Estimation of River Flood Discharge by using 2D Model

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Keywords: River Flood, Discharge, 2D Model.

Abstract: Flood disaster is still a problem in many countries in the world; therefore, it is also still important to study about the flood. There have been many flood studies conducted by researchers. Modelling is one of the topics of flood studies which is usually discussed. Two-dimensional (2D) model is commonly used in flood modelling because it provides more information compared with one dimensional (1D) model. By doing flood simulation using a 2D model, important information, particularly related to inundation area, can be obtained so that the analysis in the flood study can be more comprehensive. In this study, 2D flood model is applied to Bolango River in order to estimate its actual capacity. The modelling process is conducted by using rainfall ground stations in a period of 2010-2017, land-use map data in 2015, and a digital elevation model (DEM) by combining SRTM data and observed cross-section data. The boundary condition at the downstream is sea water level and at the upstream is the flood discharge from Bone River. The model is verified by comparing inundated area from simulation result with the observation data. The model result shows good agreement with the observed data. Based on the result, the bank-full capacity of Bolango River is 189 m3/s, which is just 30% of 25 years return period of flood discharge.

1 INTRODUCTION

River flood modelling is a tool for assessment, evaluation, and prediction of river flood risk in various scenarios (Alaghmand, et.al, 2012). Hydraulic modelling can certainly provide reliable and accurate results especially when the model can exploit the extensive information provided nowadays (Detrembleur, et.al, 2009). Not only extensive, the information needed must be accurate and up-to-date. Thus, the flood rapid assessment is very important to provide a better accurate hydraulic or flood model (Moe, et.al, 2018). There are many flood modelling software was developed to help engineers design, assess, and evaluate drainage system and provide them to analyse it in 1-D, 2-D, and 3-Dimensional model. 2D modelling is considered as a model that has a better accuracy rate than the 1D modelling (Gharbi, et.al, 2016; Yakti, et.al, 2018). And also, 2D model has been considered as the best way to simulate flood inundation due to its effectiveness and efficiency (Farid, et.al, 2017). Several considerations should be done to decide which model will be used in the study, such as the complexity of river scheme, the flow characteristic, the availability of observation data, until the capacity of hardware that will be used in flood modelling.

Flood is one of the most common natural disasters in Indonesia. Likewise, the city of Gorontalo which crossed by the Bolango River. The Bolango River has experience with flooding almost every year and it is more frequent in the last five years, such as in 2002, 2013, 2014, 2016, and 2017. This incident causes harm not only to the material but also to the victims. Flood on the Bolango River is caused by several causes such as land-use changes due to the urbanization, small river capacity, high sedimentation accumulation, and climate change also contributed to the causes of the flood in the Bolango River.

Several studies have been conducted to deal with or to reduce the flood in Gorontalo City. Lihawa and

Rizaldi, A., Moe, I., Farid, M. and Kendra, H.
Estimation of River Flood Discharge by using 2D Model.
DOI: 10.5220/0008560301370143
In *Proceedings of the 6th International Seminar on Ocean and Coastal Engineering, Environmental and Natural Disaster Management (ISOCEEN 2018)*, pages 137-143
ISBN: 978-989-758-455-8

Sutikno (2009) also reported that the problem of sedimentation was one of the causes of the flood in Gorontalo City . In 2012, Arifin et al. have conducted research on flood disaster risk maps based on several factors such as rainfall, geological conditions, soil type, groundwater table, topography and land cover. Then in 2014, Sarwono et al. had done the assessment of flood in the Province of Gorontalo to know the conditions of the drainage system, hydrological condition, and the rivers morphology. Utama et al. in 2015 reported that the Bolango River had large sedimentation problems which had a large impact on flooding. The aim of this study is utilizing the 2-dimensional flood model to analyse Bolango river capacity.

2 GOVERNING EQUATIONS

There are three types of approach models can be used in flood modelling, one-dimensional, two-dimensional, and three-dimensional. A one-dimensional model is only considered flow in one dimension (one-axis flow). Two and three-dimensional modelling allows the numerical simulation to expanse the flow from the river into others axis respectively (Paudel, et.al, 2016; DHI, 2017).

2.1 One-dimensional Hydraulic Model

The equations are used in the numerical model is the Saint Venant equations. The Saint Venant Equations is consist of the continuity and the momentum equations as given below.

Continuity

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_1 \quad (1)$$

Momentum

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(\alpha \frac{Q^2}{A}\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{n^2 gQ|Q|}{AR^{3/4}} = 0 \quad (2)$$

Where Q is discharge (m3 s-1), A is cross-sectional area (m2), q1 is a distributed lateral inflow or outflow along the x-axis from watercourse (m2 s-1), n is Manning's roughness coefficient, α is momentum distribution coefficient, g is acceleration of gravity (m s-2), R is hydraulic radius (m), and h is water level (m).

2.2 Two-dimensional Hydraulic Model

In the two-dimensional model, the equations are used in the calculation process is same, St. Venant equation. But, the equation will be derived into 2-dimensional form to calculate flow characteristics in 2-dimensional. The Saint Venant equations are written in the following form:

$$\frac{\partial h}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \quad (3)$$

$$\left[\begin{array}{l} \frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) = -gh\frac{\partial \zeta}{\partial x} - \\ \frac{gp\sqrt{p^2+q^2}}{C^2-h^2} + \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}\left(h\tau_{xx}\right) + \frac{\partial}{\partial y}\left(h\tau_{xy}\right)\right] \end{array}\right] \quad (4)$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) = -gh\frac{\partial \zeta}{\partial y} - \quad (5)$$

$$\frac{gq\sqrt{p^2+q^2}}{C^2-h^2} + \frac{1}{\rho_w}\left[\frac{\partial}{\partial y}\left(h\tau_{yy}\right) + \frac{\partial}{\partial x}\left(h\tau_{xy}\right)\right]$$

Where x and y are the horizontal Cartesian coordinates; h is the water depth; C(x,y) is Chézy resistance (m1/2 s-1); ζ(x,y,t) is the water surface elevation (m); g is the gravitational acceleration; ρw is the density of water; τxy, τxx and τyy are the depth-averaged turbulent stresses (kg m-1 s-2), and p(x,y,t), q(x,y,t) are flux densities (m3 s-1 m-1) in x- and y-directions.

2.3 Rainfall Run-off Model

The rainfall run-off model is used in this study is lumped-sum rainfall run-off model by Nakayasu model. This model is generated based on observations of several rivers in Japan. The peak discharge can be calculated by using the equation following:

$$Q_p = \frac{CAR_0}{3{,}6(0{,}3T_p + T_{0,3})} \quad (6)$$

Where C is the run-off coefficient from land use of basin; Qp is the peak discharge (m3/s); R0 is the unit rainfall (mm); A is the area of basin (km2), Tp is the time of rain starts to peak discharge (hours); T0,3 the time needed for discharge decreasing to 30% of the peak (hours)

$$Tp = tg + 0{,}8tr \quad (7)$$

$$tr = 0{,}5tg \quad (8)$$

Time concentration can be calculated follows:

For L < 15 km

$$tg = 0{,}21L^{0{,}7} \quad (9)$$

For L ≥ 15 km

$$tg = 0{,}4 + 0{,}058L \quad (10)$$

Where tg is the time of concentration (hour); tr is the effective time(hour); and L is the length of river (km). The time needed to reduce the discharge from peak discharge to 30% of peak discharge can be calculated follow:

$$t_{0,3} = \alpha.tg \quad (11)$$

$$\alpha = \frac{0{,}47(AL)^{0{,}25}}{tg} \quad (12)$$

Where α is the runoff coefficient. α = 2; for regular basin, α = 1,5; for the rising part the hydrograph is slow and falls rapidly, and α = 3; for the hydrograph rises rapidly and falls slowly.
To make a hydrograph there is a rule to make hydrograph like a Nakayasu hydrograph shape (see Figure 1).

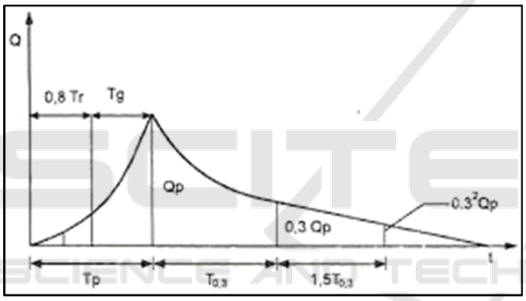


Figure 1: Nakayasu Hydrograph.

Unit hydrograph curves / rising limbs have the following equation:

$$Qa = Qp\left[\frac{1}{Tp}\right]^{2,4} \quad (13)$$

$$T \leq Tp$$

Where Qa is run-off before reaching peak discharge (m3/s); T is time (hour); Qp is peak discharge (m3/s), and Tp is time peak (hours).
The decreasing limb has the following equation:

Curve down 1:
$Tp \leq t \leq Tp + T_{0,3}$

$$Qd1 = Qp.0{,}3^{\frac{(t-Tp)}{T_{0,3}}} \quad (14)$$

Curve down 2:
Tp + T0,3 ≤ t ≤ Tp + 1,5T0,3

$$Qd2 = Qp.0{,}3^{\frac{(t-Tp+0,5T_{0,3})}{1,5T_{0,3}}} \quad (15)$$

Curve down 3:
Tp + 1,5T0,3 ≤ t

$$Qd3 = Qp.0{,}3^{\frac{(t-Tp+1,5T_{0,3})}{2T_{0,3}}} \quad (16)$$

3 DESCRIPTION OF THE STUDY AREA

This paper studies the use of 2-dimensional flood modelling to assess the capacity of Bolango River. The river flow through Gorontalo City (the south of Gorontalo). The Bolango Basin has an area of 398 km2, with the longest river in that basin is Bolango River. The length of Bolango river from upstream to downstream is around 17 km. the main section of this study, which is the river section to be observed in this study is the downstream section (Pink line on Figure 2) which have a contact with Gorontalo City.

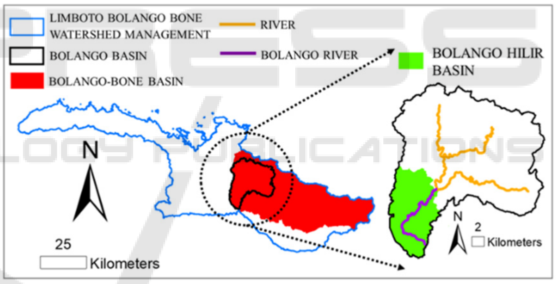


Figure 2: Bolango River Basin Location.

4 MATERIALS AND METHODS

4.1 Elevation Data

The elevation data used in this study comes from the National Aeronautics and Space Administration (NASA) from the United States. The elevation data used in this study has a level of 30 meters resolution. From the elevation data, it is known that the downstream area (Gorontalo City) has a flat height with an elevation of about 1 to 8 meters above the mean sea level (Mean Sea Level). This situation can be seen in Figure 3. While the situation in the mountains has a very high and steep slope between 1300-1500 m above the average surface of sea water.

The mountainous altitude situation in the upstream city of Gorontalo can also be seen in Figure 3.

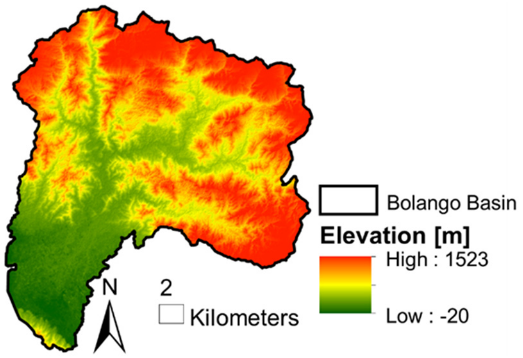


Figure 3: Elevation Data of Bolango Basin.

4.2 Land Use Data

The Gorontalo City is filled with shops and government centres as shown in Figure 4 below, where land use is filled with urban areas in 2015. It can be seen also in Figure 4 that the state of land use in the upstream part of Gorontalo is still a forest area and open land both in 2009 and 2015. However, changes in land use from rice fields or open land to urban areas will have a great opportunity to occur as shown in Figure 4. This also means that the situation of increasing urbanization will still be possible in the future.

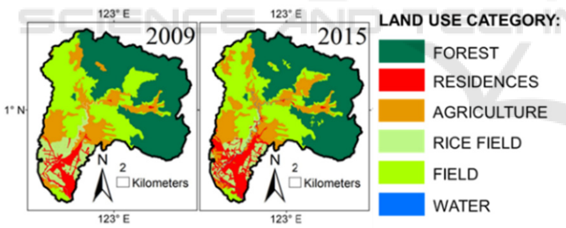


Figure 4: Land use Change.

4.3 Cross-section Data

The cross-section data used in this study is data derived from the study of Balai Besar Wilayah Sungai Sulawesi II. In Figure 5 below, is an example of a cross section measured by the BWS Sulawesi II Team. This cross-section data will be used as the initial initiation input for the inundation flood model to find out the parts that can be passed by the water in this downstream Bolango River.

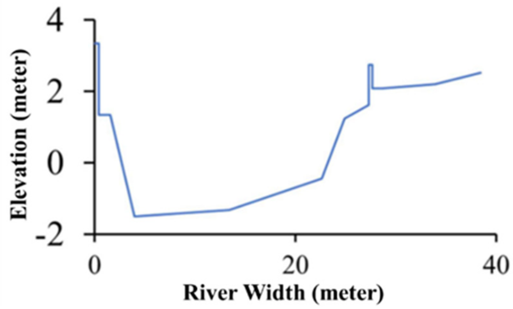


Figure 5: Example of Cross Section Bolango River.

4.4 Rain Gauge Data

Based on the spatial analysis of rain gauges from 9 stations, there are only 4 stations that have an influence on the Bolago River Basin, namely Alale Station, Longalo Station, Dulamayo Station, and Boidu Bolango Station. So that the rain gauge is used as a frequency analysis of the return period (Tr).

There are 4 out of 9 rain gauge with a daily temporal distribution on the target area that has a series of rain data that is quite good and uniform. Namely Dulamayo, Longalo, Boidu, and Alale. Also, there is a water level station (see Figure 6) to calibrate the rainfall-runoff model.

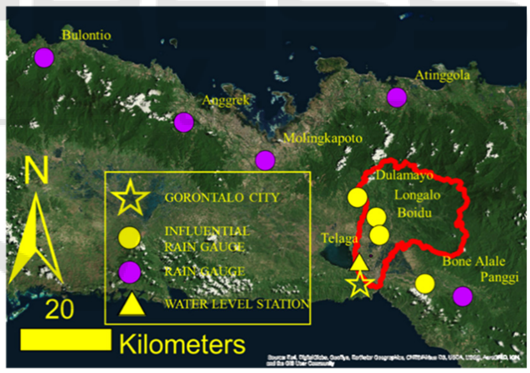


Figure 6: Rain Gauge and Water Level Station.

The calculation of the return period of rainfall based on the average area of rainfall data in Bolango Basin. The maximum daily rainfall from each year can be seen in Table 1.

Table 1: Maximum Rainfall Data.

No	Years	R_{24} Max
1	2010	55.7
2	2011	47.8
3	2012	57.8
4	2013	52.4
5	2014	65.7
6	2015	52.7
7	2016	76.6
8	2017	62.4

Then the rain calculation is done again using the Gumbel distribution. From the calculations that have been made, the following values are generated.

Table 2: Return Period of Rain.

Return Period	Probability	Rainfall (mm)
2	0.5	57
5	0.8	69
10	0.9	76
25	0.96	86
50	0.98	93
100	0.99	100
200	0.995	107
1000	0.999	123

4.5 Flow Data

Flow data were generated by Nakayasu rainfall-runoff model as described in the previous section. The relationship of rainfall and flow recorded in the calculation of the amount of discharge that affects the flooded unit in the study area. The flow hydrograph was calculated after the Nakayasu model was calibrated by observation data at Talaga Water Level Station. The calculated hydrograph flow can be seen in Figure 7

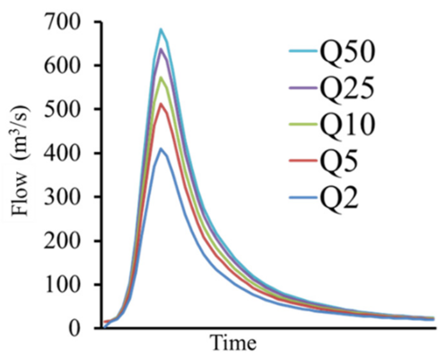


Figure 7: Flow Hydrograph.

5 SIMULATION AND RESULT

We use the 1-D hydraulic model, then coupling it with a 2-D model to do flood simulation. Before we do flood simulation we should calibrate the flood model with observation data. This is the important stage because to get the exact capacity of Bolango River we should make sure that the model we will use in flood modelling represents the actual condition of the river. Then we do the calibration process and we can see the result follow Figure 8.

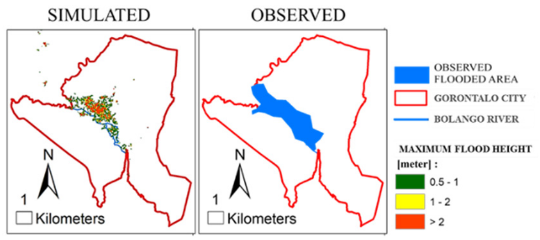


Figure 8: Calibration Result.

Figure 8 (left) the result of a simulation of inundation floods due to flooding on the Bolango River with Q25. The left one is the simulated flood situation with Q25 using the measurement data of the original cross section. The right picture is the most disaster-prone zone map. This map of disaster-prone zones comes from Arifin et al (2016). We can see that the comparison between simulation and observation has a fairly close relationship. We get some calibrated parameters data, Manning's roughness coefficient (n) for river bed is 0,03 – 0,6 and for floodplain, Manning's roughness coefficient (n) is around 0,4. That is, this flood model is quite well calibrated.

After the calibration process, the current capacity of the Bolango River bankfull can be evaluated. For the information, the results of the model calibration in this study use a return period flow (Q25). Then, we carried out several numerical simulation scenarios to testing the inundation flood model by using Q25 as input for the model. This scenario is to reduce the Q25 discharge by 0.7 times, 0.5 times, 0.32 times, 0.31 times and 0.3 times. The graph of each discharge scenario can be seen in Figure 9. Each scenario will be numerically tested using a flood inundation model.

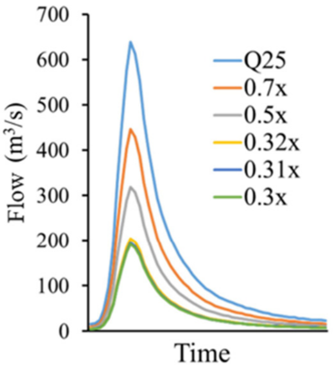
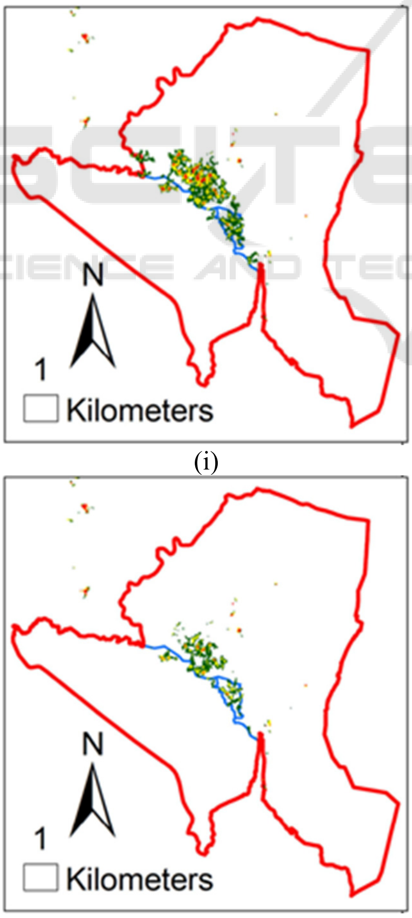


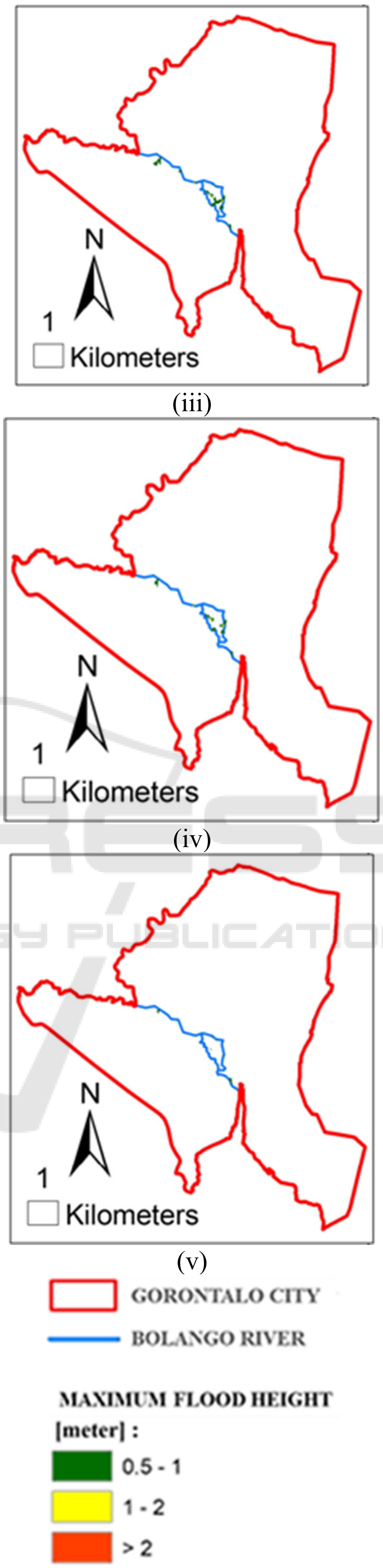
Figure 9: Flow Scenario to Evaluate the river capacity.

The flow hydrograph from each scenario are used as input for the inundation flood model. Inundation flood situation of each discharge scenario in Figure 9 can be seen from the inundation simulation results in Figure 10. For the record, the simulation of inundation results presented is the maximum inundation height in each simulation scenario.



(i)

(ii)



(iii)

(iv)

(v)

Figure 10: Flood Simulation Results: (i) 0,7 X ; (ii) 0,5 X ; (iii) 0,32 X ;(iv) 0,31 X ; and (v) 0,3 X.

From Figure 10 above we can see that with a discharge scenario of 0.3 from Q25 there is hardly any more inundation in the target area of the study area. That is, from the results of numerical simulations carried out, peak discharge with 189 m3/s is a bankfull capacity for the current Bolango River. This also means that bankfull capacity for the Bolango River is 30% of Q25. And that is below the value of flow with a return period 2-year. This bankfull capacity might decrease when the accumulation of sedimentation in the Bolango River increases following the time.

6 CONCLUSION

In this study, the inundation floods model of Bolango River was constructed. Simulation results of flood inundation from the flood inundation model have been compared with inundation observations data and have a fairly close relationship between the two. From that conclusion, the model has been calibrated and can be used to produce a flood inundation simulation. Based on the results of numerical simulations, the average maximum peak discharge capacity of the Bolango River downstream is 189 m3/s. This peak discharge situation is 30% of the Q25 return period flow. That is the amount of discharge that can be drained by the Bolango River without any inundated area along the river. The situation of the maximum discharge that can be traversed by the water in the downstream Bolango River will become smaller in capacity when considering the accumulation of sedimentation that might increase in the future.

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