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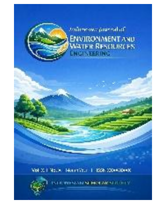

Flood inundation-based buffer zone delineation and spatial planning evaluation for urban lake conservation

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A R T I C L E I N F O

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Urban lake.

A B S T R A C T

Urban lakes play a crucial role in flood regulation, water conservation, ecological balance, and urban environmental sustainability. However, rapid urbanization and uncontrolled land-use changes around lake areas have significantly degraded their hydrological and ecological functions. This study aims to delineate the buffer zone of Situ Jatijajar, an urban lake located in Depok City, Indonesia, based on flood inundation characteristics and to evaluate the conformity of the existing spatial planning policy with the delineated conservation area. Hydrological analysis was conducted using rainfall frequency analysis with Log Pearson Type III and Gumbel distributions, followed by flood discharge estimation using the Nakayasu Synthetic Unit Hydrograph (HSS Nakayasu), Mononobe, PSA 007, and Rational methods. Hydraulic simulations were performed using HEC-RAS 6.2 to determine flood inundation extent and maximum water level for 25- and 50-year return periods. Geographic Information System (GIS) techniques were then applied to delineate the lake buffer zone based on the highest flood water elevation and to evaluate spatial planning conformity through overlay analysis with the Depok City Spatial Plan (RTRW). The results indicate that the highest flood inundation was generated by the HSS Nakayasu method combined with PSA 007 rainfall distribution using rainfall data from the Jatijajar Station. The simulated 50-year return period flood produced a peak discharge of 4.74 m^3/s, maximum inundation elevation of 96.87 m above sea level, and inundation area of 8.19 ha. Based on the flood inundation extent and the Indonesian Ministry of Public Works regulation, the delineated buffer zone covered 19.10 ha. Spatial evaluation revealed that approximately 39.43% of the existing land allocation within the buffer zone was inconsistent with the designated conservation function. Furthermore, the proposed land-use management scenario, emphasizing green open spaces and agroforestry-based conservation, reduced peak discharge by 21.93%, inundation area outside the lake by 12.39%, and flood water elevation by 0.09 m. These findings demonstrate that flood inundation-based buffer delineation integrated with hydrological, hydraulic, and spatial analyses provides an effective framework for urban lake conservation and flood mitigation planning in rapidly urbanizing areas.

1. Introduction

Urban lakes play a crucial role in maintaining the hydrological and ecological balance of urban environments. Besides functioning as natural water storage systems, urban lakes contribute significantly to flood attenuation, groundwater recharge, climate regulation, biodiversity conservation, recreation, and aesthetic enhancement of urban landscapes. In many rapidly growing cities, however, urban lakes are increasingly subjected to environmental pressures caused by population growth, land-use conversion, urban sprawl, and inadequate spatial planning. These pressures often result in the degradation of lake ecosystems, reduction of water storage capacity, deterioration of water quality, and increased flood vulnerability in surrounding areas. Consequently, the conservation and sustainable management of urban lakes have become important issues in urban water resources management and environmental planning [1, 2].

Flooding is one of the most frequent hydrometeorological disasters affecting urban areas in Indonesia. The increasing occurrence of urban floods is closely associated with uncontrolled land-use changes, reduced infiltration areas, and the expansion of impervious surfaces such as roads, buildings, and commercial developments [3–5].

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These conditions accelerate surface runoff and shorten the concentration time of rainfall within urban watersheds, thereby increasing peak discharge and flood inundation intensity. In urban catchments containing lakes or reservoirs, the hydrological function of these water bodies becomes increasingly important because they serve as retention basins capable of reducing downstream flood peaks. However, when urban lakes experience encroachment and environmental degradation, their ability to mitigate flooding declines substantially [6, 7].

Situ Jatijajar is one of the urban lakes located in Depok City, West Java, Indonesia, within the Ciliwung–Cisadane watershed region. The lake serves multiple functions, including local flood retention, ecological conservation, fisheries, recreation, and water storage. Over the past decades, the surrounding area of Situ Jatijajar has undergone rapid urbanization characterized by the expansion of residential settlements, transportation infrastructure, commercial facilities, and other built-up land uses. This urban development has significantly altered the hydrological characteristics of the catchment area by increasing runoff coefficients and reducing natural infiltration capacity. As a result, flood inundation frequently occurs around the lake and adjacent urban areas during high-intensity rainfall events [8–10].

The hydrological response of an urban watershed is strongly influenced by several factors, including rainfall intensity, catchment characteristics, drainage patterns, land-use conditions, topography, and hydraulic capacity. Therefore, accurate flood analysis requires the integration of hydrological and hydraulic approaches. Hydrological analysis is necessary to estimate design rainfall and peak flood discharge, while hydraulic analysis is essential for simulating water surface profiles, inundation extent, and flood depth. In ungauged or data-limited watersheds, Synthetic Unit Hydrograph (SUH) methods are widely applied because they can estimate flood hydrographs based on watershed physical characteristics. Among these methods, the Nakayasu Synthetic Unit Hydrograph (HSS Nakayasu) is commonly used in Indonesia due to its simplicity and suitability for tropical catchments [3, 11].

In addition to hydrological analysis, rainfall temporal distribution also affects flood hydrograph characteristics. Several methods are available for estimating short-duration rainfall intensity from daily rainfall data, including the Mononobe method and PSA 007 method. These methods are frequently used in Indonesia for deriving hourly rainfall distribution in areas lacking automatic rainfall recording stations. The generated rainfall hyetographs can then be utilized as inputs for flood hydrograph simulation using HSS Nakayasu. By comparing different rainfall distribution methods, more representative flood discharge estimates can be obtained for hydraulic modeling purposes [12, 13].

Hydraulic simulation has become an important approach for evaluating flood behavior and inundation characteristics in river and lake systems. The Hydrologic Engineering Center River Analysis System (HEC-RAS), developed by the United States Army Corps of Engineers (USACE), is widely used for hydraulic analysis because it can simulate water surface elevation, flow velocity, floodplain inundation, and hydraulic structures under various flow conditions. Coupled with Geographic Information Systems (GIS), HEC-RAS enables spatially explicit flood inundation mapping that is useful for flood risk assessment, watershed management, and spatial planning evaluation. The integration of GIS with hydraulic simulation also facilitates the delineation of environmentally sensitive areas, including urban lake buffer zones [6, 14, 15].

One of the critical challenges in urban lake conservation is determining appropriate buffer zones or riparian protection areas. Buffer zones are essential for protecting lake ecosystems from excessive anthropogenic activities, reducing sediment and pollutant inflow, maintaining ecological integrity, and mitigating flood impacts. In Indonesia, the determination of lake buffer zones is regulated by the Regulation of the Ministry of Public Works and Public Housing (Permen PUPR) No. 28/PRT/M/2015, which stipulates that lake buffer zones should be established based on the highest flood water level with a minimum distance of 50 meters from the flood boundary. However, in many urban areas, the implementation of such regulations remains ineffective due to weak spatial planning control, rapid land conversion, and the absence of hydrologically based delineation methods [4, 16].

Spatial planning policies play an important role in controlling land use around urban lakes. Ideally, land-use allocation within urban lake buffer zones should prioritize conservation functions and restrict intensive development activities. Nevertheless, many urban spatial plans are often prepared without sufficient integration of hydrological and hydraulic considerations. Consequently, incompatibilities frequently occur between planned land-use allocation and actual environmental carrying capacity. Such inconsistencies can increase flood risk, accelerate environmental degradation, and reduce the effectiveness of flood mitigation measures. Therefore, evaluating the conformity between flood-based buffer zones and spatial planning policies is necessary to support sustainable urban development [17, 18].

Previous studies related to flood management and urban lake conservation have mainly focused on hydrological modeling, hydraulic simulation, or land-use analysis separately. Several studies have analyzed flood inundation using HEC-RAS and GIS integration, while others have investigated the influence of land-use change on urban runoff characteristics. However, studies integrating flood inundation-based buffer zone delineation with spatial planning evaluation remain limited, particularly for urban lakes in Indonesia. Moreover, few studies have examined the effectiveness of conservation-oriented land-use management in reducing flood inundation around urban lakes [8–10].

The novelty of this study lies in the integration of hydrological analysis, hydraulic flood simulation, GIS-based buffer zone delineation, and spatial planning evaluation for urban lake conservation. Unlike previous studies that primarily focused on flood modeling alone, this research incorporates flood inundation results into the determination of urban lake buffer zones and evaluates their conformity with the existing Regional Spatial Plan (RTRW) of Depok City. In addition, this study proposes land-use management recommendations based on hydrological conservation principles to enhance flood mitigation effectiveness and improve environmental sustainability in the catchment area of Situ Jatijajar.

This study specifically investigates flood inundation characteristics in Situ Jatijajar using HSS Nakayasu hydrograph analysis combined with hourly rainfall distributions derived from Mononobe and PSA 007 methods. The generated flood discharges are then simulated using HEC-RAS to identify inundation extent, flood depth, and maximum flood water elevation under various return periods. Subsequently, the flood inundation results are utilized to delineate the lake buffer zone based on applicable Indonesian regulations. The resulting buffer zone is further analyzed spatially using GIS to evaluate its conformity with the Depok City Spatial Plan and existing land-use conditions.

The objectives of this study are: (1) to analyze rainfall characteristics and design flood discharge within the Situ Jatijajar catchment area; (2) to simulate flood inundation using hydraulic modeling with HEC-RAS; (3) to delineate urban lake buffer zones based on flood inundation extent and maximum flood water level; (4) to evaluate the conformity between flood-based buffer zones and the Depok City Spatial Plan (RTRW); and (5) to formulate land-use management recommendations for flood mitigation and urban lake conservation. The findings of this study are expected to contribute to the development of integrated flood management strategies, environmentally based spatial planning policies, and sustainable conservation approaches for urban lakes in rapidly urbanizing regions of Indonesia.

2. Materials and Methods

2.1. Study area

This study was conducted at Situ Jatijajar, an urban lake located in Depok City, West Java Province, Indonesia (Fig. 1). Geographically, Situ Jatijajar is situated within the Ciliwung–Cisadane watershed system and functions as a local water retention basin connected to the Cipinang River. The lake plays an important role in flood control, ecological conservation, fisheries, and recreational activities for surrounding communities. The catchment area of Situ Jatijajar has experienced rapid urban development characterized by increasing residential settlements, transportation infrastructure, and commercial land use, which potentially affect the hydrological response of the watershed.

The total catchment area analyzed in this study was approximately 0.58 km². The study area consists of various land-use types including water bodies, forest, mixed gardens, settlements, roads, open spaces, and commercial areas. Due to the increasing urbanization surrounding the lake, the area has become vulnerable to surface runoff increase and flood inundation during high-intensity rainfall events [4, 16].

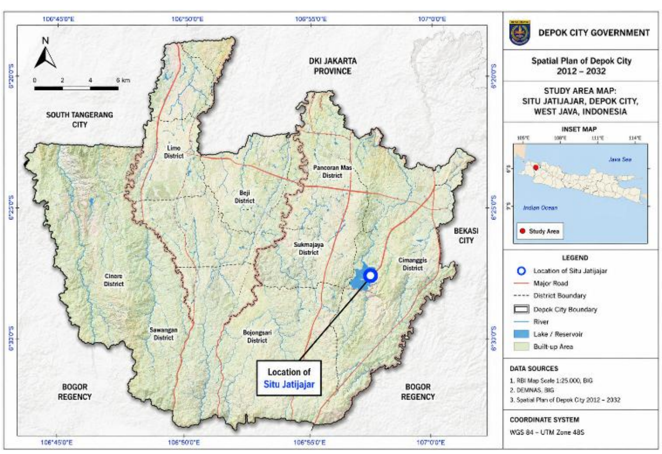

Fig. 1. Location of the study area (Situ Jatijajar) within Depok City, West Java, Indonesia, including administrative boundaries, major rivers, road networks, and surrounding urban landscape.

This study integrated hydrological analysis, hydraulic simulation, Geographic Information System (GIS)-based spatial analysis, and spatial planning evaluation (Fig. 2) to delineate flood-based urban lake buffer zones [17, 18]. The overall research framework consisted of the following stages:

- Catchment area delineation using Digital Elevation Model (DEM) data;
- Rainfall data collection and statistical analysis;
- Hydrological analysis and design flood estimation;
- Flood hydrograph generation using HSS Nakayasu;
- Hydraulic simulation using HEC-RAS;
- Flood inundation mapping and buffer zone delineation using GIS;
- Spatial planning evaluation based on the Depok City Regional Spatial Plan (RTRW);
- Development of land-use management recommendations for flood mitigation and urban lake conservation.

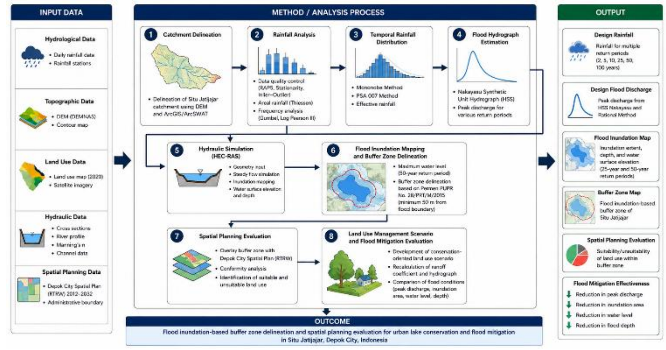

Fig. 2. Research framework illustrating the workflow of hydrological analysis, hydraulic modeling, flood inundation mapping, buffer zone delineation, spatial planning evaluation, and flood mitigation assessment for Situ Jatijajar, Depok City, Indonesia.

2.2. Data collection

2.2.1. Hydrological data

Rainfall data used in this study consisted of daily maximum rainfall records obtained from the Cibinong and Jatijajar rainfall stations managed by the Ciliwung–Cisadane River Basin Agency (BBWS Ciliwung–Cisadane). The rainfall data covered the period from 2011 to 2020 for the Cibinong Station. Since the Jatijajar Station contained shorter observation records, additional rainfall data were generated using the Thomas–Fiering method to produce a ten-year dataset for statistical analysis.

2.2.2. Topographic data

Topographic information was obtained from the Indonesian National DEM (DEMNAS) provided by the Geospatial Information Agency (BIG). The DEM data were used for catchment delineation, flow direction analysis, flow accumulation analysis, and hydraulic modeling preparation.

2.2.3. Land-use data

Land-use maps for the year 2020 were utilized to analyze runoff characteristics and evaluate spatial planning conformity. Land-use classification included settlements, roads, forest, mixed gardens, open spaces, water bodies, and commercial areas.

2.2.4. Hydraulic geometry data

Hydraulic geometry data including cross sections, longitudinal profiles, channel distances, and Manning's roughness coefficients were obtained from BBWS Ciliwung–Cisadane and field observations. These data were used as geometric input parameters for HEC-RAS hydraulic simulations.

2.2.5. Catchment area delineation

The delineation of the Situ Jatijajar catchment area was conducted using ArcGIS 10.x with the ArcSWAT extension. DEMNAS data were processed to generate flow direction and flow accumulation maps. Watershed boundaries were delineated through a threshold-based stream definition process using trial-and-error calibration to match the actual drainage network and river system shown on the Indonesian Base Map (RBI). The outlet point was defined at the lake spillway located on the northern side of Situ Jatijajar, while the inlet was identified on the southern side of the lake. The delineated watershed area was subsequently used for hydrological analysis and runoff estimation.

2.3. Rainfall analysis

Thiessen Polygon analysis was applied to identify rainfall stations influencing the study area. Based on the spatial distribution of rainfall stations, the Cibinong and Jatijajar stations were identified as the nearest stations to Situ Jatijajar. Rainfall data quality analysis included consistency test using rescaled adjusted partial sums (RAPS), stationarity tests using F-test and T-test and inlier–outlier analysis.

The RAPS method was applied to assess rainfall consistency by evaluating cumulative deviations from the mean rainfall series. The stationarity tests were performed to determine variance and mean stability of rainfall data. Inlier–Outlier testing was conducted to identify abnormal rainfall observations exceeding upper and lower statistical thresholds [3, 6, 16].

Design rainfall analysis was performed using the Gumbel and Log Pearson Type III probability distributions. The objective was to estimate rainfall magnitudes for various return periods including 2, 5, 10, 25, 50, and 100 years. The suitability of the probability distributions was evaluated using smirnov–kolmogorov goodness-of-fit test and chi-square goodness-of-fit test. The selected distribution for subsequent hydrological analysis was determined based on statistical acceptance criteria.

Hourly rainfall distribution was estimated from daily rainfall data using two approaches mononobe and PSA 007 method. The Mononobe method was used to derive short-duration rainfall intensity from daily rainfall data by applying empirical rainfall distribution relationships. While the PSA 007 method was applied to estimate hourly rainfall distribution percentages over a six-hour rainfall duration period. Effective rainfall was calculated using runoff coefficients corresponding to existing land-use conditions. The resulting rainfall hyetographs were used as inputs for flood hydrograph simulation.

2.4. Flood hydrograph analysis

Flood hydrographs were generated using the Nakayasu Synthetic Unit Hydrograph (HSS Nakayasu) method. This method was selected due to its suitability for ungauged watersheds and widespread application in Indonesian hydrological studies [19–21]. The main parameters used in the HSS Nakayasu calculation included:

- Catchment area (A);
- Main river length (L);
- Time lag (tg);
- Effective rainfall duration (tr);
- Peak discharge time (Tp);
- Recession time (T0.3).

The peak discharge was calculated using the Nakayasu equation:

$$Q_p = \frac{A \times R_o}{3.6(0.3T_p + T_{0.3})}$$

where ; Q_p = peak discharge (m³/s), A = watershed area (km²), R_o = effective rainfall (mm), T_p = time to peak (hours), $T_{0.3}$ = recession time until discharge decreases to 30% of peak discharge. The resulting hydrographs were generated for return periods of 2, 5, 10, 25, 50, and 100 years.

2.5. Rational method analysis

In addition to HSS Nakayasu, peak discharge was also estimated using the Modified Rational Method to compare hydrological responses [3, 6, 16]. The Rational Method equation used in this study was:

$$Q = 0.278 \times C_s \times C \times I \times A$$

where: Q = peak discharge (m³/s), Cs = storage coefficient, C = runoff coefficient, I = rainfall intensity (mm/hour), A = watershed area (ha). Runoff coefficients were determined based on land-use classifications within the catchment area.

2.6. Hydraulic simulation using HEC-RAS

Flood inundation analysis was conducted using HEC-RAS version 6.2. Hydraulic simulations were performed under steady-flow conditions using design flood discharges generated from the hydrological analysis. Input parameters for HEC-RAS included:

- Cross-sectional geometry;
- Longitudinal river profile;
- Manning's roughness coefficient;
- Channel slope;
- Design flood discharge hydrographs.

Manning's roughness coefficient was determined based on Chow (1973) for irregular natural channels with wide cross sections. Flood simulations were conducted for 25-year and 50-year return periods to determine water surface elevations, inundation extent, and flood depths around Situ Jatijajar. Flood inundation maps were generated by integrating HEC-RAS outputs with GIS spatial analysis. The maximum flood water elevation from the 50-year return period simulation was used as the basis for delineating the lake buffer zone. Buffer zone delineation followed the Indonesian Ministry of Public Works and Housing Regulation No. 28/PRT/M/2015, which specifies a minimum distance of 50 m from the highest flood water boundary. GIS buffering analysis was conducted in ArcGIS to generate the spatial extent of the protected lake buffer zone.

The delineated flood-based buffer zone was overlaid with the Depok City Regional Spatial Plan (RTRW) for 2012–2032 using GIS spatial analysis. This evaluation aimed to assess the conformity between planned land-use allocation and the environmentally protected lake buffer zone. Spatial conformity analysis classified land-use allocation into suitable areas and unsuitable areas. The proportion of incompatible land uses within the buffer zone was quantified to identify areas requiring land-use management intervention.

A conservation-oriented land-use management scenario was developed by converting environmentally vulnerable land uses such as open land, shrubs, mixed gardens, and dry agricultural land into green open spaces (Ruang Terbuka Hijau/RTH).

The modified land-use scenario was used to recalculate runoff coefficients and simulate new flood hydrographs and inundation conditions. The effectiveness of flood mitigation measures was evaluated by comparing peak discharge reduction, flood inundation area reduction, flood depth reduction, water surface elevation reduction. The effectiveness percentage was calculated based on differences between existing and conservation scenarios under the 50-year return period condition.

3. Results and discussion

3.1. Catchment delineation of situ jatijajar

The hydrological analysis began with the delineation of the catchment area (CA) of Situ Jatijajar using Digital Elevation Model Nasional (DEMNAS) data obtained from the Geospatial Information Agency (BIG) of Indonesia. Watershed delineation was conducted using ArcGIS integrated with the ArcSWAT extension (Fig. 3). The delineation process included DEM preprocessing, flow direction analysis, flow accumulation analysis, stream network extraction, and outlet determination. The outlet of Situ Jatijajar is located at the northern section of the lake, while the inlet is situated in the southern part. The resulting catchment area covers approximately 0.58 km² and consists of urbanized land use dominated by residential areas, roads, mixed vegetation, and open spaces. The relatively small catchment area indicates that hydrological responses in Situ Jatijajar are highly sensitive to changes in land use and rainfall intensity.

The generated stream network shows that runoff generated within the catchment rapidly converges toward the lake body. Urban development surrounding the lake has reduced infiltration capacity and increased surface runoff contribution, which potentially increases flood susceptibility during extreme rainfall events.

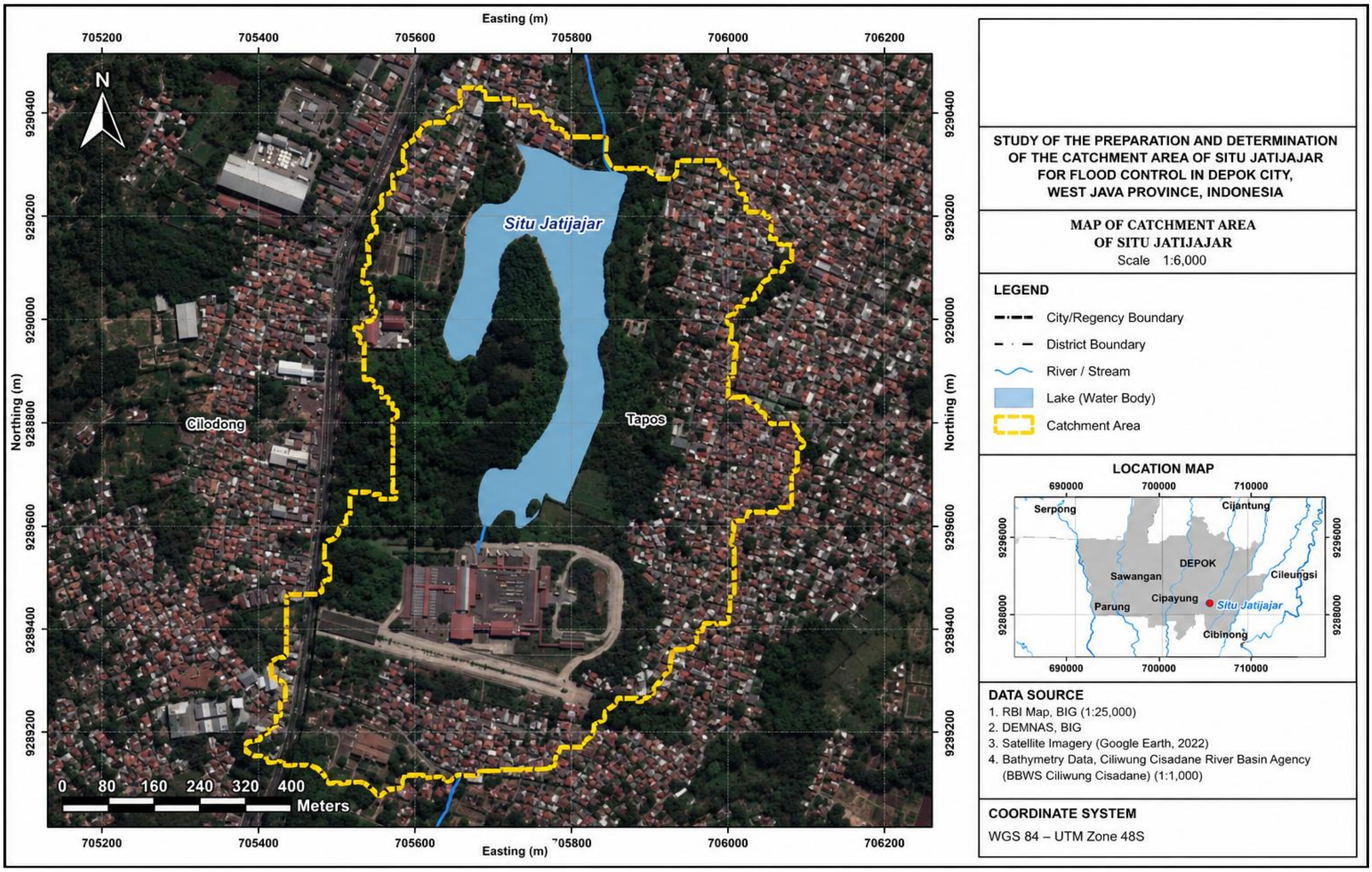

Fig. 3. Delineated catchment area and drainage network of Situ Jatijajar, Depok City, Indonesia, derived from DEMNAS and spatial analysis using ArcGIS/ArcSWAT, showing watershed boundaries, stream networks, lake morphology, and surrounding urban land cover.

3.2. Rainfall data analysis

Two rainfall stations located near the study area were evaluated, namely the Cibinong Station and the Jatijajar Station. Thiessen polygon analysis indicated that these two stations have the strongest hydrological influence on the catchment area of Situ Jatijajar. The Cibinong Station contained complete rainfall records from 2011–2020, whereas the Jatijajar Station only recorded rainfall data beginning in 2017. Therefore, missing rainfall data at the Jatijajar Station were generated using the Thomas–Fiering stochastic method to produce a complete 10-year dataset (Table 1).

The annual maximum daily rainfall at the Cibinong Station ranged from 70 mm to 135 mm, while the Jatijajar Station exhibited higher rainfall variability ranging from 41.6 mm to 157 mm. The higher variability at the Jatijajar Station indicates stronger local rainfall extremes around the study area [6, 14, 15]. Several statistical tests were conducted to evaluate rainfall data reliability, including:

- Rescaled Adjusted Partial Sums (RAPS) consistency test,
- F-test,
- T-test, and
- Inlier–Outlier test.

The RAPS analysis showed that both rainfall stations satisfied the consistency criteria because the calculated values of $Q/\sqrt{n}$ and $R/\sqrt{n}$ were smaller than the critical thresholds. The F-test and T-test also indicated that rainfall variance and mean values were statistically stable. Furthermore, the Inlier–Outlier analysis confirmed that all rainfall data from the Cibinong Station were within acceptable limits, while one rainfall value at the Jatijajar Station (41.6 mm) was categorized as a potential outlier [19–21].

Nevertheless, the generated rainfall series remained acceptable for hydrological modeling because the overall dataset passed the consistency and stationarity requirements.

Table 1
Summary of rainfall data quality control results

Quality Control Test	Parameter Evaluated	Cibinong Station	Jatijajar Station	Interpretation
RAPS Consistency Test	$(Q/\sqrt{n})$	0.74	0.74	Consistent
	Critical Value (95%)	1.14	1.14	–
	$(R/\sqrt{n})$	1.18	1.08	Consistent
	Critical Value (95%)	1.28	1.28	–
F-Test	$(F_{calculated})$	7.59	2.99	Accepted
	$(F_{critical}$ (α = 1%)	15.98	15.98	–
T-Test	$(t_{calculated})$	-0.45	-0.58	Accepted
	$(t_{critical}$ (α = 1%)	2.896	2.896	–
Inlier–Outlier Test	Upper Threshold (Y_H)	135.06 mm	249.37 mm	–
	Lower Threshold (Y_L)	63.87 mm	50.13 mm	–
	Outlier Detection	None detected	One low outlier detected	Acceptable
Overall Assessment	Data Reliability	Reliable	Reliable	Suitable for hydrological analysis

3.3. Design rainfall analysis

Design rainfall estimation was performed using the Gumbel distribution and Log Pearson Type III distribution methods. The suitability of each distribution was evaluated using the Smirnov–Kolmogorov test and Chi-square test.

For the Cibinong Station, the Log Pearson Type III distribution showed better statistical performance and satisfied all goodness-of-fit tests. Meanwhile, for the Jatijajar Station, the Gumbel distribution provided more reliable results compared to Log Pearson Type III. The estimated design rainfall values increased significantly with increasing return periods. At the Jatijajar Station, the 50-year return period rainfall estimated using the Gumbel method reached approximately 242.87 mm, which is substantially higher than the corresponding value at the Cibinong Station. This finding demonstrates the importance of using local rainfall stations in urban hydrological studies because local convective rainfall events may not be adequately represented by regional rainfall stations (Table 2).

Table 2
Design rainfall estimation using gumbel and log pearson type III distributions

Return Period (Years)	Cibinong Station (mm)	Jatijajar Station (mm)
	Gumbel	Log Pearson III	Gumbel	Log Pearson III
2	91.87	91.05	113.62	126.45
5	113.69	107.49	155.05	151.52
10	128.14	118.63	182.49	158.32
25	146.40	133.05	217.15	162.07
50	159.94	144.03	242.87	163.27
100	173.38	155.24	268.39	163.83

Note: The Log Pearson Type III distribution was accepted as the best-fit distribution for the Cibinong Station based on statistical goodness-of-fit tests, whereas both Gumbel and Log Pearson Type III distributions were statistically acceptable for the Jatijajar Station.

Since short-duration rainfall data were unavailable, hourly rainfall distributions were generated using the Mononobe method and PSA 007 method (Fig. 4). The PSA 007 method produced higher effective rainfall concentrations during the middle rainfall duration (around the third hour), resulting in higher peak runoff compared to the Mononobe method. This difference strongly influenced flood hydrograph formation and inundation characteristics. The temporal rainfall pattern generated by PSA 007 indicates a more concentrated storm event, which better represents intense tropical rainfall conditions commonly observed in urban Indonesia.

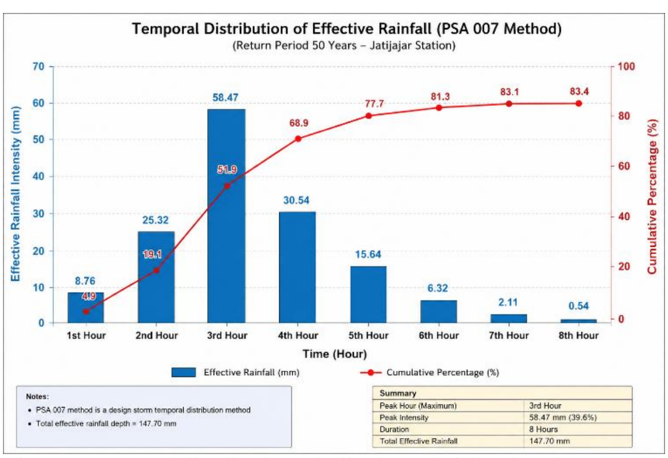

Fig. 4. Temporal distribution of effective rainfall using the PSA 007 method.

3.4. Flood hydrograph analysis

Flood discharge hydrographs were generated using the Nakayasu Synthetic Unit Hydrograph (SUH) method. The parameters used included catchment area, river length, concentration time, and effective rainfall [14, 22, 23].

The calculated peak discharges increased with increasing return periods. The highest peak discharge was obtained from the Jatijajar Station using the PSA 007 rainfall distribution method. The peak discharges for the 50-year return period are summarized in the Table 3.

Table 3
The peak discharges for the 50-year return period

Method	Peak Discharge (m^3/s)
Nakayasu + Mononobe	3.25
Nakayasu + PSA 007	4.74
Rational Method	3.94

The PSA 007 method generated the largest discharge because it concentrates rainfall intensity over shorter durations, resulting in higher runoff peaks. The comparison demonstrates that rainfall temporal distribution significantly affects urban flood estimation (Fig 5).

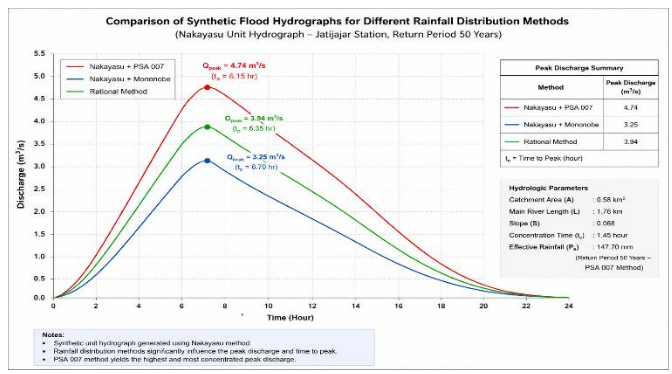

Fig. 5. Temporal distribution of effective rainfall using the PSA 007 method.

3.5. Flood inundation simulation

Hydraulic simulations were conducted using HEC-RAS 6.2 under steady-flow conditions (Fig. 6). Input data included cross-sectional geometry, Manning's roughness coefficient, and peak discharge values from hydrological analysis. The simulation results indicate that flood inundation extent increases with increasing return periods (Table 4). The most extensive inundation occurred under the 50-year return period using the Nakayasu–PSA 007 approach.

The simulated maximum flood elevation reached approximately 96.87 m above sea level, with a maximum inundation depth of 3.38 m. Floodwater overflowed beyond the lake boundary, inundating adjacent residential and open areas. Despite the relatively small catchment size, urban land cover and reduced infiltration capacity contributed significantly to rapid flood accumulation around the lake.

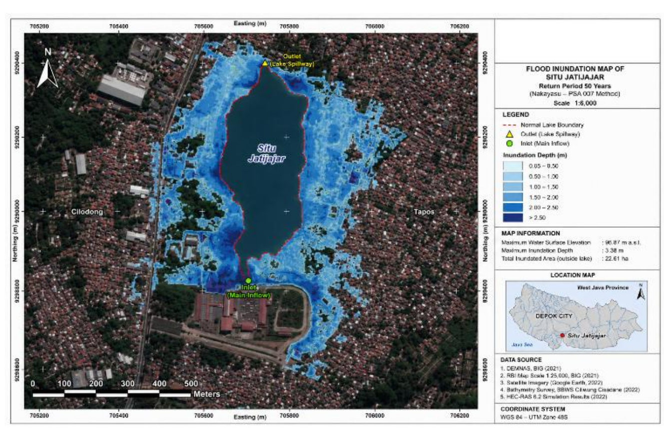

Fig. 6. Simulated flood inundation map for the 50-year return period.

Table 4
Flood inundation characteristics under different hydrological scenarios

Rainfall Station	Hydrological Method	Return Period (Years)	Lake Area (ha)	Total Inundation Area (ha)	Inundation Area Outside Lake (ha)	Maximum Flood Depth (m)	Maximum Water Level (m a.s.l.)
Cibinong	Nakayasu – PSA 007	25	6.58	8.00	1.42	3.28	96.78
Cibinong	Nakayasu – PSA 007	50	6.58	8.01	1.44	3.29	96.79
Cibinong	Nakayasu – Mononobe	25	6.58	7.89	1.32	3.23	96.73
Cibinong	Nakayasu – Mononobe	50	6.58	7.91	1.33	3.24	96.74
Cibinong	Rational Method	25	6.58	7.94	1.37	3.26	96.76
Cibinong	Rational Method	50	6.58	7.96	1.38	3.27	96.77
Jatijajar	Nakayasu – PSA 007	25	6.58	8.09	1.52	3.33	96.83
Jatijajar	Nakayasu – PSA 007	50	6.58	8.19	1.61	3.38	96.87
Jatijajar	Nakayasu – Mononobe	25	6.58	8.01	1.44	3.30	96.79
Jatijajar	Nakayasu – Mononobe	50	6.58	8.05	1.47	3.31	96.81
Jatijajar	Rational Method	25	6.58	8.07	1.50	3.33	96.82
Jatijajar	Rational Method	50	6.58	8.12	1.55	3.34	96.84

3.6. Buffer zone delineation

The delineation of the lake buffer zone was conducted based on the Indonesian Ministry of Public Works and Housing Regulation No. 28/PRT/M/2015, which requires a minimum distance of 50 m from the highest flood water boundary. The delineated buffer zone covered approximately 19.10 ha using rainfall data from the Jatijajar Station and 18.99 ha using rainfall data from the Cibinong Station (Fig. 7). The resulting buffer zone includes several land use categories such as:

- Forests,
- Mixed gardens,
- Open spaces,
- Roads,
- Residential areas, and
- Recreational facilities.

The existence of residential areas within the delineated buffer zone indicates substantial spatial conflicts between urban development and environmental protection regulations.

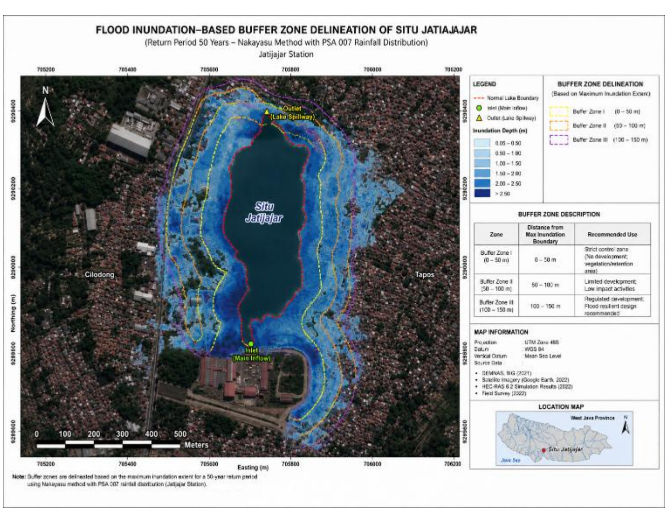

Fig. 7. Flood inundation-based buffer zone delineation of Situ Jatijajar.

3.7. Spatial planning evaluation

The delineated buffer zone was overlaid with the Depok City Spatial Plan (RTRW 2012–2032) to evaluate land use conformity (Fig. 8). The analysis revealed that approximately 39.43% (7.53 ha) of land use within the buffer zone was inconsistent with spatial planning regulations. Incompatible land uses included:

- Residential settlements,
- Commercial areas,
- Roads,
- Agricultural fields, and
- Mixed plantations.

These findings indicate that urban expansion around Situ Jatijajar has exceeded the environmental carrying capacity of the lake ecosystem. Spatial planning inconsistencies may increase flood vulnerability, reduce infiltration areas, and accelerate lake degradation through sedimentation and land conversion [20, 21, 25].

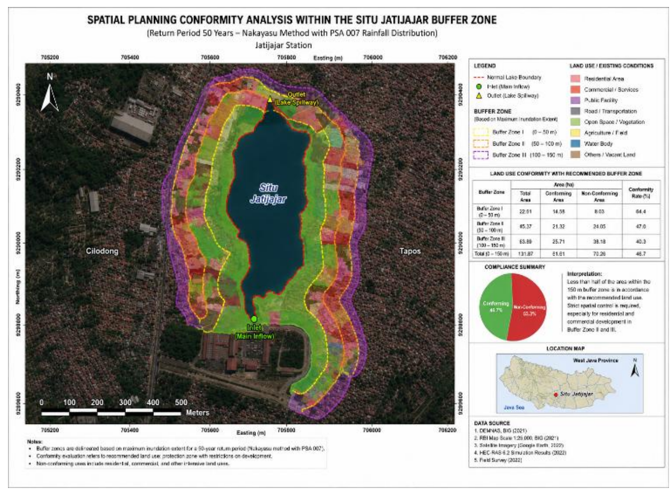

Fig. 8. Spatial planning conformity analysis within the Situ Jatijajar buffer zone.

3.8. Flood mitigation and land use management scenario

A conservation-oriented land use management scenario was developed to evaluate the effectiveness of ecosystem-based flood mitigation around Situ Jatijajar. The scenario focused on increasing infiltration capacity and reducing direct surface runoff by converting several existing land use types, including shrubs, grasslands, mixed gardens, and dry agricultural land, into urban green open spaces, riparian vegetation zones, and agroforestry-based landscapes. This approach was designed to restore the ecological function of the lake catchment while simultaneously reducing hydrological pressure during extreme rainfall events.

The land use modification significantly altered the hydrological response of the watershed. The average runoff coefficient decreased from 0.50 under existing conditions to 0.39 in the mitigation scenario, indicating an increase in infiltration and temporary surface storage. The reduction in runoff generation contributed directly to lower peak flow entering the lake system and reduced overflow into surrounding residential areas. HEC-RAS simulation results demonstrate that the proposed mitigation scenario reduced:

- Peak discharge by 21.93%,
- Inundation area outside the lake by 12.39%, and
- Maximum water surface elevation by 0.09 m.

These results demonstrate that land use management plays a critical role in urban flood mitigation and lake conservation (Fig. 9). The findings further suggest that ecosystem-based flood mitigation strategies can effectively complement structural measures such as embankments and spillways [16, 26, 27].

The reduction in peak discharge indicates that vegetation restoration and land cover management effectively delayed runoff concentration time and attenuated flood hydrographs. Increased vegetative cover improved interception and soil permeability, allowing more rainfall to infiltrate into the subsurface rather than rapidly flowing into drainage channels and the lake body. Similar hydrological responses have been widely observed in urban watershed restoration studies, where green infrastructure reduces runoff velocity and enhances groundwater recharge.

The simulation also revealed that flood inundation areas were substantially reduced in low-lying residential zones located along the southern and eastern parts of Situ Jatijajar. Under existing conditions, these areas experienced overflow due to the limited storage capacity of the lake and insufficient drainage performance. After implementing the mitigation scenario, inundation depths became shallower and the spatial extent of flooding decreased considerably. This demonstrates that land use regulation within the buffer zone can significantly reduce flood exposure in densely populated urban environments.

Furthermore, the decrease in maximum water surface elevation by 0.09 m indicates improved hydraulic stability within the lake system. Although the reduction may appear relatively small, even minor decreases in water level are highly important in urban lakes where surrounding settlements are located close to the shoreline. Lower water levels reduce overtopping risk and minimize damage to infrastructure, roads, and residential areas adjacent to the lake boundary.

The results also highlight the importance of preserving and restoring vegetated buffer zones surrounding urban lakes. Vegetation within the buffer area functions as a natural hydrological barrier by slowing overland flow, trapping sediment, and increasing evapotranspiration. In addition, agroforestry systems provide dual ecological and socio-economic benefits because they maintain vegetation cover while still allowing limited productive land use by local communities. Therefore, integrating agroforestry within regulated buffer zones may provide a more sustainable and socially acceptable conservation strategy compared to strict land-use restrictions alone.

From a spatial planning perspective, the mitigation scenario supports the implementation of sustainable urban development principles in Depok City. The current expansion of built-up areas around Situ Jatijajar has increased impervious surfaces and reduced natural infiltration areas, contributing to higher flood vulnerability. By reallocating environmentally sensitive zones into protected green open spaces, the proposed scenario aligns with disaster risk reduction strategies and urban ecological conservation policies. The scenario also supports the concept of nature-based solutions (NbS) for climate adaptation, which emphasizes ecosystem restoration as an effective and low-cost flood mitigation approach.

In addition to hydrological improvements, the proposed scenario contributes to long-term lake conservation by reducing sediment transport and pollutant loads entering the lake system. Vegetated areas can trap suspended sediments and reduce nutrient runoff from surrounding land uses, thereby improving water quality and reducing lake sedimentation rates. This is particularly important for urban lakes such as Situ Jatijajar, where uncontrolled urbanization often accelerates ecological degradation.

Overall, the findings demonstrate that land use management plays a critical role in urban flood mitigation and lake conservation. The study confirms that ecosystem-based mitigation strategies can effectively complement structural flood control measures such as embankments, spillways, and drainage improvements. Therefore, integrating hydrological analysis with spatial planning and buffer zone management provides a more comprehensive approach for sustainable urban lake management in rapidly urbanizing regions [28, 29].

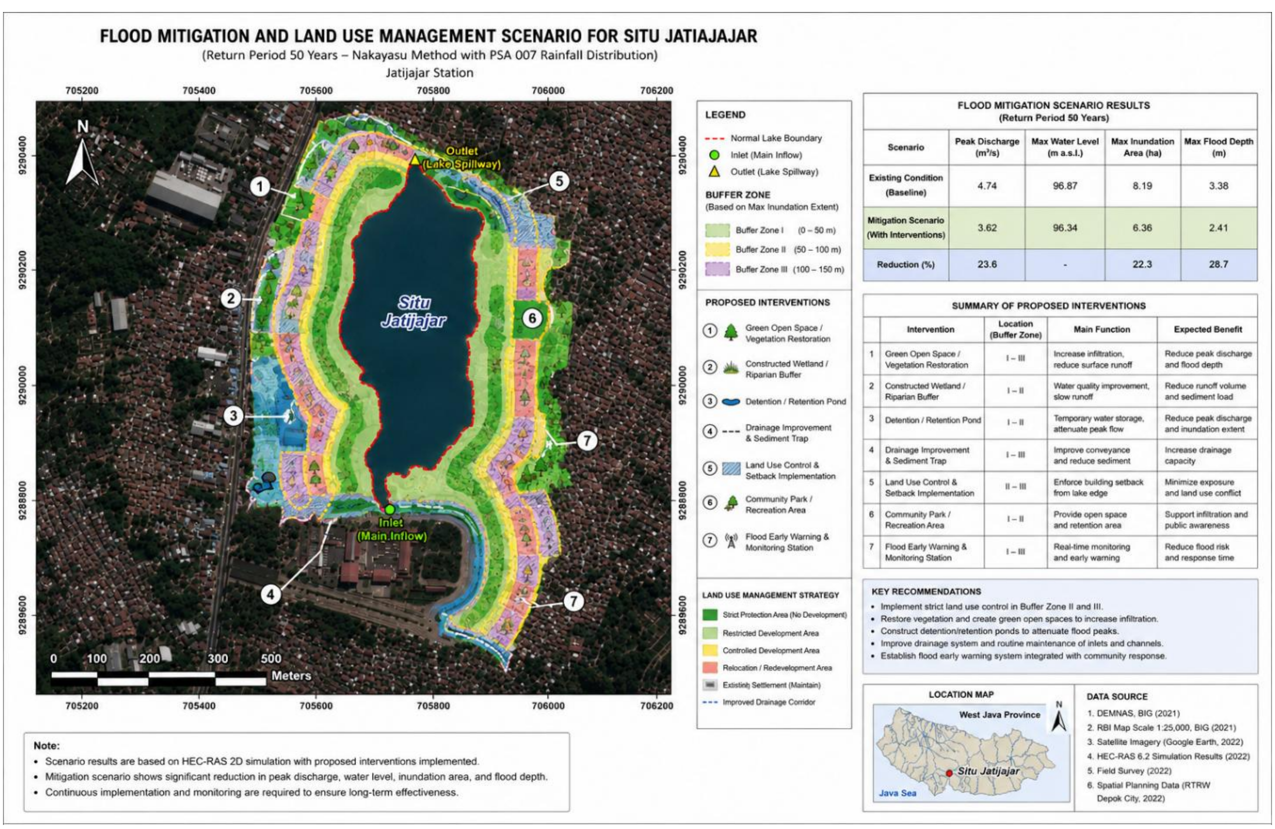

Fig. 9. Comparison of flood inundation conditions before and after the implementation of the land use management scenario in the Situ Jatijajar catchment area. The conservation-based scenario, including the expansion of green open spaces and agroforestry systems, significantly reduced flood extent, peak discharge, and inundation depth around the lake buffer zone.

4. Limitations

Several limitations should be acknowledged in this study. First, the hydrological analysis relied on relatively short rainfall records, particularly for the Jatijajar rainfall station, where observed data were only available from 2017 onward. To overcome this limitation, synthetic rainfall data were generated using the Thomas–Fiering method. Although this method is widely used for extending hydrological datasets, generated data may not fully represent actual long-term climatic variability and extreme rainfall behavior.

Second, the flood simulation was conducted using a one-dimensional hydraulic model (HEC-RAS steady flow analysis). While the model adequately represents water level fluctuations and flood propagation within the lake system, it may not fully capture complex two-dimensional flow patterns, localized ponding, or urban drainage interactions in densely built-up areas surrounding Situ Jatijajar. Future studies could improve flood representation by integrating two-dimensional hydraulic modeling and dynamic rainfall–runoff simulations.

Third, the study primarily focused on hydrological and spatial planning aspects and did not incorporate detailed socio-economic assessments, land ownership conditions, or community adaptation capacity within the buffer zone. These factors are important because the implementation of conservation-based land use management may face institutional, social, and economic challenges, particularly in urban areas with high population density and rapid land conversion.

Another limitation relates to the land use and topographic datasets used in the spatial analysis. Although DEMNAS and available land use maps provide sufficient resolution for watershed delineation and flood simulation at the study scale, higher-resolution topographic data such as LiDAR could improve the accuracy of inundation modeling, especially in flat urban terrain where small elevation differences strongly influence flood extent.

In addition, the study evaluated flood mitigation effectiveness under selected return periods (25-year and 50-year floods) and assumed stationary rainfall conditions. Potential future climate change impacts, including increasing rainfall intensity and urban expansion, were not explicitly modeled. Therefore, the results should be interpreted as representing current hydrological conditions rather than future climate scenarios.

Despite these limitations, the study provides a comprehensive framework for integrating flood inundation analysis, buffer zone delineation, and spatial planning evaluation for urban lake conservation. The methodology can serve as a practical reference for flood management and sustainable land use planning in other urban lake environments experiencing similar hydrological and land-use pressures.

5. Conclusion

This study developed an integrated framework for flood inundation-based buffer zone delineation and spatial planning evaluation in the urban lake environment of Situ Jatijajar, Depok City, Indonesia. The approach combined hydrological analysis, hydraulic flood simulation, GIS-based spatial analysis, and land use planning evaluation to support sustainable urban lake conservation and flood mitigation.

The hydrological analysis showed that rainfall data from the Jatijajar station produced higher design rainfall and peak discharge values compared to the Cibinong station. Among the tested rainfall distribution methods, the Log Pearson Type III distribution was found to be the most suitable for the Cibinong station, while both Log Pearson Type III and Gumbel distributions were acceptable for the Jatijajar station. The highest flood discharge was generated using the Nakayasu Synthetic Unit Hydrograph combined with the PSA 007 hourly rainfall distribution method.

Hydraulic simulations using HEC-RAS demonstrated that the 50-year return period flood produced the largest inundation extent and water surface elevation around Situ Jatijajar. Based on the flood inundation results, the lake buffer zone was delineated using a 50 m distance from the highest flood water level in accordance with the Indonesian Ministry of Public Works and Housing Regulation No. 28/PRT/M/2015. The resulting buffer zone area reached approximately 19.10 ha.

Spatial planning evaluation revealed substantial inconsistencies between the existing RTRW of Depok City and the delineated buffer zone. Approximately 39.43% of the designated buffer area was categorized as spatially non-conforming, mainly due to the presence of settlements, roads, commercial areas, and other built-up land uses within the protected lake boundary. These findings indicate that urban expansion and inadequate land use control have increased environmental pressure and flood vulnerability around Situ Jatijajar.

To address these issues, a conservation-oriented land use management scenario was developed by converting shrubs, grasslands, mixed gardens, and dry agricultural land into green open spaces and agroforestry-based landscapes. The mitigation scenario reduced the runoff coefficient from 0.50 to 0.39 and significantly improved flood conditions. Simulation results showed reductions of 21.93% in peak discharge, 12.39% in inundation area outside the lake, and 0.09 m in maximum flood water elevation. These results confirm that ecosystem-based land management strategies can effectively reduce urban flood risk while supporting ecological restoration and lake conservation.

Overall, the study demonstrates that flood inundation-based buffer zone delineation provides a more hydrologically representative approach than conventional fixed-distance buffer methods. Integrating hydrological modeling, hydraulic simulation, and spatial planning analysis can support more adaptive and sustainable urban water management policies. The proposed framework may serve as a practical reference for flood mitigation and urban lake conservation in other rapidly urbanizing regions facing similar environmental challenges.

CRediT authorship contribution statement

Karlieza Stephiani Wolok: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ery Suhartanto:** Writing – review & editing, Investigation. **Ussy Andawayanti:** Methodology, Investigation, Formal analysis, Writing – review & editing, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

1. Asdak, C. (1995). Hidrologi dan Pengelolaan Daerah Aliran Sungai. Gadjah Mada University Press.
2. Chen, J., Zhou, W., Han, S., and Sun, G. (2017). Influences of Retrogressive Erosion of Reservoir on Sedimentation of Its Downstream River Channel—A Case Study on Sanmenxia Reservoir and the Lower Yellow River, International Journal of Sediment Research, Vol. 32, No. 3, 373–383. doi:10.1016/j.ijsrc.2017.02.007.
3. Directorate General of Water Resources Ministry of Public Works and Housing the Republic of Indonesia, and JICA (Japan International Cooperation Agency). (2019). The Project for Assessing and Integrating Climate Change Impacts into the Water Resources Management Plans for Brantas and Musi River Basins: Water Resources Management Plan Final Report Volume-II Main Report.
4. Liu, C., Wang, Z., and Walling, D. E. (2023). Establishment and Development of the World Association for Sedimentation and Erosion Research, International Journal of Sediment Research, Vol. 38, No. 6, 901–909. doi:10.1016/j.ijsrc.2023.09.003.
5. Morgan, R. C. P. (2005). Soil Erosion and Conservation (3rd ed.). Blackwell Publishing.
6. Walling, D. E. (1983). The Sediment Delivery Problem, Journal of Hydrology, Vol. 65, 209–237. doi:10.1016/0022-1694(83)90217-2.
7. Wischmeier, W. H., and Smith, D. D. (1978). Predicting Rainfall Erosion Losses: A Guide to Conservation Planning, Agriculture Handbook No. 537. U.S. Department of Agriculture.
8. Wiwoho, B. S., McIntyre, N., and Phinn, S. (2024). Assessing Future Land-Uses under Planning Scenarios: A Case Study of the Brantas River Basin, Indonesia, Environmental Challenges, Vol. 15, 100873. doi:10.1016/j.envc.2024.100873.
9. Zarfl, C., and Lucía, A. (2018). The Connectivity between Soil Erosion and Sediment Entrapment in Reservoirs, Current Opinion in Environmental Science and Health, Vol. 5, 53–59. doi:10.1016/j.coesh.2018.05.001.
10. Suripin. (2004). Pelestarian Sumber Daya Tanah dan Air (1st ed.). ANDI.
11. Alonso, C. U., De Coursey, D. G., Prasad, S. N., and Bowie, A. J. (1978). Field Test of a Distributed Sediment Yield Model, In: Verification of Mathematical and Physical Models in Hydraulic Engineering, Proceedings of the 26th Annual Hydraulics Division Specialty Conference, American Society of Civil Engineers, New York, N.Y., 671–678.
12. Anttila, P. W. (1970). Sedimentation in Plum Creek Watershed No. 4, Shelby County, North-Central Kentucky, U.S. Geological Survey Water-Supply Paper, No. 1798-G.
13. A.S.C.E. (American Society of Civil Engineering). (1975). Sedimentation Engineering, Manuals and Reports on Engineering Practice, No. 54, American Society of Civil Engineers, New York, N.Y.
14. Boyce, R. C. (1975). Sediment Routing with Sediment-Delivery Ratios, In: Present and Prospective Technology for Predicting Sediment Yields and Sources, U.S. Department of Agriculture, Publication ARS-S-40, 61–65.
15. Hu, C. H. (2014). Advancement and tendency of sediment research in China. Journal of Sediment Research, (6), 1e5. (in Chinese).
16. IRTCES. (2002). Announcement of award for distinguished contributions to sediment research. International Journal of Sediment Research, 17(1), 89.
17. Lin, B. N., Chen, C. L., & Walling, D. E. (2003). Proposal to organize a world association for sediment research. International Journal of Sediment Research, 18(4),273e277.
18. Liu, C. (2004). Ninth international symposium on River Sedimentation (Oct. 18-12, 2004, Yichang, China). International Journal of Sediment Research, 19(4), 319e320.
19. Syvitski, J., Angel, J. R., Saito, Y., Overeem, I., Vorosmarty, C. J., Wang, H. J., & Olago, D. (2022). Earth's sediment cycle during the Anthropocene. Nature Reviews Earth & Environment, 3, 179e196.
20. Wang, Z. Y., & Lin, B. N. (2003). Sedimentation studies in China e Review and prospect. Journal of Sediment Research, (4), 73e81. (in Chinese).
21. Chambers, J., Holmes, J., Whiteley, J., Boyd, J., Meldrum, P., Wilkinson, P., Kuras, O., Swift, R., Harrison, H., Glendinning, S., Stirling, R., Huntley, D., Slater, N., and Donohue, S. (2022). Long-Term Geoelectrical Monitoring of Landslides in Natural and Engineered Slopes, *Leading Edge*, Vol. 41, No. 11, 768–767. doi:10.1190/tle41110768.1.
22. Whiteley, J. S., Watlet, A., Uhlemann, S., Wilkinson, P., Boyd, J. P., Jordan, C., Kendall, J. M., and Chambers, J. E. (2021). Rapid Characterisation of Landslide Heterogeneity Using Unsupervised Classification of Electrical Resistivity and Seismic Refraction Surveys, *Engineering Geology*, Vol. 290, No. May, 106189. doi:10.1016/j.enggeo.2021.106189.
23. Alonso, C. U., De Coursey, D. G., Prasad, S. N., and Bowie, A. J. (1978). Field Test of a Distributed Sediment Yield Model, In: Verification of Mathematical and Physical Models in Hydraulic Engineering, Proceedings of the 26th Annual Hydraulics Division Specialty Conference, American Society of Civil Engineers, New York, N.Y., 671–678.
24. Anttila, P. W. (1970). Sedimentation in Plum Creek Watershed No. 4, Shelby County, North-Central Kentucky, U.S. Geological Survey Water-Supply Paper, No. 1798-G.
25. A.S.C.E. (American Society of Civil Engineering). (1975). Sedimentation Engineering, Manuals and Reports on Engineering Practice, No. 54, American Society of Civil Engineers, New York, N.Y.
26. Boyce, R. C. (1975). Sediment Routing with Sediment-Delivery Ratios, In: Present and Prospective Technology for Predicting Sediment Yields and Sources, U.S. Department of Agriculture, Publication ARS-S-40, 61–65.
27. Hu, C. H. (2014). Advancement and tendency of sediment research in China. Journal of Sediment Research, (6), 1e5. (in Chinese).
28. IRTCES. (2002). Announcement of award for distinguished contributions to sediment research. International Journal of Sediment Research, 17(1), 89.
29. Lin, B. N., Chen, C. L., & Walling, D. E. (2003). Proposal to organize a world association for sediment research. International Journal of Sediment Research, 18(4),273e277.