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Cascading urban lakes: how spatial, temporal, and anthropogenic characteristics control lake behavior

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In rapidly urbanizing regions, interconnected lake systems play a critical role. They regulate runoff, store water, and maintain urban hydrological balance. However, their functioning is shaped by anthropogenic interventions and natural characteristics. Lake functioning also exhibits spatial and temporal variability. These challenges are particularly acute in developing cities, especially in tropical regions. Yet, we do not understand how such interconnected human-water coupled systems operate and respond to natural and human influences at different scales. This study investigates how upstream–downstream interactions, temporal changes and human interventions shape lake behavior and function. For this, we used the case study of the cascading lake network of the Hebbal-Nagavara Valley in Bengaluru, India. We developed a hydrological model to simulate runoff and sewage flows across 44 interconnected lakes. The flows were simulated under varying management scenarios. High-resolution observed data at 15-min intervals were used to calibrate the model. Results reveal that upstream lakes are more sensitive to seasonal and catchment-level characteristics. In contrast, downstream lakes are primarily influenced by accumulated upstream flows. Sewage, treated or untreated, is the dominant source. This leads to perennial conditions and reduced variability as the flows accumulate downstream. Thus, both the location within the lake cascade and the own catchment characteristics influence the water quantity in a given lake. These in turn determine whether a lake can function effectively as a flood buffer, ecological site, or storage reservoir. The findings emphasize that lake functions are dynamic and dependent on both catchment characteristics and spatial location within the network. This underscores the need for differentiated, cascade-wide management strategies to enhance urban water security. Through this study, we have developed a diagnostic typology linking lake function to spatial position, inflow type, and temporal changes.

KEYWORDS
anthropogenic impact, cascade, hydrological modeling, urban hydrology, urban lakes

1 Introduction

Lakes play multiple hydrological, ecological, and social functions. Historically, they played a critical role in water storage. They served as retention structures, protecting against droughts, floods, and monsoon variability. The physical characteristics of lakes influence their behavior and therefore their role (function) in society. Further, with rapid urbanization, over time, both

the form and function of lakes have evolved. Understanding how to manage these lakes, therefore, necessitates a deeper understanding of the interplay between the physical characteristics, lake behavior and functions.

Man-made lakes were created by damming intermittent streams with crescent-shaped earthen bunds. They often form a cascading sequence along shallow inland valleys (Devi et al., 2020). Unlike their rural counterparts, however, tropical urban lakes are characterized by shallow depths, artificial construction, and frequently hypertrophic conditions (Birch and McCaskie, 1999; Naselli-Flores, 2008).

Urban lakes are in proximity to dense populations and are subject to intensive human use and impact. Urban lakes face persistent challenges, especially in low and middle-income countries. Limited sanitation and frequent discharge of domestic sewage into water bodies compound water quality problems. Inadequate stormwater drainage and widespread impervious surfaces further disrupt the natural hydrological cycle (Oliver et al., 2019). These pressures lead to faster and more unpredictable runoff, reduce soil recharge, and increase flood risk, all contributing to the deterioration of these lakes. In addition to these challenges, urban lakes experience dynamic mixed-layer conditions, especially in tropical climates. The hydrodynamic regimes in these tropical lakes play a significant role in nutrient dynamics through sedimentation and resuspension (Kolding and van Zwieten, 2012). This accelerates the recycling of nutrients and heightens susceptibility to eutrophication compared to temperate lakes (Lewis, 2000).

Urban lakes play multiple ecosystem functions of hydrological regulation, ecological productivity and socioeconomic benefits. They contribute to the water supply, regulate runoff, provide livelihoods and recreation and support biodiversity (Li et al., 2022; Dessie et al., 2015). Their ability to act as sink-lag-source systems enables them to perform these various functions. It means they can hold water for long periods (sink), delay its release through the system (lag) or release it through seepage, evapotranspiration or spills (McLaughlin et al., 2014; Rajib et al., 2020).

But the effectiveness of urban lakes to actually fulfil these functions depends on a number of factors – both natural and anthropogenic. i.e., some of these can be changed and others cannot. Fluctuating water levels shape ecosystem productivity and species survival. For instance, fish populations benefit from gradually rising water levels and seasonal floods, while stagnant high water levels can lead to oxygen depletion and lower productivity (van de Wolfshaar et al., 2011). In some cases, increased instability in water levels has also been linked to enhanced system productivity (Kolding and van Zwieten, 2012).

Similarly, the amount of water stored in a lake at any given time determines its ability to provide water security, particularly during dry seasons or droughts. Climate-driven factors like altered precipitation and rising temperatures affect evaporation and inflow volumes. Anthropogenic factors also alter inflow. These, in turn, influence the lake's retention time (Kumar et al., 2017; Mehran et al., 2017).

Lakes also recharge groundwater. The recharge rate, however, is directly tied to fluctuations in water levels. This is because the ability of aquifers to receive infiltration depends on both storage and flow characteristics. This affects how long water remains within the system (residence time), influencing groundwater availability (Katsuyama et al., 2010).

In terms of flooding, lakes act as buffers by temporarily storing excess inflows and reducing peak flood levels. However, unlike reservoirs with controlled outlets, their flood buffering capacities are highly variable and shaped by physical forms, storage capacity and connectivity to downstream water bodies. Understanding and quantifying these water level variations is essential for effective flood management and infrastructure planning (Sun et al., 2022; Nakayama and Shankman, 2013; Zhang et al., 2017).

Lakes also serve as socio-cultural assets for cities. They provide recreational spaces, support livelihoods such as fisheries and fodder collection, and contribute to community well-being. Their multifunctional nature makes them indispensable for urban resilience in both environmental and social terms (Sen et al., 2020; Mundoli et al., 2018).

Lakes in cascading urban systems connect across landscapes through natural and human-modified pathways. Spatial position and temporal variability shape their behavior alongside anthropogenic influences. Altered connectivity shifts lakes between stable and variable states.

Volume variability between variable and stable states determines functional capacity. Different behaviors enable different lake functions. Stakeholders must thus prioritize management based on natural and anthropogenic characteristics that shape these behaviors—not isolated demands.

Natural characteristics include hydrological connectivity and spatial position. Hydrological connectivity occurs at multiple spatial and temporal scales. It ranges from local inflows within a single lake to regional flow patterns across an entire watershed. The nature of this connectivity is dynamic due to anthropogenic and natural influences (Zhang et al., 2021; Jones et al., 2017). The hydrological connectivity affects the flow of water and nutrients within a landscape. Recent research increasingly emphasizes that lakes should not be treated as isolated units but as interconnected components within a hydrological continuum. Similarly, streams are also not always independent. In many places, lakes are connected via streams. Concepts such as Lake Order, Lake Network Complexity, and Lake Hydrology have been developed to characterize how a lake is positioned within its network and how it interacts with inflows and outflows (Martin and Soranno, 2006). The nature of a lake's hydrological response, including its hydrograph shape, retention time, and susceptibility to pollution, often reflects its degree of connectivity within the landscape.

The spatial position of the lake in the landscape is another important characteristic that influences its physical, chemical, and biological properties. The position of a lake, whether located upstream or downstream, plays a central role in determining the nature of its inflows and overall functioning (Kratz et al., 1997). This concept of lake landscape position provides a framework for understanding spatial variations in lake characteristics. For example, lakes situated higher in the landscape, primarily fed by precipitation, exhibit stronger responses and slower recovery from drought compared to lower-elevation lakes that receive both surface and groundwater inputs (Fergus et al., 2022).

Anthropogenic interventions like sewage inflows (treated/untreated), diversion drains, urbanization, and encroachments alter hydrological pathways, structural connectivity (Lexartza-Artza and Wainwright, 2009) and functional connectivity (water/nutrient movement) (Lane et al., 2025; Baker et al., 2016). This modifies the water quantity, timing, quality, and flow regimes entering lakes (Srivastava and Chinnasamy, 2021; Wang et al., 2025). Urban lakes now operate as hybrid systems combining natural runoff with artificial inflows and engineered diversions.

Consequently, lakes receive a mixture of direct precipitation, upstream overflows, sewage inputs, and diverted surface runoff. This creates mixed flow regimes where natural variability is overlaid with anthropogenic signals. The resulting systems are highly dynamic and

non-stationary, making it difficult to apply a conventional hydrological model (Jiménez-Bonilla et al., 2023; Wang et al., 2025). Understanding these hybrid regimes is essential for rethinking management strategies in rapidly urbanizing regions.

Urban water systems are coupled human-water systems where human actions actively shape hydrological processes, challenging conventional modeling that treats them as disturbances (Blair and Buytaert, 2016; Blöschl and Sivapalan, 1995). Sewage remains underrepresented in modeling, which overlooks direct flows (Chegini et al., 2025; Zhang et al., 2023), applies perennial river assumptions to ephemeral streams (Pereda et al., 2020) and ignores sewage's central role in urban water balances.

In economically advanced economies, treated effluent increases flows, converting intermittent streams to perennial flows (Walsh et al., 2005; Pereda et al., 2021). By contrast, in developing cities, untreated sewage often dominates as a continuous input that elevates discharge and obscures natural rainfall-driven flow variability (McGrane, 2016; Marques and Cunico, 2023) –e.g., in Israel, streams became "perennial sewage conduits" (Tal and Katz, 2012) and the US Trinity River is sustained by effluent (Luthy et al., 2015). While untreated sewage acts as a continuous stressor that destabilizes flow regimes, modern treatment and management can partly reverse these impacts– e.g., Yarqon River restoration (Tal and Katz, 2012; Luthy et al., 2015). Methodologies for estimating ecological flow, on the other hand, have remained outdated—failing to capture timing/variability or assess sewage augmentation costs/benefits (Halaburka et al., 2013; Luthy et al., 2015). This further underscores the lack of scientific consensus and highlights the inadequacy of current modeling approaches to fully represent sewage's hydrological and ecological roles. These anthropogenic complexities demand integrated monitoring and modeling of cascade interactions, yet remain unaddressed.

All natural (connectivity, position) and anthropogenic (sewage, urbanization) characteristics are particularly pertinent in rapidly growing urban lakes of peninsular India. Peninsular India's urban lake systems feature unique cascading networks connected by natural and engineered drains.

They are both ecological and socio-economically important (Sen et al., 2020).

Most tropical lakes, despite their importance, remain ungauged (Ricko et al., 2011; Santoso et al., 2018), lacking quantification of interconnected flows and high-frequency monitoring needed for anthropogenic influences. Modeling faces uncertainties from data gaps, dynamic catchments, and unaccounted interventions (Beven, 2019; Beven et al., 2020). Decisions without understanding system functioning carry uncertain consequences (Miller and Hutchins, 2017; Ferreira et al., 2022).

This study addresses this critical gap by investigating how lake functions in urban cascading lake systems are shaped not only by catchment characteristics but also by upstream–downstream interactions and anthropogenic modifications. Such an understanding is crucial to lake restoration programs in developing cities.

2 Materials and methods

2.1 Bengaluru case study

This study investigates the cascading lake system in Bengaluru city, a city of 12.6 million people (Directorate of Economics and Statistics, 2013), in Southern India. The lake system comprises interconnected, man-made water bodies. Each lake overflows into the next via stormwater drains. These systems, typical of arid and semi-arid regions of peninsular India, were originally designed to store water, manage floods, and mitigate droughts. The region's undulating topography enables water to move naturally under gravity from upstream lakes to downstream ones, creating a chain-like hydrological connection (Srivastava and Chinnasamy, 2021). Tank cascade systems, particularly in areas with erratic rainfall and limited groundwater potential, serve multiple functions beyond storage. They facilitate groundwater recharge, support irrigation, and help mitigate the impacts of flash floods and prolonged droughts, making them essential for regional water management (Chinnasamy and Srivastava, 2021).

The cascading lake system is under pressure from urbanization, encroachment, climate change, and pollution. Poor maintenance and uncontrolled urbanization have significantly reduced the storage capacity of these manmade lakes. This loss has, in turn, altered peak flows in the city (Devi et al., 2020). Studies have shown how the lakes in Bengaluru have slowly broken the lake chain. Some lakes have been isolated for the same reason (Unnikrishnan et al., 2016; Nagendra and Ostrom, 2014). With the move from an upstream-downstream management system to an individual system, these changes are becoming more evident (Lele and Sengupta, 2018). Rapid urban growth and changing land use have impacted the hydrology, ecosystem, and infrastructure of lake catchments. These, along with climate change, make the system response even more complicated, thus creating an even greater need for the system to be studied as an upstream-downstream entity (Penny et al., 2018).

2.2 Study area

Bengaluru is located at a topographic high, at an elevation of 920 m above mean sea level (Sekhar et al., 2018; Prasad and Narayanan, 2016). Drainage occurs into four valleys (Arkavathy, Vrishabhavathy, Hebbal-Nagavara and Koramangala-Challagatta). The Hebbal-Nagavara Valley is one of Bengaluru's three major valleys (Figure 1). It is situated in the northern part of the city and covers 204.08 square kilometers. The valley is a crucial hydrological feature in the region. Currently, 44% of the valley is urbanized, with the remainder non-urban. However, this land use is rapidly changing due to ongoing urbanization. This is resulting in a transformation of the landscape and its hydrological characteristics.

The cascading lake system in Hebbal-Nagavara Valley was delineated using GIS-based hydrological tools. A Digital Elevation Model (DEM) from Cartosat (Indian Space Research Organisation (ISRO), 2019) was used to define the watershed boundaries and flow accumulation paths. The number of lakes and their connectivity were identified using satellite imagery (Google, 2021), topographic maps from Survey of India (2011), and lake databases from Karnataka Tank Conservation & Development Authority (KTCDA) (2023).

Within the city limits, the Hebbal-Nagavara Valley features an interconnected chain of cascading lakes. There are 44 lakes in total. These lakes form a complex system where water flows from each upstream lake to the next lake in the chain. This influences the hydrodynamics and ecology of the region. The cascading lake system is especially sensitive to both natural changes and human activities. This includes shifts in management practices.

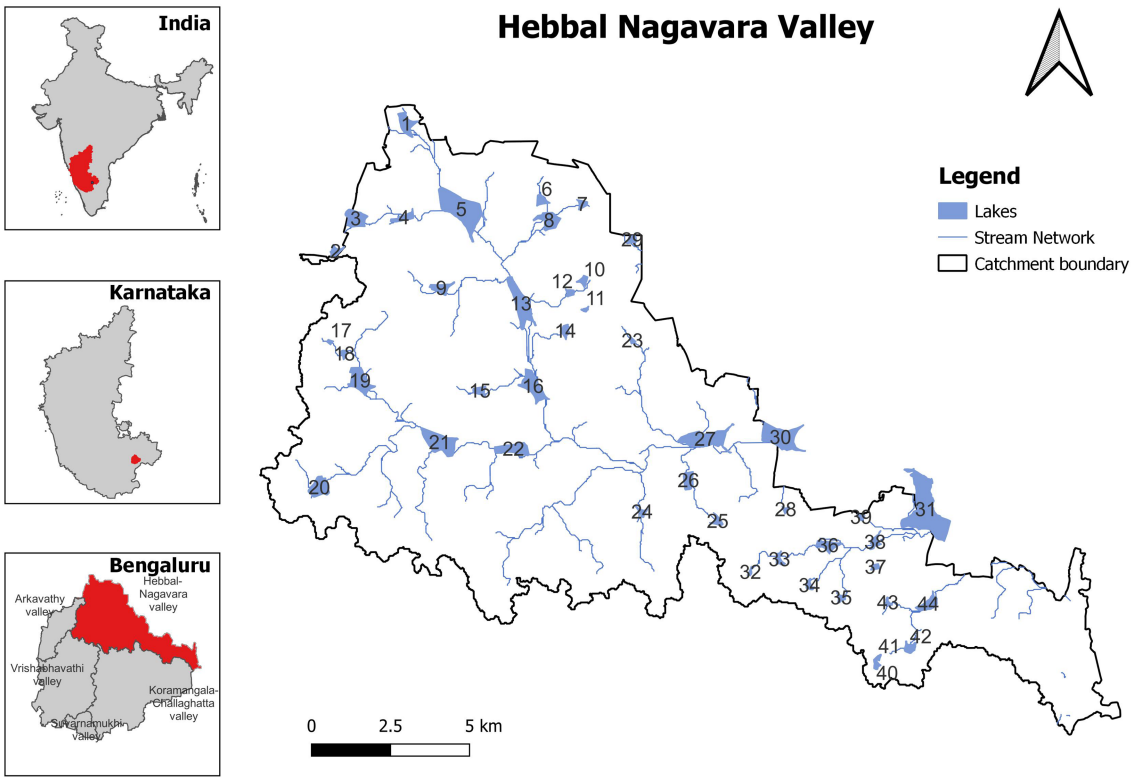

FIGURE 1
Study area map showing the Hebbal-Nagvara Valley lake network in Bengaluru, highlighting the interconnected cascading lakes analyzed in this study.

Bengaluru experiences a tropical climate, with a bimodal rainfall pattern. The region experiences two main rainy seasons: the South-West monsoon period from June to September and the North-East monsoon period from October to December (Dhanya et al., 2025). The annual precipitation in the city is approximately 820 to 900 mm (Sekhar et al., 2018), which is vital for recharging the lake system and sustaining the local ecosystem. This climatic pattern, combined with the valley's topography and urbanization, plays a significant role in shaping the hydrological processes within the cascading lake system.

Many lakes in Bengaluru have been significantly anthropogenically modified in terms of diversions and encroachments to inlets and outlets. So, additional field work was required to model them accurately. Field surveys and ground truthing were conducted to validate the GIS-based delineation and assess the condition of the lakes.

2.3 Research questions

How do water flows in urban cascading lake systems respond to upstream-downstream interactions and anthropogenic modifications in addition to catchment characteristics?

The research is guided by four sub-questions:

- What are the relative contributions of different sources (sewage, runoff, and upstream overflow) to lake inflows at different points in the cascade, and how do these vary temporally?
- How do flows vary along the cascading lake chain seasonally and across dry and wet years and how have anthropogenic modifications altered water source distributions along the cascading urban lake chain seasonally and across wet and dry years?
- Can the flow be managed through additional structures like sluice gates or diversion of treated and untreated sewage?
- How do the catchment characteristics and management choices affect what functions lakes can perform?

2.4 Research design

This study uses a custom hydrological model. It is developed to capture the behavior of urban cascading lake systems in Bengaluru. The objective is not to predict precise water levels on a daily basis. Instead, the study aims to reveal the feedback loops governing the system's behavior and to enhance understanding of the underlying hydrological and anthropogenic interactions that shape water flow and storage in these interconnected lakes.

Unlike off-the-shelf models, this hydrological model integrates both natural processes and human modifications. These processes are typical of tropical urban areas in developing countries. Core hydrological processes simulated include rainfall-runoff, evapotranspiration, and groundwater recharge. Alongside these, the model incorporates key anthropogenic components. This includes multiple sewage inflow sources: untreated sewage, centrally treated sewage, and decentralized treatment. It also includes engineered drainage infrastructure that diverts flows through the lake cascade.

We used a modular approach, segmenting the model into Hydrological, Wastewater, and Cascading modules. These modules collectively simulate water movement across the lake network. This structure supports spatially and temporally explicit representation of inflows, upstream-downstream connectivity, and anthropogenic influences. The model operates primarily on a daily time-step for all

cascading processes. Finer resolution was only used for rapid rainfall-runoff dynamics.

We used bathymetric and connectivity data from primary field surveys to parameterize the model. This enabled detailed representation of individual lake volume-area-stage relationships and hydraulic connections. Continuous water level monitoring at selected lakes further refined model calibration and validation, enhancing confidence in simulated storage and flow dynamics.

By examining system responses across scenarios, the model offers a robust framework to understand and predict how urban cascading lakes behave under multiple interacting drivers. The insights gained from this model intend to inform management decisions aimed at optimizing lake functions which are favorable to stakeholders.

2.5 Research method

2.5.1 Data collection

A field survey was conducted to validate the existence, condition, and connectivity of lakes within the cascading system. The surveys were conducted by eight students divided into groups of four over one month. Before data collection, students were provided with a comprehensive checklist containing the names and characteristics of key structures, including inlets, outlets, and diversion drains. The survey teams received training on how to identify these structures, take GPS locations, and capture standardized photographs.

For subsequent analysis, lakes in the study area were grouped into three functional types. Lakes with diversion drains are lakes where engineered channels intercept dry-weather sewage in the stormwater drain and convey it directly to the next lake downstream. They allow monsoon flows to enter the lake once water levels exceed a threshold elevation, assuming that the flows will be diluted. Upstream lakes are the first lakes in a cascade, receiving inflows only from their local catchment via stormwater drains, with no other lakes discharging into them. Downstream lakes receive water from both their own catchment and one or more upstream lakes, with excess water from upstream lakes entering through defined inlet channels or spillways (Figure 2).

On-ground assessments were carried out to verify whether the lakes were still present or had been encroached upon. As part of the survey, the connectivity of inlets, outlets and diversion drains was examined. Additionally, the presence of water in each lake was noted during the assessment period. Surveys were conducted during the monsoon season to observe whether water was flowing into the lakes, indicating active connectivity within the system. The type, dimensions, and function of inlet, outlet, and diversion structures were systematically documented. All data was recorded using ODK (Open Data Kit) forms and uploaded to cloud storage for centralized data management and analysis.

Ground truthing played a crucial role in determining whether each lake was part of the cascading system or functioned independently. This comprehensive field validation ensured the accuracy of remotely sensed data and provided essential ground-level insights into the current state of the lake network.

Bathymetric surveys were conducted to obtain depth, surface area, and volume data for each lake. It was performed for six lakes across the study area using sonar equipment mounted on a boat (Qiao et al., 2017; Levin et al., 2019). These data were used to develop stage-area, stage-volume, and area-volume relationships. To classify the lakes based on size, all lakes in the study area were divided into four categories using reference lakes. It was assumed that lakes within the same size category would share similar stage–volume characteristics. Based on the bathymetric data and using the lake outlet as a reference elevation, the stage value at which each lake would overflow was estimated.

To monitor water levels over time, Odyssey capacitance sensors were installed in five representative lakes. These sensors provided continuous stage data. For each of these lakes, stage–spillover weir relationships were established to estimate spill volumes at each time step. The recorded stage data, when integrated with the derived stage–volume curves, enabled estimation of lake storage behavior over the study period. These time-series volume estimates formed the basis for model calibration and validation in the subsequent phases of the study.

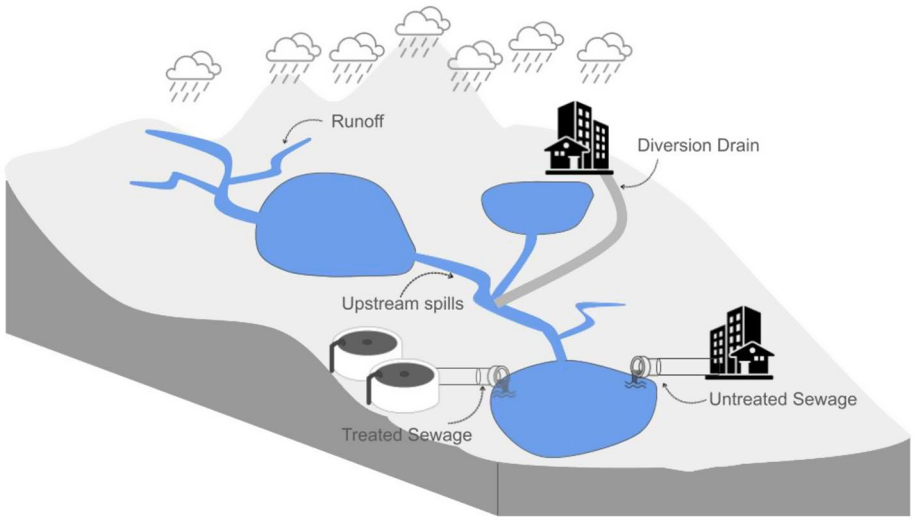

FIGURE 2
Conceptual diagram of the cascading lake system showing key hydrological and anthropogenic components.

2.5.2 Hydrological modeling

The hydrological model simulates water flows within a network of cascading urban lakes via three interconnected modules: Hydrological, Wastewater, and Cascading Modules. Each module is driven by distinct external and internal data streams (see Table 1) and operates at a temporal resolution tailored to process dynamics. The Hydrological Module simulates rainfall-runoff and water loss via evapotranspiration and groundwater recharge using high-frequency (15-min) rainfall records and landscape parameters. The Wastewater Module projects daily anthropogenic inflows from population and water use. Wastewater represents domestic municipal sewage only, subdivided into untreated sewage and treated sewage from decentralized (DSTP) and centralized (CSTP) plants. These inflows, together with upstream transfers and lake-specific outflows, are integrated in the Cascading Module to update lake storage and connectivity on a daily scale.

See Appendix A for a complete list of model equations and parameterization.

TABLE 1 Model components.

Component	Data source	Data processing
Rainfall-runoff estimation	Karnataka State Natural Disaster Monitoring Centre (KSNDMC) Rain gauge station data	SCS Curve Number Method, Direct Rainfall Method. The SCS-CN method is considered suitable for urban watersheds, where high imperviousness and low potential retention reduce sensitivity to assumptions about initial abstraction (Mishra and Singh, 2004).
Evaporation	Monthly evaporation averages [Central Water Commission (CWC), 2006]	Evaporation rate multiplied by lake surface area
Groundwater recharge	Calculated from a detailed water balance study done for a few lakes in the series.	Recharge rate multiplied by lake surface area
Sewage generation	Census population data (Government of India, 2011), Per capita water use	Empirical equations based on population trends
Spill estimation	Lake stage-discharge relationships (Figure 4) based on bathymetric surveys	Weir flow equations, rating curves
Storage	Lake stage-volume relationships based on bathymetric surveys (Figure 4)	Stage-volume relationship equations derived from bathymetric data; stage data from field measurements

2.5.2.1 Model implementation

The model components are tightly integrated, with the hydrological and wastewater modules feeding data into the cascading module (Figure 3). This structure enables a dynamic and spatially explicit simulation of interactions within lake systems. The model was developed in Python, chosen for its capacity to efficiently process large datasets and automate simulations at a daily time step.

A lake master list was created, assigning a unique identifier to each lake and establishing its connectivity within the cascade system (Table 2). Each lake was linked to its downstream counterpart to define spillover pathways and incorporate lake-specific and catchment-specific characteristics.

The hydrological processes were modeled at different temporal resolutions, reflecting their inherent dynamics. The runoff component was simulated at 15-min intervals to capture short-term variability in rainfall and surface response. In contrast, the cascading lake system was evaluated at a daily scale, corresponding to the slower nature of lake storage and discharge processes. This separation is consistent with the understanding that different components of the hydrological system operate on distinct temporal scales, shaped by landscape and flow-path characteristics (Stephens et al., 2021).

2.5.2.2 Model calibration and validation

The model was calibrated using observed spill volumes and lake storage recorded by capacitance sensors installed at selected lakes during 2022. It was done for the following lakes: Agrahara Lake (ID-11), Yelahanka Lake (ID-5), and Rachenahalli Lake (ID-16). Calibration involved adjusting key parameters to minimize discrepancies between simulated and observed values.

The following variables were iteratively refined:

- Curve Number (CN) values, which directly influence runoff generation and consequently affect the total volume of water entering the lake. Small changes in CN led to notable differences in runoff volume and spills generated. Rainfall-to-runoff time interval, refined to shorter sub-daily intervals, to capture more accurate runoff peaks and improve the simulation of inflow hydrographs.
- Weir discharge coefficient (Cd) is adjusted within the weir formula to estimate spill volume and timing consistent with stage-based observations.

Post-calibration, model validation was carried out using an independent dataset from 2023 to test model performance.

Calibration was strengthened through a multi-source triangulation approach. Lake surface areas extracted from the GEE Dynamic World dataset (Rajib and Khare, 2024) at multiple time points were used to independently estimate lake storage. These surface area measurements were converted to storage using lake-specific area–volume relationships derived from bathymetric surveys (Rodrigues et al., 2012; Liebe et al., 2005). The resulting remotely sensed storage estimates were

TABLE 2 Details of lakes in the Hebbal-Nagavara Valley collected during the ground truthing exercise.

Lake name	ID	Downstream lake ID	Number of inlets	Inlet structure type(s)	Number of outlets	Outlet structure type(s)	Presence of diversion drains (y/n)	STP releasing water into the lake (y/n)	Lake category
Harohalli lake	1	5	2	Pipe, Channel	1	Pipe	n	n	Upstream
Veerasagara lake	2	3	3	Pipe, Pipe, Pipe	1	Weir	n	n	Downstream
Atturu lake	3	4	1	Channel	1	Channel	n	n	Downstream
Puttenahalli lake	4	5	1	Channel	1	Weir	y	n	Downstream
Yelahanka lake	5	13	3	Weir, Channel, Channel	2	Weir, Channel	n	y	Downstream
Palanahalli	6	8	1	Channel	1	Weir	n	n	Upstream
Kattigenahalli lake	7	8	2	Weir, Channel	1		n	n	Upstream
Kogilu lake	8	13	3	Channel, Channel, Pipe	1	Channel	y	n	Downstream
Allasandra lake	9	13	2	Channel, Pipe	1	Weir	n	n	Upstream
Thirumenahalli lake	10	12	1	Channel	2	Channel, Channel	n	n	Upstream
Chokkanahalli lake	11	12	1	Pipe	1	Weir	y	n	Upstream
Agrahara lake	12	13	1	Pipe	1	Weir	n	n	Downstream
Jakkuru lake	13	16	3	Weir, Channel, Channel	1	Pipe	n	y	Downstream
Venkateshapura lake	14	16	1	Channel	2	Channel, Channel	n	n	Upstream
Amruthahalli lake	15	16	1	Channel	1	Weir	y	n	Upstream
Rachenahalli lake	16	27	2	Channel, Channel	2	Weir, Weir	n	n	Downstream
Narasipura lake-2	17	18	1	Channel	1	Channel	n	n	Upstream
Narasipura lake-1	18	19	2	Channel, Weir	1	Pipe	y	n	Downstream
Dodda Bommasandra lake	19	21	3	Weir, Weir, Channel	2	Weir, Weir	n	n	Downstream
J P Park lake	20	21	2	Pipe, Channel	1	Pipe	n	n	Upstream
Hebbal lake	21	22	1	Channel	1	Channel	n	n	Downstream
Nagawara lake	22	27	1	Channel	1	Channel	n	n	Downstream
Nagareshvara Nagenahalli lake	23	27	1	Channel	1	Channel	y	n	Upstream
ChellaLake lake	24	27	1	Pipe, Pipe	1	Pipe	y	n	Upstream
Horamavu lake	25	26	1	Channel	1	Channel	n	n	Upstream
Horamavu Agara lake	26	27	2	Channel, Channel	1	Channel	n	n	Downstream
KalLake lake	27	30	1	Channel	1	Weir	n	y	Downstream
Jimkenahalli lake	28	31	1	Pipe	1	Channel	n	n	Upstream

(Continued)

TABLE 2 (Continued)

Lake name	ID	Downstream lake ID	Number of inlets	Inlet structure type(s)	Number of outlets	Outlet structure type(s)	Presence of diversion drains (y/n)	STP releasing water into the lake (y/n)	Lake category
Bellihalli lake	29	30	3	Pipe, Pipe, Pipe	1	Channel	n	n	Upstream
Rampura lake	30	31	1	Channel	2	Channel	n	n	Downstream
Yelle Mallapa Shetty lake	31	201	3	Channel, Channel, Channel	2	Weir, Channel	n	n	Downstream
Vijinapura lake	32	33	1	Pipe	1	Channel	n	n	Upstream
Kowdenahalli lake	33	36	2	Channel, Channel	1	Channel	n	n	Downstream
Gangashetti Lake/ Devasandra lake	34	38	1	Channel	1	Channel	n	n	Upstream
Gunduru lake	35	38	3	Channel, Channel, Pipe	1	Channel	y	n	Upstream
Krishnarajapuram lake	36	38	2	Channel, Pipe	1	Weir	n	y	Downstream
Basavanapura lake	37	38	1	Pipe, Pipe	1	Pipe	n	n	Upstream
Shegehalli lake	38	31	1	Weir	1	Channel	y	n	Downstream
Bhattarahalli lake	39	31	2	Pipe, Weir	1	Pipe	n	n	Upstream
Doddanekundi Kunte	40	41	1	Pipe	1	Pipe	y	n	Upstream
Basavanagar lake	41	42	1	Pipe	1	Pipe	y	n	Downstream
Rajapalya Hoodi lake	42	44	1	Pipe, Pipe	1	Channel	n	n	Downstream
Hoodi lake	43	44	2	Channel, Pipe	1	Channel	y	n	Upstream
Kodigehalli lake	44	201	3	Channel, Channel, Channel	1	Channel	y	n	Downstream

compared against both field-observed storage, obtained through stage–volume relationships and model-simulated storage.

Remotely sensed surface areas, field-derived bathymetric storage relationships, and sensor-based stage data were used together to estimate lake storage. Cross-verifying these estimates enhanced model reliability, especially in urban settings with sparse ground data. In addition, direct spill measurements provided high-resolution insights into peak flow dynamics. When matched with simulated spill volumes and timing, these observations offered a robust validation of upstream runoff assumptions and overall lake response.

The model was calibrated successfully and validated using observed data from multiple representative lakes across the cascade system. Bathymetric relationships were established for four distinct lake categories. It was based on size and morphological characteristics (Figure 4): small lakes (0–20 ha), medium lakes (20–70 ha), large lakes (70–170 ha), and very large lakes (>170 ha). Stage-Volume and Area-Volume relationships were derived from detailed bathymetric surveys (Palur, 2017). This was then used to characterize the hydrodynamic behavior of each lake category.

2.5.2.3 Parameter sensitivity analysis

To address parameter uncertainty and model robustness, we conducted one-at-a-time sensitivity tests on key parameters identified by the reviewer, perturbing values within realistic literature ranges and quantifying impacts on direct model outputs (mean daily inflows for lpcd; runoff volumes for CN; peak storage for bathymetry). Tests used cascade groupings (upstream/downstream) to preserve spatial patterns (Supplementary Tables S1–S3).

2.5.2.3.1 Sewage generation (lpcd)

We adopted a base value of 150 lpcd for domestic wastewater generation and perturbed it by ±20% (120–180 lpcd). This produced proportional but buffered changes in simulated inflows: −12.2%/+10.8% for upstream lakes and −9.6%/+8.9% for downstream lakes, indicating moderate sensitivity while preserving the upstream–downstream gradients in the cascade.

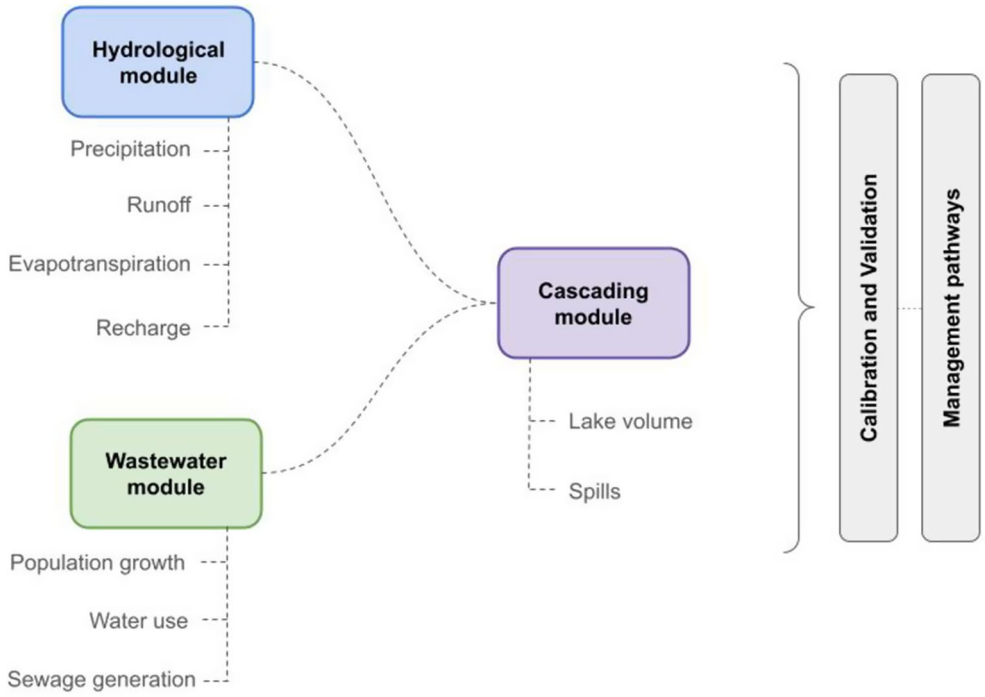

FIGURE 3
Conceptual schematic of the hydrological cascading lakes model; Blue, green, and purple boxes represent physical and anthropogenic process modules; dashed lines indicate inter-module flows; grey boxes summarize validation and management analysis steps.

2.5.2.3.2 SCS-CN

The base Curve Numbers (urban = 90, non-urban = 74) were calibrated against observed hydrograph peaks. A ± 5-point perturbation was then applied to each CN class. Runoff proved highly sensitive in the urban portions of the catchments (changes of approximately ±66–75%), while non-urban areas showed smaller but still notable responses (about ±10–33%), consistent with reports of strong CN sensitivity in heterogeneous catchments (Ajmal et al., 2015).

2.5.2.3.3 Bathymetry

Bathymetric relationships were derived from detailed surveys of 6 lakes, from which we fit 4 representative volume–stage/area–volume curves and assigned each of the 44 lakes to one of these categories based on their size. To evaluate the sensitivity and uncertainty of these scaled bathymetric relationships, we applied a ± 10% perturbation to the bathymetric curves and associated storage capacity, consistent with reported uncertainties in reservoir capacity estimates from bathymetric surveys and sedimentation studies (Huizinga et al., 2023). This resulted in a mean change of +7.3/−8.1% in peak storage across the cascade, indicating that bathymetric uncertainty translates into a similar magnitude of uncertainty in predicted storage.

Alternative morphometric groupings (e.g., width–length ratio) were explored informally: for example, Rachenahalli and Yelahanka have similar width–length ratios and Full-Tank Levels (1.6 m and 2.2 m, respectively) but very different surface areas (0.39 km^2 vs. 1.01 km^2), and applying one lake's bathymetric curve to the other produced strongly biased volumes. This indicates that, in this system, simple shape-based or FTL-based classifications do not reliably transfer bathymetry between lakes, and surface area provides a more defensible proxy for scaling bathymetric relationships.

2.5.3 Scenario modeling

Historically, lakes in peninsular India were managed using sluice gates that released excess water into downstream command areas. With urbanization, many of these sluice gates were removed or fell into disuse. Most lakes are now operated as passive systems that spill only when water levels exceed the weir crest. In response to increasing flood risk and climate variability, the municipal corporation is exploring renewed use of active infrastructure and sewage reuse to manage lake storage.

To assess the hydrological implications of such interventions, three management scenarios were implemented in the model and compared against a baseline of current (normal) operation.

(i) *Treated sewage diversion*, where inflows from decentralized and centralized treatment plants (DSTP, CSTP) were prevented from entering the lake throughout the year;(ii) *Sluice gate buffering* where 2% of lake storage volume was removed daily during summer months to create buffer capacity.; and (iii) *Complete sewage diversion*, where both treated (DSTP, CSTP) and untreated sewage inflows were fully diverted before reaching the lake. These scenarios were run for representative upstream and downstream lakes.

2.5.4 Functional mapping

For each lake, storage behavior (stable vs. variable) was diagnosed from the modeled storage time series. Based on literature-derived relationships between storage behavior and lake functions presented in the introduction, these behaviors were mapped to stakeholder-relevant functions (flood buffering, recharge, indirect reuse, ecological support) and summarized in a function–behavior matrix (Table 3), which is then used to interpret the functional roles of individual lakes. In subsequent analyses, combinations of spatial, temporal, and

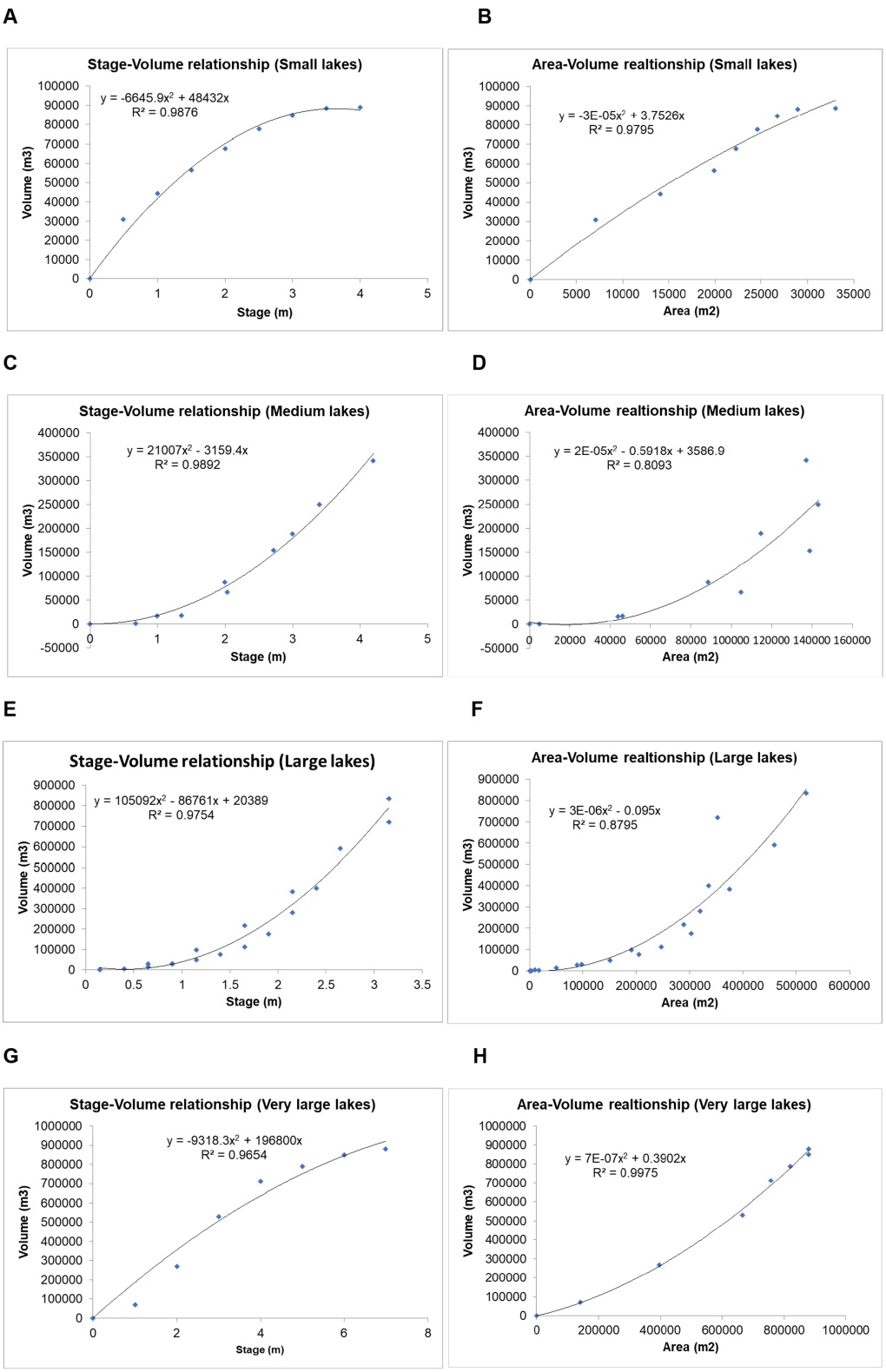

FIGURE 4
Stage-volume and area-volume relationships for small lakes 0–20 ha **(A,B)**, medium lakes 20–70 ha **(C,D)**, large lakes 70–170 ha **(E,F)**, very large lakes >170 ha **(G,H)** derived from bathymetric surveys. Very large lakes **(G,H)** show characteristic concave area-volume curves as high storage levels fill deep basin centers while surface area expansion is limited by steep side slopes.

anthropogenic characteristics are examined to identify which configurations give rise to these storage behaviors.

3 Results

3.1 Data collection

On-ground surveys revealed that lakes outside of the municipal boundary were no longer functionally connected to the cascading system due to degraded or missing inlet and outlet channels. Within the municipal boundary, 44 lakes were confirmed to be part of the active cascade (Table 2). 13 out of the 44 had diversion drains that intercepted dry-weather sewage while allowing monsoon flows to enter under the assumption of greater dilution during storms.

Bathymetric surveys enabled classification of lakes into four size classes (Figure 4)—small (0–20 ha), medium (20–70 ha), large (70–170 ha), and very large (>170 ha)—which are used in the subsequent analyses. Continuous stage data from Odyssey capacitance sensors captured strong monsoon driven water level fluctuations. Because changes were evident at a daily scale, the hydrological model was implemented with a daily time step. Combining the observed stage series with stage–volume relationships yielded lake-storage time series that reproduced observed filling and spill events and provided the basis for calibration and validation of the cascade model.

TABLE 3 Function–behavior matrix linking lake storage behavior to key urban lake functions.

Function	Behavior
Flood buffer	Emptying of storage in the summer
Recharge	Storage throughout the year, but especially in the dry months
Indirect reuse	Storage throughout the year, but especially in the dry months
Ecological	Minimum storage in dry months, presence of shallow zones for nesting

The mapping is derived from relationships between storage and function discussed in the introduction (e.g., van de Wolfshaar et al., 2011; Katsuyama et al., 2010; Sun et al., 2022; Li et al., 2022).

3.2 Hydrological modeling

We first evaluated model performance through calibration (2022) and validation (2023) against observed lake storage and spills. Figures 5–7 demonstrate the model's ability to capture both the magnitude and timing of observed hydrological responses across different lake types and seasonal conditions.

The calibrated and validated model was used to analyze spatial and temporal variations in flow and storage characteristics across the cascading lake system. The analysis focused on:

- *Spatial variability*: Comparing inflow types and quantities across the cascade, from upstream lakes to downstream lakes.
- *Temporal variability*: Assessing variations in inflow contributions during dry (2022) and wet years (2023).
- *Anthropogenic interventions*: Assessing variation in flows due to anthropogenic interventions like diversion drains and the release of untreated or treated sewage.
- *Hydrological drivers*: Identifying the dominant inflow sources influencing lake Hydrodynamics, such as rainfall-runoff, sewage inflows, and upstream spillovers.

The analyses revealed distinct patterns in storage behavior, inflow composition, and hydrological function across lake types and years (Figures 8–10).

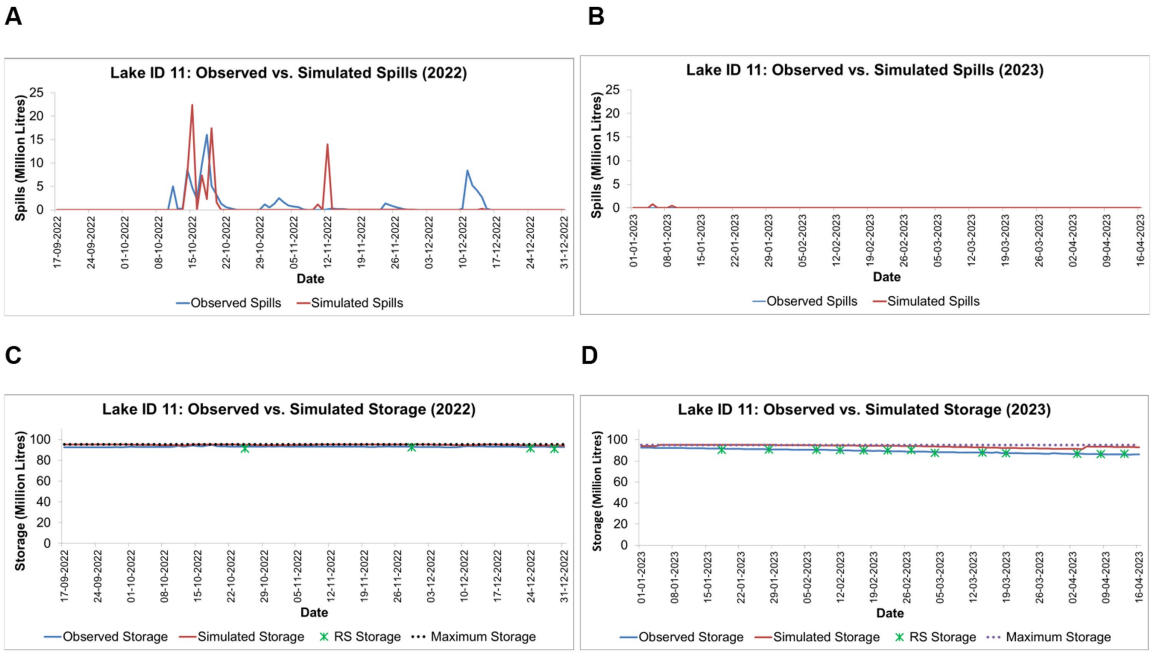

FIGURE 5
Observed and simulated daily spill volumes **(A,B)** and lake storage **(C,D)** for Agrahara Lake across 2022 (calibration) and 2023 (validation).

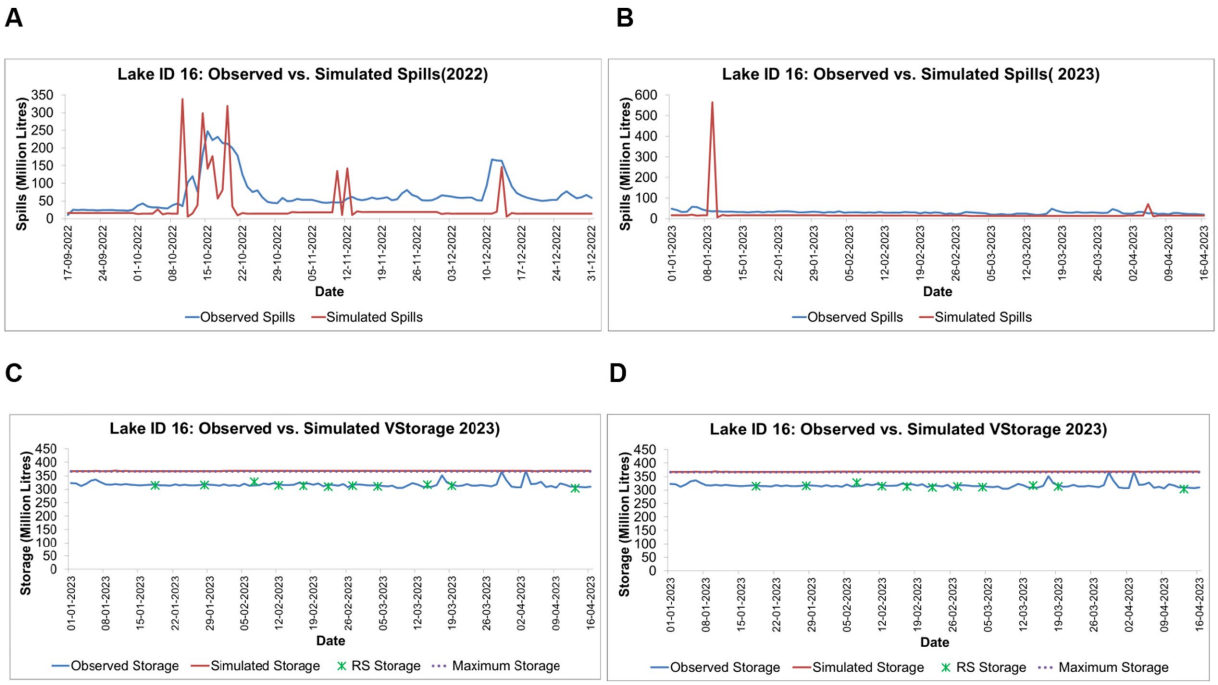

FIGURE 6
Observed and simulated daily spill volumes **(A,B)** and lake storage **(C,D)** for Rachenahalli Lake across 2022 (calibration) and 2023 (validation).

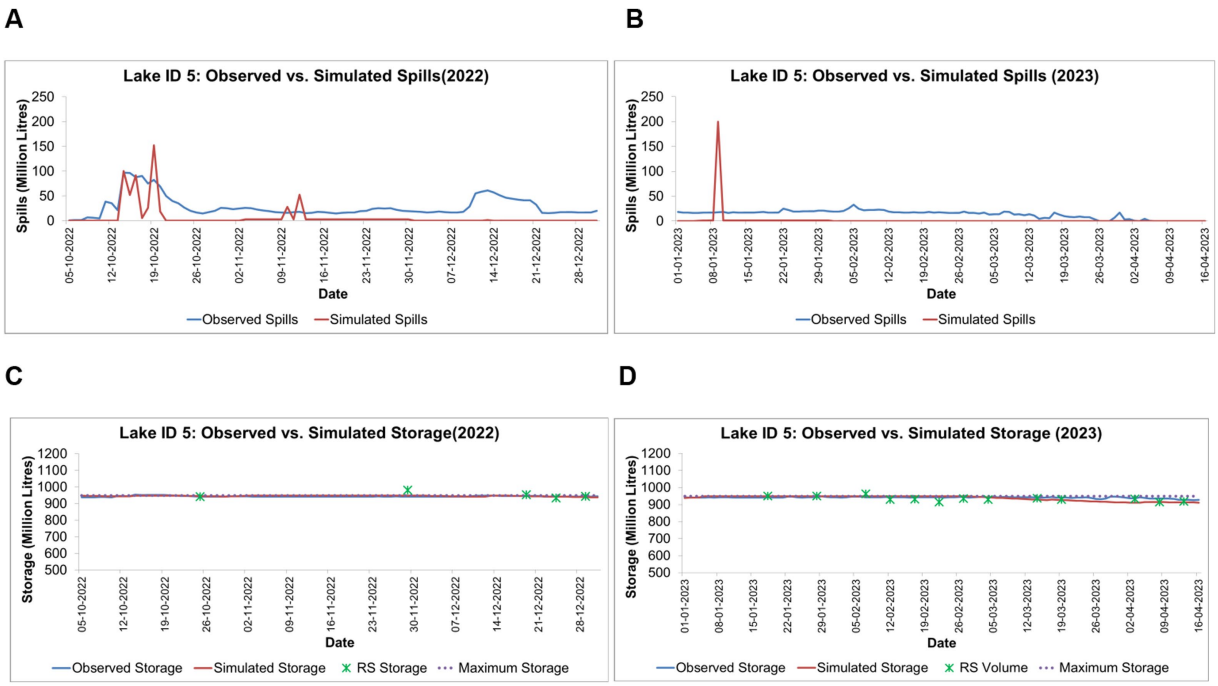

FIGURE 7
Observed and simulated daily spill volumes **(A,B)** and lake storage **(C,D)** for Yelahanka Lake across 2022 (calibration) and 2023 (validation).

Lakes exhibited distinct storage trends depending on their position in the catchment (Figure 8). This was primarily attributable to their spatial position within the basin's hydrology. In contrast, lakes classified as diversion drains displayed storage changes driven by anthropogenic factors. Notably, there were some exceptions to general trends, such as atypical stability or variability. These were linked to shifts in the sewage-to-runoff ratio, reflecting the influence of human management on hydrological regimes. This was established by source apportionment modeling.

Most observed storage variability was genuine responses to wet or dry periods. In some cases, variability in certain lakes with very small storage ranges was likely inflated by normalization effects. Overall, the dominant control over stable versus variable or reducing trajectories was the relative magnitude of sewage inflow compared to natural

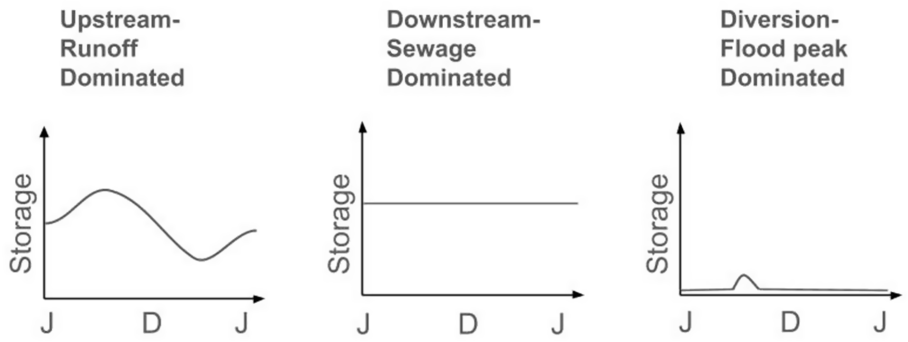

FIGURE 8
Conceptual schematic of storage trends across categories. Upstream lakes are often runoff-dominated, downstream lakes are often sewage-dominated, while lakes with diversion drains only receive flood flows, i.e., when the water level in the stormwater channel rises above the diversion weir and enters the lake.

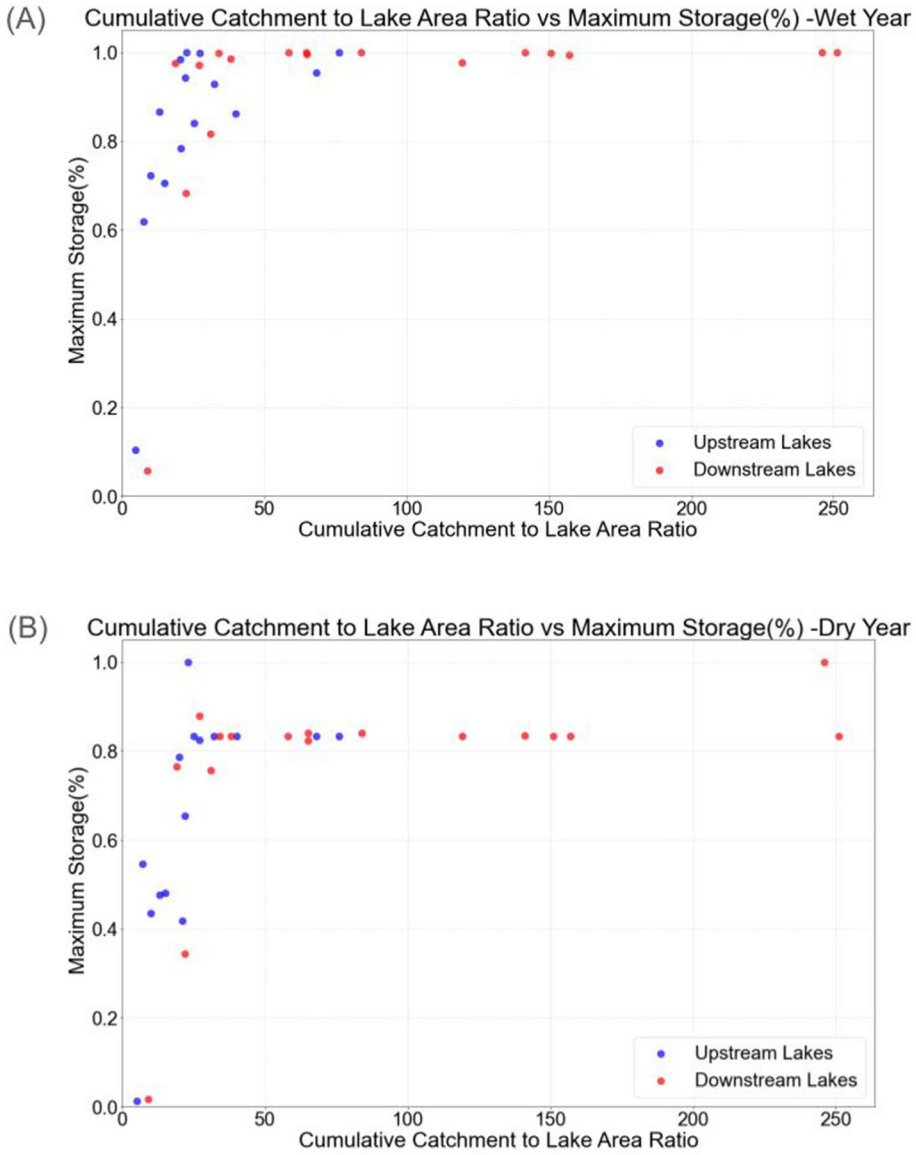

FIGURE 9
Relationship between catchment to lake area ratio and fraction of maximum storage in 2022 **(A)** and 2023 **(B)**.

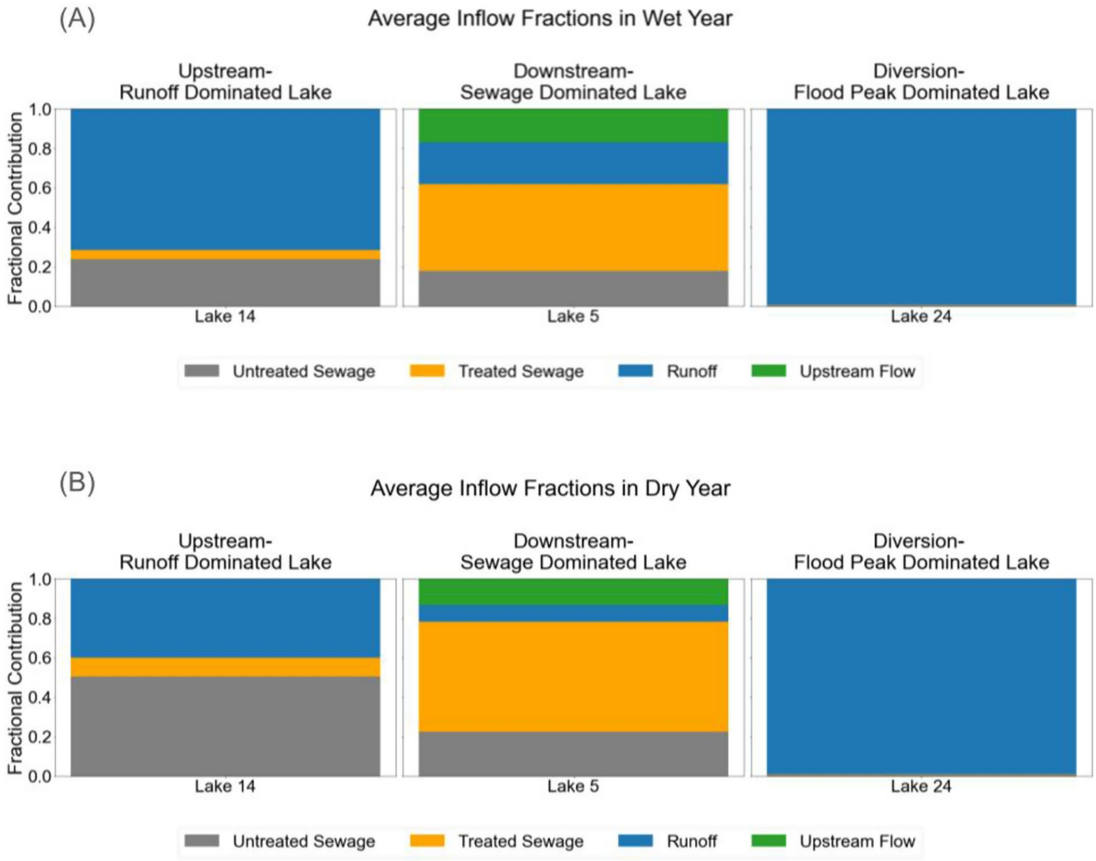

FIGURE 10
Fractional contribution of runoff, treated sewage, and untreated sewage to total annual inflows for each lake in wet year **(A)** and dry year **(B)**.

runoff. This underscores the importance of anthropogenic intervention in urban lake systems.

These results underscore that storage behavior is not solely natural response to rainfall, but is heavily modified by human-controlled inflows, particularly the sewage-to-runoff ratio.

Further analysis of the relationship between catchment-to-lake area ratio and annual lake storage utilization (Figure 9) revealed distinct patterns along the cascade. Lakes with larger catchments fill a greater fraction of their maximum capacity each year. These lakes tend to become more perennial as catchment size increases, especially in wetter conditions. This supports the view that cumulative inflows from upstream sources buffer seasonal and interannual variability, sustaining perennial conditions downstream. Likewise, lakes with larger catchments are more likely to have at least some sewage contributions.

Analysis of annual inflow composition (Figure 10) reveals spatial and temporal variations across the lake network. Upstream lakes were substantially sustained by local runoff during the wet year (2022). But, in the dry year (2023), inflows were dominated by sewage (both treated and untreated). Downstream lakes consistently exhibited inflow regimes dominated by upstream contributions and showed limited sensitivity to local inflow changes. However, these flows became more anthropogenic in the dry year as upstream lakes themselves received less runoff and more sewage. It emphasizes the increasing role of sewage in sustaining urban lake connectivity and storage during drought conditions.

In downstream lakes, the proportion of treated sewage occasionally exceeded that of untreated sewage, indicating that, within the sewage component, a relatively cleaner inflow reached these lakes. However, this may not imply high overall water quality, as the dominant upstream inflows often carry untreated sewage introduced higher in the cascade. Effective management should therefore prioritize increasing treated sewage contributions at upstream locations to improve water quality across the entire network, not just in the terminal lakes.

3.3 Scenario modeling

Three types of management scenarios were tested using the lake model. They were compared against normal condition (Figures 11A, 12A). All three scenarios are under active consideration by the city's municipal corporation.

3.3.1 Treated sewage diversion

Model simulations show that diverting treated sewage inflows (DSTP and CSTP) throughout the year increases available storage capacity, particularly in downstream lakes (Figure 11B). These lakes, which are predominantly fed by sewage, benefit more from such interventions, as buffer space is freed up to capture excess runoff and thus mitigate flood risk. In contrast, upstream lakes with smaller catchments typically receive more runoff and less sewage. Diverting treated flows either results in very little change from normal conditions (Figure 12B). It can also result in the lake remaining mostly dry throughout the year. This suggests that treated sewage withdrawal interventions are far more impactful for lakes with high anthropogenic inflow dominance, while for upstream, runoff-driven lakes, they may offer limited gains.

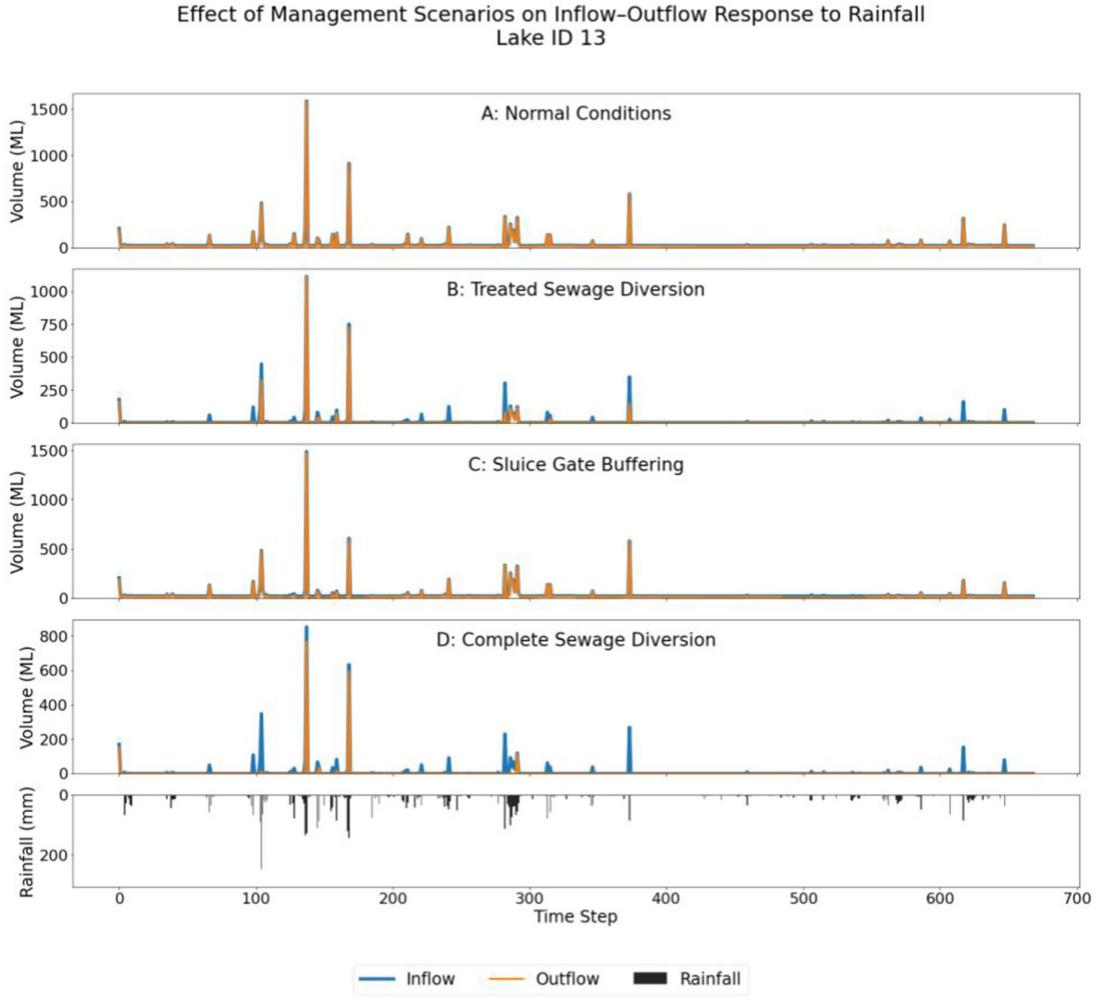

FIGURE 11
Effect of management scenarios on inflow–outflow response to rainfall for Jakkur Lake (Sewage dominated). Rainfall is shown in the bottom panel, with corresponding inflow (blue) and outflow (orange) hydrographs for four management scenarios: **(A)** – normal conditions, **(B)** – treated sewage withdrawal, **(C)** – sluice gate operation, and **(D)** – complete sewage withdrawal.

3.3.2 Sluice gate buffering

A second management scenario involved dynamically removing a fixed percentage (2%) of lake volume through sluice gates during the summer months. This intervention was much more effective in upstream lakes, where runoff events are the main source of inflow (Figure 12C). Periodic volume removal helped maintain sufficient buffers to capture peak runoff volumes and reduce instances of overflow. For downstream lakes, however, the ongoing high sewage inflow rapidly refills the lake, limiting the effectiveness of gradual removal in creating lasting buffer capacity (Figure 11C). Most of these lakes are already perennially overflowing.

3.3.3 Complete sewage diversion

A third management scenario involved diverting both treated and untreated sewage throughout the year. Diverting both treated and untreated sewage significantly reduced outflows across lake types (Figures 11D, 12D).

3.3.4 Implications by lake position

The model results highlight the need for differentiated management strategies based on lake position within the cascade.

- Upstream lakes benefit most from active volume removal techniques (sluice gate buffering), which help manage runoff-driven filling.
- Downstream lakes require stricter control or diversion of treated sewage inflows to maintain storage capacity and reduce flood risk.

This position-based strategy reflects spatial variability in inflow sources across the cascade. However, complete sewage diversion emerges as the most universally effective intervention, while "one-size-fits-all" partial strategies remain unlikely to succeed across lake types.

3.4 Functional mapping

We assessed how spatial position, temporal variability, and anthropogenic inputs translate into lake functional roles. These

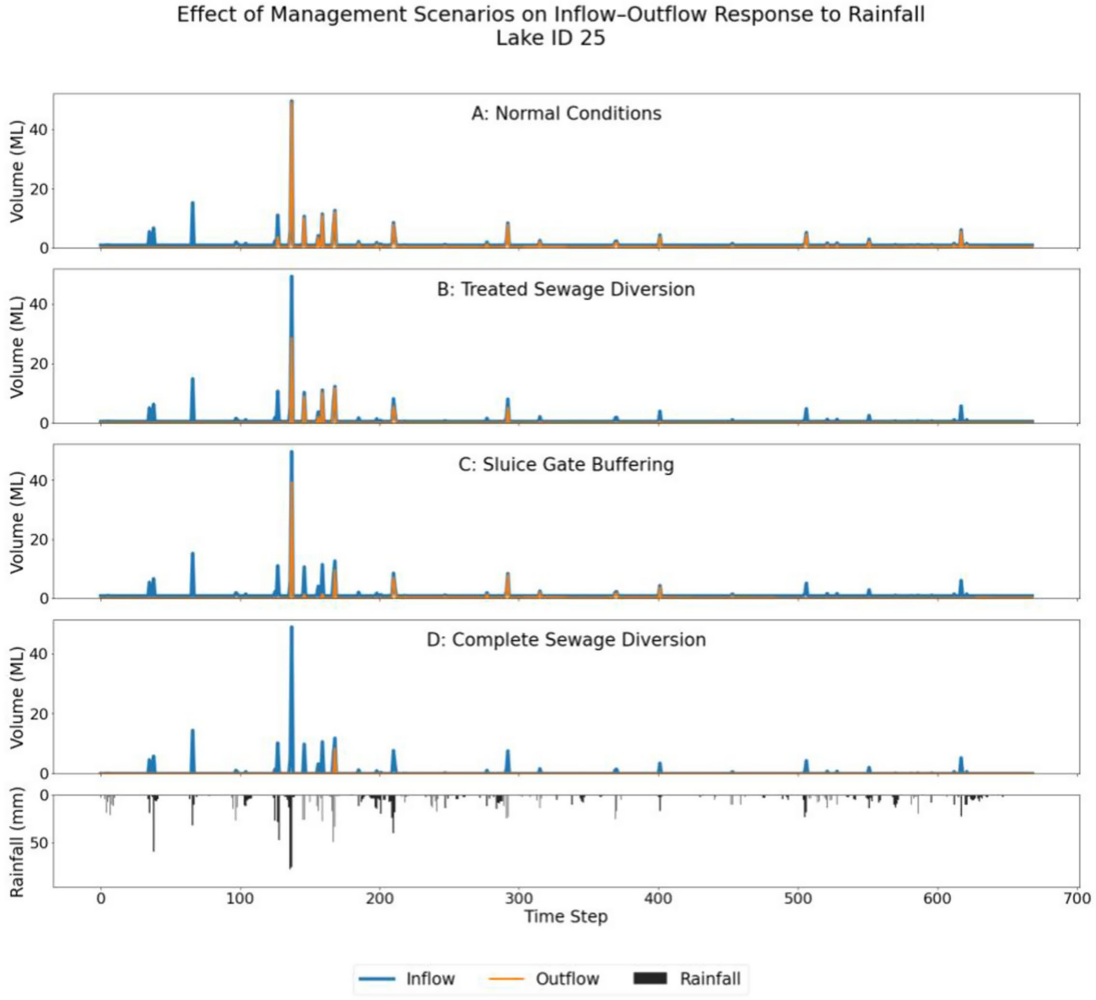

FIGURE 12
Effect of management scenarios on inflow–outflow response to rainfall for Horamavu lake (Runoff dominated). Rainfall is shown in the bottom panel, with corresponding inflow (blue) and outflow (orange) hydrographs for four management scenarios: **(A)** – normal conditions, **(B)** – treated sewage withdrawal, **(C)** – sluice gate operation, and **(D)** – complete sewage withdrawal.

characteristics shape lake storage behavior, and changes in anthropogenic inflows primarily drive deviations from expected patterns (Figure 13). By analyzing normalized storage trends and inflow composition across 44 lakes, we identified diagnostic patterns that inform restoration and management strategies.

Changes in lake storage, whether stable or variable, are thus central to determining the functional role a lake can play within the urban system (Figure 13). These diagnostic patterns allow us to identify which lakes can act as flood buffers, provide reliable storage for recharge or indirect reuse, or support ecological functions.

In particular, variable lake storage is essential for flood buffering; the ability to temporarily capture flood waters requires that the lake can accommodate surges without immediately overflowing. In contrast, stable volumes are preferred for storage and reuse functions, provided inflow quality is adequate. Moderate storage variation supports ecological functioning, providing seasonal wetting and drying regimes important for biodiversity. Importantly, the lake would need to have shallower water levels at least in part of the lake instead of maximizing the volume of storage.

Together, these results show that spatial, temporal, and anthropogenic drivers, expressed through storage behavior, dictate each lake's potential functions in the urban environment. Functional roles such as flood buffering, ecological support, and storage can only be reliably assigned where storage behaviors align with the hydrological requirements for those uses, as summarized in Figure 13.

4 Discussion

This study aimed to examine how catchment characteristics, anthropogenic modifications and upstream-downstream dynamics influence water flows in urban cascading lake systems.

Despite the growing recognition of infrastructure and watershed-scale dynamics in urban hydrology, cascading lake systems remain under examined. Most studies assess lakes in isolation, overlooking how interconnections alter their behavior and function.

Our findings help address this gap.

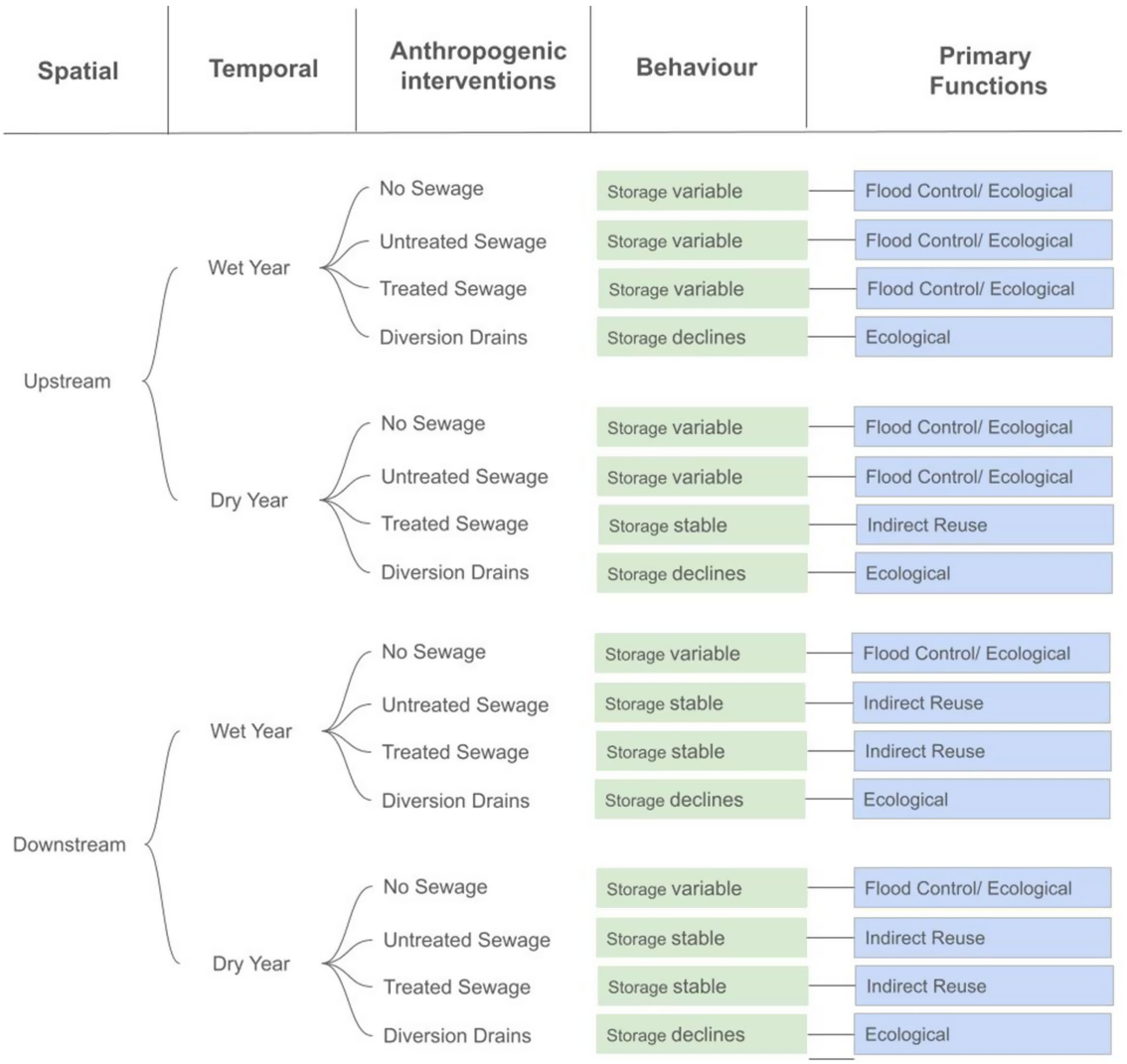

FIGURE 13
Diagnostic schematic summarizing lake function based on storage trends and inflow sources.

4.1 Downstream lakes are more influenced by accumulated upstream flows than by local catchments

Spatial position determines lake inflows. In small upstream lakes with small catchments, inflows are often dominated by local catchment characteristics – runoff, untreated sewage, and treated sewage. But because many of the upstream lakes in the Hebbal-Nagvara catchment lie on the outskirts of the city limits, where the land is undeveloped, many lakes only receive stormwater runoff.

In contrast, downstream lakes reflect the average characteristics of the whole series rather than just their own catchment. Thus, there is a shift from primarily natural flows in small upstream catchments. As we move downstream or the catchment size increases, the system begins to collect treated and untreated sewage from the urbanized areas, so the flow characteristics become predominantly anthropogenic.

Runoff contributes to storage variability, while sewage inflows bring stability, simply because runoff is seasonal (governed by Bengaluru's monsoonal rainfall) while sewage is constant (about the same amount of sewage is generated each day, with minor sub-daily variability). Thus, as we shift from natural flows upstream to anthropogenic-dominated flows downstream, lake storage becomes more stable.

Continuous sewage inputs have transformed Bengaluru's historically seasonal lakes into perennial water bodies. This has relevance for how people perceive lakes and also what functions lakes can perform. Across the system, 30% of lakes received more sewage than runoff; these proportions rose to 62% for downstream lakes and as high as 95% during dry years. These findings underscore the importance of managing sewage flows at a system scale to improve water quality and sustain flow persistence.

Anthropogenic interventions, particularly diversion drains and changes in sewage-to-runoff ratios drive deviations from baseline storage trends. Although diversion drains are put in place to improve water quality by reducing pollutant loads, they often lead to declines in lake storage. Some lakes have become almost perennially dry.

Similarly, restoration or intervention strategies cannot treat each lake in isolation. Upstream interventions (e.g., sewage treatment, diversions) will shape downstream storage much more than downstream catchment-level efforts. This supports the need for cascade-scale planning.

4.2 Variability in spatial, temporal, and anthropogenic characteristics across the cascade demands differentiated management

Because storage behavior and inflow composition vary systematically along the cascade, different parts of the system are suited to different roles. Upstream, more variable, runoff-dominated lakes are better candidates for flood buffering and ecological functions. Downstream, more stable, sewage-influenced lakes may be prioritized for indirect reuse, subject to quality constraints.

Because natural and engineered hydrological pathways form evolving networks, understanding urban watersheds as fixed, disconnected systems does not capture this complexity. Engineered structures such as sluice gates, diversion drains and in-line treatment modify both quantity and quality (Kaushal and Belt, 2012; Singh and Singh, 2019). This means that management decisions about sewage release, diversion and reuse can deliberately shift a lake's behavior and thus its feasible functions. A given lake's function is not pre-determined. It also evolves based on natural and human decisions. Recognizing this dynamic enables better cascade-wide planning and targeting of interventions.

4.3 Hydrological modeling can prove to be a useful management tool, but only if these complexities are adequately represented

This study relies on a simple stylistic hydrological model. But it attempts to parameterize the actual characteristics of Bengaluru's lake system as it exists on the ground.

Despite these strengths, the modeling framework has a few limitations that are important for interpreting the results. While the sensitivity tests for Curve Number, bathymetry and lpcd quantify how parametric uncertainty propagates to model outputs, they do not address structural uncertainties, such as alternative ways of classifying lakes into bathymetric categories, the higher accuracy that could be achieved with finer-resolution inputs (e.g., improved land-use/land-cover and elevation data), or explicit representation of lake–groundwater interactions. Taken together, these limitations imply that the model is best interpreted as providing plausible ranges and spatial patterns of storage and flows in the cascade, rather than exact predictions for any specific year or management configuration. The framework is therefore most suitable for comparing scenarios and identifying sensitive parts of the system, rather than for precise design-level sizing of individual interventions.

The hydrological model does more than simulate storage and spill data for calibration. It also acts as a diagnostic tool to understand how different characteristics shape lake behavior. Using storage outputs and inflow data, we developed a functional typology linking lake behavior to its potential roles.

By combining field-based monitoring with a simple mass-balance model, we derived lake typologies that influence which functions they can perform. Our framework (Figure 13) classifies lakes by their suitability for flood control, storage or ecological functions. This offers a practical tool for system-wide assessment and prioritization of restoration efforts. It shows which lakes are working well, which are not, and where targeted action can improve their function. Though direct water quality modeling was not conducted, established links between inflow type and water quality support these inferences. Normalized storage metrics had to be interpreted with caution in low-variability lakes, where minor changes may appear exaggerated. Future work should integrate storage and water quality monitoring to strengthen causal understanding and support scenario-based planning.

While patterns such as downstream dependence on upstream flows or greater storage in larger lakes may appear intuitive, their quantification across Bengaluru's interconnected cascade system is novel.

This marks the first system-wide analysis of urban lake cascades typical of peninsular India, a departure from rural-focused studies. Two key contributions distinguish our approach:

First, we reveal how urbanization transforms smooth inter-lake flows into threshold-dominated dynamics: upstream sluice gates create pulsed releases during runoff events, while downstream lakes oscillate between steady sewage inputs and sudden spills at capacity limits.

Second, we quantify treated/untreated sewage roles in flood buffering capacity: upstream runoff control via sluices reduces flood peaks, while downstream STP treatment/reuse stabilizes sewage flow. This revealed complementary roles across the cascade.

This advances socio-hydrology for rapidly developing cities in the Global South by quantifying cascade dynamics absent in prior single-lake studies.

While storage dynamics reveal hydrological roles within the cascade (e.g., runoff buffering and sewage dominance), inferring ecological functions such as biodiversity support would require complementary water-quality data (e.g., nutrients, dissolved oxygen), which are not available for this study. Sewage-dominated inflows suggest a risk of eutrophication, but this remains unquantified here. Future integration of systematic water-quality monitoring and water-quality modeling would be needed to refine these ecological interpretations.

Effectively managing urban lake systems, especially in rapidly changing tropical cities, requires tools that can reveal key hydrological dynamics without being overly complex (Bashford et al., 2002; Penny et al., 2018). This study demonstrates that integrating field-based monitoring with hydrological modeling enhances understanding of system dynamics and risk assessment (Stephens et al., 2021). Simpler models are both accessible and informative, enabling managers to detect trends, prioritize interventions, and design more effective restoration strategies.

Simple, integrated models grounded in reliable observations can guide both management decisions and the optimal allocation of limited monitoring resources. Simulation modeling can strategically test which observations are most valuable, particularly under uncertainty, helping prioritize data collection efforts to maximize impact (Freeze et al., 1992).

The modeling tool developed in this study offers a simplified yet powerful framework to manage lakes. It treats lakes not as isolated features but as parts of interconnected networks shaped by both natural flows and human-built infrastructure (Kaushal and Belt, 2012). This aligns with work showing that lakes in connected networks function differently from isolated basins, with serial configuration and inlet–outlet linkages driving downstream responses (Jones, 2010). By highlighting the dynamic continuum of engineered and natural flow paths, the framework identifies which lakes are functioning well and which require targeted interventions. It helps manage lakes as interconnected systems, which is crucial for them to effectively play hydrological, ecological, and socio-cultural functions.

Quantifying and monitoring flows at the system scale and not just within individual lakes is therefore essential for accurate prediction, risk assessment, and sustainable management. Traditional approaches that treat lakes as isolated units risk missing the reality of urban hydrological connectivity operating across spatial and temporal scales (Zhang et al., 2021). By capturing these system-scale interconnections, simple integrated models become accessible tools for decision-makers. They do so by supporting cascade-scale planning and design that aligns with principles of hydrological connectivity and integrated watershed management (Li et al., 2018; Yu et al., 2023).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RK: Software, Writing – original draft, Formal analysis, Writing – review & editing, Data curation, Visualization, Conceptualization, Project administration, Investigation, Validation, Methodology. VS: Resources, Software, Writing – review & editing, Supervision, Funding acquisition, Conceptualization, Writing – original draft.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2026.1778071/full#supplementary-material

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