

2D Hydrodynamic Modelling of Flood Inundation Scenarios of Krueng Peuto River at North Aceh Regency of Aceh Province

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Abstract: Krueng Peuto sub-watershed, is a part of the Krueng Keureuto watershed in North Aceh that frequently experiences flooding. At the end of 2021, an embankment broke on the Peuto River and caused river overflow and submerged hundreds of houses in 33 villages around the sub-watershed. This study aims to analyze the critical circumstance of the Krueng Peuto sub-watershed which potentially lead to Peuto River overflow, using a 2D hydrodynamic model Geo-HECRAS. The validation of flood distribution points is based on historical floods conditions, i.e. depth and area of flood inundation, with modeling results for return periods scenarios of 2, 5, 10, 25, 50, and 100 years. From the modelling results, the flood inundation area at the 25-year return period was 25.514 km², with a flood depth of 0-1 m covering an area of 8.35 km² (32.73%), a depth of 1-2 m covering an area of 6.71 km² (26.33%), and a depth of >2 m covering an area of 10.44 km² (40.95%). The validation results of the 25-year return period flood inundation with flood distribution points show that in the flood inundation area there are 17 flood distribution points or the flood inundation area already represents 81% of flood distribution points.

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1 INTRODUCTION

The problem of flooding in Indonesia is still unresolved until now, especially during the rainy season. If high rainfall is not facilitated by a good water drainage and absorption system, it will form puddles of water and cause flooding [1]. Factors causing flooding include excessive surface runoff due to saturation of water in the soil [2]. Runoff flooding is a type of flood caused by the flow of surface runoff, which is part of the rain that flows on the ground surface before entering the river system [3].

In 2010 the CivilGeo team under Chris Mader created Geo-HECRAS, a software that allows users to perform one task using GIS and HEC-RAS simultaneously [4]. Geo-HECRAS can be used in 1D, 2D, and 3D flood inundation modeling. Modeling will depend on available data or specific demands in simulating and studying flood hazards. The advantage of using Geo-HECRAS software is that it speeds up the analysis and formulation of the HECRAS model and also improves the quality and accuracy of the modeling results [5].

Krueng Peuto is a sub-watershed of the Krueng Keureuto watershed. The Krueng Peuto river also contributes to flooding in Lhoksukon and surrounding areas (North Aceh Water Resources Agency, 2010). The Krueng Peuto sub-watershed has an area of 288.025 km² with a river length of 37.646 km. At the end of 2021 (November 12, 2021), an embankment broke on the Krueng Peuto River. The breach in the embankment caused river water to overflow and inundate hundreds of houses in 33 villages spread across six sub-districts around the sub-watershed. The worst floods were in Matangkuli District, Lhoksukon District, and Cot Girek District [6]. Various flood risk reduction efforts have been carried out by the government, such as the construction of river embankments and revertment of Krueng Peuto in Lhoksukon Subdistrict and Cot Girek Subdistrict along 235 meters in 2016, and the construction of river embankments in Meucat Village, Lhoksukon Subdistrict along 2800 meters in 2010 (Aceh Water Agency, 2022).

The first step that can be taken for flood management or flood risk reduction is a study that can provide an overview of flood conditions such as discharge, overflow points, and inundation areas. One way that can be done to see areas inundated by floods is by modeling flood inundation using Geo-HECRAS software. The results of modeling using this software are flood inundation maps that can provide detailed information related to threats in areas prone to flooding so that more optimal flood mitigation can be carried out.

2 STUDY AREA

The location reviewed in this study is in the Krueng Peuto sub-watershed which is geographically located at coordinates 5°01'48.03"N - 97°19'14.44"E to 4°85'99.14"N - 97°27'66.67"E, and administratively starts from the upstream of the river in the Syiah Utama District, Bener Meriah Regency to the downstream of the river which empties into Krueng Keureuto in Lhoksukon District. The study location can be seen in **Fig. 1**.

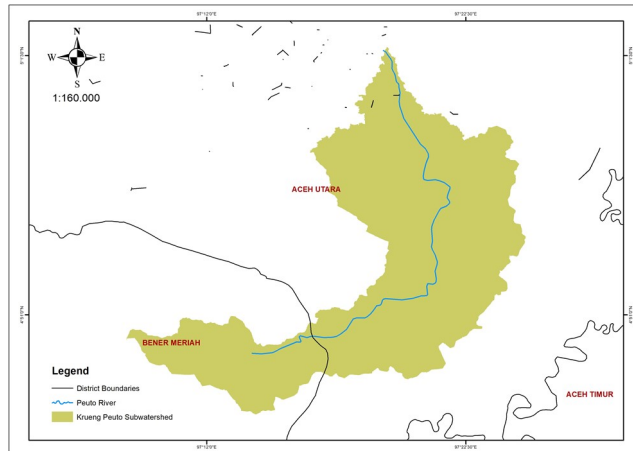


Fig. 1. Study Area

3 DATASETS

The data source used in this research is secondary data, which is data that already exists and is then collected by researchers to meet the needs of data processing in research. These data are annual maximum daily rainfall data, DEM data, land cover data, soil type data, and flood distribution point data.

The data used for this research includes:

1. Rainfall data is sourced from the Sumatra-1 River Basin Center (BWS) for 11 years (2011 - 2021). The rainfall data used comes from 5 rain gauge stations, namely Malikussaleh, Blang Pante, Alur Gading, Pantan Labu, and Jambo Ayee stations. Then the rainfall data is analyzed based on the area where the rain falls using Thiessen polygons. The rainfall data used is the annual maximum daily rainfall in mm units. Rainfall data is used to calculate the design flood discharge;
2. Digital Elevation Model (DEM) from satellite imagery sourced from the National DEM website. The data was used to obtain topographical data, determine watershed boundaries, and to calculate river slope values. The DEM data has a spatial resolution of 0.27 arcseconds or 8.1 meters using the EGM2008 vertical datum;
3. Aceh soil type map in 2020 from the Aceh Water Agency. The soil type map was used to obtain the CN value;
4. Aceh land cover map in 2020 from the Ministry of Environment and Forestry. This map is to obtain the CN value and to determine the Manning coefficient;
5. Flood distribution points in 2022 from the Aceh Water Agency. This data is used to validate the flood inundation map model.

4 METHODS

4.1 Hydrology Analysis

Hydrological analysis is used in several activities such as planning and operation of water structures, water supply, hydropower generation, flood control, erosion and sedimentation control, water transportation, drainage, pollution control, wastewater, etc. Hydrology is also

widely used in the field of civil engineering. For example, to estimate the amount of flooding caused by high rainfall, so that flood control buildings such as embankments, drainage, culverts, and bridges can be planned [7]. Hydrological analysis involves assessing the movement, distribution, and availability of water within a specific geographic area. This process is essential for various applications, including flood forecasting. Data collection is the initial step of hydrological analysis. It involves gathering essential data such as precipitation records, streamflow measurements, land use information, and topographical data. Reliable data sources and accurate data collection methods are crucial to ensure the validity of subsequent analysis. Precipitation data analysis involves examining historical rainfall records to identify trends, patterns, and variations in rainfall intensity and frequency. This step helps in understanding the climatic conditions of the area and estimating the volume of water entering the hydrological system.

Flood discharge analysis is used to determine the amount of designed flood discharge in a watershed. The designed flood discharge is the maximum designed discharge in a river or natural channel with a certain return period that can be flowed without endangering the surrounding environment and river stability [8]. In this research, flood discharge analysis is used using the Soil Conservation Service (SCS) method. The SCS method, developed by the Soil Conservation Service (now known as the Natural Resources Conservation Service), estimates runoff using the curve number (CN) concept. This method considers factors such as soil properties, land use, hydrological condition. Hydrograph development involves transforming the estimated runoff, obtained through the SCS method, into a graphical representation of streamflow variation over time. This hydrograph provides insights into the timing and magnitude of peak flows, essential for flood prediction and water resource management.

4.2 Flood Modelling

Flood modeling uses Geo-HECRAS software. Geo-HECRAS is software that allows users to work on one task by using GIS and HEC-RAS simultaneously [5]. It can be utilized to perform 1D, 2D or 3D floodplain modeling, depending on the data availability and specific requirements, in order to simulate and study flood hazards. The advantage of using Civil Geo-HECRAS is that, aside from speeding up the HEC-RAS model formulation and analysis, it enhances the quality and accuracy of the result. Moreover, some of its features include the ability to utilize range of data sources to create HEC RAS models and the option of importing HEC-RAS models, followed by swiftly georeferencing them to practical maps (Geo-HECRAS 2019).

The obtained data is then subjected to hydraulic modeling. The following are the necessary steps, as depicted in **Fig. 2**.

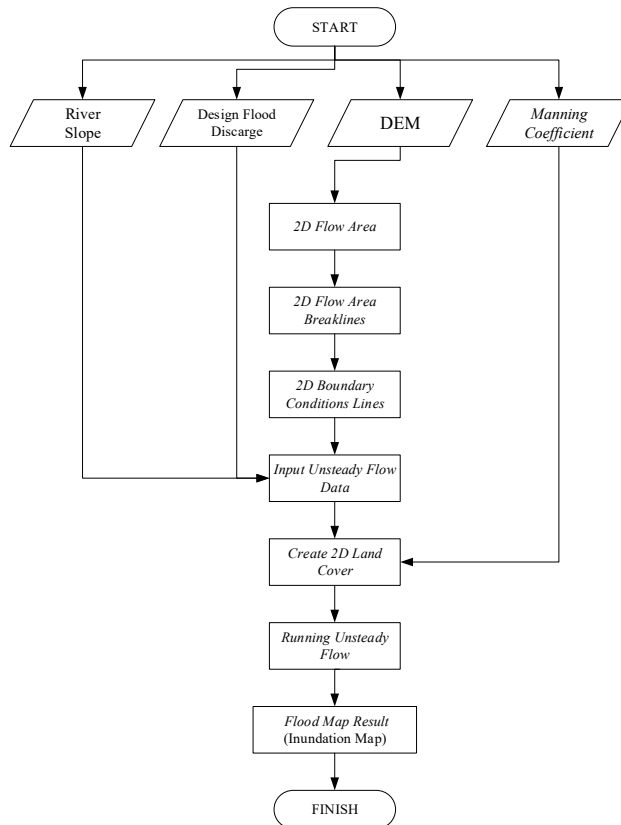


Fig. 2. Flood Modelling Diagram

4.3 Validation

Validation is a process of evaluating a model to get an idea of the level of uncertainty that a model has in predicting hydrological processes [9]. Validation is a process of evaluating a model to get an idea of the level of uncertainty possessed by a model. Validation in this study was carried out by matching the results of the flood inundation model with data on flood distribution points obtained from the Water Agency from 2003-2021. Validation is carried out by overlaying the results of the flood inundation model with data on flood distribution points. If the results after overlaying there are flood distribution points in the flood inundation model results, then the modeling results can be used to make flood inundation maps in the Krueng Peuto sub-watershed.

5 RESULT AND DISCUSSION

5.1 Krueng Peuto Sub-watershed Boundaries

The Krueng Peuto sub-watershed boundary was obtained through delineation of the sub-watershed using ArcGIS 10.5 software. The delineation or boundary line creation process is

based on the Digital Elevation Model (DEM) data of the surrounding area. It was found that the area of the Krueng Peuto sub-watershed is 288.025 km².

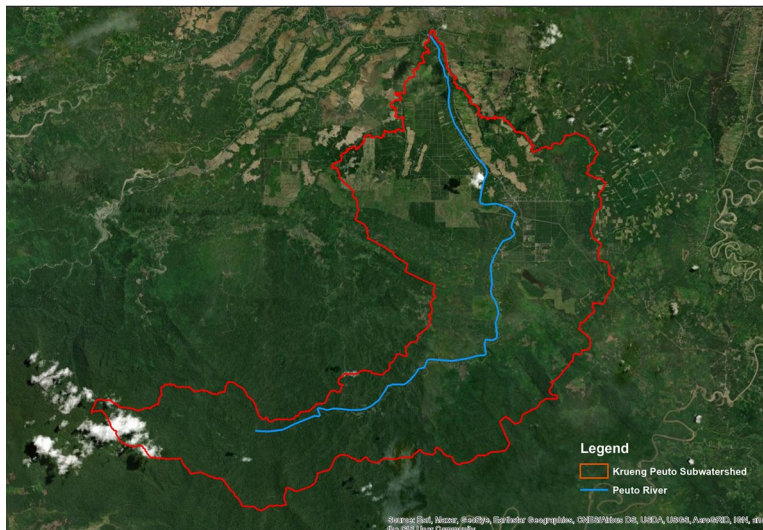


Fig. 3. Delineation of Krueng Peuto Sub-watershed

5.2 Krueng Peuto River Slope

The slope of the Krueng Peuto river was obtained using ArcGIS 10.5 software. The work is done with the slope tools on the 3d analyst tools menu. The result of the slope of the Krueng Peuto river is 0.017600125.

5.3 Hydrological Analysis

Hydrological analysis is carried out to determine the amount of designed flood discharge for each return period. In this study and planning, the rainfall data used is the annual maximum daily rainfall data from the Blang Pante, Malikussaleh, Jambo Aye, Alur Gading, and Pantan Labu rain gauge stations. The data used is data for 11 years, namely 2011 to 2021.

Hydrological analysis begins with filling in empty rainfall data. Filling in the empty rainfall data is calculated using the reciprocal method. Data filling is calculated based on data from complete rain gauge stations namely Malikussaleh, Alur Gading, and Blang Pante stations.

Area rainfall was calculated using the Thiessen polygon method. Referring to the area of influence of rainfall obtained from the creation of Thiessen polygons, there are 3 rain gauge stations that affect the Krueng Peuto sub-watershed. The rain gauge stations are Blang Pante, Pantan Labu, and Jambo Aye stations. The results of the calculation of the maximum daily rainfall distribution can be seen in **Table 1**.

Table 1. Maximum daily rainfall distribution of Krueng Peuto Sub-watershed

Polygon Area (km ²)		Rainfall (mm)			Thiessen (mm)
		Blang Pante	Panton Labu	Jambo Ayee	
		99,856	0,241	187,929	
No	Year				
1	2011	78	81	81	80
2	2012	66	70	70	68
3	2013	58	59	59	59
4	2014	85	215	197	158
5	2015	165	299	257	225
6	2016	80	87	88	85
7	2017	115	160	143	133
8	2018	80	120	109	99
9	2019	82	72	114	103
10	2020	151	228	123	133
11	2021	146	109	179	168

After obtaining the maximum daily rainfall distribution, a statistical rainfall frequency analysis is then carried out to obtain a distribution pattern that matches the existing average rainfall distribution. Designed rainfall is the possibility of high rainfall that occurs in a certain return period as a result of a series of hydrological analysis commonly called frequency analysis [8].

Based on the results of determining the frequency distribution that meets the requirements only the Log Pearson III method, so it is used for the analysis of rainfall designs for the Krueng Peuto sub-watershed. Furthermore, the calculation of the return period is done using the Log Pearson III distribution. The results of the calculation of rainfall Log Pearson III method are given in **Table 2**.

Table 2. Designed Rainfall (Log Pearson III Method)

No.	Tr (Year)	Pr (%)	k	Log Rt	Rt (mm)
1	2	50	-0,026	2,037	109,014
2	5	20	0,833	2,191	155,369
3	10	10	1,297	2,275	188,180
4	25	4	1,803	2,365	231,897
5	50	2	2,135	2,425	265,996
6	100	1	2,439	2,479	301,547

The Log Pearson III method was then tested for suitability. The suitability test was carried out using 2 methods, namely the Chi-Square Test method and the Smirnov Kolmogorov Test. From the table of Critical Chi-Square values, with $\alpha = 5\%$ and $DK = 2$, obtained = 5.991, then $f^2 < f^2_{cr}$, so the Log Pearson III method is eligible for use.

Furthermore, the calculation of testing the suitability of the Log Pearson III method with the Smirnov Kolmogorov Test was also carried out and the D_{max} value was obtained as 0.093. From the Smirnov Kolmogorov Test $D_{critical}$ value table, with 11 data and a degree of confidence of 0.05, the $D_{critical}$ value obtained is 0.396, then $D_{max} < D_{critical}$ so that the Log Pearson III method is eligible for use.

Calculation of rain intensity is needed to obtain hourly rainfall or rainfall that falls per unit time. Rain intensity is calculated using the Mononobe formula. The concentration time

(*t_c*) can be calculated with the Kirpich equation. The designed rainfall hyetograph graph for the 25-year return period can be seen in **Fig. 4**.

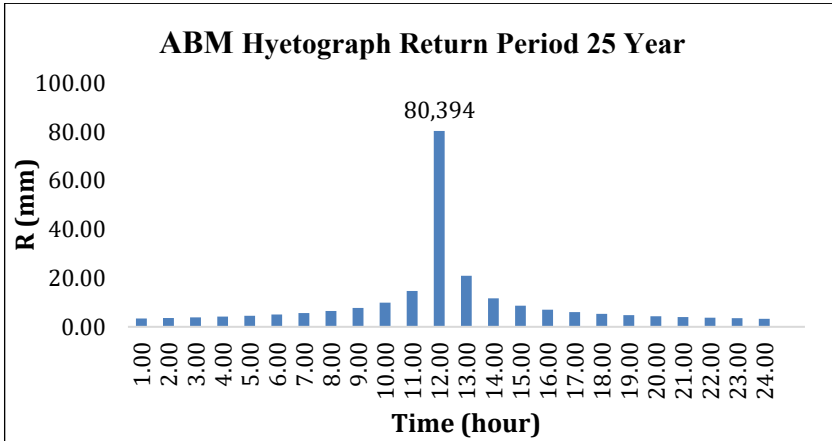


Fig. 4. Rain Hyetograph of 25 Year Return Period

In calculating flood discharge using the hydrograph method, an Excess Rainfall Hyetograph (ERH) or effective rainfall is required. ERH calculation using the SCS method requires a Curve Number (CN) value which is calculated based on land cover and soil type of the review area. From the calculation, the composite CN value for Krueng Peuto sub-watershed is 80.

After obtaining the composite CN value, the ERH calculation can be done for each return period. The calculation is continued by making the Unit Hydrograph (UHS) SCS method. The results of the Unit Hydrograph calculation of the SCS method are obtained by multiplying the peak time (T_p) and peak discharge (Q_p) by the Unit Hydrograph.

Furthermore, the calculation of the designed flood discharge is carried out by multiplying the Unit Hydrograph (UHS) value with ERH. The calculation is carried out on two different catchment areas in order to obtain different discharge values, so that flood overflow can be seen from the input of two different discharges. The upstream catchment starts from the upper reaches of the Krueng Peuto river in Syiah Utama Subdistrict, Bener Meriah Regency to Cot Girek Village, North Aceh Regency and has an area of 127.410 km². The middle catchment starts from Cot Girek Village of North Aceh Regency to Meunasah Village of North Aceh Regency and has an area of 113.577 km². The results of the calculation of the Krueng Peuto sub-watershed design flood discharge for each return period can be seen in **Fig. 5** and **Fig. 6**.

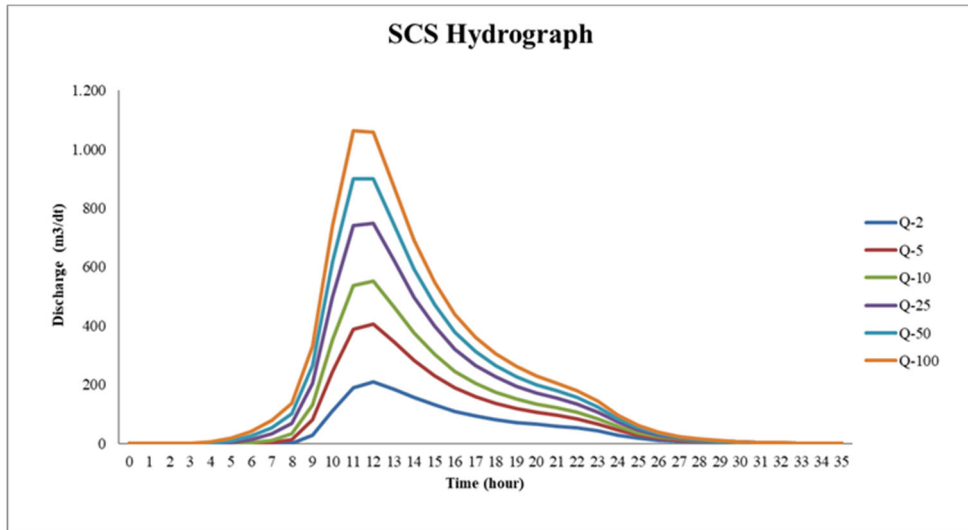


Fig. 5. Soil Conservation Service (SCS) Synthetic Unit Hydrograph upstream catchment area

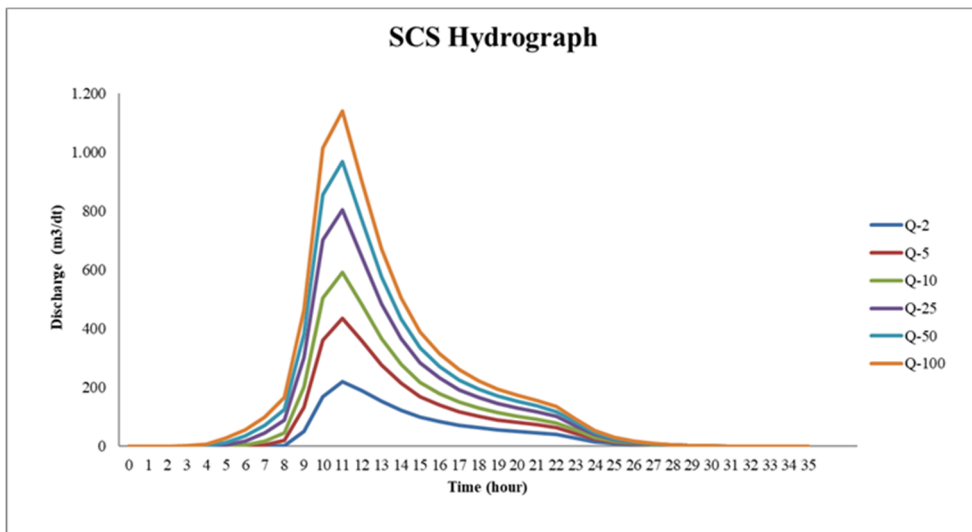


Fig. 6. Soil Conservation Service (SCS) Synthetic Unit Hydrograph middle catchment area

5.4 Flood Modelling

Flood modeling begins by making boundaries of the area where flood inundation will be seen. The area boundary or 2D Flow Area taken is from Cot Girek Village to the downstream of Krueng Peuto in Meucat Village. This menu allows users to select the shape and size of the mesh, as well as fill in the value of the channel Manning coefficient. In this modeling, an adaptive mesh shape with a spacing of 30 m and a channel Manning coefficient value of 0.06 was chosen.

Next, the boundary lines are determined which can be input as needed. In this modeling, upstream, middle and downstream lines are made. In the upstream and middle boundary lines, discharge data or flow hydrograph is entered according to hydrological analysis, and in the

downstream boundary lines, stage hydrograph data or downstream water level elevation values are entered.

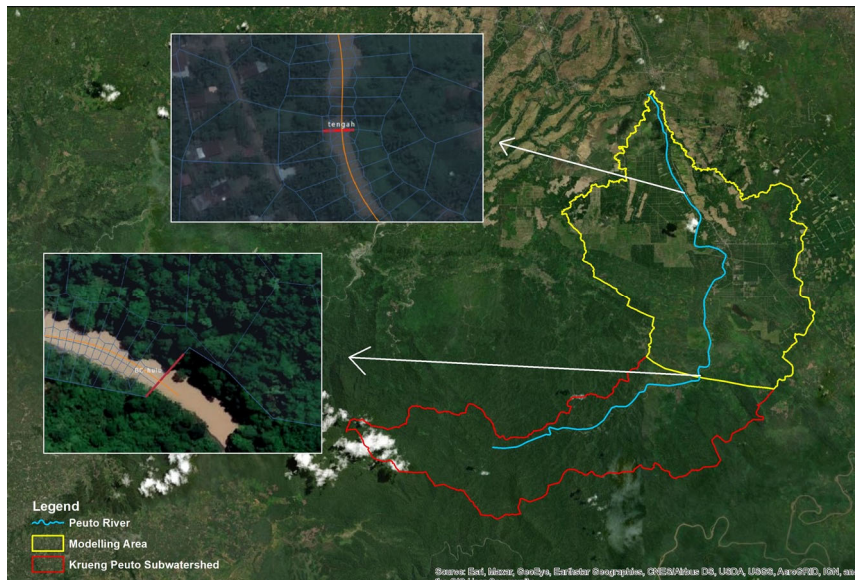


Fig. 7. Boundary Lines

5.5 Flood Inundation Map

From the modeling results, it was found that the largest flood inundation area occurred in the 100-year return period, which was 31.701 km². Based on land cover data, the inundated area is dominated by plantations with an area of 19.447 km² or 61% of the total inundation area. The results of the flood inundation map modeling for each return period can be seen in **Fig. 8** to **Fig. 13**.

Based on administrative data, several villages in several sub-districts are always affected by flood inundation. Cot Girek Village in Cot Girek Sub-district experienced an increase in inundation area for each return period. For the 2-year return period, the inundation area is 1,552 km², and for the 100-year return period, the inundation area is 4,530 km².

Table 3. Flood inundation area based on return period

Return Period (Year)	Inundation Area (km ²)
2	13,012
5	15,989
10	20,467
25	25,514
50	28,714
100	31,701

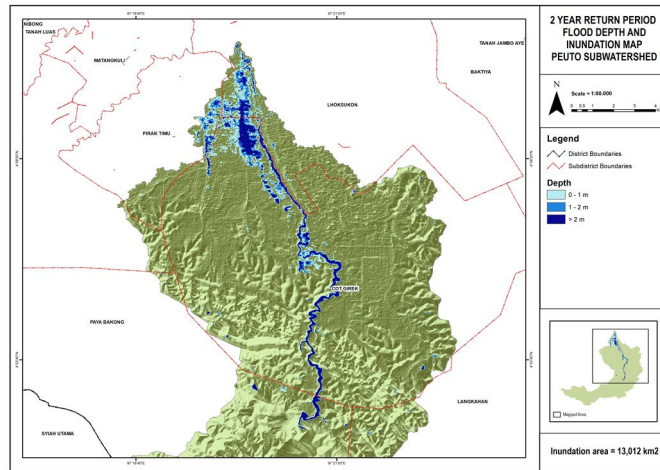


Fig. 8. 2 Year Return Period Flood Inundation Map

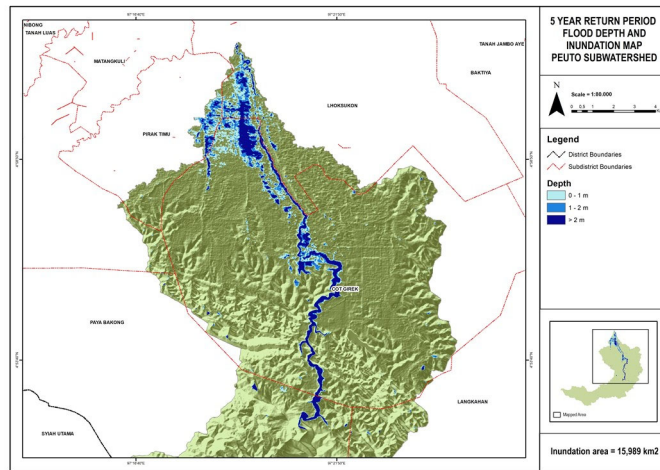


Fig. 9. 5 Year Return Period Flood Inundation Map

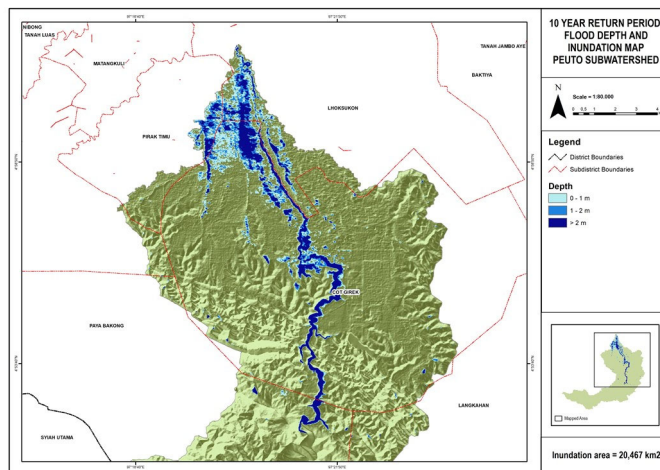


Fig. 10. 10 Year Return Period Flood Inundation Map

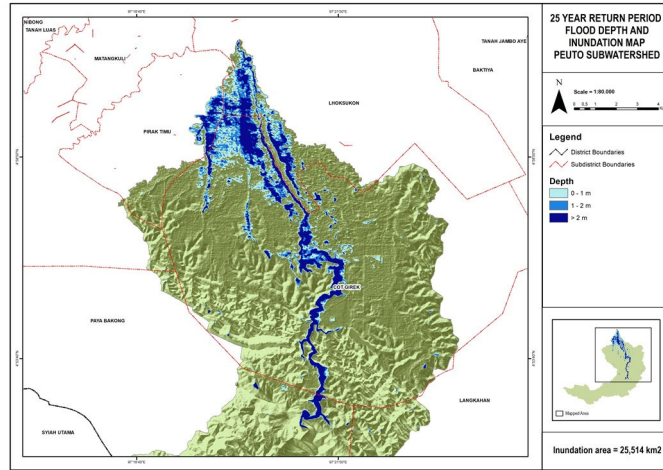


Fig. 11. 25 Year Return Period Flood Inundation Map

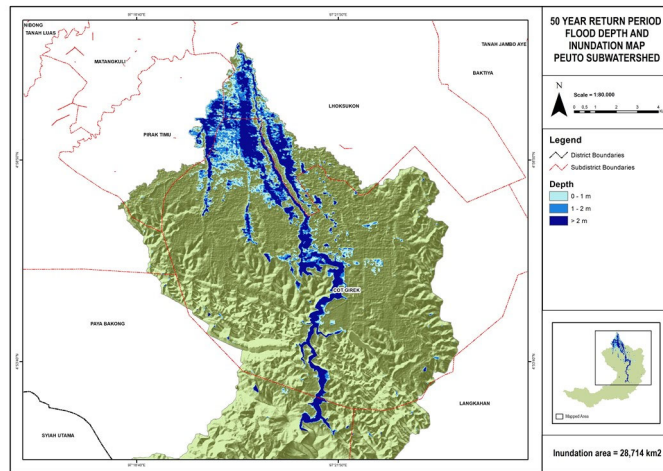


Fig. 12. 50 Year Return Period Flood Inundation Map

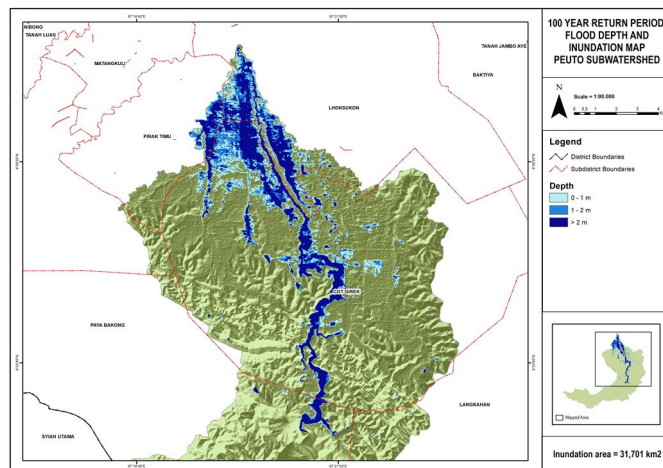


Fig. 13. 100 Year Return Period Flood Inundation Map

5.6 Validation of Flood Distribution Data

There are 21 flood distribution points in the Krueng Peuto sub-watershed area. From the results of overlaying the 25-year return period flood inundation map with the flood distribution points, a validation of 81% was obtained, namely that in the flood inundation area there were 17 flood distribution points, and the other 4 points were not in the flood inundation area. This is can be caused by DEM data for modeling is not very good, so there are areas that are not covered by flood inundation. The validation results can be seen in **Fig. 14**.

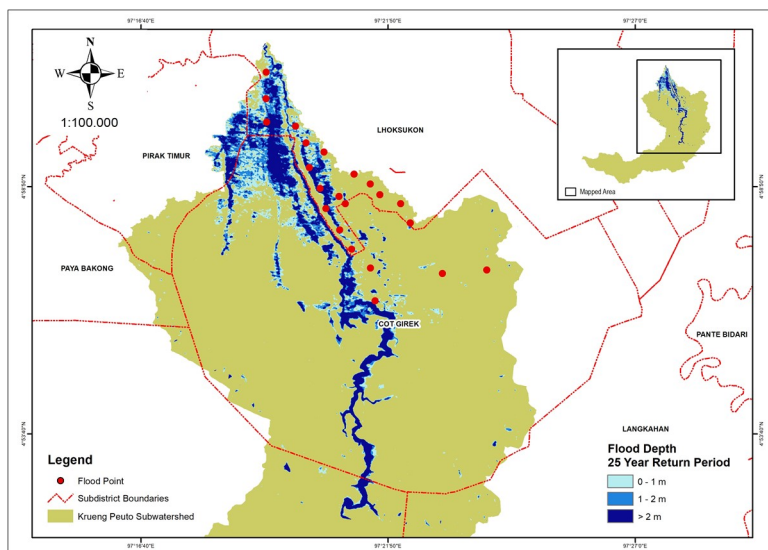


Fig. 14. Flood Inundation Validation Map for 25 Year Return Period for the Krueng Peuto Sub-watershed

6 CONCLUSION

Based on the results of the analysis carried out in the previous chapter, the following conclusions are obtained:

1. From the modeling results, the flood inundation area for the 25-year return period is 25.514 km². The area for each flood depth for the 25-year return period was obtained for a depth of 0-1 m covering 8.35 km² (32.73%), a depth of 1-2 m covering 6.71 km² (26.33%), and a depth of >2 m covering 10.44 km² (40.95%).
2. The validation results of the 25-year return period flood inundation with flood distribution points show that in the flood inundation area there are 17 flood distribution points or the flood inundation area has represented 81% of the flood distribution points.

7 REFERENCES

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