

Hydrological Modeling for Sustainable Water Resources Management in Urban Areas

^{1*} Dr. Kavya Subramaniam, Vidyadeep University of Engineering, India.

Abstract: Focusing on the urgent issue of quick, unplanned urbanization that produces water stress and flood hazards, and degrades the quality of aquatic environments through expanded impervious areas and pollution, this work simulates urban hydrologic response to such events in the Adyar River Basin, India, by applying the EPA Storm Water Management Model (SWMM). Combining the inputs of the Sentinel-2 (10-meter) land cover, GPM (global precipitation) data, and contemporary environmental sensor data streams, this work produces a predictive tool for the urban water regime. Based on the outcomes, there will be an increase in flood volume and pollutant loads in the 'Business-as-Usual' development scenario, and the consequence will be considerable harm to the water quality of the aquatic ecosystem. In contrast, 'Sustainable Interventions' (including targeted bioswales, permeable pavement, and rainfall harvesting) resulted in a reduction of runoff volumes and loads. Based on a spatial output, hot spots of high-water stress were determined, which can be useful in deciding on an optimal retrofit of infrastructure. More importantly, this study argues for a shift from a reactive 'gray infrastructure' flood management approach to a more proactive 'green infrastructure' planning approach; this is important for the decisions made. Linking hydrologic outcomes to ecosystem health indicators will allow urban planners to design and target interventions to protect aquatic ecosystems, recover the base flow of the streams, and promote long-term water sustainability. Though the complex biochemical reaction modeling and uncertainty regarding morphology in the long term will have limitations in this study's approach, this integrated framework will provide guidance to sustainable planning of aquatic ecosystem services.

Keywords: Urban Hydrology; Sustainable Management; EPA SWMM; LID Controls; Aquatic Ecosystems; Water Stress; Environmental Resilience.

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I. Introduction

The fast and often haphazard rate at which the world is becoming urbanized has resulted in the greatest pressure to date on local hydrological regimes and surrounding aquatic environments (Bao & Fang, 2012). The replacement of natural landscapes by impervious surfaces such as roads, roofs, and built structures is disrupting the natural infiltration of water by replacing it with increasing amounts of surface runoff and a greater potential for urban flooding. The changes are not only volumetric; the increased surface runoff carries pollutants, heavy metals, and nutrients, which flow directly into streams, wetlands, and the coastal environment (Baran-Gurgul & Rutkowska, 2024). This disruption of the aquatic habitat leads not only to decreased amounts of available potable water for growing cities but also to the loss of biodiversity, alteration of riparian zones, and the loss of vital ecosystem services which support the health of urban areas. Although research in hydrological modeling has created advanced tools such as SWMM, SWAT and distributed rainfall-runoff models which help simulate urban water behavior, there is still a considerable gap in applying these tools practically (Sisay et al., 2017; Burek et al., 2020; McGrane, 2016). In many cases, these models fail to incorporate the biological and ecological context of the downstream aquatic environment, as most of the models have focused solely on engineering parameters like attenuating peak flow or on increasing drainage pipe capacity. There is a definite, unaddressed need for applying models in conjunction with both biology and the ecology of the downstream water body. It appears that current urban planning methods fail to capitalize on what models can offer by providing information for nature-based solutions and for evaluating the long-term health of the downstream environment as conditions evolve under future climate and development scenarios.

Objectives:

The above-mentioned issues, this study has four objectives aiming to improve the integration of hydrological modeling into urban planning as follows;

- Quantify the hydrological response of the Adyar River basin in India for past and future Land Use-Land cover changes with a focus on the impact of increased impervious cover on variability in runoff.
- Assess the efficiency of various sustainable water management tools like nature-based solutions, low-impact development, etc. On reducing peak flow and water quality for the river basin and for the downstream area.
- Build a decision-support tool based on the correlation between hydrological outputs and measures of aquatic ecological condition to provide information on where in a stressed city sustainable planning needs to be concentrated.

The paper is divided into six sections, Section I (Abstract) presents the summary of aims, methodology, results and significance of this study to policy-making, Section II (Introduction) explains the impacts of urbanization, gaps in knowledge, objectives, Section III (Study Area & Methodology) describes the study area, input data, SWMM modeling, use of LIDs, Section IV (Results) presents comparison between different hydrological metrics, shows results from hotspot analysis, Section V (Discussion) interprets results related to hydrology and ecology and discusses positive outcomes of sustainable development, Section VI (Conclusion & Policy Implications) provides practical guidelines for urban water management and ecosystem resilience.

II. Study Area & Methodology

Study Area: Contextualizing Urban Vulnerability

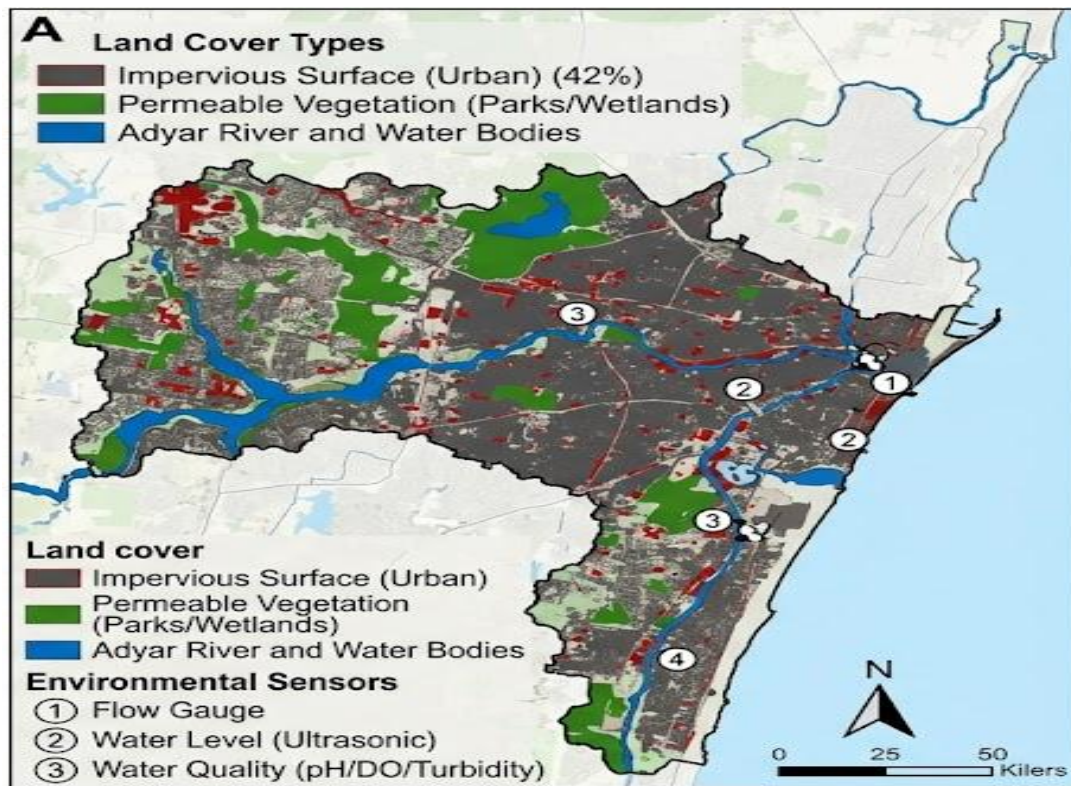


Figure 1: Land Cover and Environmental Sensor Distribution in the Adyar River Basin

This study is based on the Adyar River basin within the limits of Chennai, India, one of the major growing metropolises with a population of over 11 million. The region comes under a tropical wet and dry (Aw) climate with a high degree of variation between dry and wet seasons with regard to rainfall. Due to the variation in monsoon, which is heavy and rapid during the Northeast monsoon, there exists a high amount of hazard to urban drainage systems. Adyar River, which is a primary aquatic system being affected by urbanization. The river also acts as a main drainage outfall for urban runoff and a habitat for many species. However, rapid urbanization has resulted in a change in 42% of land use patterns from pervious vegetated areas to impervious surfaces, directly related to the recent water quality decline and increased flash floods.

Figure 1 maps the land cover types within the Adyar River basin, showing impervious urban surfaces (42%), permeable vegetation (parks and wetlands), and water bodies. It also marks locations of environmental sensors, including flow gauges, ultrasonic water level sensors, and water quality monitoring stations (pH, DO, turbidity), illustrating spatial planning for hydrological and ecological monitoring.

Model Description: Technical Simulation Framework

To simulate the interactive processes between the urban expansion and its hydrologic response, the EPA Storm Water Management Model (SWMM) is used in this research. SWMM is chosen as it has the capability to simulate the hydrologic, hydraulic, and water quality processes over a single event and in the long term in urban areas. It applies the distributed modeling to divide the whole catchment into sub-catchments and analyzes the flow between conduits, storage units, natural streams, etc. For simulation, by configuring the GI/LID control (e.g., Permeable pavement, Bioswale) and pollutants accumulated and washed-off algorithms, it simulates the hydrodynamic characteristics of the aquatic system under various urbanization levels.

Data Sources: Leveraging Remote Sensing and Sensor Networks

High-resolution, multi-source data is the key to ensuring modeling based on the current frontier of technological advancement in environmental monitoring. It takes the Land-Use Land-Cover (LULC) data from high-resolution satellite images (Sentinel-2, 10 m) and processes it using GIS for the calculation of the increase in impervious area over the past 10 years; Precipitation and meteorological data from the India Meteorological Department (IMD) and the GPM (Global Precipitation Measurement) satellite product at high time resolution. Moreover, the local real-time water level (ultrasonic sensor) and water quality data (pH, Turbidity, and Dissolved Oxygen) from a distributed sensor network along the Adyar River are used for model validation.

III. Results

The model simulations employ two major scenarios to examine how land use change and intervention policies might affect the Adyar River basin. Business-as-usual (BAU) scenario assumes present growth rates of urbanization with a persistent rise in impervious cover, yielding higher volume peak flow and higher concentration pollutant loading in the monsoon seasons. The sustainable interventions scenario introduces a few LIDs (bioswales, permeable pavements, and rainwater harvesting) in the highly dense sub-catchments to reduce the surface runoff and total mass loading of pollutants entering the water system compared to that in BAU.

The simulated hydrological parameters in different sub-catchments of the Adyar River basin are listed in table 1. Both peak flow and pollutant loads are significantly reduced in the Sustainable Intervention scenarios, indicating the effectiveness of LID measures in urban runoff and water quality enhancement. Runoff coefficient further presents the degree of reduction of surface runoff using permeable and nature-based alternatives.

Table 1: Hydrological Response Metrics under BAU and Sustainable Intervention Scenarios

Sub-Catchment / Zone	Peak Flow (m ³ /s) BAU	Peak Flow (m ³ /s) LID	Pollutant Load (kg) BAU	Pollutant Load (kg) LID	Runoff Coefficient BAU	Runoff Coefficient LID
Zone 1	12.5	8.3	450	290	0.72	0.55
Zone 2	15.2	10.1	520	330	0.78	0.58
Zone 3	9.8	6.7	380	240	0.69	0.50
Zone 4	11.6	7.9	410	270	0.71	0.53

Figure 2 shows the peak flow volumes (m/s) and total pollutant mass loads (kg) for the Adyar river basin under two scenarios, i.e., Business-as-Usual (BAU) and Sustainable Interventions (LID controls). The X-axis shows sub catchments/stations and the Y-axis shows measured flow and pollutant load. BAU and LID graphs are plotted side by side so that the changes are easily comparable. This figure clearly depicts the mitigation of hydrological stress and pollutant loads by using LID techniques.

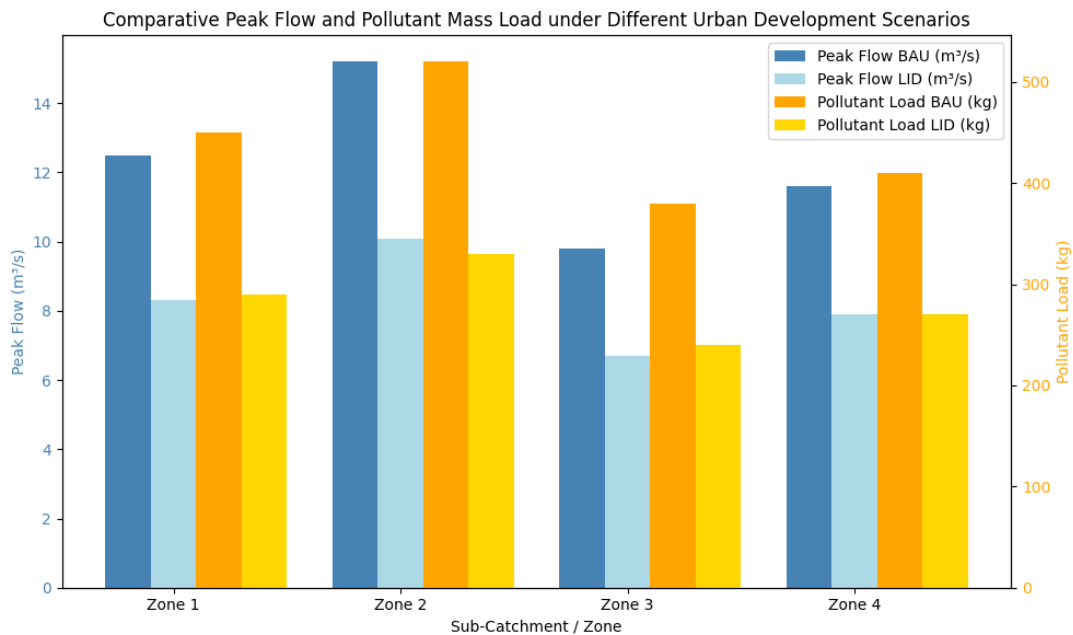


Figure 2: Comparative Peak Flow and Pollutant Mass Load under Different Urban Development Scenarios

Spatial output of the EPA SWMM model indicated significant hotspots of water stress and pollution in the entire basin. The areas found to have a high concentration of impervious surfaces directly corresponded to the zones with rapid accumulation of runoff and high loads of nutrients and heavy metals, and are hence most responsible for the degradation of the aquatic ecosystem. Mapping this output, the study indicated where placing LID in these stress areas will reduce peak flow values of downstream hydrographs to the maximum possible levels. These spatial figures provide a powerful tool for urban planners to focus on retrofiting or developing natural solutions in these urban areas to maintain their stability in urban corridors.

IV. Discussion

Interpreting the Ecological Implications

The modeling results confirm that the existing 'Business-as-Usual' approach is a major contributing factor towards aquatic ecosystem degradation (Russo et al., 2014). The disruption of the natural flow regime, the exacerbated pollutant loading, and high peak flow velocities in high impervious areas directly

lead to bank erosion, destruction of riparian habitat, and disturbance of the micro aquatic ecosystem that relies on a stable base flow condition. Elevated concentrations of nutrients and heavy metals further demonstrate that the river is being exposed to sustained toxic stress, which will ultimately impede recovery of aquatic biodiversity in the Adyar River and threaten the survival of native aquatic species.

Supporting Sustainable Management Decisions

The modeling technique provides a quantifiable link between engineering interventions and ecological restoration to establish a rationale to focus on 'Sustainable Interventions'. The results suggest shifting away from hard infrastructure to nature-based infrastructure since all green roofs, pervious pavement, and constructed wetlands may reduce the peak flow of hydrographs (Wada et al., 2017). This type of green infrastructure aims to promote local recharge and natural water filtration, and directly tackles the problem of water pollution identified by the result (Pan et al., 2018; Safavi et al., 2015). An evidence-based policy approach would enable planners to transition from reaction to proactive planning and strategically integrate LID in specific locations to maximize the ecosystem benefits, while still tackling urban flood issues (Shabani et al., 2021).

Transparency in Model Scope and Limitations

While this study develops a predictive model for urban water management, it is important to address certain limitations that the approach possesses (Cardoso de Salis et al., 2019; Geiger et al., 2012). Firstly, the model assumes a static representation of land use change, therefore, any subsequent land use alteration or dramatic change in climatic patterns will compromise the accuracy of prediction; Secondly, while the wash-off of dominant pollutants were considered in the model, biochemical process within the river and micro pollutants dynamics within the river were simplified; Therefore a local-scale study of pollutant behaviors may be needed; Thirdly, model performance is depending on the quality of input data, sensor maintenance and high-resolution data collection still needs to be monitored regularly in order to keep the model accuracy up to date (Eshtawi et al., 2016; Pereira et al., 2024; Beall et al., 2011).

V. Conclusion & Policy Implications

This study makes a novel contribution to sustainable urban water resource management by applying high resolution hydrological modeling integrated with ecosystem health indicators to produce a decision support system beyond the current, traditional segregated engineering perspective. By presenting a quantitative link between land use changes and altered hydrological patterns and pollutant loading, the research establishes a clear evidence base for the application of nature-based solutions over hard grey infrastructure to effectively shift from reactionary to resilient management practice. Three recommendations are drawn from this study that are pertinent to urban planners and water authorities: Planners are urged to adopt this proposed modeling framework to systematically map high-stress sub-catchments to pinpoint urban hotspots where proliferating impervious surfaces have the most damaging impacts on the local aquatic system health; authorities are recommended to implement Low Impact Development (LID) techniques, including Bioswales, pervious pavements, and rooftop harvesting, particularly within high-stress zones to achieve maximal attenuation of peak flow rates and reduced mass load of pollutants into the river system; and finally urban planners and water authorities should incorporate real-time environmental monitoring sensors along with remote sensing data to accurately gauge the impact of ongoing urban development on the local aquatic environment and accordingly adapt urban planning accordingly. This sustainable, evidence-based approach to managing urban waterways offers a unique opportunity for enhancing riparian ecosystem health, promoting local groundwater recharge, and achieving long-term water sustainability.

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