Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 05, May, 2025

An Assessment of Nature-Based Solutions Water Infrastructure for Flood Risk Reduction in Unplanned Area

Maman Supratman [1, 2*], Muhammad S. Badri Kusuma [1, 3], Muhammad Cahyono [4, 5], Arno Adi Kuntoro [3]

[1] *Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Jl. Ganesa No. 10, Bandung 40132, Indonesia.*

[2] *Flood Control and Drainage division of Water Resources Agency of Jakarta City, Jakarta 10150, Indonesia.*

[3] *Water Resources Development Center, Institut Teknologi Bandung, Jl. Ganesha No. 10, Bandung 40132, Indonesia.*

[4] *Civil Engineering Department, Faculty of Engineering and Sciences, Ibnu Khaldun Bogor University, Kota Bogor 16162, Indonesia.*

[5] *Center for Ecohydrology, Ecohydraulics and Engineering Science, Jl. Babakan Jeruk 1 No. 100, Bandung 40132, Indonesia.*

Received 10 January 2025; Revised 10 February 2025; Accepted 19 March 2025; Published 01 May 2025

Abstract

This study aimed to investigate the effectiveness of the Brigif Reservoir as a pioneering nature-based infrastructure solution for mitigating flood risk in the Kemang area, a significant business district in South Jakarta, and to provide a potential raw water supply for city parks. We employed coupled HEC-HMS and HEC-RAS 1D2D unsteady flow models to analyze rainfall-runoff and flood regimes before and after basin intervention in a rainfall scenario from January 2020. The flood model demonstrated highly satisfactory performance on the calibration results, as evidenced by an NSE value of 0.93 on a scale of 0 to 1. Flood risk was defined using the flood hazard, vulnerability, and capacity indices, and ArcGIS and QGIS were used to prepare and visualize the output after the model performance was qualified. The study revealed that the Brigif Reservoir could reduce the peak discharge of the January 2020 flood in the Kemang area by 19% while decreasing the risk of high-level flooding by 12%. The Brigif Reservoir, as a Nature-Based Solution (NBS) infrastructure, retains approximately 250,000 m^3 of flood discharge, which can be utilized by the local government for watering gardens and as potential raw water for residents because it meets the national surface water quality standards in dry conditions and requires additional treatment during the wet season. The potential for groundwater recharge was estimated to be approximately 250 m^3 and 6000 m^3 for one hour and one day, respectively. For future studies, it is recommended to develop non-structural actions, such as a flood early warning system incorporating machine learning that could potentially support the operational performance of the NBS infrastructure. This study proposes the implementation of a series of sustainable infrastructure solutions, including rooftop storage, underground storage, and underground retention systems, at the building scale within each sub-catchment to mitigate flood risk levels in the Kemang region from high to acceptable levels. The findings of this research will be of significant value to the Water Resources Agency in evaluating the potential application of NBS infrastructure for flood mitigation and adaptation strategies and programs in response to the impacts of global climate change.

Keywords: Brigif Reservoir; Green; Blue and Grey Infrastructures; HEC-HMS Model; HEC-RAS Model; Kemang Region.

1. Introduction

Floods are among the most dangerous disasters in Jakarta. In January 2020, approximately 30,000 urban residents were affected by natural catastrophes, necessitating temporary shelter evacuations. Floods have caused fatalities and physical and economic damage and hindered Jakarta's economic development [1]. Global research has indicated an

* Corresponding author: 35021014@mahasiswa.itb.ac.id; ms120485@gmail.com

http://dx.doi.org/10.28991/CEJ-2025-011-05-07

increasing trend in flood-related hazards, including riverine overflow, urban water inundation, fluvial erosion along watercourses, and high sedimentation rates in rivers, which are all attributed to ongoing climate change [2, 3]. Most of Jakarta's population continues to rely on groundwater for clean water because the current clean water delivery infrastructure is insufficient. This causes land subsidence, which increases the risk of flooding [4-6]. Human activities have intensified flood hazards by altering land-use patterns, modifying terrain levels, urbanizing, and encroaching on floodplains [7]. These anthropogenic influences collectively exacerbate the severity of flood hazards in affected areas [8, 9]. Flood events have shown that these types of flooding occur simultaneously, resulting in devastating floods in Jakarta. The current Jakarta flood phenomenon demonstrates that flood discharge and surface runoff are expeditiously directed towards rivers and the sea. Consequently, during periods of low precipitation or reduced river water levels, Jakarta's population experiences insufficient raw water availability and continues to extract groundwater indiscriminately, resulting in land subsidence [10].

Research on flood mitigation in Jakarta has explored multiple strategies to minimize the flood risk. These efforts have included structural interventions such as river normalization, implementing reservoirs and underground storage systems, and establishing infiltration wells and basins [11]. However, these initiatives failed to effectively reduce flood risks owing to inadequate planning and a lack of standardized design criteria. According to Sengara, the magnitude of earthquakes in Indonesia in the future will tend to increase; therefore, the possibility of dam breaks will also increase. Kusuma concluded that, in general, the quality of reservoir water in Indonesia tends to decline. Therefore, the possibility of flooding hazards generated by dam breaks will also increase owing to both inundation and pollution [12, 13]. Currently, the development of early flood warning systems is becoming an appropriate temporary solution to reduce the potential risk of this problem. Many previous studies have discussed this problem, and the current study demonstrated the successful development of an early warning model utilizing the Long-Short Term Memory (LSTM) neural network, which is capable of detecting heavy precipitation events two and four hours prior to their occurrence [14].

The findings of this investigation have potential applications as inputs to support NBS design criteria and improve understanding, planning, and work operations in future implementation [15]. Subsequently, by regulating sluice gates [16], building reservoirs and dams [13, 17], increasing drainage pump capacity [18], rainwater harvesting systems [19], enhancing river capacity, and early warning systems [20]. Several previous studies have found that existing flood mitigation methods (grey solutions) are ineffective in reducing the risk of flooding [11]. In a previous study, NBS retention ponds could reduce peak discharge by around 23% under climate change scenarios [21]. This is because the impact of the flood-generating processes was not considered in the design parameters used. Similarly, choosing reservoirs is becoming more challenging owing to the rising risk of floods caused by dam failures as well as the collateral hazard of earthquakes [12]. To date, using Nature-Based Solutions (NBS) at various scales has been a viable approach for reducing flooding issues. Consequently, implementing rainwater storage as an NBS for flood risk management is the most appropriate strategy for the sustainability of Jakarta. This strategy efficiently reduced the risk of flooding in various regions [22]. However, there is no evidence of such infrastructure in Jakarta or other Indonesian cities.

At present, numerous global studies are focusing on the implementation of infrastructure Nature-Based Solutions (NBS) for urban flood risk management. NBS requires integration with urban planning and utilization as a policy instrument to adapt to climate change; however, a policy gap persists [23]. Additionally, cities require a framework for monitoring and evaluating the effectiveness of NBS [24]. Densely populated urban areas have an urgent need for more natural retention basin-type NBS that can retain and reduce surface runoff, which should be integrated into sustainable flood risk management strategies [25]. Concurrently, NBS exhibits the potential to increase water availability during dry seasons, thereby enhancing water supply to meet demand [26]. Urban centers require an NBS framework that incorporates aspects of capacity, connectivity, and biodiversity for urban flood resilience, which can be validated through the implementation of physical infrastructure [27]. NBS must be integrated with grey infrastructure and other components and included in spatial planning to minimize flood vulnerability [28]. Furthermore, NBS demonstrates efficacy in mitigating urban heat waves and flooding resulting from climate change and urban development [29]. The integration of NBS with grey infrastructure demonstrates optimal outcomes in peak flow runoff reduction and flood mitigation; however, this necessitates validation through empirical case studies to enhance comprehension [30]. Modeling the effectiveness of watershed-scale infrastructure NBS implementation remains insufficient and necessitates additional experimental case studies to provide a more comprehensive understanding within the context of flood management [31].

Based on the literature study above, this study will fill the gap related to the effectiveness of NBS (Brigif reservoir) in urban flood risk reduction and other additional benefits by using hydrological, hydraulic, and scoring model approaches and weighted overlay with spatial visualization. The Brigif Reservoir is a hybrid infrastructure, integrating NBS and grey solutions, and is the first pilot project in Jakarta city. However, this is a sample of unplanned water infrastructure development in Jakarta, which is not clearly stated in either the strategic planning program of the Water Resources Agency or the regional medium-term development plan for the 2017-2022 report documents [32]. Moreover, the plan is subject to change every five years or when a new governor is elected. There are 15 locations, and it was clear that there is no plan for Brigif reservoir construction, as shown in Figure 1.

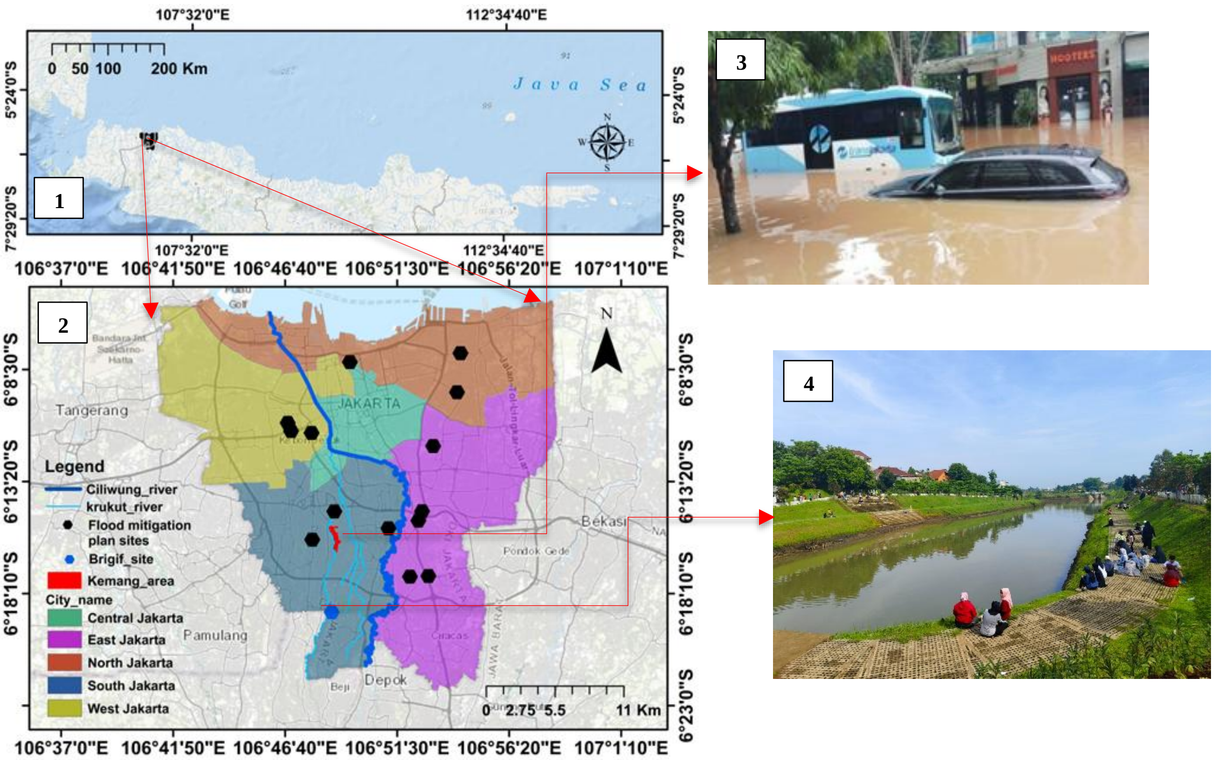


Figure 1. Regional infrastructure development plan for 2017 to 2022 of Jakarta overlayed with Brigif reservoir and Kemang area site (1 and 2), Flood event record in Kemang in January 2020 (3) and Brigif reservoir view (4)

The city applied NBS through a multipurpose retention basin linked to the Krukut River to reduce flood risk in the Kemang region. The term NBS itself is defined as “actions to protect, conserve, restore, sustainably use, and manage natural or modified terrestrial, freshwater, coastal, and marine ecosystems, which address social, economic, and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience, and biodiversity benefits” [33]. Hybrid solutions are considered the best for reducing flood hazards in urban areas [11]. It is also a part of the local and central government, the Ministry of Planning’s roadmap 2023-2030 to achieve sustainable development goals, sustainable cities and communities (11), and climate action (13) through the utilization of water storage, groundwater resources, and peak flood reduction.

Many studies have indicated that NBS-retarding basins may reduce urban flood threats [34, 35], enhance infiltration [35], increase the groundwater budget, and improve water quality. Reservoir storage is essential and can be used as an alternative water supply to meet environmental needs and sustainable water resource management [36-38]. Additionally, they contribute to socioeconomic and human well-being by providing public spaces for human activities [39-48]. A constructed wetland can reduce flood volume by an average of ~ 59% [49] and is considered an essential infrastructure owing to its co-benefits [50]. However, there remains a lack of knowledge and evidence regarding its performance on a city or regional scale in Jakarta, Indonesia. Retarded basins have also been noted to improve urban landscapes and human well-being [51, 52]. It has also been advocated for minimizing climate change effects in the form of sustainable urban water resource management, water availability, and addressing drought challenges [53-58]. Moreover, NBS has been advocated as an adaptive infrastructure that effectively reduces urban flood hazard indices [59-66].

The Kemang area is in Bangka Urban Village, whereas the Brigif retarding basin is in Cipedak Urban Village, Jagakarsa, South Jakarta. Previous research indicated that the areas around Brigif have inadequate potential for groundwater recharge. Several previous flood studies have been conducted in the Kemang area, but none have addressed NBS as an optional solution. Therefore, this study discusses the effectiveness of NBS for flood risk reduction in the Kemang area. The Kemang area is a built-up urban area where land availability is a problem in providing space for NBS, such as the Brigif Reservoir. Therefore, in addition to exploring the Brigif, this study also explored the potential for storage in commercial buildings and vacant land along the Krukut River to support the sustainability of the city and its water resources.

Flooding in the area is primarily attributed to the overflow of the Krukut River, caused by its limited capacity and extreme precipitation events. The implementation of gray infrastructure solutions, such as the normalization of the Krukut River, has been impeded by rapid urban expansion and high population density. Owing to the accelerated rate of erosion, the Kemang Stretch of the Krukut River has exhibited significant sedimentation and reduced depth. Rainfall intensity, topography, slope, and land-use alterations are identified as the principal factors contributing to flooding in

Jakarta [67, 68]. In January 2020, it was reported that precipitation events lasting more than 24 h with intensities exceeding the 100-year return period posed a substantial flood risk to the Kemang region. The flood depth in this area ranges from approximately 0.30 m to over 1.50 m, resulting in an economic loss of 960 billion rupiah. Flooding frequently because of high discharge from the upstream area, which subsequently overflows into the Kemang region. The Brigif Reservoir, which functions as an NBS infrastructure, is hydrologically connected to the Kemang Region. However, the extent of its contribution in mitigating urban flood volumes and enhancing river water quality remains unclear. Kemang's location within a basin renders it particularly susceptible to flooding owing to its high discharge from upstream rivers. Local authorities have asserted that the Brigif Reservoir could reduce flood hazards in the Kemang region. Therefore, this study is crucial for assessing its contribution to flood risk, identifying relevant and effective mitigation strategies, and evaluating the potential of the reservoir as an alternative source for raw water and groundwater recharge.

The primary objective of this study was to assess the contribution of NBS to flood risk mitigation through hydrodynamic modelling of river floods before and after construction of the Brigif Reservoir in the Kemang region. The secondary objective was to analyze the potential water quality improvement in the Brigif Reservoir storage and the potential for groundwater recharge. This study aimed to provide a more comprehensive evaluation of flood risk, particularly that resulting from upstream water release before and after mitigation measures. This study employs a case study methodology at the metropolitan scale and incorporates an NBS infrastructure to achieve this objective. Investigating the impact of NBS Brigif Reservoirs on mitigating flood hazards in the Kemang area is crucial, as site preparation is complex, time-consuming, resource-intensive, and carries potential risks, such as dam failure. This study also serves as a foundation for the implementation of NBS. Jakarta has developed numerous green infrastructures, including reservoirs, infiltration wells, and basins, without established design standards. Consequently, this NBS infrastructure warrants investigation as it will potentially serve as a standard for flood infrastructure mitigation in Jakarta for future development. Therefore, this study functions as a reference or model for decision-makers in the Jakarta government and other Indonesian cities interested in developing NBS-based reservoirs and other infrastructure for flood mitigation.

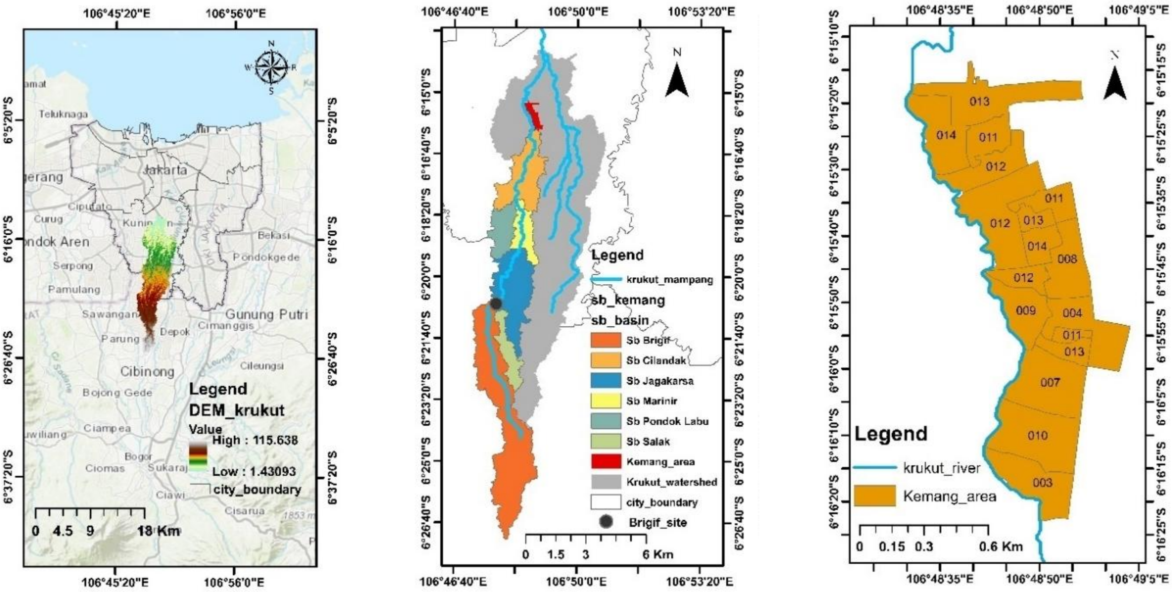
2. Study Area, Material and Methods

2.1. Study Area Description

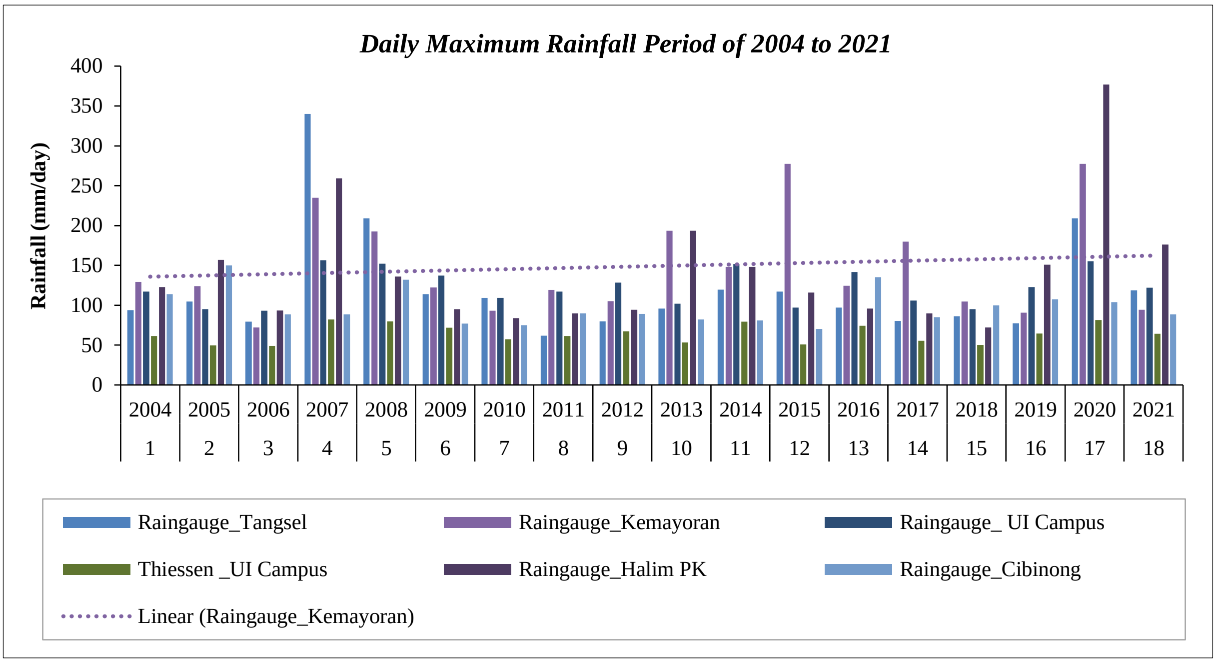
Kemang, a business district in South Jakarta, is at high risk of floods. The high risk of flooding is primarily caused by fluvial [69, 70] and pluvial floods. It is located in the lower part of the Krukut Watershed. The Krukut River drains into the West Canal Flood/Ciliwung and flows directly into the Java Sea. The Kemang region comprises a basin with an elevation lower than the surface of the Krukut River, whereas Brigif Reservoir is located at higher altitudes. The study area has a population density of approximately 18,000 individuals per square kilometer. Located in southern Jakarta, Kemang has experienced floods in previous years. It is situated within the Krukut watershed system. Hydrologically, the Kemang area constitutes a part of the downstream section of the Krukut watershed, which flows directly into the western flood channel via gravity. Its catchment area encompasses approximately 35.22 km² and is subjected to compound flooding [5], as shown in Figure 2-a and b. The downstream area of the Bendungan Hilir Village on this river has been identified as having a high flood hazard index. The river, 32 km in length, has a watershed with a catchment area of approximately 90 km². The drainage capacity was inadequate, resulting in a rainfall return period of less than two years at approximately 138 mm/d. Furthermore, the bank-full Krukut River capacity in this segment is approximately 60 m³/s, which is below the ideal design of 135 m³/s or equivalent to twenty-five years of flood discharge design (Q25). This area is situated in the downstream region of the Krukut Watershed, where the surface elevation is lower than that of the river's top embankment. Consequently, a drainage pump is necessary to regulate the volume of surface runoff over the catchment area, whereas the river surface elevation increases during heavy precipitation. Stormwater management and infrastructure in this area comprise water gates, reservoirs, and drainage pumps situated along the Krukut River.

Based on recorded rainfall data as shown in Figure 2-d, Jakarta experienced an extreme rainfall phenomenon in January 2020 where the highest rainfall reached 377 mm/day in early January 2020. This event caused flooding in several areas of DKI Jakarta, including the Kemang area in South Jakarta. This event is evidence of the impact of global climate change on the tropics.

The Brigif Reservoir, constructed in 2022, is situated in Jagakarsa, in the southern Kemang region. This reservoir was engineered using NBS elements such as natural reservoirs, city landscapes, water gates, and spillways as gray infrastructures that function not only as barriers during peak flood discharge but also possess the capacity to supply raw water, increase infiltration and groundwater budget, improve water quality, and deliver public recreation. Additionally, it mitigates the risk of structural failure due to the lateral flow seismic velocity shear stress [12, 17]. This represents the inaugural NBS infrastructure models for Jakarta and Indonesia, encompassing approximately 10 ha and 17.35 km² of the catchment area, respectively. The natural reservoir is compartmentalized into two distinct sections, the upper and lower segments, with the water surface elevation in these parts regulated by the spillway and water gates at the outlet, as shown in Figure 3. The inlet of the upper segment serves as the Salak drainage catchment area, whereas the lower part of the inflow encompasses the Krukut River itself.



(a) (b) (d)



(d)

Figure 2. The DEM of Krukut watershed (a), Sub-catchment of Kemang area (b), and the Kemang region in Neighborhood Associations identifier (NA) (c), and Rainfall maximum per year and location (d)

2.2. Materials

This study utilized diverse data types from multiple sources, including hydrological, hydraulic, social, economic, physical, and environmental. Data were obtained through direct collection and online retrieval from various governmental agencies, including the DKI Jakarta Water Resources Agency; the Jakarta Spatial Planning Agency; the DKI Jakarta Regional Disaster Management Agency; the Geospatial Information Agency; the Meteorology, Climatology, and Geophysics Agency; and the DKI Jakarta Central Bureau of Statistics. Table 1 presents a recapitulation of the data employed in analyzing the contribution of NBS as a flood risk reduction measure and its additional benefits.

Table 1. Summary of data used in the analysis of NBS for flood risk reduction

Data name	Data type	Data category	Data sources
Daily Rainfall data series (2004-2021)	Tabular	Point data	The Agency for Meteorology, Climatology and Geophysics, Water Resources Agency of Jakarta
Topographic	Digital Elevation Model (DEMNAS)	Raster (8 m × 8 m)	Geo-spatial information Agency of Indonesia
Land use and building map	Spatial data	Polygon and raster (Landsat OLI with grid 30 m × 30 m)	Spatial planning and land management Agency of Jakarta and https://earthexplorer.usgs.gov/
Curve number (CN)	Spatial	Polygon and raster (250 m × 250 m)	Water resources agency of Jakarta and Global Hydrological Soil Group at https://daac.ornl.gov/SOILS/guides/Global_Hydrologic_Soil_Group.html
Inundation map	Spatial and point data	Polygon	Water resources agency of Jakarta
Drainage and river capacity and geometry (LiDAR)	Tabular and Spatial data	Line and polygon and raster (0.25 m × 0.25 m)	Geo-spatial information Agency and Water resources agency of Jakarta
Krukut river discharge	Tabular data	number	Water resources agency of Jakarta
Infiltration rate, geological formation, soil property and groundwater table	Tabular and spatial data	Point and polygon	Water resources agency of Jakarta and Ministry of Energy and Mineral Resources
Inundation map	Spatial and point data	Polygon	Water resources agency and Regional Board for Disaster Management
Total Population, Population density, livelihood, and sex ratio	Tabular data	Number and polygon	Statistics center Agency
Water quality of Inlet and storage of Brigif reservoir	Tabular data	Number	Direct data collection by the author

This investigation utilized hydrological data spanning 18 years (2004-2021), comprising daily rainfall records collected from five rain gauges across Jakarta that were incorporated into Krukut's watershed. Prior to the frequency and distribution analyses, the rainfall dataset underwent a consistency check using a double-mass curve to ensure data quality [71]. It is essential to verify the data quality to generate a robust model. Thiessen polygons were generated based on collected data. The National Digital Elevation Model (DEMNAS), characterized by its high resolution, served as a foundation for generating spatial analysis tools in ArcGIS for the Krukut Watershed. Subsequently, the LiDAR data, along with the floodplain zone and river geometry, were delineated and incorporated into the hydraulic 1D and 2D models of the HEC-RAS.

Inundation data for 2020 were incorporated into this study and delineated based on Kemang's neighborhood associations (NAs). These data were utilized to validate and calibrate the hydraulic model by comparing several flood depth events in the simulated and field-observed data. The infiltration rate and geological data were in the form of maps collected in 2019 before the Brigif Reservoir was constructed. Soil parameters were derived from drilling measurements, and groundwater table data were gathered from monitoring wells between 2020 and 2023. These data were used to estimate the groundwater recharge potential of Brigif Reservoir.

As shown in Figure 3, Brigif Reservoir covers approximately 10 ha, with an upper area of 3.3 ha and a lower area of approximately 6.7 ha. The inflow of the upper storage comes from the Salak Drainage set with free flow, and its outflow to the lower Brigif is through the spillway and sluice gate. The inflow of the Lower Brigif originates from the Krukut River and flows back to Krukut through the sluice gate. The average depth of the upper Brigif is 5 m, whereas that of the lower Brigif is 4 m. The volumes in the upper bridge for the normal water level were estimated to be approximately 84.678 m^3 and ~143.245 m^3, whereas the depths in the bank's full capacity were 9 m and 7 m, and the volumes were estimated to be ~209.330 m^3 and 332.866 m^3, respectively.

Jakarta's land use and land cover (LULC) and the watershed system were generated using a series of satellite images from 2013 to 2023. We used satellite images because of the lack of integrated geospatial data among the local government authorities. The Krukut watershed is classified into four classes, and it is dominated by urban areas with a percentage of more than 70%, followed by vegetation with approximately 20%, bare land with approximately 8%, and water bodies with approximately 1%, as shown in Figure 4-a. The Kemang catchment area has a low spatial infiltration rate of approximately 10-50 mm/hour. These conditions are related to geological formations that can be divided into two classes: alluvial fans and inland areas. Based on the borehole logs and monitoring well data, the area predominantly consists of silty clay, sandy clay, siltstone, silty sand, and gravelly sand, as illustrated in Figure 4-f. Subsequently, the depth of the groundwater table in the Brigif Reservoir area ranged from 2 to 4 m, as illustrated in Figure 4-e. We used topography, lithology, and rainfall data because they are the most influential factors in flood events [72].

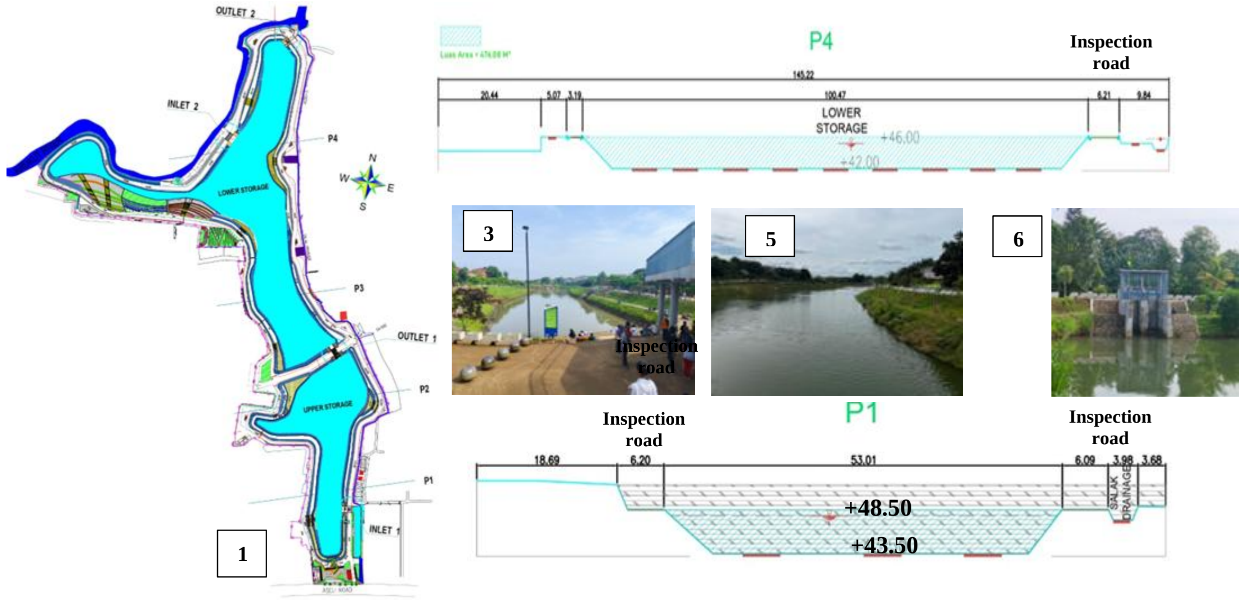
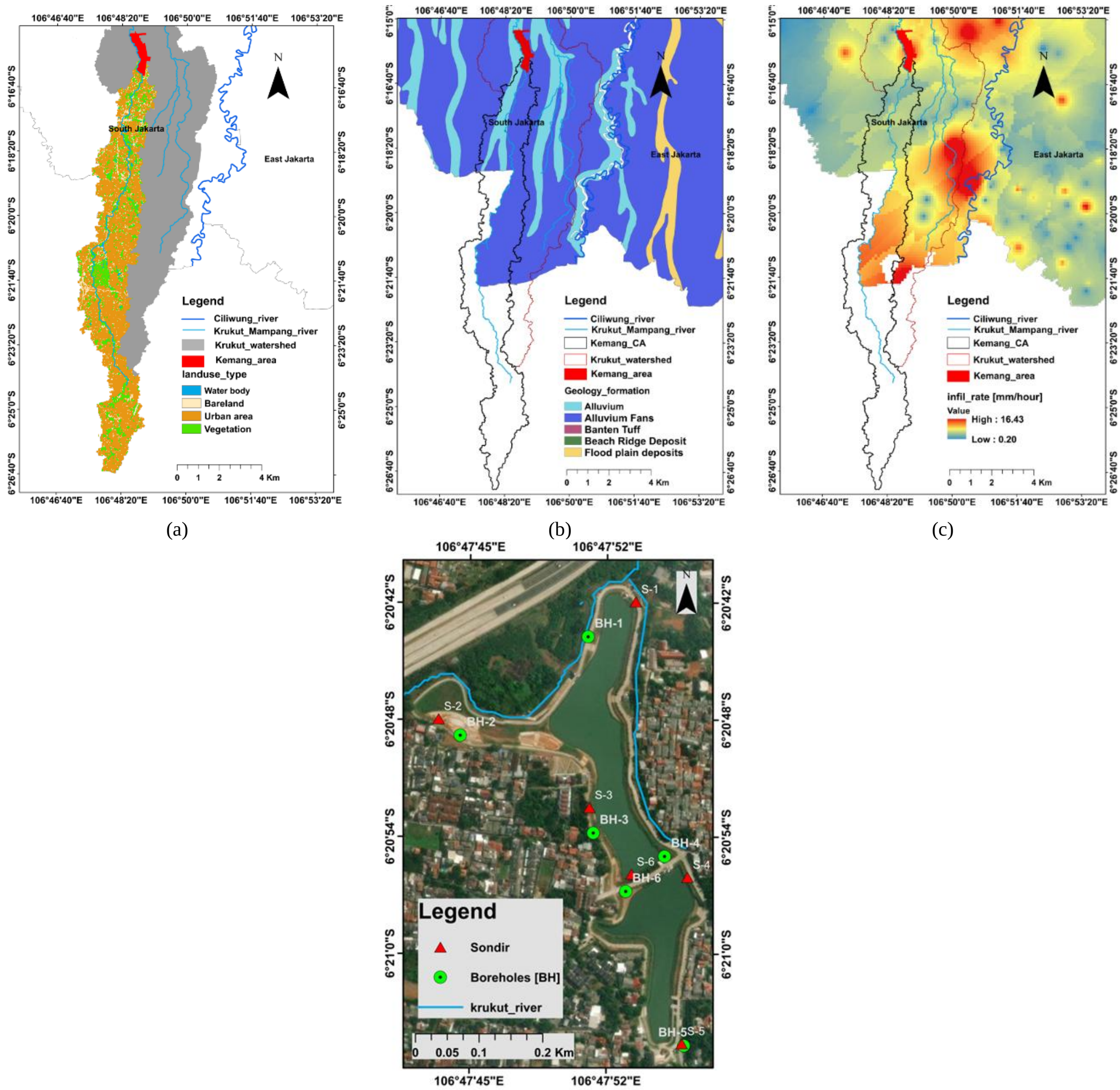
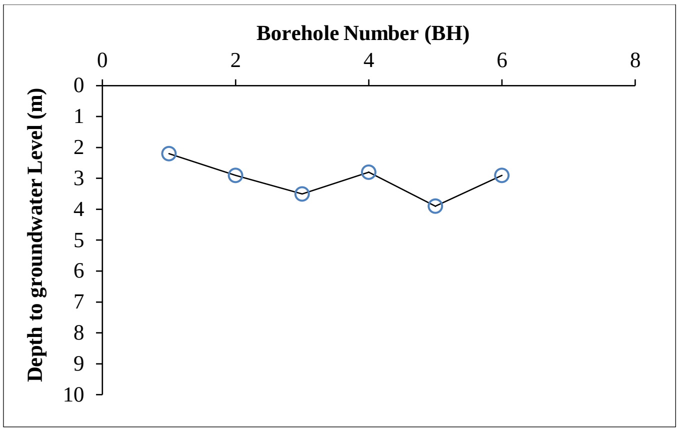


Figure 3. Layout of Brigif reservoir site (1), cross-section of Brigif upper storage (2), site view of Brigif upper storage (3) cross-section of Brigif lower storage (4) Site view of lower Brigif (5) and water gates of outlet Brigif reservoir (6)

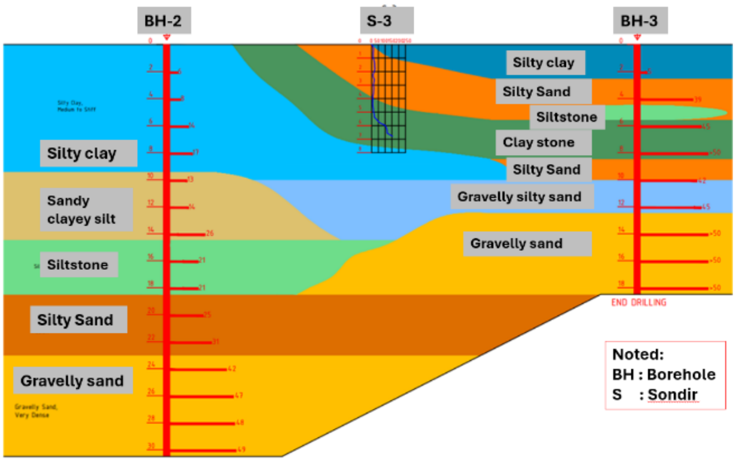


(a) (b) (c)

(d)



(d)



(f)

Figure 4. Land use of Kemang region (a), Geology formation map of Kemang region (b), infiltration rate map of Kemang region (c), Boreholes and Cone Penetration Test site sample (d), borehole site and water table (e), and lithology map of boreholes 2 and 3 (f).

2.3. Methods

DEMNAS data were processed using spatial hydrology tools in ArcGIS to generate the Krukut watershed boundary and drainage network [73, 74]. The sub-catchment boundary and stream network were established using GIS features from the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). The stream network extracted from the DEM was validated using drainage network data from Google Maps and field data. The sub-catchments of the Kemang region were then extracted using GIS features in HEC-HMS software. Landsat OLI 8 2020 and 2023 data were extracted for the land use and land cover of the Krukut Watershed using supervised classification with maximum likelihood approaches in ArcGIS before and after the construction of the Brigif Reservoir. It was classified into four classes: water body, vegetation, urban area, bare land, and impervious area percentage for ten years. It has been proven to be accurate for Land Use and Land Cover (LULC) classification [75]. These data were then combined with the bore log and the area's global Hydrological Soil Group (HSG) data, which were gathered from online resources, as well as bore log data to determine the Curve Number (CN) value along the Kemang catchment area. This number was used for hydrological analysis in the HEC-HMS model. A schematic representation of the research framework used in the analysis is shown in Figure 5.

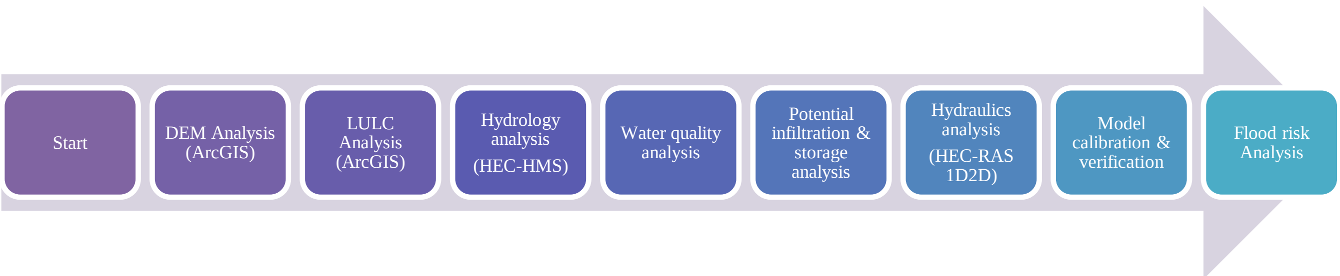


Figure 5. Research framework of assessment NBS for flood risk reduction of Kemang region

The rainfall distribution and frequency analysis were calculated for a rainfall return period of 25 years and a single event on 1 January 2020 for calibration and validation purposes. The flood discharge design for 25 years (Q25) was determined using the SCS-CN method. HEC-HMS version 4.11, HEC-RAS 6.3.1 1D and 2D were employed to analyze the hydrodynamics and assess the flood hazard indices in Krukut's watershed. The efficacy of HEC-HMS and HEC-RAS in watershed rainfall-runoff analysis and the determination of flood characteristics has been consistently demonstrated in numerous studies [34, 76–81]. HEC-HMS was used to analyze the storage capacity of the Brigif Reservoir, surface runoff, and flood discharge in the Krukut River. The losses were computed in the HEC-HMS by employing the Soil Conservation Service (SCS) Curve Number (CN) approach. The data were transformed using the SCS unit hydrograph method, assuming the absence of baseflow. The Brigif Reservoir was assumed to be entirely devoid of water at the commencement of the precipitation event. Flood discharge was used as the lateral inflow for the HEC-RAS 1D to define the maximum flood depth and flood discharge reduction in the Kemang area. Subsequently, it will be calibrated with real inundation depth data using the Nash-Sutcliffe Efficiency (NSE) coefficient for several events from 2020 to 2022. If the model meets the minimum error, it will continue to generate a 2D model to observe the area of inundation and continue the hazard, vulnerability, capacity, and flood risk analysis. Flood risk was defined by the following formula:

For the hydraulic model simulation:

$$Flood\ risk = \frac{Hazard \times Vulnerability}{Capacity} \tag{1}$$

Flood risk is defined as the hazard multiple of vulnerability divided by capacity. This was adopted by the National Disaster Risk Mitigation Policy of Indonesia (BNPB) and the Ministry of Public Works (PUPR). The calculation is based on scoring and weighted overlay. The hazard indices extracted from the hydraulic model and their criteria are listed in Table 2.

Table 2. Hazard indices criterion, adopted from National Disaster Policy

Inundation depth				
Depth (cm)	**Class**	**Rate**	**Weight (%)**	**Score**
<76	Low	1		0.4
76–150	Moderate	2	40	0,8
>150	High	3		1.2
Duration of inundation				
Duration (hour)	**Class**	**Rate**	**Weight (%)**	**Score**
< 12	Low	1		0.2
12–24	Moderate	2	20	0.4
> 24	High	3		0.6
Inundation area				
Area (m^2)	**Class**	**Rate**	**Weight (%)**	**Score**
< 100	Low	1		0.2
100–300	Moderate	2	20	0.4
>300	High	3		0.6
Inundation frequency				
The number of events	**Class**	**Rate**	**Weight (%)**	**Score**
0–5	Low	1		0.2
6–20	Moderate	2	20	0.4
> 20	High	3		0.6

Based on the Table 3, the Hazard Index (HI) is calculated as follows:

HI = 0.4 x score of flood depth + 0.2 x score of flood duration + 0.2 x score of flood frequency + 0.2 x score of inundation area. Flood hazard was classified into three levels: high, medium, and low. ArcGIS software was employed to process the data and extract the model outputs, and the results were then overlaid with the administrative boundaries of the 17 NAs using ArcGIS to determine the differences in flood hazard indices along the Kemang River. A flood vulnerability index was generated based on socioeconomic, physical, and environmental aspects. The criteria for the social, economic, physical, and environmental aspects are shown in Tables 3 to 6.

Table 3. Social aspect criterion of vulnerability

Parameter		Population density	Sex ratio	Toddler Population Ratio	Elderly population ratio
Weight (%)		60	10	10	10
Class (score)	Low (1)	<500 people km^2	< 20%		
	Medium (2)	500-1000 people km^2	20% - 40%		
	High (3)	> 1000 people km^2	> 40 %		

Table 4. Economics aspects of vulnerability

Parameter		Percentage of poor people	Vulnerable sector employees
Weight (%)		60	40
Class (score)	Low (1)	< 20%	
	Medium (2)	20 % - 40 %	
	High (3)	> 40 %	

Table 5. Physical aspects of vulnerability

Parameters	Class	Class index	Rate	Weight
Building density	Low	< 0.3	1	60%
	Medium	0.3 - 0.6	2	
	High	> 0.6	3	
Road network condition	Good	> 70 %	1	40%
	Medium	30% - 70 %	2	
	Poor	<30 %	3	

Table 6. Environmental aspects of vulnerability

Parameters	Classes	Class index	Rate	Weight
Rainfall intensity	Low	< 1000 mm	1	25%
	Medium	1000 -2500 mm	2	
	High	> 2500 mm	3	
Land use	Low	Open space (>50%)	1	25%
	Medium	Agriculture & Service (>50%)	2	
	High	Residential and industry >50%	3	
Topographic	Low	> 300 m.a.s.l.	1	20%
	Medium	20-300 m.a.s.l.	2	
	High	< 20 m.a.s.l.	3	
Distance to river	Low	> 1000 m	1	20%
	Medium	500 - 1000 m	2	
	High	< 500 m	3	
Channel condition	Good	> 70%	1	10%
	Medium	30% - 70%	2	
	Poor	< 30%	3	

The capacity index was calculated using the drainage capacity, zoning role, disaster education, and early flood warning system variables, as shown in Table 7.

Table 7. Capacity indices criterion

Parameters	Index class	Rate	Weight	Score
River capacity	Low	1	40%	0.2
	Medium	2		0.8
	High	3		1.2
Zoning regulation	Good	1	20%	0.2
	Medium	2		0.4
	Poor	3		0.6
Disaster education	Low	1	20%	0.2
	Medium	2		0.4
	High	3		0.6
Early warning system	Low	1	20%	0.2
	Medium	2		0.4
	High	3		0.6

2.3.1. Hydrologic & Hydraulics Model Set-Up

Rainfall distribution across the Krukut watershed was generated using the Thiessen polygon from five rainfall stations. The calculations of the design flood discharge for scenarios Q25 and Q50 were also compared with a Q rainfall of 150 mm/day as the threshold between heavy and extreme rainfall levels. The basin and subbasin boundaries were generated from a DEMNAS with an 8 m × 8 m spatial resolution using HEC-HMS version 4.11, and the ArcGIS spatial analysis tool hydrology. The sub-basin model was established using the Soil Conservation Service (SCS) Curve Number method, transformed with the SCS unit hydrograph, and routed using the kinematic wave method. For the RLS retarding basin, the upper storage is set with the Broad-Crested Spillway method, elevation of +47.00, length 4.7 m, and initial elevation of +46.88 m with no water gates. The lower storage spillway elevation was set at +45 m with a length of 1 m, and the initial elevation was set at +45.5° with no gates.

Hydraulic analyses were performed using HEC-RAS 1D and 2D. Once the model became stable and qualified, the analysis continued using the 2D model. The 2D model had a grid cell size of 10 × 10 m for the 2D flow area and a grid cell size of 0.25 × 0.25 m for the river geometry, which is delivered from LiDAR data. The outlet boundary situated in the West Flood Canal (Banjir Kanal Barat) was configured to represent free-flow conditions. The river width within the Krukut watershed varies between 6 and 10 m from upstream to downstream. The watershed is divided into two sub-catchments, Krukut and Mampang, with Kemang located in the Krukut sub-catchment. The hydrological model was executed in two scenarios: without and with the Brigif Reservoir. The model was operated under unsteady flow conditions for 72 h in January 2020. The accuracy of the model results was verified by comparing them with inundation depth data.

2.3.2. Water Quality Analysis and the Potential of Groundwater Recharge of Brigif Reservoir Storage

Water quality analysis was conducted at three sites: the Krukut River, the upper Brigif, and the lower Brigif. The sampling method used involved grabbing samples from a single event. The parameter sampling covered physical (temperature, total suspended solids, and color), chemical (Acidity, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), total phosphorus (P), and biological (faecal coliform and Total Coliform) aspects, which used surface water quality standards based on national government regulation no. 22/2021, as presented in Table 8. The potential groundwater recharge of the Brigif Reservoir was estimated using statistical analysis based on the infiltration rate data and the area of Brigif storage.

Table 8. Surface water quality standards

No	Parameters	Unit	Standards
A	***Physics***		
	Temperature (in-situ)	°C	Dev 3
	Total Suspended Solid (TSS)	mg/L	50
	Colour	Pt-Co-Unit	50
B	***Chemical***		
	Acidity /Ph (In-situ)	-	6-9
	Biochemical Oxygen Demand (BOD)	mg/L	3
	Chemical Oxygen Demand (COD)	mg/L	25
	Dissolved Oxygen (DO) (in-situ)	mg/L	4
	Total Phosphate (P)	mg/L	0.2
C	***Microbiology***		
	Faecal coliform	MPN/100 mL	1000
	Total Coliform	MPN/100 mL	5000

2.4. Model Calibration

In this study, the hydraulic model calibration was performed by comparing the flood depths simulated by the model with corresponding field data from several inundation events during 2020-2022. We also interviewed residents of the Kemang region to validate the flood depth. It is also used in the simulation scenarios because it is the threshold between heavy and extreme rainfall events. The performance of the model was assessed using NSE. The NSE and NSE criteria are listed in Table 9.

$$NSE = 1 - \frac{\sum_{i=1}^{N}(X_i - Y_i)^2}{(X_i - \bar{X}_i)^2} \tag{2}$$

where Xi is observed data, Yi is simulated data, $\bar{X}i$ is average observed data, N is the number of data.

Table 9. Criteria of Nash-Sutcliffe Efficiency (NSE) Value

NSE Value	Interpretation
NSE > 0.75	Good
0.36 < NSE < 0.75	Qualified
NSE<0.36	Not Qualified

3. Results and Discussion

3.1. Hydrological and Hydraulics Analysis Model

The hydrological analysis began with rainfall analysis from 2004 to 2021, followed by an analysis of regional rainfall, distribution, and frequency to establish the projected rainfall and flood discharge over a 25-year return period. These data were then merged with additional data, such as DEM, curve number (CN), and Impervious Percentage, and utilized to develop a hydrological model for the HEC-HMS. Hydrological analysis was executed using HEC-HMS, resulting in the generation of 26 subcatchments in the Krukut watershed. Kemang, positioned downstream of Brigif Reservoir, comprised three sub-catchments with a total area of approximately 15.90 km², while Brigif Reservoir itself consisted of two sub-catchments, Depok and Salak, with a combined catchment area of about 17.30 km². The overall catchment area of Kemang was determined to be approximately 33 km², as presented in Table 10. Thus, Kemang and Brigif Reservoirs were approximately 19.44% and 37.07%, respectively.

Table 10. Parameters of setting up hydrologic models

No.	Sub basin name	Area (km^2)	Initial abstraction (Ia) (mm)	Time lag (min)	Curve Number (CN)	Impervious %
1	Sb Brigif	14.72	3.24	149.62	94	89
2	Sb Salak	2.63	2.67	145.99	95	88
3	Sb Jagakarsa	6.42	2.9	173.05	95	90
4	Sb Marinir	2.01	2.73	123.36	95	90
5	Sb Pondok Labu	3.11	2.73	129.17	95	89
6	Sb Cilandak	4.4	2.79	159.34	95	91

The hydrologic simulation consisted of two scenarios: before and after the construction of the Brigif Reservoir. Before the construction of the Brigif Reservoir, the condition before it was built, which means that the model recreated it without the Brigif Reservoir, with January 2020 flooding serving as the reference point. The simulated event exhibited a precipitation rate of 157 mm/d, assuming a uniform distribution across each sub-basin. The second simulation was conducted after the development and incorporation of Brigif Reservoir into the HEC-HMS hydrological model. This methodology enables the quantification of the differential in the peak flood discharge magnitude between the two events for each subcatchment, wherein this differential also serves as the reduction value.

As shown in Figure 6, the peak discharge of subbasin Brigif reached almost 45 m³/s, whereas that of subbasin Salak reached approximately 12 m³/s. Therefore, the total inflow from the catchment area was approximately 57 m³/s, which passed the Brigif reservoir site during peak discharge in January 2020. The highest inflow of surface runoff from the lower catchment region, Brigif reservoir, is divided into four sub-basins: Jagakarsa, Pondok Labu, Marinir, and Cilandak, with each contributing to the Krukut River's peak flood discharge of approximately 29 m³/s, 17 m³/s, 11 m³/s, and 21 m³/s, respectively. The total inflow was approximately 78 m³/s, indicating that the lower catchment region of the Brigif reservoir had a greater total inflow than the upper catchment area, as shown in Figure 6, accounting for approximately 36.84% of the total. In fact, the catchment area is quite modest, at approximately 8.8%, indicating that urban areas produce more surface runoff than suburban areas. Overall, the highest possible flood discharge into the Krukut River segment in the Kemang area without the Brigif reservoir is approximately 135 m³/s.

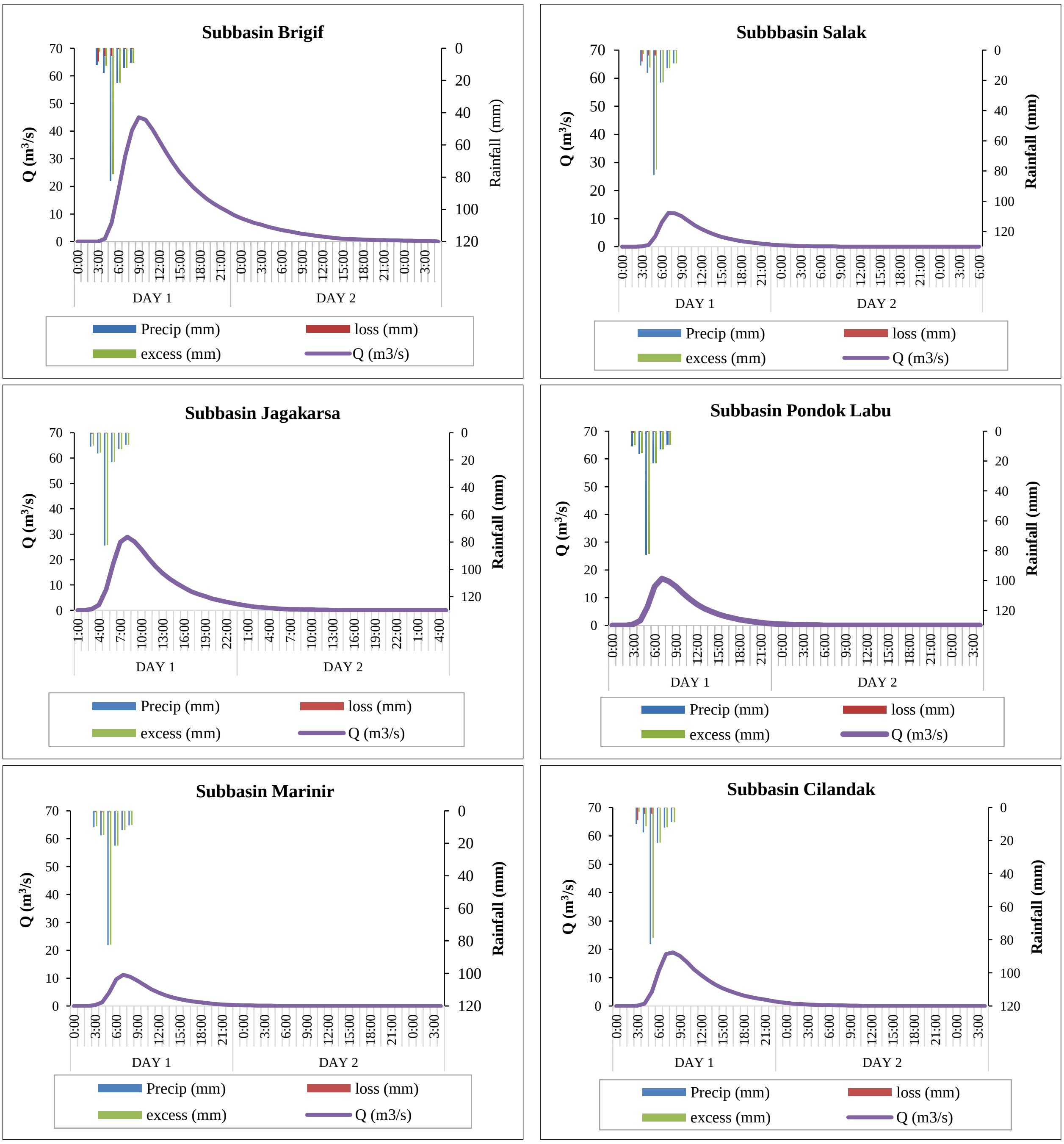
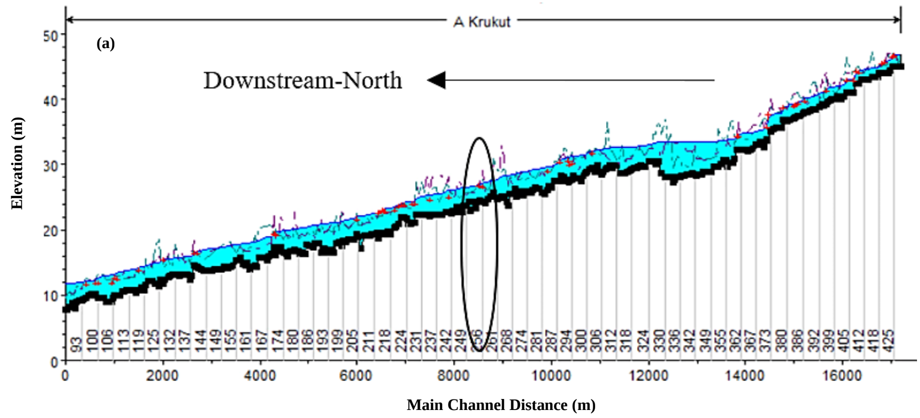


Figure 6. Flow hydrograph of each sub catchment of Kemang region

Hydraulic analysis was performed after acquiring peak flood discharge data from HEC-HMS, which were then processed in HEC-RAS 1D to determine the height of inundation in the Kemang area, as shown in Figure 7. The inundation height in the Kemang area was roughly 1.25 meters. A hydraulic study was conducted after acquiring peak flood discharge data from HEC-HMS, which were then processed in HEC-RAS 1D to determine the height of inundation in the Kemang area. The inundation in the Kemang area was approximately 1.25 m high. The inundation height value was then compared to the actual inundation data, which was 1.30 m, indicating that the model was well-qualified.



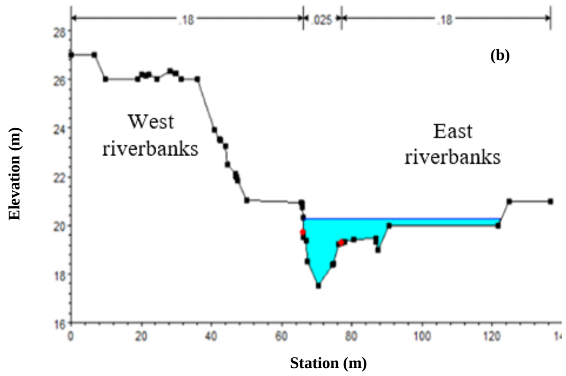


Figure 7. A long section profile of Krukut Watershed (a) and cross-section at Kemang region (b)

3.2. Model Calibration and Verification

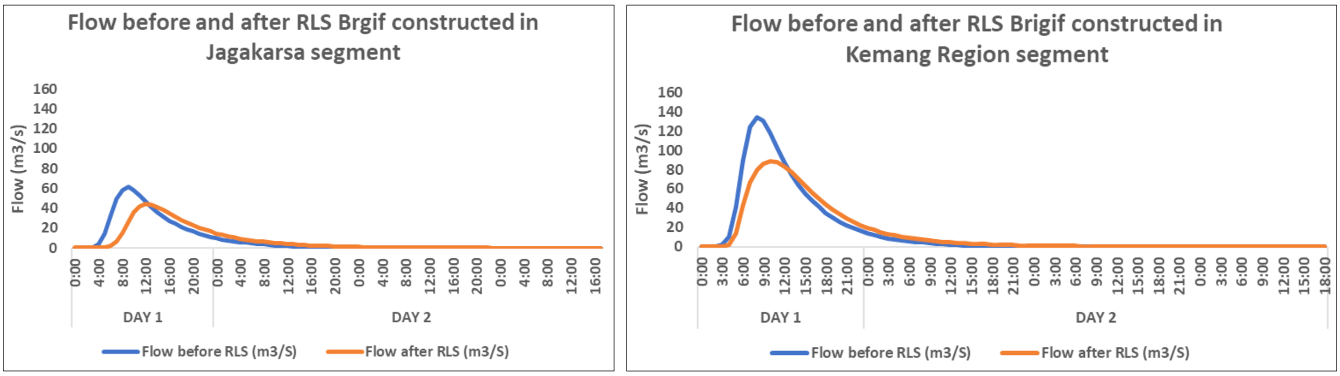
In this study, model calibration was performed by comparing the inundation height in real occurrences with the Krukut watershed hydraulic model at 13 sites for 2020–2022 flood events. Therefore, we achieved an NSE value of 0.94, indicating that the model functioned well, as listed in Table 11. In addition to the numerical data calibration, field verification was conducted by interviewing local people or workers at the model calibration point.

Table 11. Hydraulics model calibration results

Date of event	Longitude	Latitude	Flood depth observed [To]	Flood depth simulated [Tm]	$[Tm-To]^2$	$[To-To\ avg]^2$
1/1/2020	106.808336	-6.28044	0.30	0.23	0.00	0.17
1/1/2020	106.816692	-6.225354	0.30	0.25	0.00	0.17
1/1/2020	106.825028	-6.256479	0.60	0.66	0.00	0.01
1/1/2020	106.821734	-6.241222	0.15	0.50	0.12	0.31
2/20/2021	106.807676	-6.29032	0.80	0.87	0.00	0.01
2/20/2021	106.809733	-6.281907	0.40	0.43	0.00	0.10
2/20/2021	106.813682	-6.276275	0.8	0.82	0.00	0.01
2/20/2021	106.818089	-6.235252	0.71	0.64	0.00	0.00
2/20/2021	106.824404	-6.253981	0.50	0.40	0.01	0.04
2/20/2021	106.820128	-6.238473	1.50	1.42	0.01	0.63
2/20/2021	106.819795	-6.235439	1.00	0.91	0.01	0.08
10/6/2022	106.811665	-6.279282	0.35	0.32	0.00	0.13
10/6/2022	106.809839	-6.25941	1.80	1.87	0.00	1.19
	Average		**0.71**	**Total**	**0.17**	**2.84**
			NSE		**0.94**	

Based on the analysis results. The difference in the peak flood discharge before and after the Brigif Reservoir construction was obvious. This study included two observation segments: the first in the Krukut River portion of the Jagakrasa sub-basin and the second in the segment following the Cilandak sub-basin, also known as the Kemang Area.

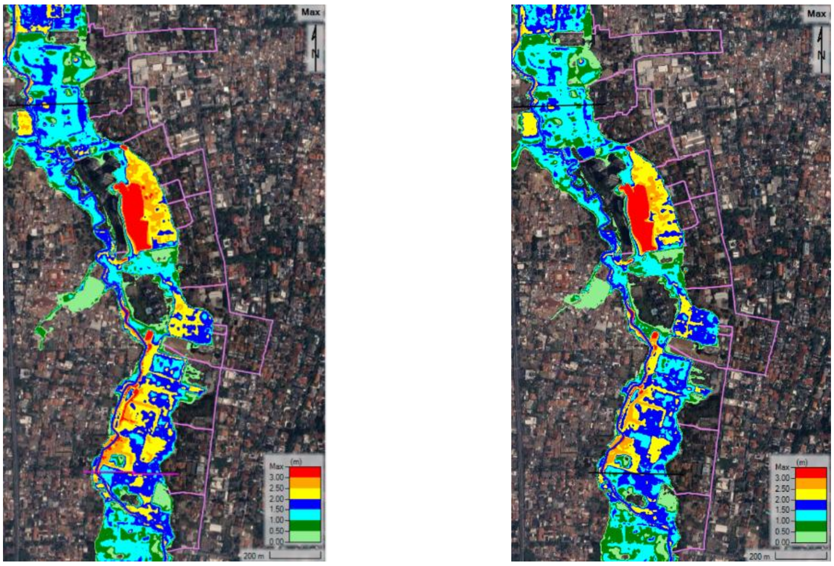
Based on Figure 8, in the first segment, the peak flood discharge was 61.70 m^3/s before the Brigif Reservoir was built; after its construction, it dropped to 26.30 m^3/s, a reduction of approximately 57.37%. In the second segment, the peak flood discharge fell from 134.30 to 79.80 m^3/s, a decrease of about 40.58%; this decrease in reduction value was caused by increased surface runoff from various subbasins, including Pondok Labu and Cilandak Marinir.



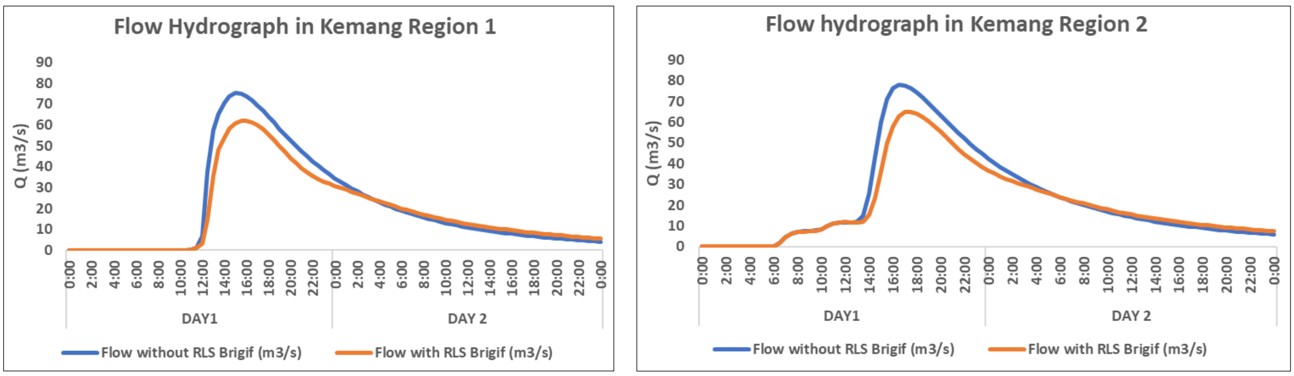
(a) (b)

Figure 8. Comparison of Peak flood discharge reduction before and after Brigif Reservoir constructed at Jagakarsa sub basin segment (a) and at Kemang region segment (b)

The findings of the peak flood flow reduction analysis on HEC-RAS 1D 2D revealed that the flood discharge reduction value before and after the construction of the Brigif Reservoir in the Kemang region was 77.93 m^3/s to 62.87 m^3/s, respectively, or approximately 19% as shown in Figure 9 c-d. Then, the maximum flood depth was decreased about 0.55 m after Brigif was constructed.



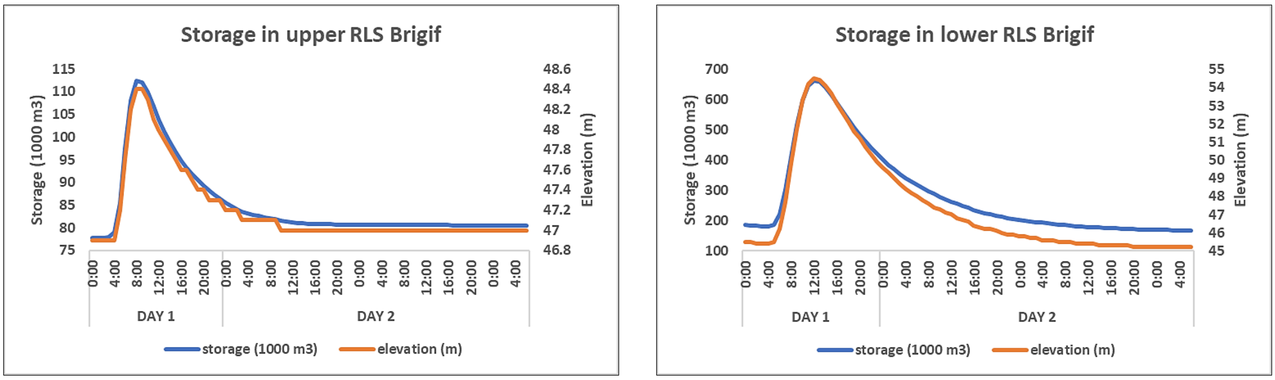
(a) (b)



(c) (d)

Figure 9. Captured images of Inundation in HEC-RAS 2D model, before Brigif reservoir (a) and after Brigif reservoir constructed (b) and flow hydrograph in Kemang region upper segment (c) and lower segment of Kemang region (d)

According to the simulation results, the Brigif Reservoir storage capacity was 80,000 m³ for the upper Brigif and 170,000 m³ for the lower Brigif, resulting in a total potential Brigif Reservoir storage of approximately 250,000 m³, as presented in Figure 10. The South Jakarta Municipal Administration can use its complete storage capacity to deliver raw water to city parks. According to the results of water quality checks in a certified environmental laboratory, both the lower and upper storage met the criteria for surface water quality standards, which refer to National Government Regulation No. 22 of 2021.



(a) (b)

Figure 10. Storage capacity of Brigif reservoir's upper area (a) and lower area (b)

As shown in Figure 11, we analysed two types of surface water quality samples under two different conditions: dry and wet. There are four sample points: Inlet Salak drainage, Upper Brigif, Inlet Krukut River, and Lower Brigif. The first sample was taken in dry conditions, and the second sample was taken in wet conditions or one day after rainfall. The investigation of the surface water quality of the river and Brigif Reservoir comprised physical, chemical, and microbiological parameters in accordance with government regulation No. 22 of 2021 on environmental administration and management. In terms of physical parameters, the TSS meets the standards under both dry and wet conditions. For chemical criteria such as BOD and COD, the concentration in the storage of the Brigif Reservoir, which covers the upper and lower areas, meets the standard under condition 1, whereas it does not meet in condition 2. Then, for microbiological parameters such as total coliforms, condition 1 meets the criteria for all stations while it did meet the criteria. This indicates that the retarding basin Brigif Reservoir, as a green-blue infrastructure, improved water quality, and storage under normal conditions met the national standard for surface water quality which might be due to the natural processing of the retention pond itself [82, 83]. Therefore, it can be used to water city parks or fire brigade reservoirs across South Jakarta.

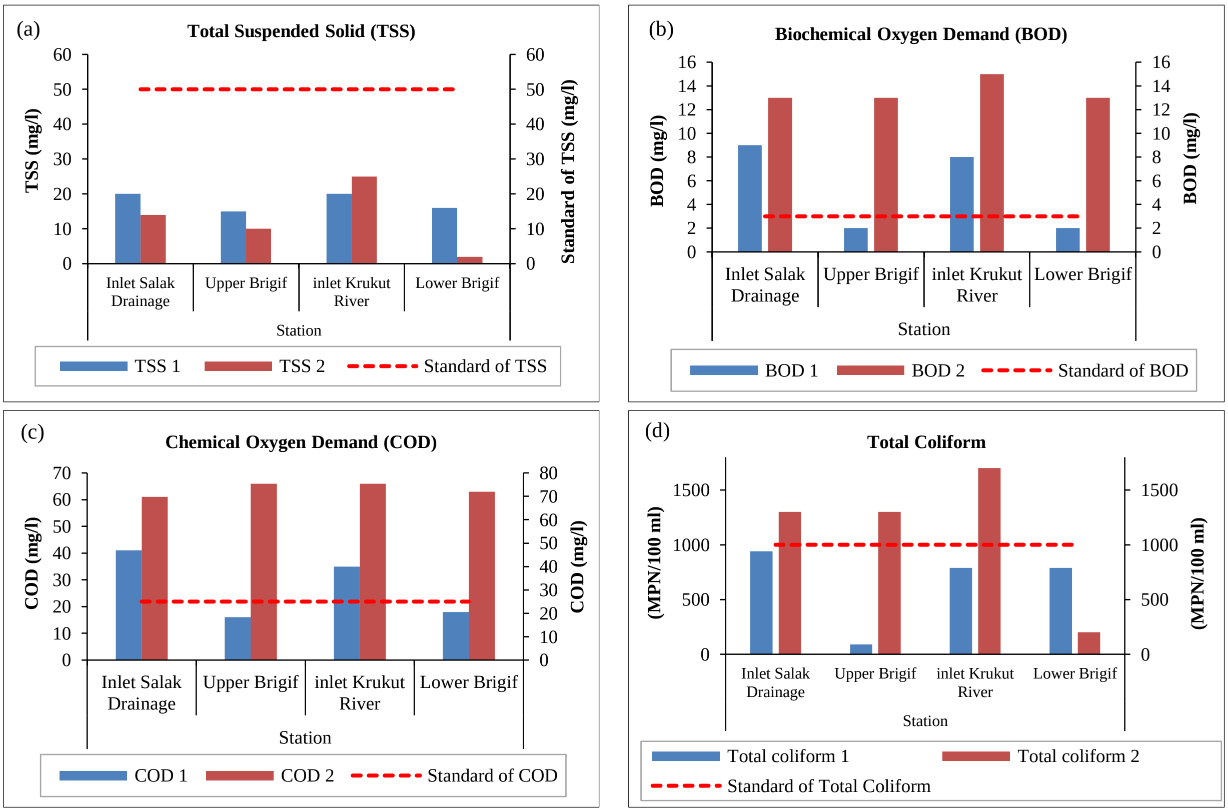


Figure 11. Water quality parameter analysis results of Brigif Reservoir storage and inlet of Salak and Brigif sub basin of Total Suspended Solid (TSS) (a), Biochemical Oxygen Demand (BOD) (b), Chemical Oxygen Demand (COD) (c) and Total Coliform (d)

3.3. Potential Infiltration of Brigif Reservoir for Groundwater Recharge

The potential infiltration of the Brigif Reservoir, calculated based on the maximum infiltration rate, was approximately 25 mm/h in both the upper and lower Brigif areas. According to the as-built drawing of the Brigif Reservoir, the delivered volumes were approximately 165 m^3 and 335 m^3 for the upper and lower parts of the Brigif, respectively. Consequently, the total potential infiltration was estimated to be approximately 250 m^3 for one hour, 6000 m3 for one day, and 22000 m^3 for one week, potentially accumulating to 180,000 m^3 in one month. Therefore, there is significant potential for additional recharge in the Jagakarsa subbasin, which supports groundwater sustainability. The results of this estimation have been compared with groundwater level data in the vicinity of the site, utilizing real-time data from groundwater depth monitoring wells provided by the Ministry of Energy and Mineral Resources and monthly monitoring data for 2024 from the DKI Jakarta Provincial Water Resources Office. Analysis indicates that the groundwater depth in the surrounding area ranges from 22 m to 25 m, suggesting that the region possesses significant potential for groundwater recharge.

3.4. Flood Hazard Index

The flood hazard index was derived from the HEC-RAS 2D unsteady flow analysis model operating under a rainfall event scenario in January 2020. The analysis of flood hazards was conducted in two scenarios: before and after the construction of the Brigif Reservoir and its impact on the Kemang Region flood. Model results were extracted using ArcGIS to transform the spatial analysis into an Excel file.

Based on Tables 12 and 13 and spatially illustrated in Figure 12, the flood hazard analysis of the January 2020 flood events in the Kemang area revealed that among the 17 Neighborhood Areas (NAs), 13 locations (76.47%) were categorized as high flood hazards, three locations (17.65%) as medium flood hazards, and the remaining one location (5.88%) as low flood hazards. Following the addition of Brigif Reservoir, the area's flood hazard index decreased, with 11 areas falling into the high hazard category (64.70%), five locations in the medium hazard category (29.41%), and one location remaining in the low hazard category (5.68%). The addition of the Brigif Reservoir reduced the high flood hazard index to moderate during the January 2020 flood incident in the Kemang area by 11.77%, resulting in two NA locations. For the low-category flood hazard index, the return fell between the two scenarios. The Brigif Reservoir has a modest influence on the area because the landscape is low and concave, allowing water to flow slowly into the river. The second issue is the inadequate flow capacity of the Krukut River, which causes overflows to the left and right sides of the floodplain.

Table 12. Flood hazard before Brigif reservoir constructed

No	NA	CA	Inundation depth (cm)	Inundation duration (hour)	Inundation frequency	Inundation area (m^2)	Total score	Hazard Index
1	14	1	1.2	0.6	0.4	0.6	2.80	High
2	12	2	1.2	0.6	0.4	0.6	2.80	High
3	13	2	1.2	0.6	0.4	0.6	2.80	High
4	9	2	1.2	0.6	0.4	0.6	2.80	High
5	7	2	1.2	0.6	0.4	0.6	2.80	High
6	12	5	1.2	0.2	0.4	0.6	2.40	Medium
7	12	1	1.2	0.6	0.4	0.6	2.80	High
8	10	2	1.2	0.6	0.4	0.6	2.80	High
9	3	2	1.2	0.6	0.4	0.6	2.80	High
10	13	1	0.8	0.6	0.4	0.6	2.40	Medium
11	11	1	0.8	0.6	0.4	0.6	2.40	Medium
12	11	5	1.2	0.6	0.4	0.6	2.80	High
13	13	5	1.2	0.6	0.4	0.6	2.80	High
14	14	5	1.2	0.6	0.4	0.6	2.80	High
15	8	2	0.8	0.6	0.2	0.6	2.20	Low
16	4	2	1.2	0.6	0.4	0.6	2.80	High
17	11	2	1.2	0.6	0.4	0.6	2.80	High

High	>2.60
Medium	2.40- 2.60
Low	<2.40

Table 13. Flood hazard after Brigif reservoir constructed

No	NA	CA	Inundation depth (cm)	Inundation duration (hour)	Inundation frequency	Inundation area (m^2)	Total score	Hazard Index
1	14	1	0.8	0.6	0.4	0.6	2.40	Medium
2	12	2	1.2	0.6	0.4	0.6	2.80	High
3	13	2	0.8	0.6	0.4	0.6	2.40	Medium
4	9	2	1.2	0.6	0.4	0.6	2.80	High
5	7	2	1.2	0.6	0.4	0.6	2.80	High
6	12	5	1.2	0.2	0.4	0.6	2.40	Medium
7	12	1	1.2	0.6	0.4	0.6	2.80	High
8	10	2	1.2	0.6	0.4	0.6	2.80	High
9	3	2	1.2	0.6	0.4	0.6	2.80	High
10	13	1	0.8	0.6	0.4	0.6	2.40	Medium
11	11	1	0.8	0.6	0.4	0.6	2.40	Medium
12	11	5	1.2	0.6	0.4	0.6	2.80	High
13	13	5	1.2	0.6	0.4	0.6	2.80	High
14	14	5	1.2	0.6	0.4	0.6	2.80	High
15	8	2	0.4	0.6	0.2	0.6	1.80	Low
16	4	2	1.2	0.6	0.4	0.6	2.80	High
17	11	2	1.2	0.6	0.4	0.6	2.80	High

High	>2.47
Medium	2.13- 2.47
Low	<2.13

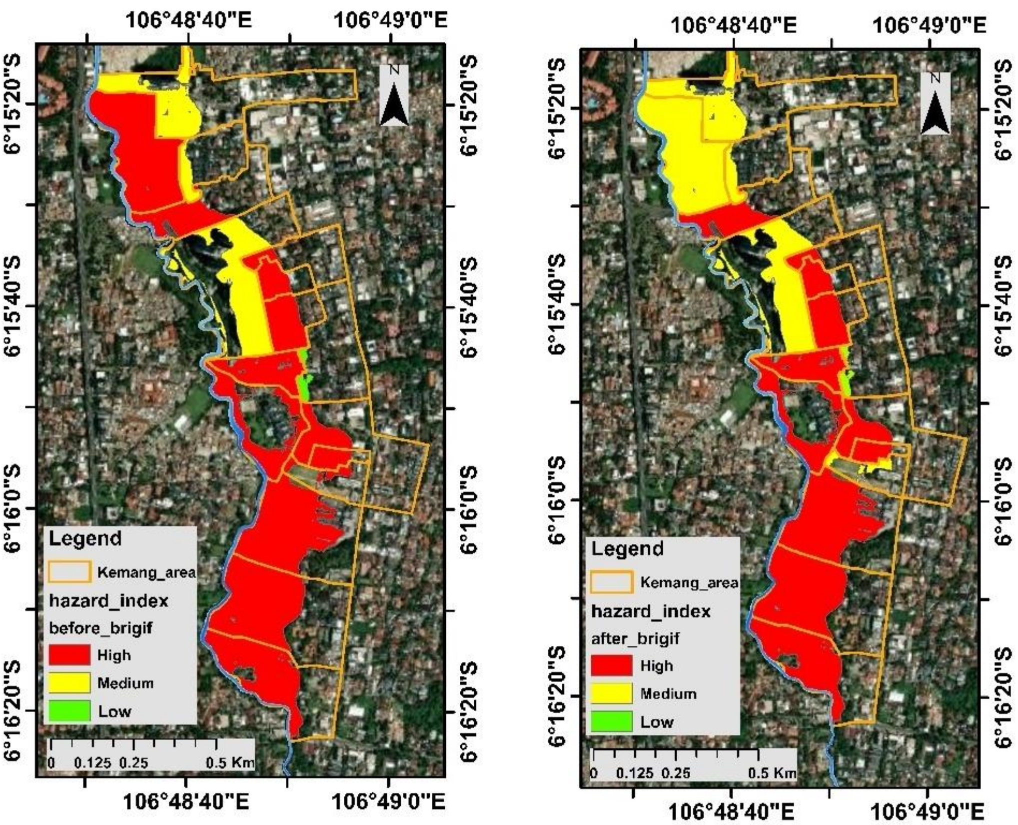


Figure 12. Flood hazard index map with scenario; before Brigif Reservoir's construction (a) and after Brigif reservoir constructed (b)

3.5. Flood Vulnerability Index

The flood vulnerability index generated socioeconomic, physical, and environmental data based on 17 NAs in the Kemang region of southern Jakarta. The vulnerability index was divided into three classes: high, medium, and low. We found that the value of social and economic aspects tended to be typical, whereas physical-like road conditions and environmental aspects, such as topography, distance to river, and channel conditions, tended to be more dynamic over NAs. After analyzing the data, we obtained the highest value (9.10) and the lowest value (8.30) and classified them into three categories. Finally, we found that this area was positioned at levels of 53% (9 NAS), 35% (6 NAS), and 12% (2 NAS), as shown in Table 14. Therefore, the Kemang region had a high flood vulnerability index.

Table 14. Flood vulnerability index of Kemang region

No	NA	CA	Social	Economics	Physical	Environment	Total score	Index Class
1	14	1	2.40	1.80	2.00	2.9	9.10	High
2	12	2	2.40	1.80	2.00	2.9	9.10	High
3	13	2	2.40	1.80	2.00	2.7	8.90	High
4	9	2	2.40	1.80	2.00	2.7	8.90	High
5	7	2	2.40	1.80	2.00	2.7	8.90	High
6	12	5	2.40	1.80	2.00	2.9	9.10	High
7	12	1	2.40	1.80	1.60	2.9	8.70	Medium
8	10	2	2.40	1.80	2.00	2.5	8.70	Medium
9	3	2	2.40	1.80	2.00	2.5	8.70	Medium
10	13	1	2.40	1.80	1.60	2.9	8.70	Medium
11	11	1	2.40	1.80	1.60	2.7	8.50	Low
12	11	5	2.40	1.80	1.60	2.5	8.30	Low
13	13	5	2.40	1.80	2.00	2.7	8.90	High
14	14	5	2.40	1.80	2.00	2.7	8.90	High
15	8	2	2.40	1.80	1.60	2.5	8.30	Medium
16	4	2	2.40	1.80	1.60	2.5	8.30	Medium
17	11	2	2.40	1.80	2.00	2.7	8.90	High

Index class	value
High	> 8.83
Medium	8.57-8.83
Low	< 8.57

3.6. Flood Capacity Index

The flood capacity index was calculated based on four parameters: river and drainage capacities, zoning regulations, disaster education, and an early warning system. The values of river and drainage capacity and the early warning system provided more dynamics than zoning regulation and disaster education parameters. After conducting the assessment, the highest value was 2.20 and lowest values were 1.6 respectively.

As a result, we found that the Kemang region is included in the low-capacity index, with a composition consisting of 70% at the low level, 24% at the medium level, and the remaining 6% at the high level, as shown in table 15 and 16. We found that river and drainage capacity and the early warning system contributed more to the level of the index, whereas zoning regulation and disaster education were relatively constant.

Table 15. Capacity index of Kemang region with Brigif Reservoir

No	NA	CA	River and drainage capacity	Zoning regulation	Disaster education	Early warning system	Total score	Index Class
1	14	1	0.40	0.80	0.20	0.4	1.80	Medium
2	12	2	0.40	0.80	0.20	0.2	1.60	Low
3	13	2	0.40	0.80	0.20	0.2	1.60	Low
4	9	2	0.40	0.80	0.20	0.2	1.60	Low
5	7	2	0.80	0.80	0.20	0.2	2.00	Medium
6	12	5	0.40	0.80	0.20	0.2	1.60	Low
7	12	1	0.40	0.80	0.20	0.2	1.60	Low
8	10	2	0.80	0.80	0.20	0.2	2.00	Medium
9	3	2	0.80	0.80	0.20	0.2	2.00	Medium
10	13	1	0.80	0.80	0.20	0.4	2.20	High
11	11	1	0.40	0.80	0.20	0.2	1.60	Low
12	11	5	0.40	0.80	0.20	0.2	1.60	Low
13	13	5	0.40	0.80	0.20	0.2	1.60	Low
14	14	5	0.40	0.80	0.20	0.2	1.60	Low
15	8	2	0.40	0.80	0.20	0.2	1.60	Low
16	4	2	0.40	0.80	0.20	0.2	1.60	Low
17	11	2	0.40	0.80	0.20	0.2	1.60	Low

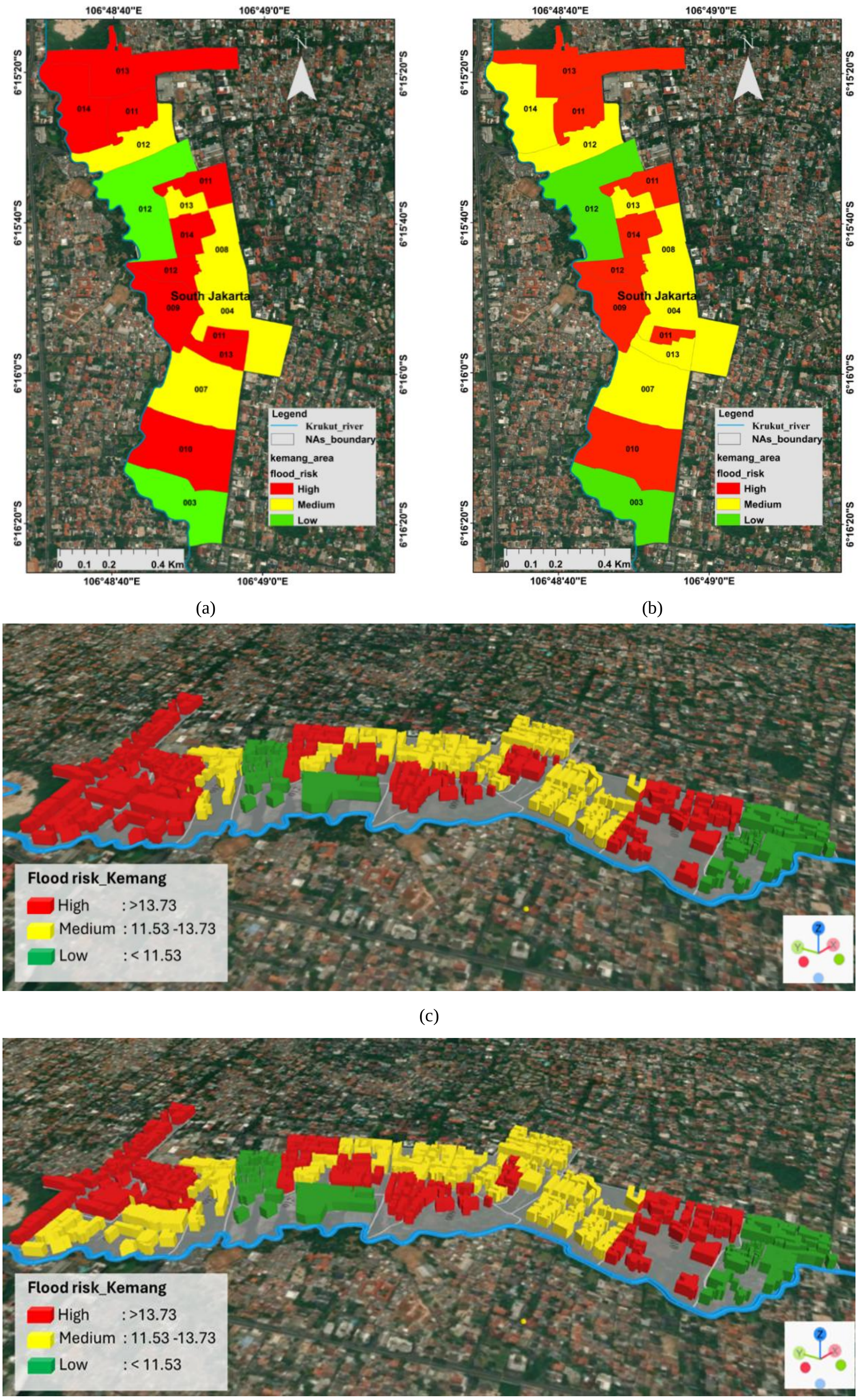
High	> 2.0
Medium	1.80-2.00
low	< 1.80

3.7. Flood Risk Analysis

A flood risk analysis of the Kemang region was conducted according to Equation 5 for rain occurrences in January 2020 in two scenarios: with and without the Brigif Reservoir. Based on the calculation findings, we divided the risk of flooding into three categories: high, medium, and low, with a maximum score of 15.93 and a minimum score of 9.49 The high class has a higher score 13.73 the medium class falls in between 11.53 to 13.73, and the low class has a lower score than 11.53 respectively. The tabular analysis results were mapped using ArcGIS and QGIS for the 3D flood risk model. We found that the Kemang area had a high (59%) or 10 NAs, medium (29%) or 5 NAs, and low (12%) or 2 NAs risk of flooding in response to rainfall in January 2020. Therefore, this area, which covers 17 NAs, is categorised as a high flood risk area that requires immediate flood mitigation measures. The results of this analysis are presented in Figures 13-a and b.

In the scenario with intervention of the Brigif reservoir in the upstream area, the Kemang area had a high risk of flooding at 47% or 8 NAs, medium with 41% (7 NAs), and low with 12% (2 NAs). Therefore, the Brigif reservoir contributes to reducing high risk to medium risk with two NAs (12%), while the low-risk level remains the same as without its intervention, as shown in Figure 14-a and b. The flood hazard index contributed the most to risk reduction, followed by the capacity index, whereas the vulnerability index remained essentially constant. Previous research has suggested that Jakarta is highly vulnerable to flooding and that it requires collaboration between the government and the community [84]. Therefore, it could be stated that the Brigif reservoir intervention is not sufficient to decrease the high fluvial flood risk levels to a low level in the Kemang region. An evaluation of the new NBS performance during peak flood discharge reduction in retention ponds revealed an effectiveness of approximately 19%, which was slightly lower than the 23% reported in global NBS effectiveness studies [21]. This may also be related to the terrain and soil lithology conditions in the Kemang Catchment area [7, 72]. Although this discrepancy may be attributed to variations in the infrastructure design and operational protocols, the overall results were relatively comparable.

To achieve a significant reduction in flood risk, the vulnerability index must be decreased with non-structural and other structural interventions that are directly related to socioeconomic, physical, and environmental factors, along with parameters in other capacity indices, such as flood disaster education, floodplain zoning regulations, and the development of the Krukut watershed flood early warning system, which can help in the operation of the inlet and outflow of the Brigif Reservoir, leading to improved performance of the NBS. The Brigif Reservoir is connected to the Krukut River, which enhances its storage capacity and future flood resilience [85]. This research can be extended through quantitative analyses of environmental life cycle, social life cycle, and cost-benefit to assess the efficacy of NBS from environmental, social community, and economic perspectives [86]. The development of an early flood warning system (FEWS) is possible because there is already a basic hydrological and hydraulic model for the Krukut watershed. This intervention could mitigate flood-related losses in both commercial and residential sectors [87]. In addition, there is still a gap between the government and the community in terms of knowledge and awareness and participation and collaboration with the private sector related to the concept, design, implementation, operation, and maintenance of NBS in flood-prone areas of Jakarta; this could be addressed by socialization and workshops.



(a) (b) (c) (d)

Figure 13. Flood risk map of Kemang region without Brigif reservoir intervention; (a) with intervention (b) and overlayed with impacted building in 3d image without intervention (c) and with intervention (d)

3.8. A Conceptual Framework for Flood Risk Reduction Strategies in the Kemang Area

Based on the results of the flood risk reduction analysis presented above, mitigating the flood risk in the Kemang area solely through the implementation of the Brigif Reservoir is insufficient. Additional interventions at the building scale are necessary to manage the high surface runoff in each Krukut sub-watershed. This approach aligns with the concept of a sponge city because studies have indicated that such facilities can more effectively control stormwater [88]. The integration of bioretention and sunken green spaces has been demonstrated to be an effective and efficient method for reducing annual runoff by 75% in urban areas while simultaneously offering socioeconomic benefits to the community [89].

To reduce the high flood risk to a low level, the city can develop integrated NBS and hard structures as a set of sustainable infrastructures, such as rooftop storage, underground storage, and permeable storage as green, blue, and gray infrastructures, as shown in Figure 15 in building scale. Rainwater harvesting can reduce urban flood areas 100% for small rainfall events and 50% for rainfall depths up to 50 mm [90]. RWH tanks could reduce annual damage by more than 30% [91], and average peak flow runoff reduction was 2.4 to 14.3% in the sub-basin [92]. Rainfall is retained in rooftop storage and then overflows into underground storage (RWH), overflows again into permeable storage, and excessive rainwater overflows into the city drainage system. Based on these reference data, we decided to use efficiency values of 10% for rooftop storage, underground storage, and permeable storage and add 19% (Brigif reservoir) for Brigif and Salak sub-basins of the peak surface runoff in each sub-basin within the catchment area of the Kemang region. Consequently, the discharge flowing into the Kemang area decreased to approximately 56 m^3/s from 135 m^3/s, representing a reduction in peak runoff of approximately 79 m^3/s (58%) of the total inflow in the Kemang area. This level falls below the bank full capacity of approximately 60 m^3/s. Under these conditions, it can be inferred that the flood hazard index in the Kemang area may potentially decrease from high to low levels, which could lead to decreasing the risk level to a low level as well.

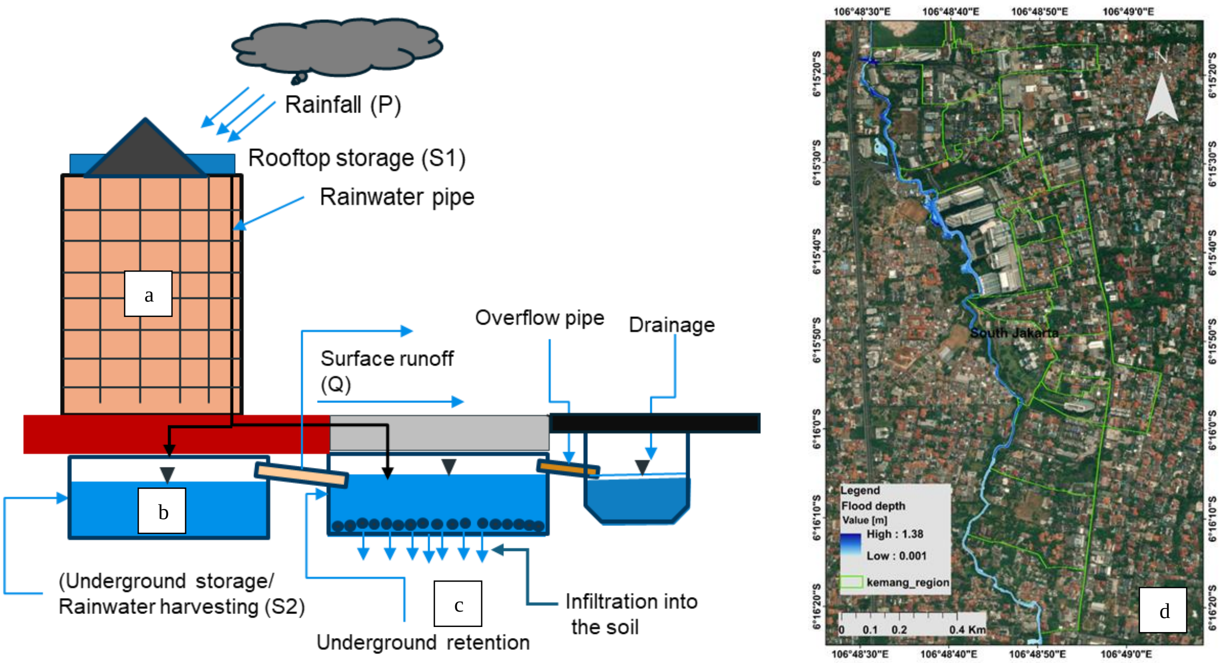


Figure 14. Proposed NBS model for flood risk reduction; rooftop storage (a), underground storage (RWH) (b) and underground retention (c) in Kemang region and captured image after it applied in each sub basin in Kemang region (d)

Nature-based solutions (NBS) represent a complex infrastructure that presents significant challenges to policymakers, the private sector, and communities in terms of conceptual knowledge, implementation, and operation and maintenance. As an initial step, the incorporation of NBS into spatial planning design within local and national policies is essential for success and long-term sustainability [93]. The discourse surrounding the planning, design, implementation, monitoring, and evaluation of NBS necessitates the involvement of relevant stakeholders from governmental bodies, the private sector, and community organizations. The implementation of NBS in flood risk management can yield beneficial implications for the environment (reducing flood peak discharge, flood height, and flood extent), the economy (mitigating economic losses due to flooding and promoting effective and efficient government budget allocation in disaster management), and society (reducing disaster risk and supporting public health through the provision of public spaces and recreational areas) [94].

For the infiltration rate and groundwater recharge, we estimated groundwater recharge using a simplified calculation based on the minimum infiltration rate data and the Brigif Reservoir storage pond area. Subsequently, we compared this estimation with the actual groundwater level data obtained from real-time groundwater level monitoring wells in the vicinity of the reservoir. The groundwater table depth data from the monitoring wells indicated a depth of approximately 22-25 meters. When compared to the reservoir depth of approximately 5 meters, this observation suggests that the area surrounding Brigif demonstrates considerable potential for sustained groundwater recharge. A previous study reported that the recharge rate of the Jakarta groundwater basin ranges from 4-20%, with an average groundwater recharge rate of 15% of annual rainfall [95]. Therefore, we calculated using Jakarta's annual average rainfall data of 2500 mm/year that the estimated groundwater flux in a year is 375 mm/year, or equal to 100 mm/day. When multiplied by the wet area of Brigif Reservoir, the estimated groundwater recharge potential is 100,000 m^3/day. This result is greater compared to the calculation using the infiltration rate, which is 12500 m^3/day. This discrepancy may occur because the calculation does not consider the actual measurement data of infiltration rate and soil type. For future research, a water balance analysis utilizing a numerical model at the scale of the Krukut watershed could be conducted.

4. Conclusion

The analysis revealed that the reduction in peak flood discharge before and after the Brigif RLS in the Kemang area represented a 19% decrease in the January 2020 flooding event, which led to flood hazard reduction of approximately 12% (two NAs) from a high to moderate flood hazard index. The vulnerability and capacity indices remained constant with and without the Brigif Reservoir because there was no intervention in the study area. Subsequently, the flood risk decreased by approximately 12% in the scenarios before and after the Brigf Reservoir intervention. In addition to peak flood reduction, the Brigif Reservoir, as an NBS infrastructure, provides additional benefits such as raw water potential, which can be utilized by local households and the government for garden irrigation and raw water consumption, as it meets the standard criteria of National Government Regulation No. 22 of 2021. It also has the potential for storage that infiltrates the soil and aquifer, leading to groundwater recharge. This study found that this reservoir could improve water quality in both the upper and lower storage areas of the Brigif Reservoir.

These results demonstrate that the structures (e.g., retarding basins) of nature-based infrastructure solutions and non-structural approaches, such as floodplain zoning, can be employed to reduce the flood hazard index in Kemang. The combined implementation of the Brigif Reservoir, rooftop storage, underground storage, and underground retention systems could potentially reduce the peak flow runoff in the Kemang catchment area by approximately 58% (from 135 m^3/s to 56 m^3/s). This reduction may lead to a decrease in flood hazards to a low level, which could subsequently result in a decrease in the overall risk. Surface runoff captured in a reservoir constitutes a viable alternative for meeting a building's daily domestic water requirements, whereas subterranean retention systems contribute to the augmentation of groundwater reserves within the catchment area. This phenomenon has the potential to reduce the rate of land subsidence, which is one of Jakarta's primary challenges. The integrated approach, incorporating the Brigif Reservoir, rooftop storage facilities, underground storage systems, and subterranean retention mechanisms, not only mitigates flood risks in Kemang but also enhances the long-term resilience and sustainability of urban water resources.

4.1. Recommendation

This study recommends that local and central government authorities apply a set of sustainable infrastructures, such as rooftop storage, underground storage, and underground retention, at the building scale in each sub-catchment to reduce the flood risk level in the Kemang region. Furthermore, the results indicate the feasibility of establishing an early flood warning system with machine learning to enhance the river capacity index and policy in the water sector and to implement a mitigation and adaptation strategy program in response to the effects of climate change.

4.2. Limitations and Future Work

Nature-based solution (NBS) infrastructure offers numerous benefits, including climate change mitigation and adaptation, water management, coastal resilience, socioeconomic improvements, biodiversity enhancement, and built environment optimization [96]. However, there is currently no established system or government policy regarding the implementation of NBS in urban areas, including their types and functions. Consequently, it is essential to evaluate the effectiveness of existing structures, such as the Brigif Reservoir. This study focused on three functional aspects: flood risk reduction, potential for alternative raw water supply storage, and groundwater recharge. Subsequently, solutions for flood mitigation in the Kemang region are proposed. The developed model can provide insights into the potential development and implementation of the NBS infrastructure for stormwater management in urban areas. The implementation of effective NBS necessitates policy formulation, community engagement, and incentivization strategies [15].

NBS infrastructure related to climate change and adaptation Future studies could assess the NBS Brigif reservoir related to the water balance and threshold of the groundwater budget model to support the development and implementation of NBS infrastructure at urban areas and catchment scales.

5. Declarations

5.1. Author Contributions

Conceptualization, M.S.B.K., M.C., and A.A.K.; methodology, M.S.B.K., M.C., A.A.K., and M.S.; software, M.S.; validation, M.S., M.C., M.S.B.K., and A.A.K.; formal analysis, M.S.; investigation, M.S.; resources, M.S.; data curation, M.S.; writing—original draft preparation, M.S.; writing-review and editing, M.S.B.K., M.C., and A.A.K.; visualization, M.S., M.S.B.K., and A.A.K.; supervision, M.S.B.K., M.C., and A.A.K.; project administration, M.S. and M.S.B.K.; funding acquisition, M.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding and Acknowledgements

The authors acknowledge the support provided by P2MI of the ITB for providing financial assistance for research needs, field surveys, and publications. We thank the Chair of the FTSL ITB Water Resources Engineering Expertise Group and the ITB Civil Engineering Postgraduate Study Program for their support and permission to conduct this research. The author is also grateful to the Head of the Water Resources Agency of Jakarta (DSDA DKI Jakarta), the Indonesian Agency for Meteorological, Climatological, and Geophysics (BMKG), the Authority for Ciliwung and Cisadane River Watersheds (BBWSCC), and the National Planning and Development Agency-Directorate (BAPPENAS) for providing the datasets used in this study.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Wicaksono, A., & Herdiansyah, H. (2019). The impact analysis of flood disaster in DKI jakarta: Prevention and control perspective. Journal of Physics: Conference Series, 1339(1), 012092. doi:10.1088/1742-6596/1339/1/012092.

[2] Capobianco, V., Palau, R. M., Solheim, A., Gisnås, K., Gilbert, G., Danielsson, P., & van der Keur, P. (2024). The potential use of nature-based solutions as natural hazard mitigation measure for linear infrastructure in the Nordic Countries. Geoenvironmental Disasters, 11(1), 27. doi:10.1186/s40677-024-00287-4.

[3] Ari Gunawan, T., Syahril Badri Kusuma, M., Cahyono, M., & Nugroho, J. (2017). The application of backpropagation neural network method to estimate the sediment loads. MATEC Web of Conferences, 101. doi:10.1051/matecconf/201710105016.

[4] Takagi, H., Esteban, M., Mikami, T., & Fujii, D. (2016). Projection of coastal floods in 2050 Jakarta. Urban Climate, 17, 135–145. doi:10.1016/j.uclim.2016.05.003.

[5] Bennett, W. G., Karunarathna, H., Xuan, Y., Kusuma, M. S. B., Farid, M., Kuntoro, A. A., Rahayu, H. P., Kombaitan, B., Septiadi, D., Kesuma, T. N. A., Haigh, R., & Amaratunga, D. (2023). Modelling compound flooding: a case study from Jakarta, Indonesia. Natural Hazards, 118(1), 277–305. doi:10.1007/s11069-023-06001-1.

[6] Chrysanti, A., Adhani, A., Azkiarizqi, I. N., Adityawan, M. B., Kusuma, M. S. B., & Cahyono, M. (2024). Assessing Compound Coastal–Fluvial Flood Impacts and Resilience Under Extreme Scenarios in Demak, Indonesia. Sustainability (Switzerland), 16(23), 10315. doi:10.3390/su162310315.

[7] Supratman, M., Kusuma, M. S. B., Cahyono, M., & Kuntoro, A. A. (2024). Flood Hazard Assessment Due to Changes in Land Use and Cover. Civil Engineering Journal (Iran), 10(12), 3874–3891. doi:10.28991/CEJ-2024-010-12-04.

[8] Alborzi, A., Zhao, Y., Nazemi, A., Mirchi, A., Mallakpour, I., Moftakhari, H., Ashraf, S., Izadi, R., & AghaKouchak, A. (2022). The tale of three floods: From extreme events and cascades of highs to anthropogenic floods. Weather and Climate Extremes, 38, 100495. doi:10.1016/j.wace.2022.100495.

[9] Rahayu, R., Mathias, S. A., Reaney, S., Vesuviano, G., Suwarman, R., & Ramdhan, A. M. (2023). Impact of land cover, rainfall and topography on flood risk in West Java. Natural Hazards, 116(2), 1735–1758. doi:10.1007/s11069-022-05737-6.

[10] Farahnaz, N., Kuntoroa, A. A., & Kusuma, M. S. B. (2020). Statistical downscaling for the projection of the keetch byram drought index in the Barito Basin. International Journal on Advanced Science, Engineering and Information Technology, 10(2), 873–879. doi:10.18517/ijaseit.10.2.10102.

[11] Vojinovic, Z., Alves, A., Gómez, J. P., Weesakul, S., Keerakamolchai, W., Meesuk, V., & Sanchez, A. (2021). Effectiveness of small- and large-scale Nature-Based Solutions for flood mitigation: The case of Ayutthaya, Thailand. Science of the Total Environment, 789, 147725. doi:10.1016/j.scitotenv.2021.147725.

[12] Sengara, W., Latief, H., & Kusuma, M. S. B. (2008). Disaster Management in Central Java Province, Indonesia. Geotechnical Engineering for Disaster Mitigation and Rehabilitation, Berlin, Springer. doi:10.1007/978-3-540-79846-0.

[13] Kusuma, M. S. B., Ragayu, R. A., & Cahyono, M. (2009). Development study of turbulent κ-ε model for recirculation flow III: Two dimension recirculation flow in a reservoir. ITB Journal of Engineering Science, 41 B(1), 1–16. doi:10.5614/itbj.eng.sci.2009.41.1.1.

[14] Enung, Kusuma, M. S. B., Kardhana, H., Suryadi, Y., & Rohmat, F. I. W. (2022). Hourly Discharge Prediction Using Long Short-Term Memory Recurrent Neural Network (Lstm-Rnn) in the Upper Citarum River. International Journal of GEOMATE, 23(98), 147–154. doi:10.21660/2022.98.3462.

[15] Keech, D., Clarke, L., & Short, C. (2023). Nature-based solutions in flood risk management: Unlocking spatial, functional and policy perceptions amongst practitioners in South-West England. Nature-Based Solutions, 4, 100096. doi:10.1016/j.nbsj.2023.100096.

[16] Kesuma, T. N. A., Kusuma, M. S. B., Farid, M., Kuntoro, A. A., & Rahayu, H. P. (2022). an Assessment of Flood Hazards Due To the Breach of the Manggarai Flood Gate. International Journal of GEOMATE, 23(95), 104–111. doi:10.21660/2022.95.3055.

[17] Prakoso, W. G., Irawan, P., & Mahfudz, M. (2020). Hydrological Risk Valuation on the Design of Sukamahi Dry Dam, Bogor, West Java. IOP Conference Series: Earth and Environmental Science, 556(1), 012014. doi:10.1088/1755-1315/556/1/012014.

[18] Ignatius, S., Soeryantono, H., Anggraheni, E., & Sutjiningsih, D. (2019). Analysis of flood inundation in North Sunter on the North Sunter Polder system performance. IOP Conference Series: Materials Science and Engineering, 669(1), 012039. doi:10.1088/1757-899X/669/1/012039.

[19] Sari, S. P., & Suhendri. (2018). Potential of Rainwater System for Domestic Building in Jakarta. IOP Conference Series: Earth and Environmental Science, 152(1), 012002. doi:10.1088/1755-1315/152/1/012002.

[20] Farid, M., Pratama, M. I., Kuntoro, A. A., Adityawan, M. B., Rohmat, F. I. W., & Moe, I. R. (2022). Flood Prediction due to Land Cover Change in the Ciliwung River Basin. International Journal of Technology, 13(2), 356–366. doi:10.14716/ijtech.v13i2.4662.

[21] Theochari, A. P., & Baltas, E. (2024). The Nature-Based Solutions and climate change scenarios toward flood risk management in the greater Athens area—Greece. Natural Hazards, 120(5), 4729–4747. doi:10.1007/s11069-024-06409-3.

[22] Costa, S., Peters, R., Martins, R., Postmes, L., Keizer, J. J., & Roebeling, P. (2021). Effectiveness of nature-based solutions on pluvial flood hazard mitigation: The case study of the city of Eindhoven (the Netherlands). Resources, 10(3), 24. doi:10.3390/resources10030024.

[23] Corgo, J., Cruz, S. S., & Conceição, P. (2024). Nature-based solutions in spatial planning and policies for climate change adaptation: A literature review. Ambio, 1599–1617. doi:10.1007/s13280-024-02052-1.

[24] Pellerey, V., & Torabi Moghadam, S. (2025). A place-based framework for assessing the effectiveness of inclusive climate actions for nature-based solutions in cities. Journal of Cleaner Production, 486, 144566. doi:10.1016/j.jclepro.2024.144566.

[25] Azadgar, A., Gańcza, A., Asl, S. R., Salata, S., & Nyka, L. (2025). Optimizing nature-based solutions for urban flood risk mitigation: A multi-objective genetic algorithm approach in Gdańsk, Poland. Science of The Total Environment, 963, 178303. doi:10.1016/j.scitotenv.2024.178303.

[26] Bayissa, Y., Srinivasan, R., Hunink, J., Nyolei, D., Moges, S., de Andrade Costa, D., Tadesse, D., Melesse, A., & Tilahun, S. (2025). Evaluating the potential of Nature-based solutions to mitigate land use and climate change impacts on the hydrology of the Gefersa and Legedadi watersheds in Ethiopia. Journal of Hydrology: Regional Studies, 57, 102130. doi:10.1016/j.ejrh.2024.102130.

[27] P, A., N.R, C., & Firoz C, M. (2024). A framework for urban pluvial flood resilient spatial planning through blue-green infrastructure. International Journal of Disaster Risk Reduction, 103(February), 104342. doi:10.1016/j.ijdrr.2024.104342.

[28] Ghosh, P., Sudarsan, J. S., & Nithiyanantham, S. (2024). Nature-Based Disaster Risk Reduction of Floods in Urban Areas. Water Resources Management, 38(6), 1847–1866. doi:10.1007/s11269-024-03757-4.

[29] Ferrario, F., Mourato, J. M., Rodrigues, M. S., & Dias, L. F. (2024). Evaluating Nature-based Solutions as urban resilience and climate adaptation tools: A meta-analysis of their benefits on heatwaves and floods. Science of the Total Environment, 950. doi:10.1016/j.scitotenv.2024.175179.

[30] Esraz-Ul-Zannat, Md., Dedekorkut-Howes, A., & Morgan, E. A. (2024). A review of nature-based infrastructures and their effectiveness for urban flood risk mitigation. WIREs Climate Change, 15(5), e889. doi:10.1002/wcc.889.

[31] Zhu, Q., Klaar, M., Willis, T., & Holden, J. (2024). A Quantitative Review of Natural Flood Management Research. WIREs Water, 12(1), 1765. doi:10.1002/wat2.1765.

[32] BAPPEDA. (2022). Regional medium-term development plan. BAPPEDA Jakarta Provincial Government, Jakarta, Indonesia. Available online: https://bappeda.jakarta.go.id/rpjmd/ (accessed on April 2025).

[33] IUCN. (2020). IUCN Global Standard for Nature-based Solutions: a user-friendly framework for the verification, design and scaling up of NbS: first edition. In IUCN Global Standard for Nature-based Solutions: a user-friendly framework for the verification, design and scaling up of NbS: first edition. IUCN International Union for Conservation of Nature, Gland, Switzerland. doi:10.2305/iucn.ch.2020.08.en.

[34] Sari, P., Legono, D., & Sujono, J. (2018). Performance of Retarding Basin in Flood Disaster Risk Mitigation in Welang River, East Java Province, Indonesia. Journal of the Civil Engineering Forum, 4(2), 109. doi:10.22146/jcef.31938.

[35] Ferreira, C. S. S., Kašanin-Grubin, M., Solomun, M. K., Sushkova, S., Minkina, T., Zhao, W., & Kalantari, Z. (2023). Wetlands as nature-based solutions for water management in different environments. Current Opinion in Environmental Science and Health, 33. doi:10.1016/j.coesh.2023.100476.

[36] Wurbs, R. A. (2021). Monthly river flows in Texas for natural and developed conditions. Water Cycle, 2, 1–14. doi:10.1016/j.watcyc.2020.10.001.

[37] Zhao, Y., Ji, B., Liu, R., Ren, B., & Wei, T. (2020). Constructed treatment wetland: Glance of development and future perspectives. Water Cycle, 1, 104–112. doi:10.1016/j.watcyc.2020.07.002.

[38] El Bouzidi, A., Anouar, A., & Bouzziri, M. (2024). Management and valuation of rainwater by alternative techniques, case of the university of Settat, in Morocco. Water Cycle, 5, 109–120. doi:10.1016/j.watcyc.2024.03.001.

[39] Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., & Sanchez, A. (2019). Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. Journal of Environmental Management, 239(March), 244–254. doi:10.1016/j.jenvman.2019.03.036.

[40] Auerswald, K., Moyle, P., Paul Seibert, S., & Geist, J. (2019). HESS Opinions: Socio-economic and ecological trade-offs of flood management-benefits of a transdisciplinary approach. Hydrology and Earth System Sciences, 23(2), 1035–1044. doi:10.5194/hess-23-1035-2019.

[41] Babí Almenar, J., Elliot, T., Rugani, B., Philippe, B., Navarrete Gutierrez, T., Sonnemann, G., & Geneletti, D. (2021). Nexus between nature-based solutions, ecosystem services and urban challenges. Land Use Policy, 100. doi:10.1016/j.landusepol.2020.104898.

[42] Chiu, Y. Y., Raina, N., & Chen, H. E. (2022). Evolution of flood defense strategies: Toward nature-based solutions. Environments, 9(1), 2. doi:10.3390/environments9010002.

[43] Christiana, D. W. (2023). Building Resilience through Nature-based Solutions: Exploring the Urban-Rural Linkages in Flood Mitigation Strategies for Jayapura. Smart City, 3(2), 3. doi:10.56940/sc.v3.i2.3.

[44] Guimarães, L. F., Teixeira, F. C., Pereira, J. N., Becker, B. R., Oliveira, A. K. B., Lima, A. F., Veról, A. P., & Miguez, M. G. (2021). The challenges of urban river restoration and the proposition of a framework towards river restoration goals. Journal of Cleaner Production, 316. doi:10.1016/j.jclepro.2021.128330.

[45] Ibrahim, A. S., Al Zayed, I. S., Abdelhaleem, F. S., Afify, M. M., Ahmed, A., & Abd-Elaty, I. (2023). Identifying cost-effective locations of storage dams for rainfall harvesting and flash flood mitigation in arid and semi-arid regions. Journal of Hydrology: Regional Studies, 50, 101526. doi:10.1016/j.ejrh.2023.101526.

[46] Kaiser, N. N., Ghermandi, A., Feld, C. K., Hershkovitz, Y., Palt, M., & Stoll, S. (2021). Societal benefits of river restoration – Implications from social media analysis. Ecosystem Services, 50. doi:10.1016/j.ecoser.2021.101317.

[47] Reu Junqueira, J., Serrao-Neumann, S., & White, I. (2022). Using green infrastructure as a social equity approach to reduce flood risks and address climate change impacts: A comparison of performance between cities and towns. Cities, 131, 104051. doi:10.1016/j.cities.2022.104051.

[48] Xu, C., Tang, T., Jia, H., Xu, M., Xu, T., Liu, Z., Long, Y., & Zhang, R. (2019). Benefits of coupled green and grey infrastructure systems: Evidence based on analytic hierarchy process and life cycle costing. Resources, Conservation and Recycling, 151, 1–10. doi:10.1016/j.resconrec.2019.104478.

[49] Kõiv-Vainik, M., Kill, K., Espenberg, M., Uuemaa, E., Teemusk, A., Maddison, M., Palta, M. M., Török, L., Mander, Ü., Scholz, M., & Kasak, K. (2022). Urban stormwater retention capacity of nature-based solutions at different climatic conditions. Nature-Based Solutions, 2, 100038. doi:10.1016/j.nbsj.2022.100038.

[50] Ruangpan, L., Vojinovic, Z., Plavšić, J., Curran, A., Rosic, N., Pudar, R., Savic, D., & Brdjanovic, D. (2024). Economic assessment of nature-based solutions to reduce flood risk and enhance co-benefits. Journal of Environmental Management, 352. doi:10.1016/j.jenvman.2023.119985.

[51] Tayefi Nasrabadi, M. (2022). How do nature-based solutions contribute to urban landscape sustainability? Environment, Development and Sustainability, 24(1), 576–591. doi:10.1007/s10668-021-01456-3.

[52] Ramírez-Agudelo, N. A., Badia, M., Villares, M., & Roca, E. (2022). Assessing the benefits of nature-based solutions in the Barcelona metropolitan area based on citizen perceptions. Nature-Based Solutions, 2, 100021. doi:10.1016/j.nbsj.2022.100021.

[53] Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (2016). Nature-based solutions to address global societal challenges. IUCN International Union for Conservation of Nature, Gland, Switzerland. doi:10.2305/iucn.ch.2016.13.en.

[54] Jakubínský, J., Prokopová, M., Raška, P., Salvati, L., Bezak, N., Cudlín, O., Cudlín, P., Purkyt, J., Vezza, P., Camporeale, C., Daněk, J., Pástor, M., & Lepeška, T. (2021). Managing floodplains using nature-based solutions to support multiple ecosystem functions and services. WIREs Water, 8(5), e1545. doi:10.1002/wat2.1545.

[55] Mubeen, A., Ruangpan, L., Vojinovic, Z., Sanchez Torrez, A., & Plavšić, J. (2021). Planning and Suitability Assessment of Large-scale Nature-based Solutions for Flood-risk Reduction. Water Resources Management, 35(10), 3063–3081. doi:10.1007/s11269-021-02848-w.

[56] Oral, H. V., Carvalho, P., Gajewska, M., Ursino, N., Masi, F., van Hullebusch, E. D., Kazak, J. K., Exposito, A., Cipolletta, G., Andersen, T. R., Finger, D. C., Simperler, L., Regelsberger, M., Rous, V., Radinja, M., Buttiglieri, G., Krzeminski, P., Rizzo, A., Dehghanian, K., … Zimmermann, M. (2020). A review of nature-based solutions for urban water management in European circular cities: A critical assessment based on case studies and literature. Blue-Green Systems, 2(1), 112–136. doi:10.2166/bgs.2020.932.

[57] Qi, Y., Chan, F. K. S., Thorne, C., O'donnell, E., Quagliolo, C., Comino, E., Pezzoli, A., Li, L., Griffiths, J., Sang, Y., & Feng, M. (2020). Addressing challenges of urban water management in chinese sponge cities via nature-based solutions. Water (Switzerland), 12(10), 2788. doi:10.3390/w12102788.

[58] Edamo, M. L., Bushira, K. M., Ukumo, T. Y., Ayele, M. A., Alaro, M. A., & Borko, H. B. (2022). Effect of climate change on water availability in Bilate catchment, Southern Ethiopia. Water Cycle, 3, 86–99. doi:10.1016/j.watcyc.2022.06.001.

[59] Balzan, M. V, Zulian, G., Maes, J., & Borg, M. (2021). Assessing urban ecosystem services to prioritise nature-based solutions in a high-density urban area. Nature-Based Solutions, 1, 100007. doi:10.1016/j.nbsj.2021.100007.

[60] Battemarco, B. P., Tardin-Coelho, R., Veról, A. P., de Sousa, M. M., da Fontoura, C. V. T., Figueiredo-Cunha, J., Barbedo, J. M. R., & Miguez, M. G. (2022). Water dynamics and blue-green infrastructure (BGI): Towards risk management and strategic spatial planning guidelines. Journal of Cleaner Production, 333. doi:10.1016/j.jclepro.2021.129993.

[61] Biswal, B. K., Bolan, N., Zhu, Y. G., & Balasubramanian, R. (2022). Nature-based Systems (NbS) for mitigation of stormwater and air pollution in urban areas: A review. Resources, Conservation and Recycling, 186, 106578. doi:10.1016/j.resconrec.2022.106578.

[62] Fowdar, H. S., Neo, T. H., Ong, S. L., Hu, J., & McCarthy, D. T. (2022). Performance analysis of a stormwater green infrastructure model for flow and water quality predictions. Journal of Environmental Management, 316. doi:10.1016/j.jenvman.2022.115259.

[63] García Sánchez, F., & Govindarajulu, D. (2023). Integrating blue-green infrastructure in urban planning for climate adaptation: Lessons from Chennai and Kochi, India. Land Use Policy, 124, 0–3. doi:10.1016/j.landusepol.2022.106455.

[64] Nehren, U., Arce-Mojica, T., Barrett, A. C., Cueto, J., Doswald, N., Janzen, S., Lange, W., Vargas, A. O., Pirazan-Palomar, L., Renaud, F. G., Sandholz, S., Sebesvari, Z., Sudmeier-Rieux, K., & Walz, Y. (2023). Towards a typology of nature-based solutions for disaster risk reduction. Nature-Based Solutions, 3, 100057. doi:10.1016/j.nbsj.2023.100057.

[65] Schindler, S., Sebesvari, Z., Damm, C., Euller, K., Mauerhofer, V., Schneidergruber, A., Biró, M., Essl, F., Kanka, R., Lauwaars, S. G., Schulz-Zunkel, C., van der Sluis, T., Kropik, M., Gasso, V., Krug, A., Pusch, M. T., Zulka, K. P., Lazowski, W., Hainz-Renetzeder, C., … Wrbka, T. (2014). Multifunctionality of floodplain landscapes: Relating management options to ecosystem services. Landscape Ecology, 29(2), 229–244. doi:10.1007/s10980-014-9989-y.

[66] Wang, Y., Huang, C., Wu, G., & Wang, W. (2022). Status and challenges of water resources and supply in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) of China. Water Cycle, 3, 65–70. doi:10.1016/j.watcyc.2022.05.001.

[67] Maheng, D., Bhattacharya, B., Zevenbergen, C., & Pathirana, A. (2024). Changing Urban Temperature and Rainfall Patterns in Jakarta: A Comprehensive Historical Analysis. Sustainability (Switzerland), 16(1), 1–20. doi:10.3390/su16010350.

[68] Zhang, H., Liu, X., Xie, Y., Gou, Q., Li, R., Qiu, Y., Hu, Y., & Huang, B. (2022). Assessment and Improvement of Urban Resilience to Flooding at a Subdistrict Level Using Multi-Source Geospatial Data: Jakarta as a Case Study. Remote Sensing, 14(9), 2010. doi:10.3390/rs14092010.

[69] Wijayanti, P., Zhu, X., Hellegers, P., Budiyono, Y., & van Ierland, E. C. (2017). Estimation of river flood damages in Jakarta, Indonesia. Natural Hazards, 86(3), 1059–1079. doi:10.1007/s11069-016-2730-1.

[70] Budiyono, Y., Aerts, J. C. J. H., Tollenaar, D., & Ward, P. J. (2016). River flood risk in Jakarta under scenarios of future change. Natural Hazards and Earth System Sciences, 16(3), 757–774. doi:10.5194/nhess-16-757-2016.

[71] Gao, P., Li, P., Zhao, B., Xu, R., Zhao, G., Sun, W., & Mu, X. (2017). Use of double mass curves in hydrologic benefit evaluations. Hydrological Processes, 31(26), 4639–4646. doi:10.1002/hyp.11377.

[72] Riazi, M., Khosravi, K., Shahedi, K., Ahmad, S., Jun, C., Bateni, S. M., & Kazakis, N. (2023). Enhancing flood susceptibility modeling using multi-temporal SAR images, CHIRPS data, and hybrid machine learning algorithms. Science of the Total Environment, 871, 162066. doi:10.1016/j.scitotenv.2023.162066.

[73] Shahimi, S. N. A., Halim, M. A., & Khalid, N. (2021). Comparison of Watershed Delineation Accuracy using Open Source DEM Data in Large Area. IOP Conference Series: Earth and Environmental Science, 767(1), 012029. doi:10.1088/1755-1315/767/1/012029.

[74] Li, L., Yang, J., & Wu, J. (2019). A method of watershed delineation for flat terrain using sentinel-2A imagery and DEM: A case study of the Taihu basin. ISPRS International Journal of Geo-Information, 8(12), 528. doi:10.3390/ijgi8120528.

[75] Zafar, Z., Zubair, M., Zha, Y., Fahd, S., & Ahmad Nadeem, A. (2024). Performance assessment of machine learning algorithms for mapping of land use/land cover using remote sensing data. Egyptian Journal of Remote Sensing and Space Science, 27(2), 216–226. doi:10.1016/j.ejrs.2024.03.003.

[76] Ben Khélifa, W., & Mosbahi, M. (2022). Modeling of rainfall-runoff process using HEC-HMS model for an urban ungauged watershed in Tunisia. Modeling Earth Systems and Environment, 8(2), 1749–1758. doi:10.1007/s40808-021-01177-6.

[77] Hassan, Z., Razali, N. H. M., Kamarudzaman, A. N., Salwa, M. Z. M., & Nordin, N. A. S. (2023). Preliminary Study on Flood Simulation using the HEC-HMS Model for Muda River, Malaysia. IOP Conference Series: Earth and Environmental Science, 1135(1), 012021. doi:10.1088/1755-1315/1135/1/012021.

[78] AL-Hussein, A. A. M., Khan, S., Ncibi, K., Hamdi, N., & Hamed, Y. (2022). Flood Analysis Using HEC-RAS and HEC-HMS: A Case Study of Khazir River (Middle East—Northern Iraq). Water (Switzerland), 14(22), 3779. doi:10.3390/w14223779.

[79] Mishra, B. K., Rafiei Emam, A., Masago, Y., Kumar, P., Regmi, R. K., & Fukushi, K. (2018). Assessment of future flood inundations under climate and land use change scenarios in the Ciliwung River Basin, Jakarta. Journal of Flood Risk Management, 11, S1105–S1115. doi:10.1111/jfr3.12311.

[80] Nkeki, F. N., Bello, E. I., & Agbaje, I. G. (2022). Flood risk mapping and urban infrastructural susceptibility assessment using a GIS and analytic hierarchical raster fusion approach in the Ona River Basin, Nigeria. International Journal of Disaster Risk Reduction, 77(January), 103097. doi:10.1016/j.ijdrr.2022.103097.

[81] Tunas, I. G., Arafat, Y., & Azikin, H. (2019). Integration of Digital Elevation Model (DEM) and HEC-RAS Hydrodynamic Model for flood routing. IOP Conference Series: Materials Science and Engineering, 620(1), 012026. doi:10.1088/1757-899X/620/1/012026.

[82] Corsita, L., Muntalif, B. S., & Salami, I. R. S. (2014). The Hydrological Regimes,Water Quality Assesment and Trophic Status Of The Reservoir (Case Study: Jatiluhur Cascade Citarum Reservoir). International Conference on Latest Trends in Food, Biological & Ecological Sciences (ICLTFBE'14) July 15-16, Phuket, Thailand. doi:10.17758/iaast.a0714022.

[83] Wardhani, E., & Sugiarti, Z. A. (2021). Jatiluhur Reservoir Water Quality Analysis at Various Depths. Precipitation Journal: Communication Media and Environmental Engineering Development, 18(3), 400–411. doi:10.14710/presipitasi.v18i3.400-411.

[84] Nasution, B. I., Saputra, F. M., Kurniawan, R., Ridwan, A. N., Fudholi, A., & Sumargo, B. (2022). Urban vulnerability to floods investigation in jakarta, Indonesia: A hybrid optimized fuzzy spatial clustering and news media analysis approach. International Journal of Disaster Risk Reduction, 83, 103407. doi:10.1016/j.ijdrr.2022.103407.

[85] Lu, P., Sun, Y., & Steffen, N. (2023). Scenario-based performance assessment of green-grey-blue infrastructure for flood-resilient spatial solution: A case study of Pazhou, Guangzhou, greater Bay area. Landscape and Urban Planning, 238, 104804. doi:10.1016/j.landurbplan.2023.104804.

[86] Chairat, S., & Gheewala, S. H. (2024). The conceptual quantitative assessment framework for Nature-based Solutions (NbS). Nature-Based Solutions, 6(July), 100152. doi:10.1016/j.nbsj.2024.100152.

[87] Zang, Y., Meng, Y., Guan, X., Lv, H., & Yan, D. (2022). Study on urban flood early warning system considering flood loss. International Journal of Disaster Risk Reduction, 77(May), 103042. doi:10.1016/j.ijdrr.2022.103042.

[88] Yin, D., Chen, Y., Jia, H., Wang, Q., Chen, Z., Xu, C., Li, Q., Wang, W., Yang, Y., Fu, G., & Chen, A. S. (2021). Sponge city practice in China: A review of construction, assessment, operational and maintenance. Journal of Cleaner Production, 280, 124963. doi:10.1016/j.jclepro.2020.124963.

[89] Li, Q., Wang, F., Yu, Y., Huang, Z., Li, M., & Guan, Y. (2019). Comprehensive performance evaluation of LID practices for the sponge city construction: A case study in Guangxi, China. Journal of Environmental Management, 231(October), 10–20. doi:10.1016/j.jenvman.2018.10.024.

[90] Freni, G., & Liuzzo, L. (2019). Effectiveness of rainwater harvesting systems for flood reduction in residential urban areas. Water (Switzerland), 11(7), 1389. doi:10.3390/w11071389.

[91] Jamali, B., Bach, P. M., & Deletic, A. (2020). Rainwater harvesting for urban flood management – An integrated modelling framework. Water Research, 171, 115372. doi:10.1016/j.watres.2019.115372.

[92] Custódio, D. A., & Ghisi, E. (2023). Impact of residential rainwater harvesting on stormwater runoff. Journal of Environmental Management, 326. doi:10.1016/j.jenvman.2022.116814.

[93] Huynh Thi Ngoc, C., Back, Y., Funke, F., Hauser, M., & Kleidorfer, M. (2024). Implementation of Nature-Based Solutions in Urban Water Management in Viet Nam, a Comparison among European and Asian Countries. Sustainability (Switzerland), 16(20), 8812. doi:10.3390/su16208812.

[94] Sciuto, L., Licciardello, F., Giuffrida, E. R., Barresi, S., Scavera, V., Verde, D., Barbagallo, S., & Cirelli, G. L. (2025). Hydrological-hydraulic modelling to assess Nature-Based Solutions for flood risk mitigation in an urban area of Catania (Sicily, Italy). Nature-Based Solutions, 7. doi:10.1016/j.nbsj.2024.100210.

[95] Nugraha, G. U., Lubis, R. F., Bakti, H., & Hartanto, P. (2021). Groundwater Recharge Estimation Using Water Budget and Water Table Fluctuation Method in the Jakarta Groundwater Basin. Indonesian Association of Geologists Journal, 1(1), 25–38. doi:10.51835/iagij.2021.1.1.12.

[96] Ershad Sarabi, S., Han, Q., L. Romme, A. G., de Vries, B., & Wendling, L. (2019). Key Enablers of and Barriers to the Uptake and Implementation of Nature-Based Solutions in Urban Settings: A Review. Resources, 8(3), 121. doi:10.3390/resources8030121.