Nature-Based Solutions for Flood Mitigation in Metropolitan Areas

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ABSTRACT

Flooding is a globally common problem in metropolitan areas including Jakarta, Indonesia. The increased intensity and frequency of rainfall caused by climate change and rapid urbanization have raised the risk of flooding in urban areas. One solution is to implement polders to mitigate flooding in coastal metropolitan areas. Regrettably, the current polder system is inadequate for managing flooding due to rapid land-use changes and regional expansion. This study analyzes flood control in the Jakarta region using the East Sunter Polder System, which experienced flooding in both 1990 and 2020 despite the implementation of the polder system. The polder system, consisting of four catchment areas—Petukangan, KBN 1/Sukapura, KBN 2, and Kebantenan—faces drainage challenges exacerbated by rainfall. To mitigate flood risks, Nature-Based Solutions (NBSs) have been implemented, including retention ponds and long storage systems. Hydrological and hydraulic analyses were conducted using HEC-HMS and HEC-RAS, and ArcGIS was employed for floodplain integration. This study underscores the significance of incorporating NBSs in urban flood management, demonstrating how they enhance resilience and mitigate flood risks. By integrating NBSs into the urban planning framework, the findings suggest that flood risk management can be significantly improved, leading to better preparation and long-term sustainability for managing natural hazards.

Keywords-flood; HEC-HMS; HEC-RAS; NBSs

I. INTRODUCTION

Flooding is a prevalent issue in urban regions including Indonesia. The heightened intensity and frequency of rainfall due to climate change [1, 2] compounded by rapid urbanization has increased the risk of flooding in metropolitan areas. The combination of population growth and scarcity of green open spaces and water catchment areas, replaced by impermeable infrastructure with inadequate water absorption capacity, prevents rainwater from infiltrating the ground, causing it to flow directly into the urban drainage system, which frequently cannot manage high volumes, leading to flooding [3]. To overcome this problem, a sustainable solution using a holistic approach that can be functionally useful is needed. One approach that can be used is the Nature-Based Solution (NBS) approach, which adopts natural processes for addressing environmental challenges such as flooding, drought, and climate change [4, 5]. Some examples of NBS implementation to address urban flooding are the development of green open spaces, the application of green roofs and walls, the restoration of natural rivers and canals, bioretension and rain gardens, use of permeable pavement materials, planting mangroves and coastal forests, and creation of retention ponds and artificial wetlands [6, 7]. This solution is more suitable for flood reduction in urban areas because, in addition to affecting environmental sustainability, it also benefits society and the economy, particularly in the context of climate change and rapid urbanization [8].

The selection of the NBS application to be used is highly dependent on the type of flooding that occurs and the characteristics of the location [8, 9]. For urban areas, although some riverbank areas, such as wetlands to facilitate infiltration, have been restored, the risk of flooding is still high. For coastal cities, such as Jakarta, the risk of flooding is exacerbated by rising sea levels that affect the urban drainage capacity through the effects of backwater [10, 11]. Therefore, flood management in urban areas such as Jakarta requires a combination of drainage systems, retention ponds, embankments surrounding the area, and pumps/floodgates as inseparable units of water management. This type of water management system is called a polder and is used to remove water from lowlands and ward off floodwater in delta and watershed areas [12, 13]. A polder area is characterized as a low-lying region where gravity drainage is unfeasible, necessitating isolation and protection from the surrounding environment by the construction of embankments. The polder region possesses an independent drainage system, and when feasible, drainage canals may be constructed to converge into a substantial collecting channel before being directed to the pump house [14, 15]. The uniqueness of this system is that there is a detention pond, known as an infiltration pond that is designed to collect stormwater for a specific duration of time combined with the use of pumps to channel the excess storage to discharge. These detention ponds have been suggested as the best alternative stormwater management for reducing flood peaks [8, 16]. However, their effectiveness in reducing stormwater runoff and peak flow has not been evaluated in the reviewed literature. Studies have shown that a single large retention pond is more cost-effective than a collection of small ponds for reducing flood peak flows [17]. Therefore, this study assesses the use of detention ponds as NBSs to determine its effectiveness in reducing flooding in urban areas.

II. STUDY LOCATION AND METHODOLOGY

The location of this research is one of the Jakarta metropolitan areas, called the East Sunter Polder System, located in the north and east of Jakarta, Indonesia [18]. Geographically, the location of the eastern polder system is at 6° 11' 1.008" S to 6° 6' 24.005" S and 79° 5' 7.716" W to 79° 3' 33.235" W. The study area has an altitude from 0 to 16 m. The morphological form of the plains is formed by alluvium and clastic rock deposits. The height difference between the lowest and highest elevations is ± 16 m, with a dominant slope of 5% to 15%, as shown in Figure 1.

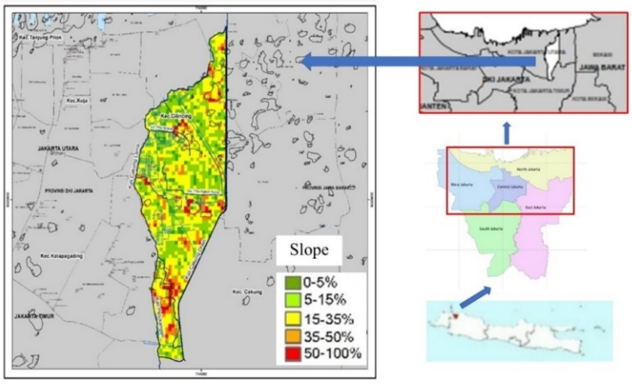
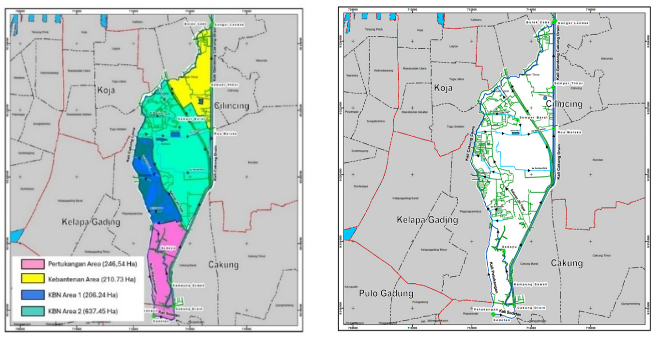


Fig. 1. East Sunter Polder System in Jakarta.

Based on data from 2021 [19], inundation during rainfall often occurs in several areas with the inundation height being between 5 and 100 cm. This is due to significant Land-Use Land Cover (LULC) changes caused by the expansion of urban areas from 1990 to 2020. The impact of the expansion of urban areas is the emergence of various developments in Jakarta, such as roads, houses, offices, warehouses, and other buildings that reduce the available land. Based on the flood control master plan of 1991, drainage system management is divided into eight drainage zones [18], where the division is based on watershed boundaries (Figure 2(a)).



(a) (b)

Fig. 2. (a) Sub catchment area and (b) drainage system of the East Sunter Polder System.

As for flood control, considering the characteristics of Jakarta city, which has an elevation of +6 m above sea level and land subsidence, the excess water cannot use the gravity flow method, so the area has the potential to be built as a polder system. The drainage system of the study area, namely the East Sunter Polder System, is divided into four catchment areas: the Petukangan Catchment area with an area of ±245 Ha, the KBN 1/Sukapura catchment area with an area of ±206 Ha, the KBN 2 catchment area with an area of ±637 Ha, and the Kebantenan catchment area with an area of ±211 ha, as shown in Figure 2(b). The receiving water bodies are the Cakung Drain, Gendong Cakung Drain, and Cakung Lama Rivers. The land use in the east sunter polder system area is shown in Table I. As shown in Table I, the permeable area in the East Sunter is 16.21%.

TABLE I. LAND USE IN THE STUDY AREA

Land Use	Percentage
Retention	1.54%
Residential	27.81%
Industry	44.42%
Land	14.67%
Agriculture	1.30%
Field	0.04%
Health services	0.15%
School	0.89%
Government offices	0.31%
Religious facilities	1.77%
Tourism facilities	0.46%
Cemetery	0.66%
Station	4.03%

III. METHODOLOGY

The following procedures were part of the process used to create floodplain maps (Figure 3).

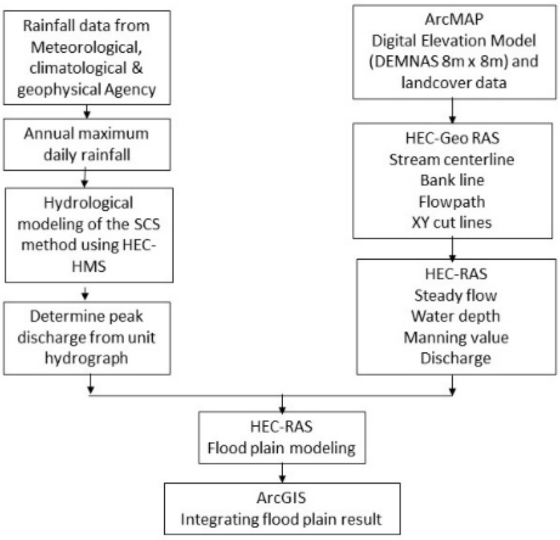


FIG. 3. Flowchart for HEC-HMS and HEC-RAS, modified from [20].

A total of 10 years of rainfall data from three rainfall stations from an open-source meteorological, climatological, and geophysical agency website were coonsidered [21]. Floods with different return periods can be obtained by (a) analyzing the frequency of floods using the available observed discharge data, (b) creating a dem using Demnas data [17], (c) using ArcGIS to delineate the watershed and drainage network, (d) using HEC-HMS for hydrology analysis, (e) applying HEC-RAS to multiple potential flow scenarios corresponding to floods with different return periods, and (f) creating a floodplain map using ArcGIS integration.

A. Hydrology Analysis

Three rainfall stations were used for the Cakung polder system, namely the Pulo Gadung Rain, the Rorotan, and the Kodamar stations. The duration of the rainfall observations obtained was 10 years from to 2011-2020 for the three rainfall posts. Peak discharges during different return periods are required to determine the water surface profiles and amount of flooding under different flood intensities. Flood frequency analysis of the Cakung Drain was conducted to ascertain the flood peaks for different return periods. The five most commonly used frequency distribution functions for estimating extreme floods are log-normal distribution, Pearson distribution, Gumbel 's or extreme value distribution, Log-Pearson Type III (LPT-III) distribution, and normal distribution. These distributions were used for frequency analysis. Using a 95% confidence interval, the Kolmogorov-Smirnov (KS) test was used to determine the best distribution for estimating flood peaks. The LPT-III distribution computes the rainfall intensity for a range of durations and return periods using logarithmic transformation. To ascertain the return period values for the dataset, we employed LPT-III to examine the highest yearly rainfall events. LPT-III is considered more appropriate for rainfall design analysis than other approaches. The results of the investigation verified that LPT-III is suitable for this examination.

B. Runoff Analysis

The NRCS runoff estimation method is typically used for urban flooding. This method has been published by the United States Department of Agriculture (USDA). The equations used are:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{1}$$

$$S = \frac{25400}{CN} - 254 \tag{2}$$

$$T_C = 0.0195 L^{0.77} Y^{-0.385} \tag{3}$$

$$T_L = 0.6\, x\, T_C \tag{4}$$

where Q is the of run-off discharge (m^3/s), P is the average rainfall (mm), I_a is the initial abstraction before runoff occurs, S is the potential retention after rainfall occurs, CN is the NRCS runoff Curve Number, T_c is the concentration time (min), T_L is the lag time (min), L is the channel length (m), and Y is the average slope of the sub-catchment (m/m).

The Kinematic Wave method in an alternative empirical UH model, HEC-HMS, includes a conceptual model of the watershed response. This model represents the watershed as an open channel (a very wide open channel), with inflow to the channel equal to the excess rainfall. Then, equations that simulate unsteady shallow water flow in the open channel were solved to calculate the watershed runoff hydrograph [22].

$$S_f = S_O - \frac{\partial y}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} \tag{5}$$

where S_f is the energy gradient, S_O is the bottom slope, V is the flow velocity, Y is the hydraulic depth, X is the flow length, and g is the gravitational acceleration.

Numerous hydrological studies have extensively used the HEC-HMS model [23-26] to calculate flood water discharge hydrographs. A hydrograph explains the circumstances and features of a watershed. Consequently, the form of the hydrograph is altered in tandem with changes in the properties of the watershed. Therefore, to create a flood hydrograph that closely resembles the features of the Belibis River watershed, the sub-watershed area, length, and height of the river must be included in the HEC–HMS software model of the proposed flood. After all data were collected and processed, the process was continued with modeling on the HEC-HMS. In general, modeling on HEC-HMS consists of three sub-models: the Loss Model (using SCS Curve Number), the Transform Model (Using SCS Unit Hydrograph), and the Baseflow Model [27]. Modeling in HEC-HMS was conducted with two scenarios according to the existing scheme and the NBS schemes. The modeling scheme for HEC-HMS is shown in Figure 4. In this case study, the SCS Curve Number approach was used to calculate the loss rate due to the infiltration process. The initial loss, curve number, and imperviousness are among the parameters that must be supplied for the SCS Curve number in the HEC-HMS simulation. The parameter curve number is an empirical assumption made regarding various parameters related to soil layer porosity and land usage.

FIG. 4. The considered HEC-HMS model.

C. Hydraulic Analysis

The ArcGIS export file was imported into the HEC-RAS once each land class had *n* values assigned to it, and all necessary geometric data were completed. The watershed delineation, validation of watershed boundary, and determination of soil texture were based on the open-source data of Digital Elevation Data [28], watershed boundary [29], and soil-type map [30]. Transferring geometric data from ArcGIS to HEC-RAS was necessary for this process. The next stage was to provide the boundary conditions and steady flow data to the steady flow editor. The peak flows were entered into the HEC-RAS to calculate the expected flood level [31]. Levels along river lengths pass through the basin's inhabited areas. Following data entry, a thorough flow study was conducted using the HEC-RAS model. The prototype produced a thorough study report, including the discharge at each cross-section, flow depth, and additional details. The results were exported as an RAS Mapper export file once all the problems were fixed to ArcGIS. Following the creation of the floodplain and the water surface, the RAS Mapper export file was loaded into ArcGIS to produce a map of the natural floodplain.

IV. RESULTS AND DISCUSSION

The Belibis retention pond was used to reduce the existing flood discharge. It can be seen from its design, which has an area of 5 ha and a height of 4 m, that the inflow value that will enter the Belibis retention pond is approximately 25 m^3/s. This inflow is obtained from two main channels, namely from the Gubuk Genteng channel and the Progo river. In the presence of the retention pond, water from these two channels will first be collected in the retention pond and then released with a pump system. This was done to reduce the peak flood discharge. As shown in Figure 5, the red and blue lines represent the discharge at the initial and proposed conditions, respectively. There is a significant decrease in the discharge of approximately 37 m^3/s due to the diversion of the flow.

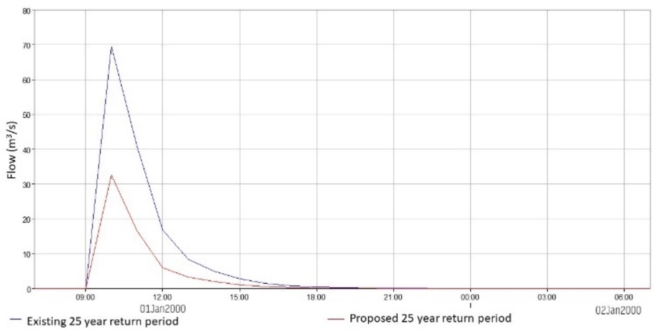
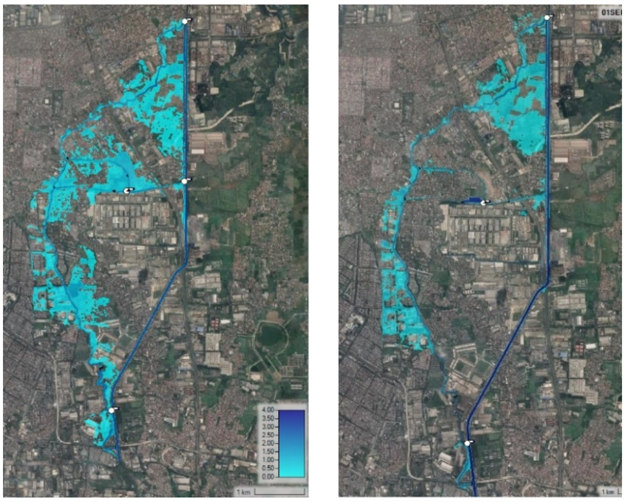


Fig. 5. Flood discharge.

Figure 6 illustrates that the establishment of the Belibis retention pond and supplementary storage diminished the flooded area by 46%, likely attributable to the reduction in peak surface runoff [31]. Authors in [32] researched rural water and sediment control basins in the USA and illustrated the efficacy of small-scale, nature-based methods for flood management. Authors in [33] performed a comparable study in Iowa, modeling the effects of 133 headwater dams within a 660 km² watershed. The dams, with capacities between 23,436 m³ and 15,591,201 m³, have the potential to diminish peak discharge in the primary river by 20–70%, based upon the frequency of events. Although these tiny dams had a negligible influence on frequent, low-discharge occurrences (e.g. a 2-year recurrence interval), their efficacy diminished during infrequent, high-magnitude events, such as a 1000-year recurrence interval, owing to lower surface runoff.



(a) (b)

Fig. 6. 2D Modeling results of (a) existing and (b) NBS using retention pond and long storage.

The Belibis retention pond, with its enhanced storage capacity, provides an effective option for managing anticipated flood flows linked to a 25-year return time. To achieve effective flood control, it is important to restore the river to its natural condition, facilitating enhanced flood management results [34]. The combined effects of climate change and urbanization on runoff characteristics indicate the need for adaptive retention systems that can dynamically respond to changing inflow patterns [35].

V. CONCLUSIONS

This study was conducted considering the East Sunter Polder System in Jakarta, Indonesia, which is affected by inundation during rainfall due to land cover changes caused by urban expansion. The polder system was divided into four catchment areas: Petukangan, KBN 1/Sukapura, KBN 2, and Kebantenan. The drainage system is divided into four areas, with the Cakung Drain, Gendong Cakung Drain, and Cakung Lama Rivers as the receiving water bodies. The methods used for hydrological and hydraulic analysis were HEC-HMS and HEC-RAS, respectively. ArcGIS was used to integrate the floodplains. The Belibis retention pond and additional storage reduced the flooded area by 46%, likely due to the decrease in peak surface runoff. Nature-Based Solutions (NBSs) are implemented in the flood mitigation scenario using retention ponds and long storage. This study provides significant insights on the use of large-scale retention ponds, such as the Belibis pond, in urban flood management. Nevertheless, many critical elements in the execution of the scenario require investigation, including the sustained effectiveness of retention ponds throughout various precipitation and climate conditions, as well as the sedimentation rates within the pond. Future research should investigate the integration of nature-based and structural interventions to improve flood resilience across various occurrence frequencies, assessing the performance of these integrated systems under diverse extreme weather scenarios.

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