Development of flood inundation maps as an initial assessment for flood disaster mitigation - a case study of selagan river basin

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Abstract. Flood is a natural disaster that often occurs in Bengkulu Province. One of which occurred at the Selagan River Basin which caused in several sub-districts in Mukomuko District to be flooded. Government must be fast and precise in resolving future flooding problems in the Selagan River Basin. In solving the problem, initial assessment data is certainly needed, one of which is a flood inundation map, so that later the infrastructure that is built is right to solve the flooding problem that occurred in the Selagan River basin. This study was conducted to model section of the Selagan River for flood inundation forecasting with the help of digital elevation model (DEM) Data, hydrological data, river characteristics data, geographical information system(GIS). Those data is used to create a flood inundation model that is built with hydrodynamic modules which consist of rainfall runoff module, flood routing and inland flooding by using the MIKE software. Simulations of flood inundation that has been made are compared using inundation observation data at flood locations, so the results of flood inundation maps occur at this time can be a preliminary assessment for flood mitigation in the future.

1. Introduction
The flood is a major problem in Indonesia and it mostly happens in urban area. Due to changes in land use, the volume and area of inundation will increase following the escalation of urbanization area [1]. Bengkulu is one of the provinces in the western island of Sumatra. Its natural contour is mostly passed by large rivers so that most of the rivers often flood during the rainy season with high rainfall intensity and long duration. One of them occurred in the Selagan river basin which empties into the Mukomuko District with an area of 720 km². To date, no study has ever been carried out on Selagan River Basin that develop flooding by considering river by 1-Dimensional and 2-Dimensional simulations supported by quantitative. More ever, National Disaster Management Agency (BNPB) in Bengkulu
Province for operational data still uses conventional methods in flood data processing [2]. Flood is a condition where in areas that are topographically and geomorphologically dry inundated by water that occurs due to the level of drainage that has been saturated to collect water and the ability of infiltration of water into the soil that reaches the maximum limit [3]. Flood control requires a suitable applied hydrology concept in producing a model that is close to the actual conditions [4]. The location of case study as shown in Figure 1.

Figure 1. Flood target evaluation in Bengkulu Province

Flood-prone areas are areas that are easy or have a tendency to be hit by floods, this happens if there is an overflow of water caused by a cross section of the river channel that lacks capacity [5]. The process of flood inundation mapping is an essential component of flood risk management because flood inundation maps do not only provide accurate geospatial information about the extent of floods, but also, when coupled with a geographical information system, can help decision makers extract other useful information to assess the risk related to floods such as human loss and environmental degradation [6]. Then it is necessary to know when the flood event will occur and the magnitude of its impact.

2. Literature review

2.1. Flow hydrograph

Unit hydrograph is a hydrograph of direct flow resulting from effective rain that occurs evenly throughout the watershed with a fixed intensity in a set time unit [7]. The hydrological model needed to determine the flowing discharge that can be used is the synthetic unit hydrograph of the Nakayasu method [8]. Until now the results were quite satisfying and this method requires several characteristics of the flow region parameters as follows: time of peak magnitude, The grace period from the center of the rain to the center of the hydrograph (time log), time base of hydrograph, catchment area, length of the longest channel. The formula of nakayasu unit hydrograph is as follows (Chow, 1988).

\[ Q_p Q_p = \frac{C \cdot A \cdot R_0}{3.6 \cdot (0.3 \cdot T_p + T_{0.3})} \]  

(1)

Where Qp is flood peak flow rate (m³/s), C is runoff coefficient, Ro is unit rain (mm), Tp is time interval from the beginning of the rain until the flood peak unit (hour), T_{0.3} is the time required by a decrease of peak discharge up to 30% of peak discharge (hour). The Nakayasu Method synthetic hydrograph chart as shown in Figure 2.
Figure 2. Rising and decreasing limb at synthetic unit hydrograph Nakayasu Method

The above formula is an empirical formula, so its application to a watershed must be preceded by a selection of suitable parameters namely Tp and rain distribution patterns to obtain a hydrograph pattern that matches the observed flood hydrograph. Flood hydrograph is calculated with the following equation:

\[ Q_k = \sum_{i=1}^{n} U_i - P_{n-(i-1)} \]  

Where \( Q_k \) is Flood discharge at the k th hour (m³/s), \( U_i \) is Ordinate unit hydrograph (i = 1, 2, 3 .. .n), \( P_n \) is Net rain in succession (n = 1,2,..n)

2.2. Flood routing

Flood tracking and routing activities in flood-prone zones must be done as soon as possible so as not to lose evidence of inundation characteristics that have occurred [9]. Flood routing in the river is calculated using a continuous equation, and the momentum equation from unsteady flow [4].

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left[ \frac{Q^2}{A} \right] + gA \frac{\partial h}{\partial x} + \frac{n^2 gQ|Q|}{AR^{4/3}} = 0 
\]

Where \( Q \) is discharge (m³/s), \( A \) is cross-sectional area (m²), \( q \) is lateral inflow or outflow distributed along the x-axis from the watercourse (m²/s), \( n \) is Manning’s roughness coefficient, \( \alpha \) is momentum distribution coefficient, \( g \) is acceleration of gravity (m/s²), \( R \) is hydraulic radius (m), \( h \) is water level (m), \( \beta \) is runoff parameters, \( t \) is time (s).

2.3. Inland flood module

Two-dimensional model is considered as a high-accuracy model to do flood modeling lately [10]. Two-dimensional unsteady equations consist of continuity equations and momentum equations, solved numerically in the flood-flooding model in floodplains. This inundation model is based on the MIKE platform.

\[
\frac{\partial h}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 
\]

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( p^2 \frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left( pq \right) + gh \frac{\partial c}{\partial x} + \frac{gp\sqrt{p^2 + pq^2}}{C^2 - h^2} - 1 \rho_w \left[ \frac{\partial}{\partial x} (ht_{xx}) + \frac{\partial}{\partial x} (ht_{xy}) \right] = 0 
\]

\[
\frac{\partial q}{\partial t} + \frac{\partial}{\partial y} \left( \frac{q^2}{h} \right) + \frac{\partial}{\partial x} \left( pq \right) + gh \frac{\partial c}{\partial y} + \frac{gp\sqrt{p^2 + pq^2}}{C^2 - h^2} - 1 \rho_w \left[ \frac{\partial}{\partial y} (ht_{xy}) + \frac{\partial}{\partial x} (ht_{xy}) \right] = 0 
\]

Where \( C(x,y) \) is Chézy resistance (m²/s²), \( \rho_w \) is water density (kg/m³), \( \zeta(x,y,t) \) is water elevation (m), \( g \) is acceleration of gravity (m/s²), \( h(x,y,t) \) is water depth (m), \( \tau_{xx}, \tau_{xy}, \text{and} \tau_{yy} \) are components
of effective shear stress \((kg/m^2 s^2)\), \(p(x, y, t)\), \(q(x, y, t)\) are flux densities \((m^3/m s)\), in the x- and y-directions respectively.

2.4. Spatial linear method
There are several methods to obtain the spatial extent of flood. The primeval yet most certain method for obtaining the extent of flood is to integrate the flood elevation information from high water marks of floods observed at various spatial locations [11]. Data observations of flood events that are lacking at the location can be anticipated using spatial linear methods, where the location is likely to be affected and frequent flooding is taken as much as possible to be connected in a straight linear line to get the possibility of inundated areas. The method for Spatial Flood Observation Maps in the river and flood plain as shown in Figure 3.

![Figure 3. Linear method for estimating Spatial Flood Observation Map](image)

By using this method, it is expected that the development of spatial flood observations in the Selagan River can be done. The results of spatial flood mapping may be overestimated in terms of the extent of flood affected.

2.5. Initial assessment of flood mitigation
Flood inundation maps that have been built on a watershed can be used for many things in order to reduce the impact of flooding on locations and create integrated flood management. Several criteria are considered in flood mitigation are the performance level of the flood defense works at a given time, the topography of the site, and the size of the population protected [12].

3. Methodology
Methodology of implementing this work starts from Collection of datasets such as Digital Elevation Data, hydrological data for discharge, rainfall data, tidal data and cross section data that can be used. Development of hydrodynamic module and inland flood module to obtain maps of inundation simulation results on the Selagan River and calibrated with an observation map. The methodology for Development of Flood Inundation Maps as Shown in Figure 4.
4. Result and Discussion

4.1. Contour transformation of watershed areas with DEM data
Selagan River Basin has a very varied elevation from -2 meters to 1950 meters above the average sea level with varying elevation situations such as those where housing is generally located in the middle and most downstream area. While many other areas are utilized as oil palm plantations. Situation of the Selagan River that passes through many of these districts is still very natural. So often the area is close to the Selagan River. This is very susceptible to the effects of floods during the heavy rainy season in the Air Selagan watershed. The elevation data used can be obtained from the Japan Aerospace Exploration Agency from Japan or often shortened by JAXA and additional information that the resolution used in the current watershed data is 30 meters resolution as displayed in Figure 5.

4.2. Observation of the cross section of the selagan river
The width of the river in the Selagan Watershed varies from 30 to 60 meters. Information on the width of the river in the Selagan Watershed can be using Google Earth Imagery and randomly selected

Figure 4. Flowchart of theoretical framework

Figure 5. Three dimensional view (DEM data) of Selagan Watershed
locations. In this Selagan River cross section observation, 69 points were taken in the Selagan River Basin which can be seen in Figure 6.

![Figure 6. Measurement location of cross section of Selagan River](image)

4.3. Development of spatial observation maps
Spatial observation maps can be made by observing and collecting data about flood events that have occurred in the field and processed using the Spatial Linear Method as displayed in Figure 7. The results of this spatial map can be used as a comparison and calibration of the flood models that we are developing, so that inundation maps we make it are more accurate.

![Figure 7. Flood observation map](image)

4.4. Development of the selagan watershed flood model
Development of flood inundation models requires diverse supporting data, such as: hydrological data, tidal data, river cross section, DEM data and other supporting data needed as an approach, where the entire data will be processed into a flood inundation map that is expected to be able describe the actual results at the location.

4.4.1. Hydrological data analysis. Hydrological data is needed to input data in the form of flood design debits into flood model calculations. The steps in the hydrological analysis are as follows: determine the watershed, determine the area of influence of the rain station, determine the area of land use, analyze design rainfall with a recurrence intervals and calculate the design flood discharge based on the amount of design rainfall. Peak flood discharge in Selagan River Basin base on recurrence intervals as shown in Table 1.

From the calculation results of the analysis chosen Nakayasu hydrograph model in producing design flood discharge because it has a large space and has the same pattern with the characteristics of the Selagan River. Each flood discharge is re-evaluated using input every time, namely recurrence intervals Q2, Q5, Q10, Q25, Q50, and Q100-Year floods as shown in Figure 8. Then, every discharge is repeated on every river in the Selagan watershed in the routing and simulation using the 2-dimensional model.
Table 1. Peak flood discharge recurrence intervals in Selagan River Basin

| Selagan River | Peak Flood Discharge Recurrence Intervals (m³/s) |
|---------------|-----------------------------------------------|
|               | Q2   | Q5   | Q10  | Q25  | Q50  | Q100 |
| River 1       | 100  | 132  | 150  | 179  | 202  | 220  |
| River 2       | 21   | 28   | 31   | 37   | 42   | 46   |
| River 3       | 221  | 293  | 331  | 395  | 446  | 485  |
| River 4       | 63   | 83   | 94   | 112  | 127  | 138  |
| River 5       | 96   | 127  | 144  | 172  | 194  | 211  |

Figure 8. Discharge recurrence intervals on rivers in the Selagan River Basin

4.4.2. Tidal Analysis. Tidal data is really needed as a description of the water level elevation in the downstream river or approaching the estuary, so that the flood inundation model in the downstream has been calibrated with tidal elevation. From the results of the tidal investigation taken in 2017 conducted by the BWS Sumatera VII office in Bengkulu. Tide assessment is also carried out for the forecast intervals of 20 years from the date of observation. The tidal reference elevations can be found in the Table 2.

Table 2. Tidal reference elevations in Selagan River Estuary

| Reference elevations            | Peilschaal (cm) | MSL (cm) | LWS (cm) |
|---------------------------------|-----------------|----------|----------|
| Highest High Water Level (HHWL) | 163             | 72       | 141      |
| Mean High Water Spring (MHWS)   | 145             | 54       | 123      |
| Mean High Water Level (MHWL)    | 124             | 33       | 103      |
| Mean Sea Level (MSL)            | 91              | 0        | 69       |
| Mean Low Water Level (MLWL)     | 57              | -34      | 35       |
| Mean Low Water Spring (MLWS)    | 36              | -55      | 15       |
| Lowest Low Water Level (LLWL)   | 22              | -69      | 0        |
4.4.3. Simulations of inundation flood for the selagan watershed and map calibration. Flood inundation model that was built consisted of a rainfall-runoff module, flood routing and an inland flood simulation, by modeling floods due to river overflows by integrating 1-dimensional river models with MIKE HYDRO RIVER and models of above ground inundation flow with MIKE 21 and create 2-dimensional model component with MIKE FLOOD. The aim is to create a 2-dimensional inundation flow model above ground level for a flood modeling due to river flooding that is integrated between integrated river flow and the area inundated. Inundation floods that occur in this watershed has been quantitatively evaluated by including a number of data entries to produce a precise map, so it is necessary to calibrate the data from the modeling results compared to observation map as shown in Figure 9.

![Figure 9](image_url)

**Figure 9.** Comparison of flood inundation maps between modeling and observation map

As a comparison of the results of inundation floods with spatial observations have fairly close relationship and the same distribution patterns. That is, at present, this simulation is quite well calibrated at recurrence intervals 10-year flood. The inundation simulation results will then be presented for Q2, Q5, Q10, Q25, Q50, and Q100-year floods as shown in Figure 10.

![Figure 10](image_url)

**Figure 10.** Results of flood inundation simulations and their extent in the Selagan Watershed

Results of inundation flood simulation in Selagan River show their effect on the extent and volume of flooding, where the area of flood inundation with 2 year recurrence intervals (Q2) increases 175% towards 100-year flood and area of inundation increased by 11.54% of the 50 year recurrence interval to 100-year flood as shown by Figure 11. The change in flood area increased with the increase in the recurrence intervals. The change in flood extent below shows a linear relationship between the area and the simulation recurrence intervals.
4.5. Initial Assessment of flood Mitigation Based on Flood Inundation Maps

Inundation maps is a data that is needed in planning the concept of disaster mitigation, where the map will be the basis for the government to develop the concept of effective flood management so as to achieve integrated flood management. Inundation maps obtained from the results of modeling and have been calibrated with conditions that have occurred at the site, are expected to be a tool for conducting initial assessments and quick steps in initiating flood disaster mitigation. Synchronization of flood inundation map with Subdistricts map as shown in Figure 12.

Inundation maps that we use as flood hazard map development are map with recurrence interval of 100 year, so that the worst possibility of the impact of flooding can be avoided. Based on the synchronization results of the flood inundation map with the administrative area, it can be obtained the area of the flood affected area in each subdistrict, so that the subdistrict that is most affected by flood can be measured. Inundation areas in the subdistricts as shown in Table 3.

Table 3. Inundation areas in the subdistricts along Selagan Watershed

| Sequence of Potential Flooding | Inundation Areas in Subdistricts are Based on Recurrence Interval Floods (Q) |
|-------------------------------|-----------------------------------------------|
| Subdistricts                  | Q=2 yr (Area) km² | Q=5 yr (Area) km² | Q=10 yr (Area) km² | Q=25 yr (Area) km² | Q=50 yr (Area) km² | Q=100 yr (Area) km² |
|-------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 1 Teras Terunjam              | 1.86             | 2.59             | 2.67             | 3.09             | 3.43             | 3.85             |
| 2 Selagan Raya                | 1.12             | 2.00             | 2.27             | 2.93             | 3.26             | 3.51             |
| 3 Mukomuko                    | 1.08             | 1.82             | 2.18             | 2.92             | 3.23             | 3.68             |
| 4 V Koto                      | 0.53             | 0.70             | 0.78             | 0.93             | 1.03             | 1.13             |
| 5 Penarik                     | 0.04             | 0.11             | 0.21             | 0.31             | 0.46             | 0.58             |
| 6 Air Dikit                   | 0.02             | 0.02             | 0.02             | 0.02             | 0.02             | 0.03             |

From the Table 3, it can be seen that there are three subdistricts that have experienced flooding with a fairly large area in Teras terunjam subdistrict, Selagan raya subdistrict, Mukomuko subdistrict.
In the framework of the initial assessment of flood disaster management, this inundation map can be improved to become a flood hazard map, the basis for creating an early warning system, education to the community and other mitigation measures to a more specific level.

5. Conclusions and recommendation

Based on the development of flood inundation maps in the Selagan Watershed can be concluded and recommended as follows,

5.1. Conclusions
1. Flood inundation maps based on flood model simulations have been compared with spatial observations, the result is the flood models are well calibrated at recurrence intervals of floods Q = 10 years and Changes in flood inundation areas increase with increasing recurrence intervals, an increase in flood area shows a linear relationship between the area and the recurrence interval of the simulation.
2. Subdistricts affected by flood from upstream to downstream in the numerical simulation of flooding during the recurrence interval 2, 5, 10, 25, 50 and 100-year floods show that the most affected subdistricts are those located in the middle to the estuary. Namely, Selagan Raya, Teras Terunjam and Mukomuko. For example, for recurrence intervals Q-100 year flood, Teras Terunjam subdistrict is flooded with an area of 3.85 $km^2$, Selagan Raya subdistrict is flooded with an area 3.51 $km^2$ and Mukomuko subdistrict is inundated 3.68 $km^2$.
3. The final result in this paper is that the Flood inundation map is used as an initial assessment in carrying out flood mitigation in the future based on the priority scale of the affected subdistrict based on the flood recurrence that occurred in the Selagan watershed and to make a flood hazard map using recurrence interval used are Q-100 year flood, so as to provide security to residents along the Selagan watershed.

5.2. Recommendation
1. For the further action it is necessary to update the flood inundation map that has been adjusted to the spatial plan of the Mukomuko district so that can be developed to act on more specific mitigation plans such as: evacuation routes, places of refuge, energy availability, and water availability for flood victims.
2. Early warning systems need to be built on the Selagan Watershed in the form of infrastructure that has artificial intelligence so that it can provide information more quickly to affected residents.
3. Flood control structures need to be created with the aim to reduce the area of inundation on floodplains, reduce flood stage, peak discharge and reduce flood duration.
4. Need to develop a master plan on Integrated Flood Management which includes all actions regarding human safety and sustainable development within the overall framework of Integrated Water Resources Management.

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