme rainfall (frequency and magnitude) – highest (WD2)	Max five-day precipitation index	>150	>100	>50	<50	mm
	Extreme precipitation total index	>150	>100	>50	<50	mm
	Extreme precipitation frequency	>10	>6	>2	<2	days
River flooding (WD3)	Flood hazard: For climate hazards where hazards or risk mapping is available this would be exposure in the high probability maps (e.g. for flood hazard and risk maps may be the % AEP (Annual Exceedance Probability)	10	1	0.1	0	%
Ground Instability / landslides (WD9)	Landslide danger (The factors that influence landslide exposure are gradient of the slope, rainfall intensity and saturated soils, snowmelt, deforestation and other changes in land use and earthquakes)	Very high /High	Medium	Low	Very low	
Aridity and drought (WD4 & WD5) / Water availability	Aridity Actual	>4	2-4	1-2	<1	
	Consecutive dry days	>60	40-60	20-40	<20	days
	Duration of meteorological drought	>4	2-4	<2	0	months
	Magnitude of meteorological drought	>10	5-10	<5	0	
Wildfire (WD6)	Days of high fire danger	>80	20-80	<20	0	days
Air quality (WA3)	Legal limits for air quality monitoring have been exceeded (current exposure) or expected to be exceeded (future exposure)	>1/5a	>2/10a	>1/25a	0	Nr of times

Table 10. Classification of drought based on SPI [142] and SPEI [143].

SPI or SPEI values	Drought category
>2	Extreme wet or humid
1.99 – 1.50	Severe wet or very humid
1.49 – 1.00	Moderate wet or humid

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0.99 – -0.99	Normal
-1.00 – -1.49	Moderate drought
-1.50 – -1.99	Severe drought
< - 2.00	Extreme drought

3.4. Research on Risk Assessment of Water Infrastructure

3.4.1. Definitions and Initial Comments

The International Organization for Standardization (ISO) [146] defines risk for critical infrastructure as "the combination of the consequences of an event or hazard and the associated likelihood of its occurrence", while according to the European Commission "risk means the potential for loss or disruption caused by an incident and is to be expressed as a combination of the magnitude of such loss or disruption and the likelihood of occurrence of the incident"[3]. IPCC [147] defines risk as "the potential for adverse consequences for human or ecological systems" and notes that risk is not always consistent across different works and it is continuing to evolve.

Typically, risk assessment combines the analyses of likelihood and impact that are often summarized in the "risk matrix", to identify the significant climate hazards for the WI system, whose risk must be managed and reduced to an acceptable level. In the likelihood analysis of a WI system to a climate hazard the probability of this hazard to occur within the lifespan (or timescale; see section 3.1.1) of the WI system is estimated, while in the impact analysis the consequences of this hazard on the WI system are determined. Usually, the risk assessment of a WI system is performed for all potentially significant climate hazards. It is important to note that WI systems can often be exposed to multiple hazards that can be independent single hazards, compounded or cascaded climate hazards [148]. In such cases, a multi-hazard risk assessment is required that considers multiple parameters to assess climate risk holistically; see section 4.

3.4.2. Methodologies for Risk Assessment

There are various methodologies and risk assessment tools in the literature. The main categories of risk assessment methods are the following: (1) qualitative, in which the rate or score risk is based on a person's (safety manager-engineer) perception or judgment of the likelihood and severity of the impacts, (2) quantitative, in which the risk is considered as a quantity that can be estimated and expressed using equations and real incident's data; the risk value is often expressed in percentages and indicates the probability of the risk occurring, and (3) semi-quantitative, in which qualitative and quantitative methods are used, for example by expressing likelihood using an equation and the impacts using a rating or score or description [54].

Risk assessment aims mainly at quantifying the characteristics of the hazard(s) and the magnitude of perceived impacts considering the specific components of a WI system that both make it vulnerable to the assessed hazards and capture the capability and adaptation measures to respond to them [149]. Water infrastructure operate as a system of systems, thus impacts on one network may propagate to others and understanding the full extent of cascading failures is hard to ascertain [150]. The German Development Cooperation (GIZ) [151] proposed a consolidated Guide for Climate Risk Management Plans in Small and Medium Sized Water and Wastewater Systems with a strong focus on non-EU countries, providing access to climate simulations for quantitative impact assessment and also proposing stakeholder engagement. Becher et al. [152] introduced a comprehensive stress-testing framework for multi-hazard risk assessment of WI systems including a large set of spatially coherent drought, cyclone, pluvial and fluvial flood events leading to an assessment of "customer disruption days" as an indicator of impacts.

In the UK climate risks are taken into account actively when planning major new WI, such as wastewater and water projects, while for small projects only flood risks are usually considered [153]. In existing WI systems, operators and owners are often faced with the challenge of reconciling adaptation options across a range of aging assets, which are designed with differing specifications, are exposed to various environmental conditions and have various usage and maintenance regimes; these aspects need to be combined to determine how assets may respond to CC. The implemented

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approach depends on the asset's characteristics, such as its fragility and capacity, and can involve an analysis of network-wide effects considering CC impacts, degradation of the service performance, and network recovery that depends on the restoration properties of the network, such as the number of backup or redundant components. The climate risk can be assessed considering the loss of infrastructure services and the effects on economic growth, social wellbeing and environmental protection. The Climate Policy Initiative (CPI) focused on the assessment of finance flows for WI systems and their consistency with the five principles of climate resilience [154]. The International Institute for Sustainable Development (IISD) proposed the Physical Climate Risk Assessment Methodology as a common framework for the impact assessment of physical climate risks on WI investments [155], providing a common language for addressing climate risks between the infrastructure and insurance sectors; this methodology translates physical climate risks and adaptation measures to key performance indicators, including internal rate of return and life cycle costs, across possible future scenarios. In the literature, there are several examples of climate variables, such as freeze-thaw and temperature, which can accelerate WI deterioration [156]; this brings the element of predictive maintenance into climate risk assessment, which is often overlooked is CC assessment studies, although it is very important since WI systems age and deteriorate.

There is much research on the estimation of probability, return period and severity of climate hazards. Most of these research works deal with acute climate hazards and thus they involve extreme exposure indicators, such as the daily maximum temperature [157], the extreme daily precipitation [158] and the maximum and minimum temperatures, the maximum precipitation and snow rate, and the maximum wind speed [159]. In these works, real or synthetic time series (i.e. produced via modeling, such as Monte Carlo simulations) of indicators are fitted to probability distributions, such as the Generalized Extreme Value (GEV). Regarding probability scaling, EC [1] proposes five scales that are expressed qualitatively and quantitatively (% of occurring per year), which are (1) rare - the hazard is highly unlikely to occur (5%), (2) unlikely - the hazard is unlikely to occur (20%), (3) moderate - the hazard is as likely to occur as not (50%), (4) likely - the hazard is likely to occur (80%), and (5) almost certain - the hazard is very likely to occur (95%). The impacts of a climate hazard on a WI system and the associated cost of damage depend on the characteristics of the hazard, the strength of the WI, and other external factors. For example, the impacts of a flood on a WWTP depends on: (a) the flood characteristics, such as the maximum water depth and the maximum water velocities, (b) the characteristics of the WWTP, such as the tanks and buildings of the WWTP, and (c) external factors, such as the cost for sediment and debris removal from the area of WWTP that were brought by the flood. EC [1] proposes the use of a table for the estimation of the magnitude of impacts (consequences) across six risk criteria, which are noted as "risk areas" in Table 2, and five magnitude scales of consequences that are: insignificant = 1, minor = 2, moderate = 3, major = 4 and catastrophic = 5; these scales are described qualitatively, except for the financial risk area. For some hazards the likelihood and the impacts are expected to change during the lifespan of the WI system; thus, EC [1] proposes to perform the impact analysis by dividing the lifespan of the WI project into several shorter periods of duration equal to 10-20 years. These criteria can be applied to estimate the impacts for every hazard on the WI and its components; moreover, particular attention should be paid to weather extremes and cascade effects [1].

The basic categories of damages to a WI system due to climate hazards are (1) direct or indirect, depending on whether they are experienced in a direct or indirect manner, and (2) tangible or intangible, depending on whether they can be quantified in monetary terms or not [160]. For example, in the case of flooding of a WWTP, damages are direct tangible such as these of the tanks and buildings of the WWTP due to their direct contact with the floodwaters, direct intangible such as the loss of human life due to flooding, indirect tangible such as the interruption of the treatment processes, and indirect intangible damages such as health deterioration due to diseases caused after the flood by contaminated water or food. The relevant research, which belongs mainly in the natural hazard sciences, often focuses on direct tangible impacts, while a large body of literature is available on how to model and assess direct tangible flood losses, such as ex post assessments of direct flood impacts or ex-ante cost assessment methods, see for example the review by Meyer et al. [161].

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Most of the literature focuses on asset damage, which can be estimated using multivariate models and damage curves (or functions). Multivariate models employ statistical techniques, such as Multiple Linear Regression, Bayesian Network, Artificial Neural Network, and Random Forest, as basis for the estimation of direct damages; they are conceptual or developed (and validated) for specific areas. In most of the applications, damage curves refer to flood hazards and they usually focus on the direct tangible damage; moreover, in almost all models flood (water) depth is treated as the determining factor for expected damage, sometimes complemented by other parameters, such as water velocity, flood duration, water contamination, precaution, and warning time [162]. Damage curves are used to calculate the expected monetary damage of a specific WI system as a percentage of a pre-defined asset value (relative function) or directly in financial terms (absolute function). Recent research has focused on the development of damage curves for pluvial flooding; however, progress has been hindered by the availability of pluvial flood risk data and the lack of damage records for pluvial events [163].

Contrary to the large number of publications on asset damage (that is the first risk area of EC [1]) there are not much research work on the risk areas of safety and health, environment, social, and reputation. In natural hazard research, a growing body of literature has addressed different aspects of losses of human life due to floods, including ex-post assessments of flood fatalities, and approaches that can be used ex-ante to predict flood mortality [160]. Also, McClelland and Bowles [164] performed an overview of methods for the loss of life during river, coastal and dam break floods, Allaire [165] performed a review of the empirical literature in the fields of economics and civil engineering on the socio-economic costs of floods and other hydrometeorological disasters, Del Giudice et al. [166] developed two models that evaluate (1) damage to the productive part of a territory affected by floods and (2) damage related to the environmental aspects, and Nobanee et al. [167] conducted a bibliometric analysis of reputational risk and sustainability, which revealed that the amount of research output within this field is limited.

3.5. Research on the Assessment of Adaptation Measures for Water Infrastructure

3.5.1. Definitions and Initial Comments

There are a very large number of research works on climate adaptation measures due to the importance of this area to problem solving of the adaptation of WI to CC and to the variety of adaptation measures; see section 3.5.1. Most of the research work has been performed in the identification of adaptation options, while the number of works in their appraisal is small. The integration of adaptation measures into the design and the operation of a WI system to improve its climate resilience [1] is a practical task; thus, the relevant research works are limited. It is worthwhile noting that in Climate-ADAPT it is stated that "there is an increasing volume of literature and experience on adaptation options, appraisal and planning [168,169], as well as related resources [170] in the Member States. More information on adaptation planning in the Member States is available on Climate-ADAPT [171]".

The number of adaptation options and the number of relevant research works are indeed very large; subsequently, there are various categorizations of adaptation options in the literature, whose most common and simplest is the categories of structural and non-structural adaptation measures. However, for the methodological examination of the large number of research works, a more detailed and systematic categorization is required, such as the system of Key Type Measures (KTM) by Climate -ADAPT. The KTM system was developed to report climate adaptation actions in the EEA member countries and thus to provide a standardized way of communicating various adaptation measures to better support adaptation policy process across the EU [172]. The KTM measures are presented in Table 11 with indicative research works.

Table 11. Adaptation measures and indicative research works [172].

Categories of adaptation measures	Indicative research works and their subject
A1: Policy instruments	Policy instruments for green infrastructure [173]; Policy developments [174]; Green economy [175].

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A2: Management and planning	Re-orientation of strategic water policy options in water resources management and engineering ([176]; modification of existing water resource planning and management standards in water conservancy projects [177]; enforcement of framework for multifunctional design of green infrastructure to mitigate urban flooding [178]; adaptive governance, institutional design principles for local common pool resources systems and social-ecological framework analysis for drought management [179]; evaluation of structural and non-structural adaptation measures to reduce flood risk [180]; vulnerability and adaptability evaluation of water management that can be used as guidelines for the management of water resources and agriculture [181].
A3: Coordination, cooperation and networks	Collaborative approach involving participation from various groups of stakeholders to reduce drought effect [182].
B1: Financing and incentive instruments	Incorporating blue/green options in urban adaptive approaches [183].
B2: Insurance and risk sharing instruments	Municipal flood risk sharing in Canada [184].
C1: Grey options	High floor houses for reducing pluvial flood effect [185]; grey solutions for reducing urban flooding [186].
C2: Technological options	Seasonal forecasting for decision making in water management [187]; Early Warning System (EWS) for reducing exposure, vulnerability and risk for citizens and city assets [188]; EWS together with hard and soft adaptation measures [189]; timely information on water resources and water saving technologies in agricultural water management [190]; risk modelling to identify cost-effective investments and protection measures under future climate change and socio-economic / demographic conditions to reduce flood risk [191]; detection of ecological drought through data analysis [192]; downscaling to perform regional climate experiments to identify the influence of global warming on heavy rainfall and rainfall volume in order to contribute to the expert committees for adaptation planning [193].
D1: Green options	Riverbank vegetation [194]; planting trees for reducing surface urban runoff [195]; green infrastructure for reduction of urban flooding [186]; paddy fields for flood risk reduction [196]; cascade method in dam building for flood control [197]; reducing the impacts of sea level rise and saline intrusion by developing salt-tolerant crop varieties [181]; nature based pilot projects [198]; valuation of costs and benefits of NBS on climate adaptation against drought [199].
D2: Blue options	Modelling of new drainage system using the sponge city concept to reduce urban flooding [200]; analysis of the lower Brisbane River flood dynamics for flood adaptation through a Coastal Reservoir Technique [201].
E1: Information and awareness raising	Aspects of the on-going citizen engagement for RESILIO, the Blue Green roofs program of Amsterdam [202].
E2: Capacity building, empowering and lifestyle practices	Stakeholders' involvement in the definition of local future socio-economic scenarios, in the development of adaptation strategies, and in the validation of the model being developed for the area [203].

EEA [29] emphasizes the importance of governance and institutional measures and states that the key priorities for policy action include: (1) conducting assessments and implementing measures to enhance the resilience of critical infrastructure on a systems level, and (2) incorporating climate projections into the Eurocodes (European standards to guide the structural design of buildings and

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civil engineering works) that are currently being updated. However, these standards are largely based on historical climate data; to account for future climate risks during the lifetime of current infrastructure, these standards need to incorporate climate projections based on CC scenario analyses, including worst-case scenarios, particularly for critical infrastructure. Similarly, in the UK the use of common formalised standards of resilience is suggested, such as the ISO 14091 standard [204], across different infrastructure sectors including the WI sector to help building systemic resilience across the whole infrastructure system.

- The Climate Change Adaptation Resource Center of the United States Environmental Protection Agency (USEPA) offers eight adaptation actions to assist water utilities in preparing for likely climate threats [205]. Four of these measures deal with physical and technological measures, such as grey (new, rehabilitated, upgraded, or replaced) physical infrastructure (see Table 11; category C1) and technological options (category C2), such as EWSs, hazard / risk mapping and service / process applications. The first five are:
- Construction of new infrastructure (on-site power sources, such as solar, wind and biogas), repair and retrofit facilities (implement saltwater intrusion barriers, improve pumps for backflow prevention, increase capacity for wastewater and storm water collection and treatment).
- Increase of treatment capabilities to ensure effluent and water supply meets standards.
- Increase system efficiency (electrify fleet vehicles, shift to telework schedules, and change lighting).
- Monitoring operational capabilities by taking inventory of existing infrastructure, identifying and protecting vulnerable facilities.
- One USEPA's measure dealing with Nature Based Solutions and Ecosystem-based Approaches (see Table 11; category D) is the modification of the land use via the utilization of green infrastructure to manage stormwater is also one of the USEPA measures [205].
- Three measures offered by USEPA [205] belong in the knowledge and behavioral change measures (category E); these are the following:
- Modeling climate risk, such as the modeling of sea level rise and storm surge to inform appropriate sitting of critical infrastructure.
- Modification of water demand, such as the public outreach to reduce waste and inefficiencies and the co-work with farmers to adopt micro-irrigation technology.
- Planning for Climate Change, such as educating staff on climate change and developing costal restoration plans to protect utilities and emergency response plans.

3.5.2. Methodologies for the Assessment of Adaptation Measures

Adaptation options are often evaluated using a Multicriteria Decision Analysis (MCDA) that usually includes economic, environmental, and social aspects, and when feasible, the involvement of stakeholders. The economic aspects that are generally one of the most important can be evaluated via a cost-benefit analysis, which is usually accompanied by uncertainties impacting decision-making. Hallegatte [206] performed a state-of-the-art review of CC adaptation strategies in water management and noted that in the evaluation of different CC adaptation options, the economic aspects were included in only about a third of the reviewed articles, while they were not included in most of the studies on NBS [207]. However, in recent studies, there is an increasing interest in incorporating the economic aspects into the evaluation, optimization, and selection phases of CC adaptation strategies. The environmental aspects, which are also very important in the evaluation of adaptation options (especially grey), were incorporated in only a few of the adaptation options [208]. The social aspects are usually assessed by measuring socioeconomic and demographic factors that affect the community's capacity to cope with hazards [209]. Regarding stakeholders participation, Bojovic et al. [210] investigated the e-participation, which is defined as "a social activity facilitated by information and communication technologies that assures the interaction among citizens, public administration, and politicians, as critical stakeholders, in the decision-making process" [211], in the MCDA of CC adaptation measures using the following criteria: (1) effectiveness, (2) efficiency, (3) environmental performance, (4) side effects, (5) contribution to the resolution of conflicts, and (6) performance under uncertainty.

4. Discussion and Proposals for Future Research

In the previous three sections, the main aspects of the hydro-environment research on the adaptation of WI to CC were systematically presented using a typology that classifies this research into five categories each consisting of research areas, as shown in Table 2; for these areas, indicative research works were critically presented and discussed. This presentation revealed that there are a limited number of research works in category I (Description of Water Infrastructure), while the research work in the categories II to IV is very large including extensive reviews that identify research gaps and propose future research. Therefore, more research is needed in category I and its research areas are described in the text that follows.

The identification of the components of the WI is a very important task of the adaptation procedure of WI to CC. Typically, it can be performed combining (a) practical experience, and (b) literature, such as papers, books, technical reports, design standards and other documents. It is important to typologize the components for all WI categories (water supply, wastewater, and stormwater systems), so that all components are included in the assessment, even if some of these are considered minor. For example, in one of the very few relevant publications dealing with the vulnerability of Vancouver Sewerage Area infrastructure to CC [212], it is mentioned that the effect of "extreme rainfall" (see WD2; Table 1) can be significant on manholes, flow and level monitors; these components are not even mentioned in the existing guides [50,51], where it is simply stated that the main impacts of this hazard are "on pluvial flood probability and hazard to infrastructure and on drainage system design parameters". It is noted, however, that the increase of the number of the components is expected to result in more complicated subsequent analyses; to avoid these complications, in these analyses the detailed components of a WI system can be grouped into a reasonable number of categories. Indicatively, the components of a Dam and Reservoir System can be topologized and grouped into the following five categories [213]:

- Inflow (I), i.e. the incoming river water.
- Processes or functions (P), such as storage for irrigation and water supply (P1), flood control (P2), hydropower generation (P3), and recreational and aesthetics (P4).
- Assets (A), such as the earthfill or concrete dam (A1), the spillway (A2), the auxiliaries (A3), the monitoring and control system (A4), and the buildings (A5).
- Outflow (O) for water supply (O1), energy production (O2), environmental flow (O3) and flushing (O4).
- Supporting infrastructure (S), such as power (S1), communications (S2), and transportation (S3).

These categories are consistent with the sensitivity themes and the risk areas proposed by EC [1]; thus, they can be used in the sensitivity and impact analysis, respectively; subsequently, they can also be used in the assessment of the adaptation options.

The identification of the potential hazards for each WI component (based on Table 1) requires an initial knowledge of the impacts of these hazards on the WI components (see for example Table 3) in order to perform the sensitivity analysis; this knowledge can be acquired via a systematic literature review and cooperation with experts of WI. Then, in–depth knowledge is probably needed for the analysis of CC impacts, which requires the establishment of the relationships "climate hazard – WI component" for all potential hazards and components. Ideally, these relationships can be quantitative; however, this requires a large amount of data and extensive mathematical modeling, for example using Computational Fluid Dynamics (CFD) models. This procedure can be facilitated by (a) the typologization of climate hazards (see Table 1) and their grouping (see section 1), and (b) the typologization of the potential impacts of the groups of climate hazards for each group of the WI components.

In most of the WI projects climate indicators are selected among the indicators proposed by recognized organizations [89–92]. However, there is an urgent need to develop new indicators, at least for the main WI categories; such as the "beach vulnerability index" developed for the assessment

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of beach erosion vulnerability [214]. The "indicators' analysis" is one of the most important and most difficult tasks of the adaptation procedure of WI to CC. Practically, for every existing or new indicator that represents the basic physical mechanisms of a specific climate hazard, well-defined correlations with specific WI components should be determined. The indicators' analysis requires the cooperation of climate scientists and hydrologists with experienced researchers and engineers specialized in WI; furthermore, it requires a large amount of data and extensive research and experience. For example, in the vulnerability analysis performed by Metro Vancouver [212], only for one pair of "component-indicator" that is the "Monthly Combined Sewer Overflow Volume - Average Monthly Rainfall" a solid linear relationship with a coefficient of determination equal to 0.97 was found, while for all the rest pairs of components-indicators much of the specific data were not available or difficult to acquire; in these cases the analysis was performed using assumptions based on professional judgment and information reviewed and, in some cases, limited calculations using engineering data available. Furthermore, in Metro Vancouver [212] it is stated that the reasons for the absence of these data are: (1) the climate hazards do not place a direct load on the collection system and the WWTP, for example the hazard "extreme precipitation" (WD2) affects wet weather loads, but it does not impact the WWTP directly, (2) in many cases the relationship "climate effect on a WI component – climate indicator directly impacting the WI component" is unavailable, and (3) in cases where there may be a relatively direct impact of a climate variable on the infrastructure, such as the mean sea level that affects ground water elevations and uplift forces on buried infrastructure, the wide range of individual infrastructure elements (i.e. parts of the WI components) at the site precludes the performance of simplified calculations. Forzieri et al. [138] also noted that a literature survey is needed "to explain the channels through which the CC impacts are transmitted". Research is also needed for the development of efficient methods for the determination of the scales and thresholds of the indicators (see Table 9), such as statistical approaches, for example cluster analysis and non-linear least-squares regression [215]. Moreover, the values and scales of climate indicators need to be adjusted to local conditions; this can be achieved via a more detailed downscaling and subsequently development of high-resolution maps with values of indicators at local scale, because their current values cannot always be applied in all countries and locations. For example, the thresholds of the Fire Weather Index (FWI) of the Canadian Fire Weather Index System, which are adopted and proposed by the European Forest Fire Information System (EFFIS) for assessing the level of fire danger in Europe, are too low for the case of Greece [215].

In a comprehensive overview of recent works on CC modeling in the Mediterranean basin, Noto et al. [216] described the challenges and uncertainties in CC modeling and impact analyses and discussed the most relevant sources of uncertainty related to CC aiming at gaining awareness of CC impact studies interpretation and reliability; they stated that despite the progress achieved in recent years in the field of CC and its impact on water resources, results and outcomes should be treated with due caution since any future climate projection and derived implications are inevitably affected by a certain degree of uncertainty arising from each different stage of the entire CC modeling chain. These uncertainties were also discussed by other researchers; for example, Kourtis and Tsihrintzis [208] noted that uncertainties in climate projections and bias correction are still significant and need to be reduced. The latest CMIP6 global climate simulations may produce more accurate CC impacts as a result of ongoing climate model advancements [217]; this would be beneficial to the vulnerability, impacts, adaptation, and climate service communities. Nevertheless, the current horizontal resolution of these simulations are still coarse (horizontal resolution about 100km x 100km and lower). Thus, additional computational and human effort is needed to downscale these climate projections to a higher resolution to better resolve local climatological features. This can be achieved by either dynamical or statistical downscaling. However, both approaches exhibit advantages and disadvantages. Specifically, dynamical downscaling is a computationally demanding method that replicates local climates using information from climate models and physical principles incorporated into the model's code. Due to the demanding nature of this approach prioritization in the simulations is sometimes decided. For instance, in the expected EURO-CORDEX climate simulations, although the four main SSP–RCPs (SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5) are identified as high priority

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in the IPCC-AR6 the community identified SSP1-2.6 and SSP3-7.0 as the top priorities for the EURO-CORDEX simulations while SSP2-4.5 and SSP5-8.5 were selected as the second and third priority scenarios, respectively [218]. In addition, a number of GCMs that meet certain requirements in terms of availability, plausibility, future spread, and independence have been given priority by the EURO-CORDEX community [219]. On the contrary statistical downscaling is less computationally intensive; however, it depends on the availability of reliable long-term observational records for a number of variables from gridded observational datasets or station data to establish strong predictor-predictand relationships and to modify the raw model output, respectively [220].

Huddleston et al. [221] noted that there is a need to develop innovative approaches for the measurement of the adaptive capacity of WI systems. Regarding risk assessment, flood damage assessments could be greatly improved. Recent research has focused on the development of damage models for pluvial flooding; however, progress has been hindered by the availability of pluvial flood risk data and the lack of damage records for pluvial events [222,223]. Thus, more research is needed on the validation and transferability of damage curves. The determination of the "acceptable risk level" is also a crucial step of the risk assessment procedure; it is usually performed by experts undertaking the assessment and depends on the risk that the project promoter is prepared to accept. For example, there may be components of the WI system that can be considered as "non-essential"; when the cost of adaptation measures for these components outweigh the benefits of avoiding the risks, then, the best option could be to allow them to fail under certain circumstances. It is significant to develop scientific methods combined with experts' solicitation to determine the acceptable risk for WI systems. Research is also required for the development of methods for combined risk estimation from multiple hazards [140]. Multiple climate-related hazards threaten the WI services and their resilience, and frequently result in cascading events within the interdependent WI network and other interconnected types of critical infrastructure. Understanding and managing the risks and performance of WI systems, considering transitional and systemic societal risks is a prerequisite for climate resilient societies. The establishment of integrated risk assessments considering multi-hazards risk and associated multi-dimensional vulnerability assessment should be considered, whereas the impacts should be considered holistically including Environmental Impact Assessments, Societal Impacts and Resilience and those pertinent to the Financial and Insurance Sectors. The risk assessment should be the driving vehicle to guide WI to reinforce their resilience capacities to prevent, protect against, respond to, resist, mitigate, absorb, accommodate and recover from climate related incidents and extreme events that have the potential to disrupt the provision of essential services. These are related to physical, technical, financial, security, emergency and organizational measures and should reflect the determined risk levels. Therefore, it is important to place a holistic climate risk and resilience assessment as a focal point of WI governance. Following the recommendations from risk-informed assessments [224] and engineering principles can provide support in addressing policy trade-offs selecting climate adaptation solutions for WI with a new focus on nature-based solutions, and community-focused approaches.

The research works on the adaptation of WI to CC are numerous and some of them include proposals for specific research subjects. Indicative subjects are as follows:

- Sustainable Urban Drainage Solutions (SUDS). Better understanding in needed; the design of SUDS using single synthetic rainfall events and assuming ideal hydrological preconditions can be misleading [225].
- Nature Based Solutions (NBS). More focus is required on applications and economic assessment employed for urban-flood management [207].
- Green infrastructure. Improved models and tools, field and laboratory research, and evaluation of data from increasing application of green infrastructure practices are needed [226].
- Blue and green infrastructure. Research is needed to face lack of capacity, expertise, knowledge, budgetary constraints, poor governance, lack of baseline data, perception of poor services, shortage of space; and competition with other land uses [227]; data for valuation are also needed [228].

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- Urban runoff. Attention should be paid on qualitative aspects (not only to quantitative aspects), and to other measures, such as plans of maintenance and rehabilitation, public awareness, flood forecasting and warning, mobility measures and insurance measures [208].
- Desing and management of WI systems. New methods should be developed for the adaptive design and management, for example using systems thinking and flexibility [229].

Finally, the emerging trends in hydro-environmental research aim at achieving global water goals, such as the SDG6, considering links and relationships, such as the water-energy-food nexus, and in an integrated way. Innovative advanced modelling methods based on data science, such as AI and digital twins [230,231], are combined with innovative technologies using new materials, such as membranes and nanotechnology [232], and new solutions are being developed, such as (i) smart water management systems and tools using data analytics, innovative sensors, machine learning algorithms and internet of things, and (ii) efficient monitoring and EWSs using AI and other data science tools [233], which are expected to improve the resilience of WI to CC.

5. Conclusions

The hydro-environment research on the adaptation of WI to CC research is vast and includes various terminologies and methods for all adaptation aspects. The adaptation procedure of WI to CC can be significantly improved when this hydro-environment research is known to the developers of guidelines for the adaptation of infrastructure to CC. To facilitate this knowledge transfer, a literature review was performed to identify the main aspects of this research, which are systematically and critically presented, and discussed using typology and indicative research works. According to this typology, the hydro-environment research is classified into the following five categories, which are based on the EC guidelines and correspond to the five steps of the adaptation procedure of WI to CC: (I) description of the WI, (II) CC assessment, (III) vulnerability assessment, (IV) risk assessment, and (V) assessment of adaptation measures.

This research work revealed that there are a limited number of research works in the category I; thus, more research combined with experts' solicitation are needed, mainly on (i) the identification and typologization of the components of the WI, (ii) the typologization of the climate hazards on WI and their impacts on its components, and (iii) the identification and typologization of indicators for WI and their thresholds. The research work in categories II to V is extensive and rapidly increasing; moreover, it includes reviews that identify research gaps and propose future research.

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