Numerical Analysis in Dengkeng River Using Nays2DFlood

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Abstract Flooding is one of the disasters that occur in almost all regions of Indonesia every year. The National Disaster Management Agency of Indonesia (BNPB) recorded 1,999 flood disasters since the beginning of 2018 until October 2018 causing 4,157 people dying and disappearing. Dengkeng River is a tributary of the Bengawan Solo River that experiences flooding problems when the rainy season arrives. Previous studies have produced one-dimensional river (1D) which does not provide detailed information of flooding modelling and analyzed sedimentation rates from secondary data. However, there is rare research and detailed observation on this subject in this area. Therefore, flood simulation models are required to identify flood-prone areas. In this study, a two-dimensional (2D) river model using the International River Interface Cooperative (iRIC) Nays2DFlood software from Japan has been used to observe flood-prone areas around the Dengkeng River and field observation was done in prone areas. The results showed that the Cawas sub-district tends to have the highest flooding potential due to the overflow of the Dengkeng River. On the other hand, the result of field observation showed sediments that settled in Tukuman Weir are dominated by coarse sand and gravel that tend to be influenced by the upstream in Merapi Volcano. Moreover, flood damage continues to occur as the consequences of riverbank erosion and high sedimentation at specific locations on the Dengkeng River.

Keywords River Model, Nays2DFlood, Flood, Field Observation

1. Introduction

Flood disaster often occurring in Indonesia causes material and non-material losses. Dengkeng River is a tributary of the Bengawan Solo River that experiences

flooding every year. Dengkeng watershed is located among six regions, namely Klaten, Sukoharjo, Wonogiri, Sleman, Gunung Kidul, and Boyolali, where upstream of the river is located in Merapi volcano. In terms of economic aspects, Dengkeng River has a significant contribution to the sustainability of the agricultural business in the area traversed by this river [1]. The area of Dengkeng watershed is 822.153 km², where more than 50% of the total area is very prone to flooding [2] [3]. Losses in agriculture due to floods that hit several sub-districts in Klaten Regency reached 2,338 hectares or around 7.3 billion rupiah (BPPD Klaten 2017). The main cause of the flooding is the severity of sedimentation and riverbank damage. Consequently, when heavy rainfall comes, the capacity of the river cannot accommodate the overflow. Dengkeng watershed areas are lowland areas with inappropriate land uses and have a type of lithosol soil with a reasonably low infiltration value; thus it is possible to create a pool of water that causes flooding [4]. Based on the previous study, climate change has occurred in the Dengkeng River as seen by the increase in temperature and rainfall which directly affect land use patterns, water availability, flood control performance, local social and economic development [5]. Moreover, human progresses such as urbanization and structural defences (e.g., levees, dams, sea walls) have a significant influence on the movement and severity of flooding, ameliorating impacts in some cases, but amplifying them in others [6]. Previous studies in Dengkeng River have produced one-dimensional river (1D) modelling and analyzed sedimentation rates from secondary data [7]. Therefore, flood simulation models are required to identify flood-prone areas. In this study, a two-dimensional (2D) river model using the International River Interface Cooperative (iRIC) Nays2DFlood software from Japan has been applied to observe flood-prone areas around the Dengkeng River. This model is able to simulate two-dimensional horizontal (2D) flow, sediment transport, morphological changes from bottom depth, and erosion in rivers.

2. Literature Review

Flood Risk Analysis & Hazard Assessment

There are many flood risk management methods can be applied to reduce destruction and manage flood risk. Proper estimation for flood risk is challenging and needs careful consideration of a number of factors, including watershed properties such as size, topography, and land use, etc. It is important to define which types of the flood are most common before a hazard assessment is implemented since, in most cases, the selection of hazard and risk modelling methods depend on that. The common concepts are valid for the other types of floods, while technical note focuses on fluvial floods. The objective of flood hazard assessment is to comprehend the probability that a flood of a particular intensity will happen over an extended time [8]. Hazard assessment intends to estimate this probability over periods of years to decades to contribute risk management activities. Intensity usually indicates a combination of flood depth and horizontal flood extent. Moreover, other intensity measures such as flow velocity and flood duration can also be important depending on the situation.

iRIC Nays2DFlood

Nays2DFlood is one of iRIC solver that is used for flood flow analysis developed by Professor Yasuyuki Shimizu from Hokkaido University. Nays2DFlood relies on unsteady 2-dimensional plane flow simulation by using boundary-fitted coordinates as the general curvilinear coordinates, which allows both channel banks and floodplain edges to be fitted to the coordinate system [9]. This solver has been applied for a flood flow analysis of rivers over a wide range of length scales, from small streams to the Mississippi. Nays2DFlood is also used for the flood process analysis of primitive rivers and rivers in developing countries because the solver does not require river channel data. This model has succeeded in simulating flooding in several countries, for example, flooding in the city of Kabul by using modified DEM data in 2016 [10].

Model Equation

The solver divides flow motion into two coordinate systems, namely the orthogonal coordinate system (x, y) and the curve linear coordinate system or moving boundary fitted coordinates.

Continuity Equation:

$$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0 \quad (1)$$

Momentum Equation:

In the x direction,

$$\frac{\partial h}{\partial t} + \frac{\partial(hu^2)}{\partial x} + \frac{\partial(huv)}{\partial y} = -gh\frac{\partial H}{\partial x} + \frac{\tau_x}{\rho} + D^x + \frac{F_x}{\rho} \quad (2)$$

With,

$$\frac{\tau_x}{\rho} = C_f u \sqrt{u^2 + v^2} \quad (3)$$

$$D^x = \frac{\partial}{\partial x} \left[v_t h \frac{\partial u}{\partial x} \right] + \frac{\partial}{\partial y} \left[v_t h \frac{\partial u}{\partial y} \right] \quad (4)$$

$$\frac{F_x}{\rho} = \frac{1}{2} C_D a_s h_v u \sqrt{u^2 + v^2} \quad (5)$$

In the y direction,

$$\frac{\partial(hv)}{\partial t} + \frac{\partial(huv)}{\partial x} + \frac{\partial(hv^2)}{\partial y} = -gh\frac{\partial H}{\partial y} + \frac{\tau_y}{\rho} + D^y + \frac{F_y}{\rho} \quad (6)$$

With,

$$\frac{\tau_y}{\rho} = C_f v \sqrt{u^2 + v^2} \quad (7)$$

$$D^y = \frac{\partial}{\partial x} \left[v_t h \frac{\partial v}{\partial x} \right] + \frac{\partial}{\partial y} \left[v_t h \frac{\partial v}{\partial y} \right] \quad (8)$$

$$\frac{F_y}{\rho} = \frac{1}{2} C_D a_s h_v v \sqrt{u^2 + v^2} \quad (9)$$

Where, h is water depth, t is time, u average velocity of direction x, v is flow velocity in the y-direction, g is an acceleration of gravity, H is an elevation of water level, τ_x is component of river bed shear stress direction x, τ_y is component of river bed shear stress direction y. Details on the calculations are provided on the iRIC web page.

3. Research Methodology

Type of Research

This type of research is a quantitative descriptive study combining the results of numerical analysis of the Nays2DFlood software in Dengkeng River with the results of field observations in the form of Grain Size Analysis.

Study Area

The study area is located in Dengkeng River that is part of the Bengawan Solo River area, as shown in Figure 1 below. Administratively, the study area covers several regencies in Central Java province but the most extensive administrative area of the Dengkeng watershed is in Klaten Regency including the districts of Kemalang, Manisrenggo, Karangnongko, Jatinom, Tulung, Polaharjo, Delanggu, Karangnongko, Kebon Arum, Jogonalan, Gantimwarno, Wedi, Bayat, Cawas, Trucuk, Pedak, Karangdowo, and Ceper. The area of Dengkeng watershed is 822.153 km² where upstream of the river is located in Merapi volcano. Topographically Dengkeng watershed is at an elevation of 75-2000 m above sea level. The lowest height (75-100m) is in Karangdowo Sub-district, and Cawas Sub-district and the highest elevation is in Mount Merapi (Pemalang and Musuk Sub-districts). Regarding the slope of the Dengkeng watershed, the majority are in the flat category, ranging from 0 - 8%. In addition, the Dengkeng River is classified as a sloping surface flow pattern or (Mild) profile because the riverbed slope is higher than the critical slope [11]. The land use is dominated by rice fields (> 45%), settlements (25%), forests (17%), dry land agriculture (9%), and other land uses around 4%.

In general, climatic conditions in the Dengkeng River are relatively similar to other regions in the Solo River,

which is a wet tropical climate with the characteristics of the rainy and dry seasons. Winds from the southwest and northwest that usually blow in November to April result in the rainy season. While the dry season lasts from July to October caused by winds blowing from the south and southeast.

Research Stages

The method used in this study is a numerical analysis and field surveys as can be seen in the flowchart of Figure 2 below.

Figure 1. Dengkeng Watershed (Undip Disaster Study Center, 2017)

Figure 2. Research Stages

Figure 3. Location of field observation in Dengkeng River; (1) Jeto Weir, (2) Jembatan Tengah Weir, (3) Talang Weir, and (4) Tukuman Weir

The numerical analysis was used Nays2DFlood software including Dengkeng River in Klaten, Sukoharjo. Elevation data used is SRTM with Q5th discharge, and rain data used are from 2002 to 2016 from the nearest rainfall station on the Dengkeng River.

Based on a previous study in 2017, there are 67 riverbanks along the Dengkeng River in critical condition [12]. In this study, fieldwork was conducted at four points in the Klaten area, namely in Jeto Weir, Jembatan Tengah Weir, Talang Weir, and Tukuman Weir as seen in Figure 3. Tukuman Weir is a water structure located in Plosowangi village, Cawas sub-district, Klaten. This weir is used for irrigation needs in the village that irrigates around 280.8 hectares of the agricultural area [13]. Field observations were carried out by taking sediment samples at the location and measuring 10 cm into the sediment taken, as shown in Figure 4 and Figure 5 below. Besides, checking the condition of the river is done, including the condition of the river embankment and also the type of sediment that settles in the field. Furthermore, those samples from the observation site were brought to the Soil Mechanics Laboratory of Diponegoro University to examine grain size analysis.

Figure 4. Taking a sediment sample in Dengkeng

Figure 5. Measuring the high of sediment location

4. Result and Discussion

This area of the numerical simulation using Nays2DFlood is Dengkeng River which includes Klaten and Sukoharjo, Central Java, Indonesia. Some data were used in simulation, such as a base map, elevation data, flow discharge, and rainfall data.

The grid of Dengkeng River and The result of flood simulation from upstream to downstream can be seen in Figure 6. The simulation results are only in the form of the general area, and then ArcGIS 9.3 software is used to get specific inundation areas in Dengkeng River.

Based on the final analysis using ArcGIS 9.3, there are six areas affected by the flood that mostly come from Klaten district and follow Sukoharjo district that was showed in blue colour shown in Figure 7. As shown in Table 1, Cawas sub-district is the most prone area with inundation 43%. On the other hand, the lowest number of inundation is from Trucuk sub-district (0.976%). The previous flood in 2018 recorded that Cawas sub-district was the area most severely affected by flooding.

(a)

(b)

Figure 6. (a) Grid of river model and (b) Result of flood simulation

Figure 7. Affected area of flood simulation using ArcGIS software

Table 1. Inundation areas of Dengkeng River

No	District	Sub-district	Area		
			Region (m ²)	Inundation Area (m ²)	%
1	Klaten	Bayat	37812164	1561778	4.130
2	Klaten	Cawas	28926514	12536875	43.340
3	Klaten	Trucuk	28507481	278337	0.976
4	Klaten	Karangdowo	21550213	1446212	6.711
5	Sukoharjo	Weru	45759413	1035292	2.262
6	Sukoharjo	Tawang Sari	56049814	2802738	5.000

Field observation was carried out in areas where flooding frequently occurs each year. Observations were made in the dry season of August 2019. As shown in Figure 8a, the water level tends to be low in the dry season, resulting in a lot of sedimentary deposits in Jeto weir. Around Jeto Weir is dominated by tree debris where there are many trees around the river that are vulnerable to dropping their branches. In addition, Figure 8b shows that there is a lot of household waste accumulated near the gate of Tukuman Weir with a low water level.

Not only household waste, but also around Tukuman Weir has a sedimentary deposit on the riverside and middle of the Dengkeng River as shown in Figure 9a. Moreover, Riverbank in the Tukuman Weir tends to spill the material into the river because it will be destroyed by the seasonal

flood, as shown in Figure 9b. In some places, the condition of the Dengkeng riverbank is quite steep, and the soil conditions are relatively soft. In terms of river classification, Dengkeng River is classified as a river that tends to be straight but is dynamic in nature with considerable potential for change. There are several structures across the river, both weirs, and bridges. The existence of a weir has a dual function namely irrigation and detaining erosion. Some river segments have been installed riverbank protectors with stone pairs. The physical condition of Dengkeng river water is relatively better and clearer compared to other rivers in the Solo. This situation can occur because the upstream of the river originates from Mount Merapi, and there are fewer pollutants entering the water.

(a)

(b)

Figure 8. (a) Tree debris in Jeto Weir and (b) Household waste in Tukuman Weir

(a)

(b)

Figure 9. (a) Sedimentary deposit in Tukuman Weir and (b) Riverbank of Tukuman Weir

Figure 10. Grain Size Distribution in Tukuman Weir

The result of the field observation is shown in Figure 10. It represents Grain Size Distribution in Tukuman Weir. It shows that coarse sand has 36.89% of sediment and gravel has 33.54% of sediment. Then, fine sand has 28.19%, and silt has a small amount of sediment, 1.38%. At the same time, clay is not found at the field observation. From this result, we assume that a high amount of gravel and coarse sand tend to be found in most parts of the inundation area. The upstream of the Dengkeng River is located on Merapi volcano, thus making sediments that settle in the Dengkeng River tend to be brought from the mountain.

5. Conclusions and Suggestion

This research presented the situation of the affected area by using numerical simulation and field observation. The result of numerical simulation showed flood inundation mapping, which has a tendency to predict real flood condition in Dengkeng River, makes Cawas sub-district is the most potential area for flooding. On the other hand, field observation showed sediments settled in Tukuman Weir are dominated by coarse sand and gravel. Sediment characteristics in the Dengkeng River tend to be influenced by the upstream of the river, which is located on the Merapi Volcano and sudden flash flood. By conducting research with two dimensions and field research, it is hoped that it will add a reference for flood mitigation and prevention in the Dengkeng Watershed, thus saving millions of dollars in investments. Other issues, penalties for dumping garbage in the river should be re-affirmed because there is a lot of household waste around the Dengkeng River, making the river loses its capacity. Although the simulation is successfully performed, it just roughly described the flood phenomena in Dengkeng River. Therefore, improving the research is needed to predict the situation of a flood near to the real situation.

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