A CLIMATE –RESPONSIVE CONCEPTUAL FRAMEWORK FOR ASSESSING WATER ECOLOGICAL CARRYING CAPACITY IN URBAN WATERSHED

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A CLIMATE – RESPONSIVE CONCEPTUAL FRAMEWORK FOR ASSESSING WATER ECOLOGICAL CARRYING CAPACITY IN URBAN WATERSHED

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Abstract: Rapid urbanization and climate variability have degraded water quality and reduced the resilience of urban watershed. This study proposes a climate-responsive conceptual framework for assessing Water Ecological Carrying Capacity (WECC) in urban environments. The framework integrates hydro – climatic indicators, urban – climatic dynamics, and adaptive policy interventions, structured within the Driver–Pressure–State–Impact–Response (DPSIR) model. It is designed to evaluate the dynamic interactions between urban growth, climate variability, and freshwater ecosystem thresholds. A systematic review of 14 studies from Asia and beyond provides empirical support for the framework. Indicators such as streamflow variability, urban land use, water temperature, and governance capacity are categorized within the DPSIR components to illustrate the multifaceted nature of WECC. The study highlights how hydro – climatic and socio – economic stressors interact to influence the vulnerability and resilience of water ecosystems. Figures and tables within the paper visualize these interactions and simulate feedback loops under various environmental and policy scenarios. While the model presents a comprehensive and adaptable framework, it is based on secondary data and lacks validation through localized, real-time application. Nevertheless, it serves as a strategic tool for anticipating and addressing urban water sustainability challenges. It encourages the use of integrated, climate – informed planning approaches and provides a foundation for future research and policy in climate – sensitive regions. This study underscores the importance of evaluating WECC not as a static measure but as a dynamic function shaped by ecological, social, and climatic processes.

Keywords: *Water Ecological Carrying Capacity (WECC); Climate Change; Urban Watershed; Socio – economic*

I. INTRODUCTION

Water ecological carrying capacity (WECC) reflects the importance of water supply for human activities which can be delineated by the quality of ecosystem services provided by its land coverage of water resources areas (Fadhilah *et al.*, 2021). In addition, water ecological carrying capacity enables the application of tangible procedures of sustainable development concept to deliver some viable recommendations for water resources management.

The concept of sustainable development requires the preservation of natural environment while pursuing socio – economic

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development. In particular, this perception demands the harmony between the water ecosystem and the socio – economic development (Yang *et al.*, 2015). In order to ensure the effective function of urban watershed to provide ecosystem services for urban ecosystem, it is necessary to regard urban watershed, such as river with the concept of socio – ecological systems since it contains the interactions between human beings and the river ecosystem. A notable study on the water quality index of urban lakes in Depok City was previously conducted by Hendrawan *et al*, (2020) during the period of 2017 - 2019, revealing that 9 of 20 urban lakes had deteriorated to a heavily polluted status from their initial state of low to moderate polluted.

Urban watersheds are increasingly strained by the combined pressures of accelerated urbanization and climate change. The Water Ecological Carrying Capacity (WECC) represents a selected criterion for identifying the ecological system limit to absorb human-induced pressures sustainably. WECC models at present are primarily static and inadequately include the growing impacts of climate variability and extremes. To manage water resources sustainably in urban areas, especially under climate stress, it is essential to adopt climate-responsive frameworks that integrate environmental, social, and technical dimensions. Zaizay and Huseyin, (2024) emphasized that the interdependence of water supply, energy systems, and climatic variability forms a foundational consideration in designing new policy-oriented instruments.

As climate change increasingly redefines hydrological cycle via altered precipitation regimes, increased temperatures, and increased frequency of extreme weather, therefore, there is an urgent need to return and expand the WECC framework. This paper proposes a climate-resilient conceptual framework to assess the Water Ecological Carrying Capacity (WECC) of urban watersheds. The framework integrates three key components: projected climate impacts on water ecosystems, the ecosystem's capacity to support ecological functions, and the overall ecological health of the water system. This framework also captures how urban residents interact with water resources, thereby reflecting the social role of urban watersheds. In particular, the combine pressures of climate change and rapid development are likely to increase negative impacts on urban watershed systems. To address this, the framework presented herein simplifies complex interactions by identifying specific climate-sensitive indicators, particularly those linked to water quality criteria that convey both vulnerability and resilience in urban watersheds.

However, there is a lack of empirical studies to assess Water Ecological Carrying Capacity to inform about the indicators and impacts of human pressure and climate change on freshwater ecosystem, especially urban watershed. Although a considerable body of WECC research has emerged, particularly in China, with studies such as Ding *et al.*, (2015) and Yang *et al.*, (2015) focusing on the impacts of socio – economic development on the water ecosystem that deliver the practical recommendations for sustainable urban growth, these efforts frequently neglect to comprehensively address the compounded effects of climate change on urban watersheds. This emphasizes the urgent need for a climate-responsive evaluation model that captures the multidimensional stressors affecting water ecosystems in urban environments.

In support of this argument, several studies further highlight the limitations of existing frameworks. For instance, Xu *et al* (2011) underscored the importance of index system of water ecological carrying capacity for evaluating the interaction amongst all supporting systems that affecting the regional water environmental management. Meanwhile, Zeng *et al.*, (2011) explored the use of geo-spatial techniques to provide the analysis of aquatic ecological carrying capacity for identifying the pressure of human activities on the freshwater ecosystem of the most populated district in China. However, this study was primarily centered on the index of pollutants without investigating the impact of climate change. Likewise, Li *et al*,(2021) adopted the Pressure-State-Response (PSR) model to examine ecological carrying capacity in designated ecological function area in China, focusing on structural ecosystem support without integrating climate variables. Another specific study of water ecological carrying capacity was also established by David *et al.*, (2015), attempted to analyze the impact of cage aquaculture on the aquatic environment in southeastern Brazil without investigating the impact of climate change.

As highlighted by Yang *et al.*, (2015), assessing Water Ecological Carrying Capacity (WECC) is vital for delineating the capacity of water ecosystems to sustainably support socio – economic growth. However, in the context of intensifying climate change, this assessment must evolve to consider new and emerging pressures. The catchment area of a water resources located in urban areas is also essential to gain more concern since it has been greatly converted into settlement areas that dispose more pollutant into the water bodies that function as the reservoirs for overland flow (Lukiyansah *et al* , 2020). Hence, urban water resources must be assigned as the common pool for preserving freshwater for livelihood and projecting the importance of sustainable development to simultaneously occur in a city. To accurately measure the dynamic mechanisms of resource supply, consumption, and ecological stress, especially under climate variability, this study proposes a climate-responsive conceptual framework that simulates interactions between urban society and aquatic ecosystems. This framework aligns with the growing need to integrate climate variables into WECC evaluations, thereby enhancing the capacity of urban water systems to adapt to future uncertainties.

II. METHODOLOGY

This study adopts a climate-responsive theoretical framework grounded in an extensive review of interdisciplinary literature to identify key indicators essential for assessing Water Ecological Carrying Capacity (WECC) in urban watersheds. Building upon the conceptual model outlined in the previous section, the methodological approach integrates climate science, urban ecology, and water resource management to evaluate the multifaceted pressures on freshwater systems. The assessment is structured to capture three primary dimensions: (1) the projected impacts of climate change on urban hydrology and ecosystem services, (2) the ecological support capacity of freshwater systems for climate adaptation and mitigation, and (3) the overall health and resilience of the urban water ecosystem.

The framework guides the simulation of interactions between socio – economic activities and environmental stressors, particularly those intensified by climate change. It also provides a basis for analyzing thresholds in Water Ecological Carrying Capacity (WECC). Through this integrated perspective, the study aims to provide an indicative tool that aligns urban sustainability goals with adaptive water governance under a changing climate. Moreover, understanding the variability in regional Water Ecological Carrying Capacity (WECC) requires a holistic analysis of interconnected factors, particularly climate dynamics, socio – economic development, and population growth. As these factors increasingly interact in complex and often non-linear ways, it becomes essential to adopt frameworks that can capture their systemic relationships.

The Driver – Pressure – State – Impact – Response (DPSIR) framework, widely applied since the late 1990s, provides such a mechanism by mapping out cause-effect relationships among human and ecological systems. Within this structure, Drivers refer to the underlying socio – economic trends fueling resource demand; Pressures encompass both anthropogenic and climate-induced stressors, including emissions, land-use change, and extreme weather events; State describes the condition of ecosystems under cumulative stress; Impact reflects the ecological and societal consequences of these changes; and Response represents adaptive policies and interventions aimed at safeguarding sustainability (Cheng *et al.*, 2023). Integrating the DPSIR framework into the assessment of urban watershed WECC allows for a climate-responsive perspective that not only recognizes emerging threats but also informs resilient planning strategies.

2.1. Framework Development

Recent research conducted by Bu *et al.*, (2020) conceptualized the WECC as comprising three interdependent sub – systems, namely: water resources, water environment and water ecology that require the reflection of socio – economic development and environmental impacts.

As explained by Riyadi *et al*, (2018), a set of evaluation indicators for WECC should cover the field of economic, social, resource, environmental, technical, and management. A framework is developed by integrating indicators that are particularly sensitive to climate variability, such as drought and flood frequency, rainfall variations, and ecosystem stressors, which reflect the vulnerability of water resources under changing climatic conditions (Jia *et al.*, 2018). As illustrated in Figure 1, the conceptual model synthesizes these indicators within a dynamic systems framework to simulate the interaction of key drivers, including climate change, urbanization, and policy interventions, on ecological thresholds.

This framework provides a comprehensive approach to assessing and managing Water Ecological Carrying Capacity (WECC) in the context of climate change and urbanization. It integrates three key dimensions as follows:

1. Hydro – climatic indicators: Hydro–climatic factors such as streamflow variability, precipitation variability, and water temperature trends are linked to critical impacts including water supply instability, flood recurrence, and reduced dissolved oxygen.

2. Urban – climatic dynamic indicators: Urban dynamics, including urban expansion, water consumption per capita, and impervious surface ratio—contribute to ecosystem services disruption, negative water balance, and stress in aquatic organisms.

3. Climatic policy interventions: The framework also emphasizes the role of adaptive governance through governmental,

institutional, and community actions that drive climate adaptation policies, urban water management strategies, and community-based initiatives.

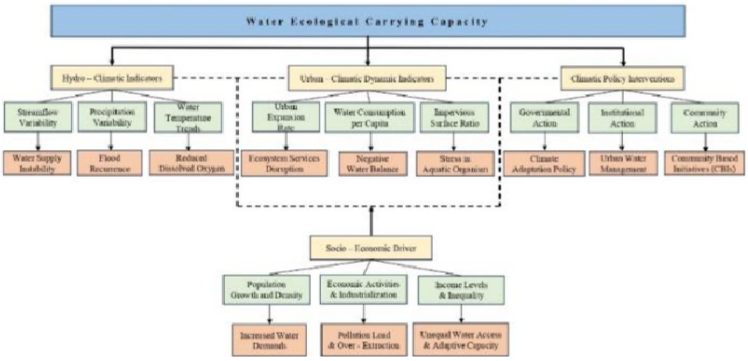

Figure 1. Climate-Responsive Conceptual Framework for Assessing Water Ecological Carrying Capacity (WECC) in Urban Watersheds

Complementing these pillars is a foundational layer of socio – economic drivers, including population growth and density, economic activities and industrialization, and income levels and inequality. These drivers contribute to increased water demands, pollution load and over-extraction, and unequal water access and adaptive capacity, respectively. The model not only illustrates current WECC conditions but also facilitates scenario-based planning and policy design by incorporating socio – economic stressors, hence enhancing the framework's relevance for long-term, equitable, and climate-resilient water governance.

Socio – economic pressure comprises the combined effects of water consumption, water pollution, and ecological degradation. The support capacity of the water ecosystem represents its inherent ability to sustain socio – economic development while withstanding anthropogenic stressors, thereby maintaining a relatively stable state (Yang *et al.*, 2015). The improvement of the ECC assessment has evolved from a certain single factor (e.g. vegetation productivity, land use intensity and available water resources) to a comprehensive index system since the self-regulation and self-recovery characteristics of ecological environment comprise a variety of indicators, which are susceptible to climate variability and changes in human consumption and activity.

In regards with climate change impacts, the framework further considers how changing climatic condition such as changes in precipitation patterns, temperature fluctuations, and the streamflow variability event can alter the availability, consumption, and quality of regional water resources. These climate-related variables highlight the significance of the selected indicators in reflecting dynamic environmental stressors that affect water ecological carrying capacity. These hydro-climatic indicators are not isolated. Subsequently, they interact with urban-climatic dynamics and socio – economic drivers, compounding stress on water systems. For instance, streamflow variability may result in unstable water supply, while shifts in precipitation intensity and frequency contribute to flood recurrence. Similarly, rising water temperatures reduce dissolved oxygen levels, threatening aquatic ecosystems. The urban dimension amplifies these effects through impervious surface expansion, elevated water consumption rates, and rapid urban sprawl, leading to ecosystem service disruptions, negative water balance, and physiological stress in aquatic organisms.

Furthermore, these environmental stressors are magnified by socio – economic drivers such as population growth, industrial development, and inequality, which increase water demand, intensify pollution loads, and limit equitable water access and adaptive capacity. The framework emphasizes the relevance of these interconnected indicators in reflecting the multidimensional impacts of climate change on water ecological carrying capacity. By integrating climatic policy interventions through governmental, institutional, and community action the model supports adaptive governance strategies aimed at mitigating climate risks and enhancing the resilience of urban water systems.

2.2. Data Collection and Analysis

Table 1 provides a comprehensive compilation of operational indicators derived from recent global and regional studies related to Water Ecological Carrying Capacity (WECC). These indicators have been systematically organized according to the Driver – Pressure – State – Impact – Response (DPSIR) framework, which underpins the climate-responsive conceptual model presented in Figure 1. Furthermore, to improve clarity and highlight the systemic role of each indicator, Table 1 applies color-coded grouping based on the DPSIR (Driver – Pressure – State – Impact – Response) framework. Each indicator is classified by its function within the WECC system: blue for drivers, red for pressures, yellow for states, green for impacts, and purple for responses. This visual classification helps readers identify key patterns and interactions more easily.

The literature from 2018 to 2024 reveals a dynamic and evolving exploration of Water Ecological Carrying Capacity (WECC) across various regions in Asia. Throughout this period, researchers have progressively expanded the scope of analysis, integrating environmental, hydrological, and socio – economic dimensions. Most studies focus on keywords such as “water ecological carrying capacity,” “water resources,” and “ecological security” reflecting a growing interest in linking ecological concerns with sustainable development goals. The indicators used range from water supply, demand, and pollution levels to land use, GDP growth, urban water consumption, and aquatic environmental quality. These multifaceted indicators provide a comprehensive view of the challenges and pressures facing water systems in urban and river basin contexts.

Table 1. Operational Indicators Representing DPSIR Components in the Climate-Responsive WECC Framework

No.	Year	Keywords	Indicator(s)	Location	Key Findings	DPSIR
1.	2018	Water ecological carrying capacity	water supply, water demands	Malang watershed	status of water carrying capacity in Metro and Bango sub-watershed was at high risk (Riyadi *et al*, 2018)	Pressures

No.	Year	Keywords	Indicator(s)	Location	Key Findings	DPSIR
2.	2018	Water environmental carrying capacity	Water environment carrying status, water resource carrying status, exploitation and utilization potential of water environmental carrying capacity, water environmental vulnerability	China watershed	water environment vulnerability in the west is higher than that of central and eastern provinces due to different locations along the main rivers (Jia *et al*., 2018)	Drivers
3.	2019	Water resources, ecological carrying capacity	Water resources global balance factor, regional average multi-year production capacity, global average production capacity of water resources, production factor of regional water resources	Yan'an, Shaanxi Province	water resources ecological footprint in Yan'an was greater than the ecological carrying capacity of water resources (Zhao *et al*, 2019)	State
4.	2020	Water environment carrying capacity	Environmental quality, water resources and social economy	Nanjing city (The Yangtze River)	the WECC comprehensive index of Nanjing (including Yangtze River) increased with a slow growth rate (Xu *et al*., 2020)	State
5.	2020	Water ecological carrying capacity	Water resources, water environment, water environment purification index, water ecology	Changzhou city watershed	The overall optimal scenario showed the safe carrying capacity, which the urban domestic sewage may have a greater impact on water environment carrying capacity at specific locations (Bu *et al*., 2020)	Impacts
6.	2021	Water ecological carrying capacity,	water resources, socio – economic, ecological	Yangtze River Economic Zone	ecological carrying capacity of the Yangtze River was at low level due to the focus of development mode of GDP	Drivers

No.	Year	Keywords	Indicator(s)	Location	Key Findings	DPSIR
		water resources	elements		quantity growth (Chen *et al.*, 2021)	
7.	2021	Water ecological carrying capacity	Water resource system, socio – economic system, eco-environment system	Han River Basin	the pressure of the water resources carrying capacity will further increase, the water consumption climbing to 20.5 billion m^3 in total (Deng *et al.*, 2021)	Pressures
8.	2022	Water environmental carrying capacity	Water environment carrying capacity index	Yellow River Basin, Gansu Province, China	the WECC value of the Gansu section of the Yellow River Basin was slowly increasing from 2015 – 2020 (Jin *et al.*, 2022)	State
9.	2022	Water environmental carrying capacity, urban water consumption, land use	Water resource system, socio – economic system, eco – environment system	Pearl River Delta	water resources carrying capacity was found to be related with precipitation (Zhou *et al.*, 2022)	Pressures
10.	2022	Water ecological carrying capacity, urban water consumption, spatial demographic factors	Water ecological carrying capacity, land use, population density, water consumption	Tehran, Iran	residential land use had the strongest positive correlation with water consumption in all seasons. deteriorated areas can signal lower ecological carrying capacity, particularly in the face of climate variability and seasonal demand spikes (Tayebi *et al.*, 2022)	Impacts
11.	2023	Water resource carrying capacity	water resources systems, socio – economic system, ecosystem, the obstacle degree	Yellow River Basin	overall improvement of the WRCC in the YRB's nine provinces was good, except in the downstream region was poor (Sun *et al*, 2023)	Pressures
12.	2023	Water resource carrying capacity	Water resource carrying capacity, ecological environment, socio – economic	Manas River Basin	regional water resources and socio – economic factors have more significant impacts on carrying capacity than ecological and environmental factors (Gulishengmu *et al.*, 2023)	Drivers

No.	Year	Keywords	Indicator(s)	Location	Key Findings	DPSIR
13.	2024	Water ecological security	Water ecological security, water resources socio – economic, ecological environment	Hexi Corridor, Northwest China	pressure system consistently had the highest obstacle level especially from ecological and urban environmental water use (Sun *et al.*, 2024)	Responses
14.	2024	Water ecological carrying capacity, green total factor productivity	Water resources, water environment, aquatic environment, water security	Jiangsu Province, China	water resource efficiency, water environment improvement, and industry innovation positively impacted GTFP (Gu *et al.*, 2024)	Responses

Notes: DPSIR color – code grouping: (Drivers); (Pressures); (State); (Impacts); (Responses)

III. RESULT AND DISCUSSION

In regards with the consequences of climate change, the rise of global temperature leads to the warmer temperature of freshwater ecosystem and coastal wetlands, thus a large number of urban watershed throughout the world are suffering from climate-induced harmful algae blooms and eutrophication (UNESCO & UN-Water, 2020). Despite the fact that urban watershed, such as river provides many benefits related to human needs and living organism, however its global status of water resources availability has been at an alarming state which creates the constraint that impedes the rapid development to fulfil the basic demands of growing population (Lu *et al.*, 2017). The global water demand shows an increasing projection percentage of 55% through the year 2000 until 2050. On the other hand, the world would deal with the 40% of water scarcity by the year 2030 if the global stakeholders are unlikely to create a cutting-edge mechanism to adapt to the future challenges of water resources (UNESCO & UN-Water, 2020). Besides, Woolway *et al.*, (2020) stipulated that lake as freshwater ecosystem becomes one of vital indicators of natural resources that able to indicate any effects of climate change due to its physical responsiveness to climate variations. Given its ability to imply with the global hydrologic cycle, lakes respond to climate change through some parameters such as the rise of surface water temperatures, the high rate of water evaporation and alterations of mixed layer depth. These changes directly affect water availability and overall quality. A regional case study in Southern Nigeria recorded a consistent trend of decreasing rainfall duration coupled with increased intensity over three decades, exacerbating soil erosion, flooding, and runoff volume (Christy Chidiebere *et al.*, 2024).These findings underscore the need for WECC frameworks to account for dynamic hydrological responses to climate change.

According to Ansari *et al.*, (2011), eutrophication continues to be one of the major issues affecting water quality in urban lakes, although the intensity of its impact varies by region. Even in scenarios where climate change brings increased precipitation, it does not guarantee improved water storage or ecological stability. In fact, high-intensity rainfall may exacerbate nutrient runoff and pollution, leading to further water quality degradation. Human-induced pressures have also amplified environmental impacts in urban watersheds. These include intermittent flows of rivers and lakes, degradation of riparian and aquatic ecosystems, loss of biodiversity, land subsidence, and deteriorating groundwater quality. The socio – economic effects of water dynamics include damages from subsidence, impaired fisheries and decreased crop yields, costs to transform industrial structures and restore riparian and aquatic ecosystems, and health effect from water pollution. Though economic efficiency and conservation may seem to be in conflict with social concerns, it is essential to provide a strategic step to achieve water sustainability through controlling total water demand and reduce activities (Xu *et al*, 2011).

As illustrated in Figure 1, hydro-climatic indicators such as streamflow variability and temperature anomalies were shown to directly reduce the carrying capacity of urban water ecosystems, particularly when coupled with urban dynamics like impervious surface expansion and elevated per capita water use. These interactions reinforce that WECC is not static; it fluctuates based on ecological resilience, infrastructure quality, and the intensity of socio – economic pressures. This conceptual framework allows for a more dynamic and scenario-based assessment of WECC, moving beyond static thresholds to emphasize resilience, ecological response, and policy relevance. By recognizing those socio – economic drivers, such as population growth and industrial development, intensify ecological stress, the results reinforce the urgent need for multi-level interventions. Therefore, this study contributes a strategic basis for developing sustainable, equitable, and climate-resilient water governance systems, especially in rapidly urbanizing and climate-sensitive tropical regions.

The relationship between Figure 1 and Table 1 is critical for translating the conceptual structure into measurable dimensions. While Figure 1 visualizes the systemic interactions between drivers, pressures, states, impacts, and responses within a climate-responsive WECC model, Table 1 operationalizes this structure by listing specific indicators for each component. These indicators are ranging from temperature anomalies and urbanization rates to water quality metrics and policy interventions that enable the practical application of the framework in real-world assessments. Together, the figure and table demonstrate how dynamic climate and urban development variables interact within a measurable and adaptive ecological system, supporting evidence-based water governance.

Importantly, the model shows that interventions, especially those promoting climate-sensitive governance are key to preventing systemic thresholds from being crossed. Where proactive policies are absent, pressures continue to build, leading to ecological collapse or service failure. Therefore, future applications of this framework should prioritize identifying ecological tipping points and aligning water resource planning with climate scenarios and socio – economic projections. The analysis also supports that integrating climate-sensitive indicators—such as streamflow variability, precipitation shifts, water temperature trends, and urban expansion—can offer a more nuanced and responsive evaluation of Water Ecological Carrying Capacity (WECC). The compounded pressures from both urbanization and climate change require adaptive governance models that include not only governmental regulations but also institutional innovation and community-based initiatives. When modelled within a DPSIR framework, these indicators highlight the interconnected pathways through which climatic and human factors impact freshwater ecosystems.

These global observations affirm the need for localized, systems-based assessments. Applying the climate-responsive WECC framework developed in this study, key variables were organized under the DPSIR model to simulate the systemic impacts of urban and climatic stressors as illustrated in Figure 2. Regionally, studies listed in Table 1 were conducted across various significant locations. The inclusion of case studies from multiple regions, including China, Iran, and Indonesia, demonstrates a broad contextual application and supports the feasibility of the proposed framework across diverse environmental and socio – economic conditions. The results reveal substantial spatial differences in WECC. For instance, areas such as the central and eastern provinces of China tend to exhibit higher water environment vulnerability due to uneven resource distribution and industrial development. In urban contexts like Nanjing and Changzhou, urban sewage treatment and slow environmental improvement have been critical limiting factors. The Han River Basin and Manas River Basin studies highlight increasing water consumption pressure and the role of socio – economic factors in WECC decline, respectively.

The Drivers, such as urban population growth and economic development, are prominently illustrated in studies from the Yangtze River Economic Zone, Tehran, and the Manas River Basin. For example, the Tehran case (Tayebi *et al.*, 2022), shows how residential land use and population density serve as spatial-demographic indicators driving water demand and ecological stress. Similarly, the Han River Basin study (Deng *et al.*, 2021), documents increased water consumption climbing to 20.5 billion m^3, aligning with economic intensification and urban expansion.

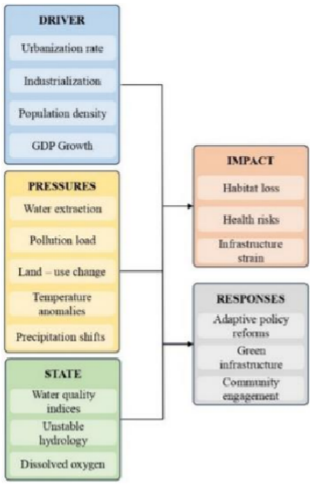

Figure 2. Integrated DPSIR Simulation of Climate-Responsive WECC

Pressures are typically manifested through water extraction, pollution loads, and climate-induced variables. Multiple studies, such as those conducted in Malang (Riyadi *et al*, 2018) and the Yellow River Basin (Sun *et al*, 2023), show how both anthropogenic and hydro-climatic pressure such as high exploitation levels or precipitation change directly affect water systems. The study in Gansu Province (Jin *et al.*, 2022) provides insight into water environment carrying capacity trends over five years, reflecting both anthropogenic and climate-based stressors.

The State of the water ecosystem is represented by indicators such as the water environment vulnerability index, ecological footprint, or ecosystem degradation. For instance, the Yan'an study (Xu *et al.*, 2020), used ecological footprint analysis to determine that the region's consumption outpaced its water ecological carrying capacity, illustrating a critical imbalance between resource use and sustainability. Likewise, Nanjing's assessment (Xu *et al.*, 2020), shows a slow growth in WECC index despite improvement initiatives, suggesting persistent ecological strain.

Impacts, such as degraded ecosystem services and deteriorating water quality, are evident across the dataset. In Changzhou (Bu *et al.*, 2020), urban domestic sewage was identified as a major contributor to water quality degradation, highlighting the vulnerability of urban rivers to point-source pollution. Similarly, a study conducted in Tehran (Tayebi *et al.*, 2022), linked areas with low WECC to aging infrastructure and seasonal variability in water demand. These factors contribute to infrastructure strain through overburdening, exemplifying how socio – ecological feedbacks can escalate into more severe consequences including water supply instability and biodiversity or habitat loss.

Responses are comparatively less documented in some of the earlier studies but have emerged more prominently in recent works, particularly in China, namely Hexi Corridor (Sun *et al.*, 2024) and Jiangsu Province (Gu *et al.*, 2024). In these regions, the incorporation of green total factor productivity (GTFP) and policy innovation is shown to positively influence WECC through enhancing water use efficiency and ecological resilience. These findings validate the response layer of the DPSIR framework and support the model's emphasis on adaptive governance incorporating public participation, policy alignment that support green infrastructure, and institutional capacity.

Collectively, Table 1 substantiates the climate-responsive WECC framework by bridging conceptual theory with empirical evidence. It reveals the evolution of WECC research from static capacity assessments to more nuanced, dynamic analyses incorporating climate variability, urban expansion, and socio – ecological feedback loops. The indicators derived from these studies not only validate the model's structure but also emphasize the importance of localized data and region-specific planning. The trends suggest that successful WECC management requires integrative policies that consider urban morphology, climate anomalies, and ecological thresholds in tandem.

This tabular synthesis also underlines that while numerous studies have approached WECC from an environmental or resource-based standpoint, few have explicitly incorporated climate variables into their core methodology. By embedding hydro-climatic and socio – economic indicators within a unified DPSIR model, this study offers a more comprehensive and future-oriented assessment tool, relevant for cities in tropical and climate-sensitive regions.

The study conducted by Tayebi *et al.*, (2022) provided real-world validation of how physical and demographic factors contribute to Pressures and State changes within the DPSIR model. The use of indicators like deteriorated areas, building age, and land use is consistent with the urbanization and infrastructure variables, while seasonal water demand and population dynamics illustrate climate-induced variability and socio – ecological interactions. Conversely, some areas, such as Jiangsu Province, show a more optimistic outlook by demonstrating how improved water use efficiency and environmental policy innovation can positively influence green total factor productivity (GTFP) (Gu *et al.*, 2024). Recent research trends show a shift from static assessments to dynamic modelling and performance evaluation, especially in connecting WECC with economic and ecological resilience. The 2024 studies in particular (Gu *et al.*, 2024 ; Sun *et al.*, 2024), emphasize ecological security and the interaction between water management and industrial innovation. Collectively, these studies underline the necessity of region-specific strategies, integrated water resource management, and policy interventions to sustain WECC.

The conceptual framework that provides a foundation of this study visualizes how systemic stressors like climate variability, urban expansion, and policy responses affect the sustainability of urban freshwater ecosystems. The tabulation validates the theoretical dimensions of Figure 1 by mapping actual measurement variables (e.g., streamflow variability, water quality metrics, urbanization rates) to each DPSIR component. Figure 2 portrays how the interrelated variables defined in Figure 1 and quantified in Table 1 behave within a systemic feedback loop work. Together, these elements provide a complete and practical tool for managing urban water resources under the pressure of climate change and urban growth.

This study is based on secondary data and literature, without real-time validation in specific urban watersheds. While the DPSIR framework helps structure complex interactions, it may not fully capture local or seasonal variations. Future studies should apply the model to specific case studies using primary data and dynamic simulation tools for greater accuracy.

IV. CONCLUSION

This study presents a climate-responsive conceptual framework for assessing Water Ecological Carrying Capacity (WECC) in urban watersheds. In contrast to traditional models, which often overlook climate variability and socio – ecological interactions, this research integrates hydro-climatic indicators, urban dynamics, and adaptive policy responses within a comprehensive DPSIR structure. The use of interdisciplinary indicator, from streamflow variability to socio – economic stressors enhance the capacity of the framework to reflect the complexity and vulnerability of urban water ecosystems in the face of rapid urbanization and climate change.

As urban regions continue to grow and climate-related uncertainties intensify, this framework offers a practical tool for policymakers, planners, and water managers to anticipate, assess, and address the multidimensional challenges of urban freshwater ecosystems. Future research should focus on applying this framework across various climatic and socio – political contexts, refining its indicators based on localized data, and exploring the thresholds at which water ecosystems shift from resilience to collapse.

Ultimately, integrating climate sensitivity into WECC assessments is no longer optional as it is essential to securing water sustainability, ecological balance, and urban resilience in this critical decade for climate action.

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