Eco-hydrology and Hydraulics of Urban Watersheds – A Resilience Approach

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ABSTRACT

Urban water system managers face a set of interrelated water security challenges as they pursue the goals of sustainable sources of water, mitigating flood hazards, and improving water quality. These challenges are often subject to change (and hence highly uncertain) due to the coupled effects of hydro-climatic variability, socio-economic trends, and regulatory reforms. To meet these intersecting goals, we present a mechanistic framework with illustrative examples that evaluates an urban water system's resilience under future uncertainty. By employing principles from engineering design, ecosystem science, and social equity studies, our Resilient Urban Water Systems (ReUWS) framework explores the potential of effectively combining green and gray infrastructure (GGI) in an urban watershed while prioritizing stakeholder and community engagement throughout the lifecycle of water system projects. A nested set of hydrology, ecosystem, and hydraulic models are developed with data flow among them defining the boundary and initial conditions for each other. An example is shown with the Baltimore water system on an approach to evaluate the effects of GGI hybrids on major water security metrics. The corresponding engineering designs, ecosystem service potentials, and measures of equitable access to services are also analyzed using the framework. The results evaluate performance of the existing systems under future conditions and also compare different GGI-based strategies for improving resilience in urban water systems. The findings of the study help to evaluate the potential for using GGI strategies to cope with changing climate extremes and other environmental factors as well as social change. Tradeoffs derived from the case studies also can be used to adjust local/regional policies and regulations.

Keywords: Resilient Urban Water System; Green-Gray Infrastructure; Baltimore Water System; Ecosystem Services; Eco-Hydrology and Hydraulics; Social Equity

Introduction

Water systems face a set of interrelated water security challenges as they pursue the goals of meeting demands from several fronts including domestic, industrial, agricultural, and urban sectors. Traditionally, urban water systems are designed to store and divert water (both surface- and groundwater), mitigate flood hazards, and treat supply and effluent to protect human and environmental health. Besides the use of gray infrastructure to meet urban-demand-oriented services, water systems also include natural elements that provide a wide set of ecosystem services and co-benefits (MEA 2005). Often these natural elements share cultural values with non-majority groups (Speed et al. 2016). Due to the siloing of urban water research and policy implementation, there exists a lack of interdisciplinary coordination among multiple agencies and jurisdictions. One of the major challenges in conducting such research is the absence of unified modeling frameworks and decision support systems (DSS) (Tickner et al. 2017). Such frameworks or DSS tools are expected to holistically evaluate a system's performance in terms of eco-hydrological dynamics and hydraulic connectivity while ensuring equitable distribution of services and benefits rendered by the system across different population groups. Sources of uncertainties, e.g., hydro-climatological differences and variations, socio-economic trends and practices, and regulatory reforms (as a response to technological advancements), further complicate the dynamics and complexity of the systems.

Figure 1 shows a hypothetical setting that highlights multi-faceted human actions that influence the dynamics of an urban water system receiving imported water supply. In this example, an agricultural/rural system is located upstream, while an urban water system is located downstream. It illustrates how agricultural activities from the upstream system may cause water quality concerns for the downstream system. The figure also shows the eco-hydrologic and hydraulic connectivity (and their subsequent geophysical processes) between the upstream and downstream systems. As an example, flood risk for the downstream system is affected by both the upstream and local hydro-climate, land use, and hydraulic features as shown in the figure. Moreover, socio-economic conditions, infrastructure regulations, and policy applications may be shared among several agencies and jurisdictions (along with their national, regional, and local hierarchies), which may vary significantly between the upstream and downstream systems. Such differences and dynamic flows contribute to disparity and asymmetry in the larger system (i.e., both the upstream and downstream systems combined) in terms of services, benefits, and risks.

A recent review (Vörösmarty et al. 2018) has suggested that in principle, combining green and gray infrastructure (GGI) strategies can be quite useful in dealing with intersecting water security goals, but requires sufficient comprehensive analysis and participatory governance. Significant technical, managerial, and financial challenges exist in applying GGI strategies across rural and urban watersheds (and at their interfaces) and requires unified and collective efforts from physical and social scientists, economists, policymakers, and public stakeholders (Bunn 2016; Vörösmarty et al. 2018). Hence, in this study, we present a resilient urban water system (ReUWS) framework, which integrates technological advancement, eco-hydrological dynamics, and hydraulic connectivity in a bottom-up, dynamic approach with feedback loops and adjustments from stakeholders and community members. The approach is designed to maintain fairness and socio-economic equity, by ensuring stakeholder engagement and community participation throughout the project initiation to implementation phases.

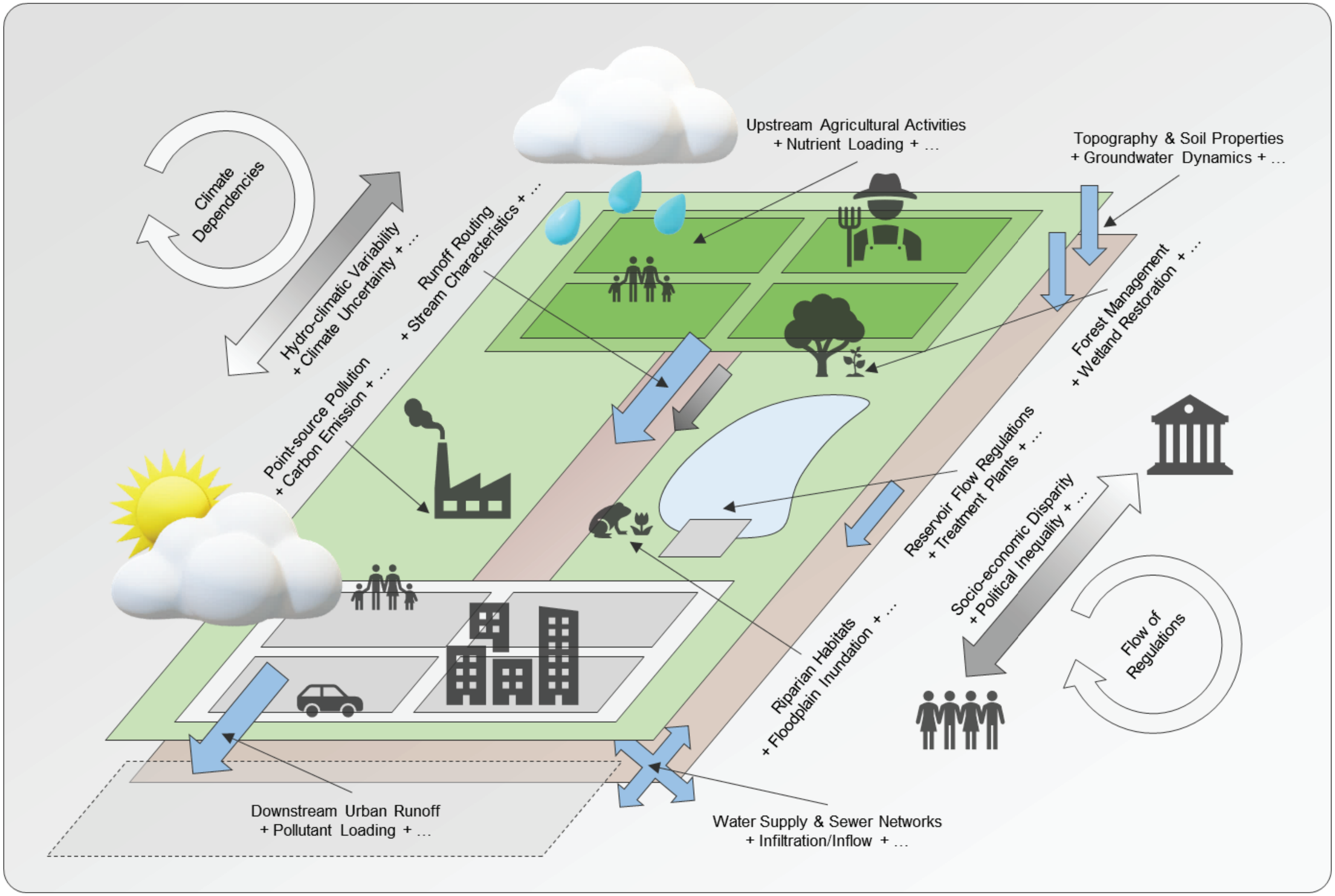

Figure 1: A schematic diagram showing the major components and their interactions in an urban water system and its upstream activities and water services contributions. The system may continue further downstream as shown by the dotted area. Blue arrows indicate a common flow topology of water. Uncertainty parameters (e.g., hydro-climatic variations, socio-economic trends, and regulatory reforms) can vary significantly between the upstream and downstream locations as shown by double-headed arrows with gray-scale gradients and circular coils suggesting asymmetry, variation, dependence, and dynamic flow.

In the context of this paper, the *resilience* of a system is considered to be its ability to adapt and develop over time during extreme conditions. As resilience relates to persistency, absorptivity, adaptability, and transformability capacities of a system, it is considered a prerequisite for sustainable development (Louis et al. 2016). Hence, the overarching objective of this study is to present a framework to meet several intersecting water security goals including sustainable supply of water, mitigation of flood threats, and improvement of water quality. In the process, we evaluate the efficacy and trade-offs of GGI strategies in meeting these goals. We describe the framework in detail, followed by an example based on the Baltimore water system to illustrate how the framework can be effective in achieving resilience in a water system.

ReUWS Framework

The ReUWS framework is divided into five sectors: (1) Sector S1: Establish Policy, Regulations, & Practices, (2) Sector S2: Design Green-Gray Infrastructure Alternatives, (3) Sector S3: Evaluate Ecosystem Services/Trade-offs & Co-benefits, (4) Sector S4: Simulate the System and Quantify Supply, Flood, and Quality Metrics, and (5) Sector S5: Choose Appropriate Solution(s) (Figure 2). The framework contains two external loops: loop 1 among S1, S2, and S3; and loop 2 among S3, S4, and S5. Loop 1 provides policy suggestions and adjustments, while loop 2 allows the stakeholders and community members to evaluate the system's performance relative to their goals and values. There is also an internal loop between S2 and S3, which allows choosing the GGI design alternatives based on the ecosystem services and co-benefits the systems provide. Together these loops capture the dynamics of the system and ensure stakeholder participation and community engagement throughout the life cycle of a system (from project initiation to implementation).

The first sector S1 considers the local and regional laws, policies, regulations, practices, and pricing that govern the rights, ownership (access and entitlements), obligations, and usage of water resources within a system. The second sector S2 provides a portfolio of green infrastructure alternatives that may include enhanced tree cover, bio-retention cells, rain gardens, green roofs, infiltration trenches, permeable pavements, rain barrels (rainwater harvesting cisterns), rooftop disconnections, vegetative swales, etc. It also takes into account the interconnected complementary green and gray components and built and natural networks of surface/subsurface flow paths (as shown in Figure 2). This sector also takes into account the connections to upland and wetland ecosystems that are an intrinsic green infrastructure-based component of the management system. Hence, an inventory of coupled GGI strategies, which are permitted within the purview of S1, along with their trade-offs is analyzed in this sector. The eco-hydrological processes, hydraulic connectivity among existing and proposed GGI networks, and functional signals/modeling parameters of the proposed systems are essential details to be gathered or evaluated in this sector (e.g., Tamaddun et al. 2018). The third sector S3 evaluates the associated ecosystem services and co-benefits of each of the strategies outlined under S2. Specific examples of such services and co-benefits (e.g., provisioning, regulating, supporting, and cultural) can be found in MEA (2005).

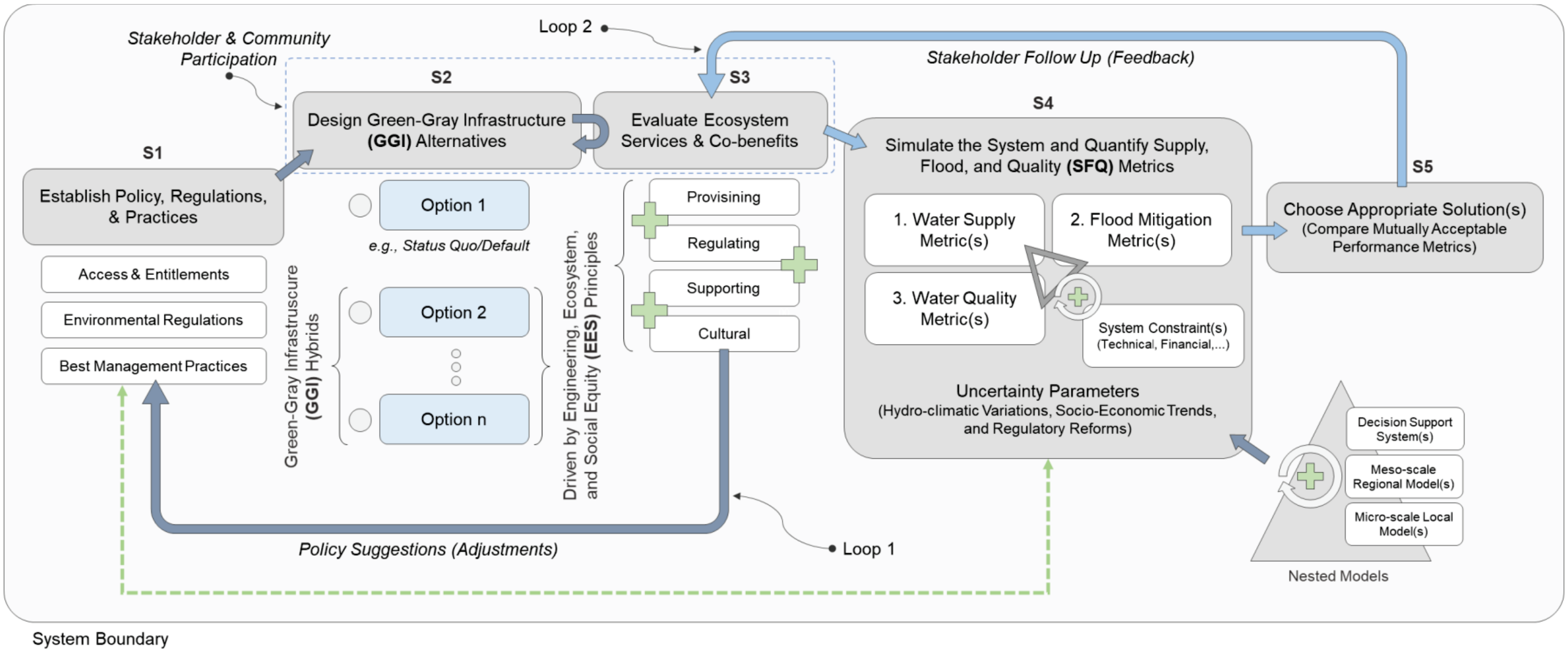

Figure 2: ReUWS framework and its major sectors (shown as S1 through S5). Arrows indicate the typical flow of information, whereas overlaps and inter-linkages are shown by plus signs, circular coils, and double-sided arrows. The two major loops are shown by two different shades of blue. Stakeholder engagement and community participation in sectors S2 and S3 are shown by the blue dotted box. The double-headed green arrow suggests the direct link between S1 and S4. A simplified version of the nested models (i.e., a series of inter-linked lower- to higher-abstraction level models placed in a hierarchy), which run at the back end of S4, is shown on the bottom right corner. The entire system runs within a defined system boundary (bound both spatially and temporally).

The fourth sector, S4, is where the entire system is simulated and several water supply, flood mitigation, and water quality metrics are quantified under future scenarios. These future scenarios are also subject to change based on uncertainties introduced by hydro-climatic variability, socio-economic trends, and regulatory reforms. This sector contains a set of interconnected models (e.g., hydrologic models, ecosystem models, and hydraulic models), where each of them has its strengths in terms of simulating certain biogeophysical processes. Collectively, they also offer capabilities (from limited to extensive) to evaluate GGI potentials across a system. These models are also capable of defining the initial and boundary conditions for each other when run in conjunction/parallel to each other within a system. An example of such interconnected models is shown in Figure 3.

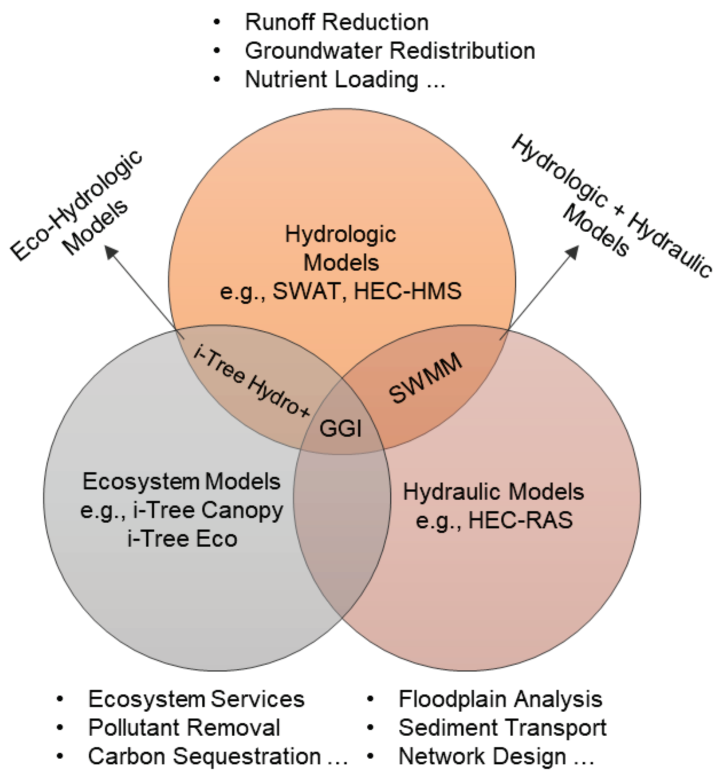

Figure 3: Venn diagram showing the examples of specific models and their intersecting functionalities in designing GGI-based urban water systems among hydrologic, hydraulic, and ecosystem models.

Hydrologic and ecosystem models (some offer eco-hydrologic coupling features) such as the U.S. Army Corps of Engineers' HEC-HMS, U.S. Department of Agriculture's SWAT, RHESSys (https://github.com/RHESSys/RHESSys/wiki), and i-Tree Hydro (Wang et al. 2008; Yang et al. 2013), combined are capable of simulating processes such as runoff generation, groundwater redistribution, nutrient loading, ecosystem service potential, pollutant removal, and carbon sequestration. Models with hydraulics capabilities like the U.S. Army Corps of Engineers' HEC-RAS and the U.S. Environmental Protection Agency's (EPA) SWMM can provide floodplain analysis, sediment transport, and network design functionalities. The overlap of these types of models and their respective specialties is highlighted in Figure 3. Hence, this sector aims to maximize the GGI potentials in meeting several water security goals by using engineering, ecosystem, and social equity principles to render a resilient system.

These models can be placed in a hierarchical structure (as shown on the bottom-right of Figure 2), where the locally-distributed models with higher complexity are placed at the bottom and interactive DSS tools (e.g. Leonard et al. 2019) (with higher-level functionality) are placed at the top. The middle layer works as a bridge that evaluates the trends and patterns detected in the lower level, tests a set of hypotheses, and translates that information to the high-level DSS (Figure 2). The set of model examples mentioned above can either be used as a lower-level or a mid-level model (or both) depending on the type of system being analyzed.

The final sector S5 compares the results among the different design alternatives outlined within S2 and evaluates their performance (based on the simulation results rendered in S4) in meeting predefined water supply, flood mitigation, and water quality metrics. The option(s) that performs satisfactorily well, based on its resilience against uncertainty parameters (resulting from hydro-climatic, socio-economic, and regulatory changes), is considered to be the best or robust solution(s). A description of such multi-objective decision scaling can be found in Poff et al (2016). Based on the results obtained from S5, the stakeholders and community members can provide their feedback through loop 2 (as shown in Figure 2). If none of the strategies perform satisfactorily in future scenarios, more flexible design solutions and management practices will be required. Such policy suggestions and adjustments can be recommended through loop 1. As seen from Figure 2, the entire framework allows iterative modeling and incremental evaluation, which also promotes participatory governance by ensuring stakeholder and community engagement throughout the process.

Baltimore Water System: Conceptual Application of ReUWS

In this section, the Baltimore water system is presented as a heuristic study to illustrate the nature of intersecting water security challenges. Later, we also discuss how the ReUWS framework can be utilized in dealing with such challenges.

Existing Challenges

Figure 4 (left) shows the locations of reservoirs (supply sources) and treatment plants (both supply and wastewater) in and around Baltimore City. It also shows the median household income in each of the census block groups in the region. The locations of recent flood events (occurred from 2016 to 2019) are shown in Figure 4 (middle and right) as well. They also show the percentage of non-white population and reduction of runoff due to tree cover across each of the census block groups in the region.

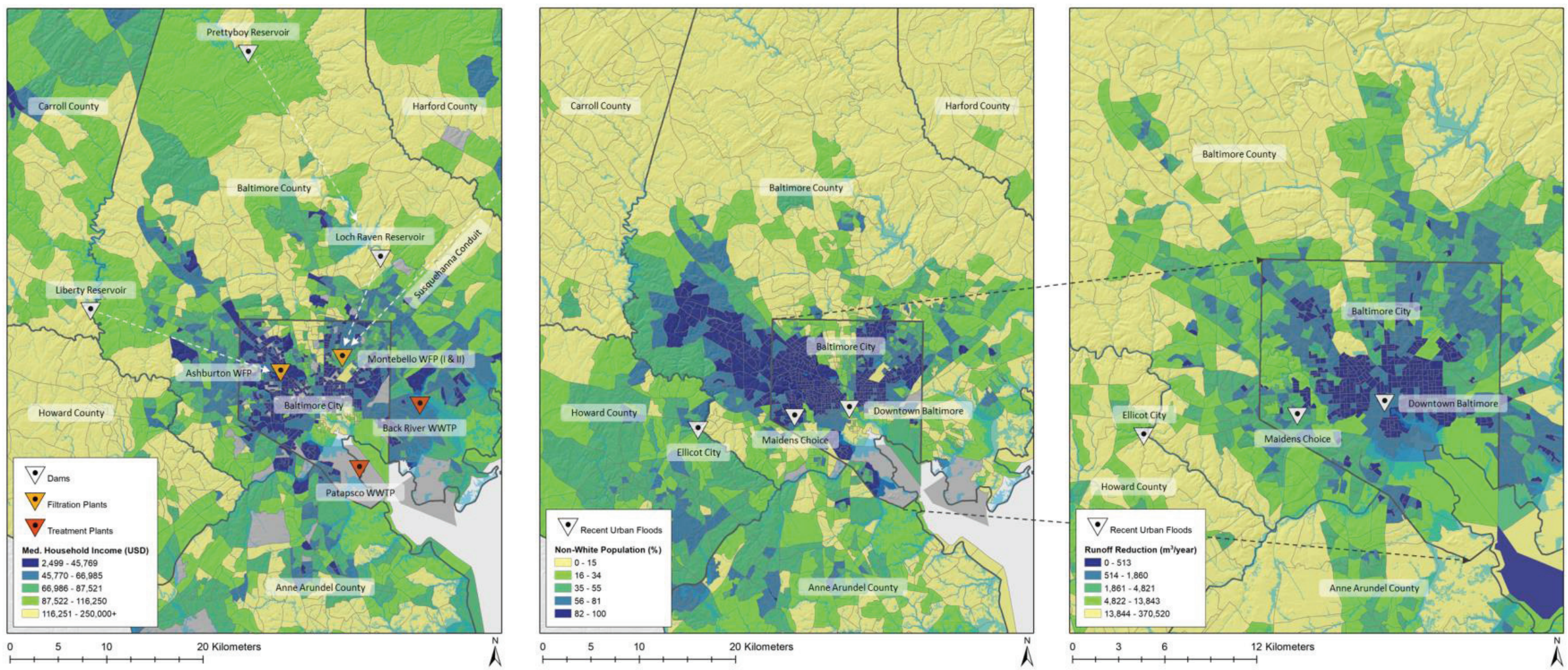

Figure 4: (Left) Map showing the locations of reservoirs/dams, water filtration plants (WFPs), and wastewater treatment plants (WWTPs) in and around Baltimore City. Median household incomes (in USD as major quantiles) are shown across each census block group. (Middle) Map showing non-white population percentage (as major quantiles) and (right) reduction of runoff due to tree cover (in m3/year as major quantiles) across each census block group in and around Baltimore City along with the locations of recent urban floods in the region. [Data source: American Community Survey Data, 2018; Baltimore City Department of Public Works, 2020; U.S. EPA EnviroAtlas i-Tree Model for Baltimore, MD, 2017]

From a water utility perspective, we can see that the City receives water from reservoirs that are all located outside the city boundary. There are water filtration plants and wastewater treatment plants (located within or near the City) that supply and treat water for the City and its five surrounding counties (Figure 4). Besides the three reservoirs, the region also receives water from the Susquehanna River that flows through the states of New York, Pennsylvania, and Maryland, making it the longest trans-boundary river on the east coast of the United States. Even though water is not regularly drawn from the river (except for the time of persistent rainfall deficit, which last occurred in 2002), studies suggest that this river may be utilized as a continuous source in the future (BC-DPW 2020).

The City is also currently under a consent decree with the U.S. EPA to comply with the Clean Water Act, which requires upgrading its aging wastewater infrastructure and eliminating sanitary sewer overflow into roads, streams, and rivers. There has also been a series of severe flood events in the region (as shown in Figure 4) in recent years. Among the flood victims, low-income non-white populations have been disproportionately impacted (Figure 4 left and middle) and many such communities have yet to recover from their losses. Figure 4 (right) also shows that the low-income non-white neighborhoods have a lower potential of runoff reduction due to tree cover compared to middle- to high-income communities with a majority white population (based on American Community Survey Data 2018; U.S. EPA EnviroAtlas i-Tree Model for Baltimore, MD 2017). Baltimore's water system is one of the oldest in the nation, and challenges in its upkeep and evolution have included severe budgetary limitations, major socio-economic challenges, and climate change. Hence, the inclusion of social equity principles to ensure equitable access to and distribution of services and benefits is considered one of the key objectives of our presented ReUWS framework.

Future Challenges

Figure 5 shows potential future mean daily precipitation and mean daily maximum temperature in the region based on downscaled, bias-corrected general circulation models. The ensembles are generated based on 32 CMIP5 model simulations with RCP 4.5 (Joshi et al. 2020). These simulations suggest that the regions experiencing higher precipitation are also expected to get warmer in the coming years. Based on the trends of these simulations (Tamaddun et al. 2019a & b), one can also extrapolate that the climate conditions of the region are expected to become more severe with frequent flood events and long-term droughts.

The Baltimore City Department of Public Works has already invested in a range of projects to reduce surcharging to avoid sanitary sewer overflow, which is responsible for major nutrient loading into Baltimore's surrounding rivers and streams and causes severe water quality concerns. Increased pipe size and installation of bypass and backwater valves are examples of gray strategies that are being implemented in the sanitary sewer system and water treatment plants in Baltimore. In conjunction with these gray measures, strategic use of green infrastructure may produce significant improvement in dealing with surcharging and associated water-related issues. Hence, we can use the ReUWS framework to provide alternative supply sources, reduce runoff and flood risks, mitigate heat island effect, and improve water quality by maximizing GGI potentials

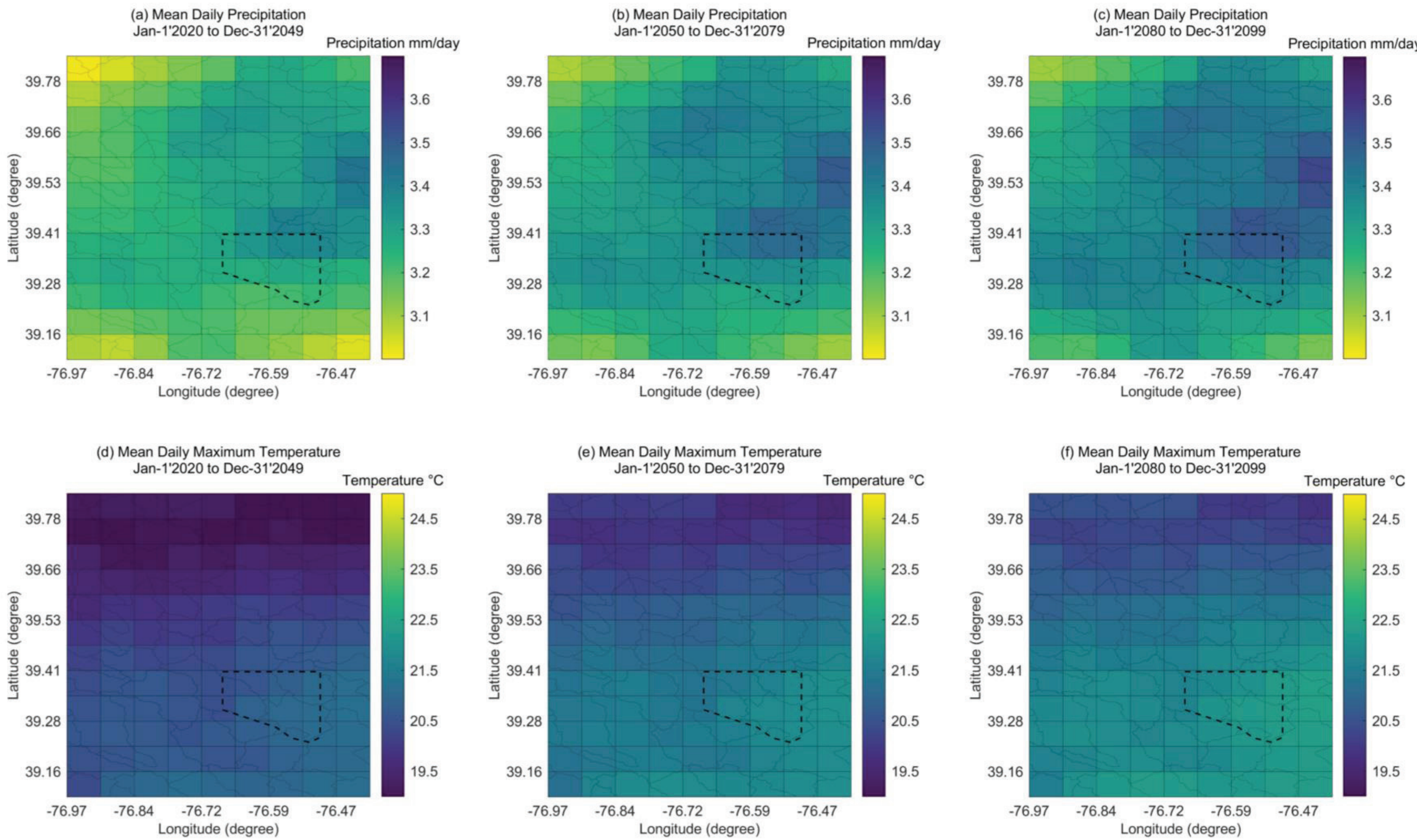

Figure 5: (1st row) Mean daily precipitation (mm/day) and (2nd row) mean daily maximum temperature (°C) from 2020 to 2049, 2050 to 2079, and 2080 to 2099, at 1/16 degree spatial resolution grid cell based on downscaled and bias-corrected GCMs (the average is calculated based on 32 CMIP5 model simulations) using RCP 4.5 (630 ppm of CO_2 concentration). Warmer (cooler) color suggests lower (higher) precipitation and higher (lower) temperature. The black dotted line represents the boundary of Baltimore City.

Application of ReUWS

The use of low impact development approaches such as rainwater harvesting, vegetative swales, rain gardens, and increased urban tree canopy can reduce runoff generation and nutrient loading. Such strategies may also lower groundwater tables resulting in reduced sewer infiltration. Harvesting and repurposing (followed by effective and equitable distribution) of stormwater can also reduce dependence on the reservoir supply. Such multi-purpose strategies could be quite useful for Baltimore as it faces a potential increase in periodic water supply scarcity, floods, and economic hurdles among many communities.

The ReUWS framework and its nested-modeling structure can be used to evaluate available GGI strategies and their overall benefits. For example, RHESSys and i-Tree Hydro+ (which includes i-Tree CoolAir) can be used to estimate groundwater tables, soil saturation levels, runoff production, and heat island effects, which are all relevant to the Baltimore City water system. The produced runoff can be fed through HEC-RAS to estimate potential flood magnitude and frequency impacts. SWMM and i-Tree Hydro+ can be used to evaluate storm sewer surcharging and water quality impacts. These models, at the lower-level, can simulate local hydro-geophysical processes to help define potentials of various GGI strategies, e.g., strategies specific to urban areas of Baltimore City with its upstream contributing watersheds. Mid-level models can address many trans-boundary issues in terms of water allocation, usage, and disposal. The developed DSS tools can work as a common platform among community members, stakeholders, and modelers to engage and work towards unified goals and practices.

Hence, in addition to the already taken gray measures by the City as discussed earlier, strategic and equitable use of coupled green infrastructure, with the added participatory functionality provided by the ReUWS framework, may produce significant improvement in dealing with several intersecting water security challenges including sustainable supply of water, mitigation of flood threats, and improvement of water quality. By ensuring stakeholder engagement and community participation throughout the project initiation to implementation phases, ReUWS can help provide equitable services to different population groups under future conditions influenced by hydro-climatic, socio-economic, and regulatory changes.

Conclusions

This study presented a resilient urban water system (i.e., ReUWS) framework to achieve a GGI-based urban water system with the capacity to change and develop over time under uncertainties from hydro-climatic variability, socio-economic trends, and regulatory reforms. Principles drawn from engineering design, ecosystem science, and social equity concepts help to formulate this interdisciplinary and community-oriented approach. We demonstrate the use of ReUWS to develop a water management system that integrates technological advancement, eco-hydrological dynamics, and stakeholder participation at different stages of design and implementation. This framework allows for an evaluation of alternative pathways in achieving resilient water systems and outlines the processes of deriving meaningful findings from the major interacting sectors within a dynamic water system. The nested-modeling framework may facilitate converting the decision-making process from intuitive actions to evidence-based effective and acceptable solutions. We expect that by adopting this framework, by blending advanced engineering paradigms, maximizing ecosystem service potentials, and establishing social equity principles, in future studies, we will engage a wide range of stakeholders to identify and apply GGI alternatives that promote urban water system resilience.

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