Analysis of Compound Flooding in the Cakung Drain Area, DKI Jakarta Province

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Abstract. Cakung Drain is an artificial river located downstream of the Cakung and Buaran Rivers, established as part of Jakarta's flood control infrastructure. Administratively, the upper section of Cakung Drain is located in East Jakarta, while the lower section is in North Jakarta. The current capacity of Cakung Drain is insufficient to handle the flow during flood conditions, leading to persistent flooding in the area. Flood conditions downstream of Cakung Drain are exacerbated by the potential for Compound Flood, resulting from the simultaneous occurrence of two extreme conditions. Various initiatives to manage floods have been implemented in the Cakung Drain area. This study aims to evaluate the flood risk in the Cakung Drain area before and after the implementation of flood management structures, considering the impact of discharge and tidal conditions downstream influenced by waves and storm surges. Flood modelling is executed using HECRAS software employing both 1D and 2D approaches. The study's findings reveal that the flooded area under existing conditions spans 7.065 km². Under design conditions, flooding persists with an area of 4.15 km², attributed to flood overflow in downstream areas where embankments have not been constructed.

1 Introduction

DKI Jakarta is known as a flood-prone area, experiencing floods nearly every year. Between 2002 and 2019, the number of individuals affected by floods in Jakarta reached 2 million [1]. The causes of these floods can be divided into two categories: natural and non-natural. Natural factors contributing to floods in the study area include rainfall, soil type, and the slope of the terrain. On the other hand, non-natural factors leading to floods encompass changes in land usage and insufficient drainage capacity [2]. Geographically, 40% of DKI Jakarta has an elevation lower than sea level [3]. Jakarta is in proximity to coastal regions and is downstream of multiple rivers. The combination of these geographical conditions heightens Jakarta's susceptibility to the potential calamity of

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floods [4]. Flooding in Jakarta's coastal zones is compounded by land subsidence at a rate of 1-15 cm/year [5] and a sea level rise of 12 mm/year [6].

Efforts to mitigate flooding in Jakarta have been underway for an extended period. In 1973, the Jakarta government undertook structural development initiatives [7]. One of which was the construction of Cakung Drain. Cakung Drain is an artificial canal located in East Jakarta and flows downstream to North Jakarta, spanning 9.8 km. It channels the Cakung and Buaran rivers, which eventually flow into Jakarta Bay. The construction of Cakung Drain aims to reduce flooding in the Cakung River area. According to the flood model for the year 2014, overflow occurred along Cakung Drain, reaching a maximum height of 2 meters upstream [8]. Based on the 2020 Jakarta flood map by BPBD DKI Jakarta, there are still flooded areas around Cakung Drain (**Fig. 1**).

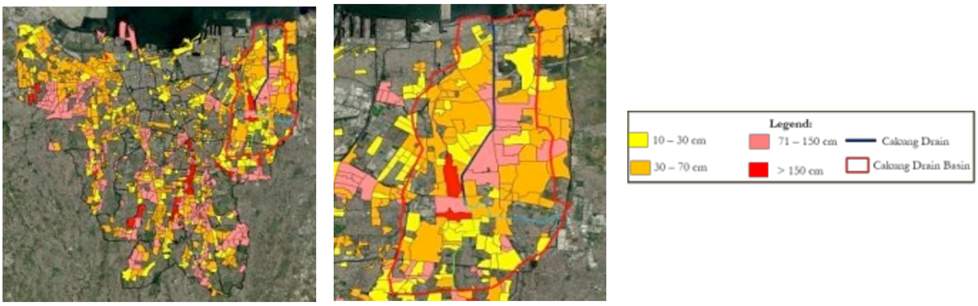

Fig. 1. Jakarta 2020 flood map

The Cakung Drain area is prone to flooding due to its proximity to the coast. In this coastal area, there is the potential for compound flooding. Compound flooding occurs when multiple flood-inducing factors, such as elevated water levels, precipitation, and increased river discharge, coincide or closely follow each other [9]. Within the Cakung Drain area, the risk of compound flooding emerges when there is a substantial discharge from the upstream coinciding with a high tide downstream, leading to an elevated water level downstream compared to normal conditions. The conditions conducive to compound flooding in coastal areas are primarily influenced by four factors: (1) the combination of tidal and high astronomical tide (storm surge); (2) waves generated either locally or remotely (storm waves); (3) river flow; and (4) direct surface runoff [10]. In coastal regions, the severity of compound flooding intensifies during intense rainfall events accompanied by storm conditions [11].

Several efforts have been made to reduce flooding in the Cakung Drain area, such as the design normalization of Cakung Drain through the Jakarta Emergency Dredging Initiative (JEDI) in 2010 and the construction of embankments at the mouth of Cakung Drain from 2021 to 2023. Therefore, this research discusses the flood conditions in the Cakung Drain area before and after the implementation of flood management measures. The flood modelling undertaken in this research considers various factors that could potentially elevate the risk of compound flooding in the Cakung Drain area. These factors encompass the impact of flood discharge, tides, waves, and storm surges on the extent of flooding in the Cakung Drain area.

2 Method

2.1 Hydrological analysis

The hydrological analysis is performed to forecast the planned flood discharge for a specific return period [12]. The data utilized includes rainfall data spanning 18 years (2004-2021). In conducting the hydrological analysis, the HECHMS software is utilized, known for its minimal margin of error in determining the planned flood discharge [13] [13_suzana]. The hydrological analysis employs the SCS-CN (Soil Conservation Service Curve Number) method, and the formula for this method is presented in the **Table 1.**

Table 1. Formulas and methods for hydrological analysis calculations

No	Parameter	Equation
1	CN Composite (CN)	$CN = \frac{\sum(CN_i \text{x} A_i)}{A}$ (1)
2	Initial Abstraction (I_a)	$I_a = 0{,}2\ \mathrm{S}$ (2)
3	Maximum Retention Potential (S)	$S = \frac{25400}{CN} - 254$ (3)
4	Time lag (t_p)	$t_p = C_1 C_t (LL_c)^{0.3}$ (4)
5	Rain Distribution	*PSA 007 6 Hours* (5)

2.2 Tide analysis

Tide analysis is conducted to obtain tide predictions. One of the tide prediction methods is the least square method. This method yields a relatively low RMSE value, indicating a close representation of the true tidal conditions [14]. In this study, the tide data used consists of observations from the Kolinlamil Station over a period of 30 days. By employing the Least Square Method, tide predictions for 18.6 years are obtained

2.3 Wave analysis

The purpose of wave analysis is to predict waves with a specific repeating period. In this paper, extreme wave conditions are utilized, specifically a repeat period of 100 years. The formation of waves is determined by utilizing wind data obtained from ECMWF over a duration of 15 years (2008-2022). The wave modelling technique is based on the Shore Protection Manual 1984. Parameters essential for wave prediction based on wind include: (1) Wind speed, (2) Fetch, (3) Duration of gust, (4) Wind direction. [15]. Formulas and methods used in wave analysis are presented in the **Table 2**.

Table 2. Formulas and methods for wave analysis calculations

No	Parameter	Equation
1	Fetch (Feff)	$F_{eff} = \frac{\sum Xi \cos \propto i}{\sum \cos \propto i}$ (6)
2	Height correction ($U10$)	$U_{10} = U(z)(\frac{10}{z})^{\frac{1}{7}}$ (7)
3	Stability correction (U)	$\mathrm{U} = R_T U_{10}$ (8)
4	Wind stress Faktor	$U_A = 0.72U^{1.23}$ (9)
5	Frequency Distribution	Log normal, Log Pearson, Normal, Gumbel (10)
6	Frequency Distribution Test	Chi-Square (11)

2.4 Hydrodynamic analysis

The use of hydrodynamic modelling aims to determine the correlation between wave impact and water level in the estuary. The software, Mike21, is capable of generating hydraulic models that replicate hydraulic phenomena while considering changes in water levels [16]. The information utilized in hydrodynamic modelling encompasses water bathymetry data, wave height and period, along with tidal data.

2.5 Storm surge analysis

The analysis of storm surge is utilized to ascertain the extent of tidal surge impacted by occurrences of storm surge [17]. Forecasting storm surge events in the Jakarta region involves applying one of the computations outlined in the WMO guidelines for storm modelling, specifically, the empirical Silvester storm surge prediction method [18]:

$$\frac{S}{d} = \frac{(K_{10}U^2 \quad {}_{10}L)}{2gd^2} \tag{12}$$

The computation of Storm Surge values is conducted for each wind occurrence from the northwest direction, leading to the determination of maximum Storm Surge values between 2008 and 2022. The assumption is based on earlier research, indicating that storms persist for 24 hours and the surge peak aligns with the highest tidal water level [11].

2.6 Hydraulic analysis

A capacity assessment of the canal was conducted through hydraulic analysis, considering the hydraulic features within the watershed [12]. The hydraulic modelling employed the

HEC-RAS software, utilizing the Unsteady Flow method and producing outcomes in both 1D and 2D. The equations used in the unsteady modelling are derived from the principles of mass conservation (continuity) and momentum conservation [19]. The formula equations are presented in the **Table 3**:

Table 3. Formulas for unsteady modelling calculations

No	Parameter	Equation
1	conservation of mass (continuity)	$\frac{\partial A_T}{\partial_T} + \frac{\partial Q}{\partial_x} = q_t \qquad (13)$
2	conservation of momentum	$\frac{\partial Q}{\partial t} + \frac{\partial (Q\ V)}{\partial_x} + g\ A(\frac{\partial Z_s}{\partial_x} + s_f) = 0 \qquad (14)$

Compound flood modelling in the Cakung Drain area occurs during extreme rainfall and extreme tides. In the Cakung Drain area, these conditions typically occur in February. Hydraulic modelling is conducted with several scenarios. The boundary conditions upstream involve the flood discharge for the planned return period, while downstream conditions involve various tidal surges. In the modelling, the highest tide coincides with the peak discharge. Detailed boundary conditions for each modelling scenario can be found in the **Table 4.**

Table 4. Downstream and upstream boundary conditions in several scenarios

Scenario	Upstream	Downstream	Geometry Condition
1	Q 25 :	Spring Tide	Existing
2		Spring Tide + Wave	Existing
3		Spring Tide + Storm	Existing
4		Spring Tide + Wave	Design
5		Spring Tide + Storm	Design

3 Result and discussion

3.1 Hydrological modelling

Based on the delineation results, the total area of the Cakung Drain watershed is 81.15 km^2, with a length of 9.8 km for the Cakung Drain channel. The calculated planned discharge for a return period of 25 years in the Cakung Drain area is 186.40 m^3/s.

3.2 Condition of HWL in the tidal surge scenario

The tidal analysis indicates a Highest Water Level (HWL) of 1.43 m due to tidal surges at the mouth of Cakung Drain. Wave analysis for a 100-year return period reveals a wave height of 4.54 m with an 11.4-second duration. Following hydrodynamic modelling, the

HWL influenced by waves is determined to be 1.46 m. Storm surge calculations yield a surge amplitude of 0.9, resulting in a storm-induced HWL of 2.35 m (**Fig. 2**).

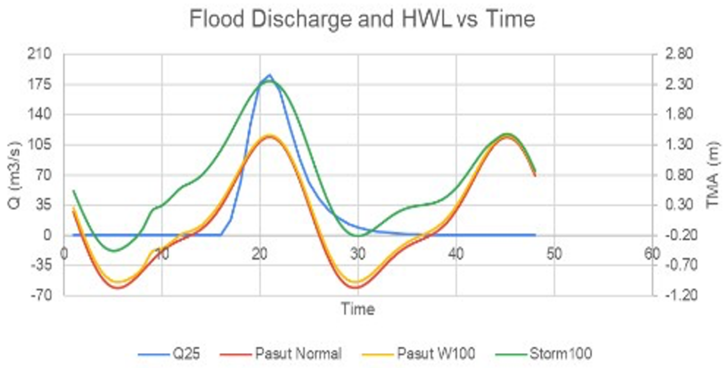

Fig. 2 Graph of distribution of flood discharge and tidal surges

3.3 Hydraulic modelling

The modelling results for scenarios 1-3 in the current condition indicate flooding in the upstream, middle, and downstream areas of Cakung Drain. The inundation area is consistent in the upstream and middle regions, while in the downstream area, it expands proportionally with the rising HWL values in each scenario. Figures illustrating the simulation results for 1D and 2D scenarios 1-3 are available (**Fig. 3**).

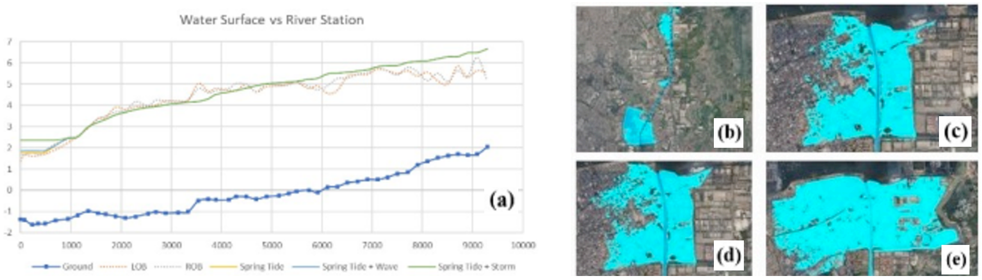

Fig. 3 (a) 1D flood modelling in existing condition; (b) 2D flood modelling in the upstream and middle regions; (c) 2D flood modelling downstream in scenario 1; (d) 2D flood modelling downstream in scenario 2; (e) 2D flood modelling downstream in scenario 3.

In scenario 4, where the discharge is based on Q25 and HWL is affected by waves, there is no flooding along Cakung Drain. However, scenario 5, influenced by storm surge, results in overflow in the estuary area without embankments, specifically 450 – 1176 m downstream from Cakung Drain. Visualization of the simulation results for 1D and 2D scenarios 4 and 5 is presented in the **Fig. 4**.

The flooding impact in each scenario is observed in two administrative cities: North Jakarta and East Jakarta. **Table 5** displays the extent of flooding in each affected neighbourhood.

Fig. 4 (a) 1D flood modelling in existing condition; (b) 2D flood modelling in scenario 4; (c) 2D flood modelling in scenario 5

Table 5. Flooded area calculation on several scenarios

	Flood Area (km²)				
Name	**1**	**2**	**3**	**4**	**5**
Flood cause Discharge	2.680	2.680	2.680	-	-
Flood cause Tide and Discharge	1.203	1.339	4.385		4.15
East Jakarta	**1.863**	**1.863**	**1.863**	**-**	**-**
Rawaterate	0.733	0.733	0.733	-	-
Cakung Barat	1.130	1.130	1.130	-	-
North Jakarta	**2.02**	**2.156**	**5.202**	**-**	**-**
Kalibaru	0.084	0.133	0.81	-	0.62
Semper Timur	0.59	0.591	1.24	-	0.7
Rorotan	0.094	0.095	0.095	-	-
Cilincing	1.165	1.25	2.97	-	2.83
Sukapura	0.087	0.087	0.087	-	-
Total	**3.883**	**4.019**	**7.065**	**0**	**4.15**

4 Conclusion

The HECRAS modelling results indicate that the Cakung Drain area is susceptible to flooding. In the absence of flood control structures (scenarios 1, 2, and 3), widespread flooding occurs in most of the Cakung Drain area, impacting 7 neighbourhoods. The total flooded area due to discharge is 2.68 km². In the downstream area, compound flooding occurs, expanding as the tide rises. During Spring Tide, the downstream inundation area is 1.203 km², Spring Tide affected by waves is 1.339 km², and during a storm, it reaches 4.385 km². Conversely, after implementing flood control structures in scenario 4, there is no more flooding in the Cakung Drain area. However, in Scenario 5, flooding occurs during high tide influenced by a storm, covering an area of 4.15 km² and affecting three neighbourhoods. This is attributed to overflow of compound flooding in the downstream area without embankments, specifically 450 - 1176 m from the downstream of Cakung Drain. To mitigate flooding in the estuary area, embankment design is necessary up to a distance of 1176 m from the downstream of Cakung Drain.

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