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Integrated Modeling of Nature-Based Solutions for Flood Mitigation and Enhancement of Ecosystem Services in the Kupang City Watershed

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Abstract

Flooding in Kupang City has increasingly been associated with watershed degradation, urban expansion, reduced infiltration capacity, and the region's semi-arid climatic characteristics, highlighting the need for sustainable flood-mitigation strategies. This study aimed to evaluate integrated Nature-based Solutions (NbS) for reducing flood risk and enhancing ecosystem services in the Kupang City watershed. A quantitative approach was applied using hydrological and system-dynamics modeling. Rainfall, land-cover, soil, population, and spatial data were analyzed using ArcGIS, HEC-HMS, Powersim Studio 10, and the InVEST model. The Oesapa Besar watershed was selected as the representative case. The results showed that HEC-HMS generated a 100-year return-period peak discharge of 325.80 m^3/s, while calibration using the Snyder unit hydrograph and Green-Ampt infiltration method supported the reliability of the design-flood analysis. NbS interventions, including vegetation enhancement, green infrastructure, and retention ponds, reduced the Curve Number (CN) from 79.27 in 2015 to 76.60 in 2050 and decreased surface runoff from 71.95 mm to 71.45 mm. The InVEST analysis also indicated a more stable annual water yield and improved urban flood-mitigation capacity through enhanced infiltration and water retention. The study concluded that integrated NbS modeling provides an effective basis for sustainable, ecosystem-based watershed management and long-term flood resilience in Kupang City under continued urban development and future climate-related hydrological pressures.

INTRODUCTION

Floods are natural events that occur frequently due to increased rainfall intensity and duration, land-use changes, and human activities that degrade natural environments (Bai et al., 2025). Flooding occurs when water discharge exceeds the capacity of a river or other water body, causing water to overflow and inundate surrounding areas (Romshoo et al., 2018). Flood vulnerability in a particular area is influenced by rainfall characteristics, social factors such as population conditions, and physical factors such as land cover, slope, drainage density, and landform characteristics (Tate et al., 2021).

Based on the Regulation of the Minister of Public Works and Housing No. 04/PRT/M/2015 concerning the Criteria and Determination of River Basin Areas, the watersheds in Kupang City are part of the Noelmina River Basin Area, which includes the Osmo, Dendeng, Oesapa Besar, and Pasir Panjang watersheds, as well as portions of the Baumata, Salak, and Kolana watersheds. The major rivers within this area include the Liliba, Alak, and Dendeng Rivers. These rivers are strongly influenced by climatic conditions, particularly rainfall, resulting in considerable fluctuations in discharge between the dry and rainy seasons (Oo et al., 2020). Based on the Kupang City Regional Spatial Plan Draft Regulation (Ranperda RTRW) (2025), several locations prone to flooding caused by river overflow are situated in Naikoten, Kuanino, Bello, Kelapa Lima, and Naioni.

Flooding in Kupang City is closely associated with the degradation of watershed functions resulting from the reduction of permeable land as urban development continues to expand (Fitrawan et al., 2026; MARENDRAPUTRA et al., 2026; Primadipta et al., 2025; Sani et al., 2026; Suratama et al., 2026). According to Statistics Indonesia (BPS) of Kupang City (2025), Kupang City covers an area of 18,027 ha, of which 10,127.40 ha are occupied by settlements, 5,090.05 ha by green belts, and 735.57 ha by industrial areas. These land-use conditions contribute to a high volume of surface runoff. An increase in the runoff coefficient causes the volume of surface runoff to rise considerably during rainfall events (Amnifu & Bastian, 2025), thereby adversely affecting communities in flood-prone areas and threatening the sustainability of groundwater-related ecosystem services during the dry season (Bara et al., 2025).

The Nature-based Solutions (NbS) approach is increasingly recognized as an effective and sustainable flood-mitigation strategy (Lee & Song, 2024). This approach emphasizes the restoration and optimization of natural ecosystem functions through measures such as upstream forest restoration, riparian-zone rehabilitation, agroforestry, and the restoration of wetlands and green open spaces as water-retention and infiltration areas (Arifin et al., 2023; Rani et al., 2026). In addition to mitigating flood risk, NbS can improve environmental quality, conserve biodiversity, and strengthen social resilience to climate change (Candra Partarini & Wirastri, 2024).

The urgency of this research lies in developing an integrated modeling framework capable of quantitatively simulating the effectiveness of NbS (Mudenda et al., 2025). The framework integrates HEC-HMS to analyze surface runoff and infiltration before and after the implementation of NbS (Guido et al., 2023) with the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model developed by the Natural Capital Project to map and assess ecosystem services (Duarte et al., 2016). Previous research by Pakungwati et al. (2025) found that, during 2014–2023, 54 villages in Purbalingga Regency were exposed to flooding over an area of 6,453.30 ha, with recommended NbS measures including floodplain restoration, river renaturalization, bioretention, and urban agriculture. Hidayah et al. (2025) also demonstrated that NbS scenarios simulated using HEC-HMS significantly reduced flood discharge in selected areas.

Based on this background, the study entitled "Integrated Modeling of Nature-Based Solutions for Flood Mitigation and Enhancement of Ecosystem Services in the Kupang City Watershed" addressed three research questions: (1) how does the design flood discharge simulated using HEC-HMS compare with the discharge estimated using the Snyder unit hydrograph and Green-Ampt infiltration method; (2) how effective is NbS modeling in reducing flood risk; and (3) how can NbS be applied to enhance ecosystem services using the InVEST model? Accordingly, this study aimed to compare flood-discharge estimates generated by HEC-HMS with those obtained using the Snyder unit hydrograph and Green-Ampt infiltration method, evaluate NbS scenarios for reducing flood risk, and assess the application of NbS for enhancing ecosystem services using the InVEST model in the Kupang City watershed.

This research is expected to contribute theoretically to the development of an integrated approach combining hydrological modeling and ecosystem-service assessment in a semi-arid climatic context (Chen et al., 2023; Geng et al., 2025; Li et al., 2022; López-Ballesteros et al., 2026; Moazeni et al., 2025; Wei et al., 2024). Practically, the findings are expected to provide scientific input for the preparation of the Kupang City Regional Spatial Plan (RTRW) and for the formulation of ecosystem-based watershed management policies that complement conventional structural or gray-infrastructure approaches.

METHOD

Research Design

This study employed a quantitative approach using hydrological analysis and system-based modeling to evaluate the potential of Nature-based Solutions (NbS) for flood mitigation in the Kupang City watershed. The research involved collecting primary and secondary data on the hydrological and physical characteristics of the watershed, analyzing watershed characteristics and rainfall, estimating design flood discharge using HEC-HMS, calibrating and validating the model, assessing land-cover and population changes, modeling NbS scenarios using Powersim Studio, and evaluating ecosystem-service improvements using the InVEST model.

Research Location and Time

The research was conducted on watersheds located in the administrative area of Kupang City, located at the geographical coordinates of 10°36'14"–10°39'58" S and 123°32'23"–123°37'01" E, with the boundaries of the eastern area of Central Kupang District, south of West Kupang District, west of the Semau Strait, and north of Kupang Bay and the Sawu Sea. The research area includes the Osmok watershed, Salak watershed, Dendeng watershed, Pasir Panjang watershed, Oesapa Besar watershed, and Baumata watershed. The research period was carried out in June–October 2026.

Populations, Samples, and Data Types

The research population is all hydrological, spatial, and administrative data related to the condition of the Kupang City watershed. Rain data samples are in the form of rainfall data from 7 rain stations (Eltari, Bello/Sikumana, Oepoi, Lasiana, Naioni, Mapoli, and Alak) with a minimum data length of 20 years, population component data with a time span of the last 10 years (2015–2025), and land cover data for the last 1 year. Primary data was obtained through field observation, while secondary data included BMKG/BWS NT II ground station rain data, GPM satellite rain data from Nasa Giovanni (2005–2025), real discharge data from the Nusa Tenggara River Region II staff gauge, population administration data from BPS/BAPPEDA Kupang City, DEMNAS data from the

Geospatial Information Agency, land cover maps of the Ministry of Environment and Forestry overlaid against the Indonesian Terrain Map, and hydrogeological maps from the Directorate of Geology and Environmental Management.

Watershed Characteristics Analysis

Watershed characteristics were analyzed using National Digital Elevation Model (DEMNAS) data with a resolution of 14 meters through the HEC-GeoHMS feature in ArcGIS. After the outlet point is determined, the process of fill sink, flow, stream, catchment, and drainage line is carried out to automatically model the watershed boundary based on topographic data, so that the watershed area, river length, river slope, and watershed density are obtained.

Rainfall Data Analysis

Ground station rainfall data was collected from existing rain stations in the Kupang City watershed with a span of 20 years (2005–2025). Satellite rain data is downloaded through the giovanni.gsfc.nasa.gov website in the final round GPM format according to the grid of the research watershed location, with specifications as shown in Table 1.

Table 1. GPM-IMERG Satellite Rain Data Specification

Parameters	Remarks
Satellite Rain Data	GPM-IMERG
Data Length	20 years (01 January 2005 – 31 December 2025, Final Run)
Scope	60°N – 60°S
Grid Resolution	0.1° latitude/longitude
Temporal Resolution	30 minutes

Source: NASA Giovanni Website, 2026

The feasibility of rain data was tested through trend absence tests, stationary tests, persistence tests, and outlier tests, followed by correlation evaluation of ground station data using correlation coefficients, Root Mean Square Error (RMSE), and Nash-Sutcliffe Efficiency (NSE). Correction of satellite data was made to ground station data with the highest correlation using a probability curve approach to obtain error values before and after correction.

Rain Analysis Plan

The corrected Annual Maximum Daily Rainfall (HHMT) data were analyzed using the Generalized Extreme Value (GEV) distribution with the help of the Hydrognomon 4 software, supplemented by the Chi-Quadratic and Smirnov-Kolmogorov distribution match tests. The effective rain distribution used the 24-hour Huff-1 rain cumulative distribution pattern as shown in Table 2, due to the limitations of hourly rainfall data in the study area.

Table 2. Cumulative Distribution of Huff-1 Rain Duration 24 Hours

Hour	Percentage (%)	Hour	Percentage (%)
1	5,0	13	1,5
2	9,0	14	1,5
3	13,5	15	1,4
4	13,9	16	1,4
5	10,6	17	1,3
6	10,0	18	1,3
7	6,9	19	0,9
8	4,9	20	0,9
9	3,8	21	0,9
10	3,7	22	0,8
11	2,6	23	0,8
12	2,6	24	0,8

Source: Ministry of PUPR: Director General of Natural Resources-Dam Center, 2019

Flood Discharge Analysis Plan

The planned flood discharge was analyzed using the Synthetic Soil Conservation Service Unit (HSS SCS) Hydrograph at HEC-HMS, which consists of three main components, namely the water loss process, the hydrographic transformation of the runoff unit, and the bottom flow process. Water loss is calculated using the SCS Curve Number (CN) method based on the classification of land cover and Hydrologic Soil Group (HSG) as a result of overlay land cover maps and hydrogeological maps. The unit hydrographic transformation uses the lag time parameter, which is 0.6 times the concentration time. Four main methods were applied in HEC-HMS, namely the Loss Method (SCS Curve Number), Transform Method (SCS Unit Hydrograph Delmarva type), Baseflow Method (Recession, with initial discharge 0.01, recession constant 0.9, and ratio to peak 0.1), and Routing Method (Muskingum-Cunge) using river length and slope parameters.

Discharge Calibration and Validation

Calibration was carried out by comparing the flood discharge hydrograph of the SCS-CN method with the Snyder method based on Green-Ampt water loss, in accordance with the provisions of SNI 2415-2016 which requires the comparison of several methods when the flood discharge cannot be calibrated directly against the measurement data. The soil physical parameters for HSS Snyder were obtained from the watershed map overlay against the Harmonized World Soil Database (HWSD) map, including suction values, hydraulic conductivity, and porosity, while the peaking coefficient was calibrated in the range of 0.4–0.8 until the peak discharge was close to the SCS-CN HSS result.

Population Component Analysis

The population growth rate was calculated by the exponential method Pt = P0.e^rt, while the population projection was calculated by Pt = P0(1+r)^t, with Pt = population in the tth year, P0 = initial population, r = population growth rate, and t = time span. The data used includes the number of population, births, deaths, immigration, and emigration for the period 2015–2025.

Modeling Nature-Based Solutions with Powersim Studio 10

NbS modeling uses a dynamic systems approach with Powersim Studio 10 software to analyze the interactions between environmental, social, and hydrological components of the watershed. Stock variables include vegetation cover area, soil infiltration capacity, and water volume in watersheds; flow variables include surface runoff, water infiltration, and land cover change; while auxiliary variables include rainfall, runoff coefficient, infiltration capacity, and Curve Number values. The model is developed through a Causal Loop Diagram that describes the cause-and-effect relationship between variables, then transformed into a quantitative Stock Flow Diagram. The model output is in the form of changes in flood peak discharge, surface runoff, infiltration capacity, and watershed ecosystem conditions due to the application of NbS.

Ecosystem Services Analysis with InVEST Model

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model is used to evaluate ecosystem functions such as water flow regulation, flood control, and soil conservation due to the application of NbS. InVEST main input data is shown in Table 3.

Table 3. InVEST Model Input Parameters

InVEST Parameters	Required Input Data
LULC Raster	Land Use Map
Soil Groups	Soil Type Map (Group A–D)
Rainfall Depth	Maximum Daily Rainfall
Biophysical Table	Curve Number (CN) Value

Source: Martin Jančovič, 2013

The two main analysis models used are Annual Water Yield, to estimate the annual amount of water produced by watersheds, and Urban Flood Risk Mitigation, to analyze the ability of ecosystems to reduce the risk of urban flooding through water infiltration, water retention by vegetation, and water storage by soil. InVEST outputs are in the form of flood vulnerability change maps, runoff change maps, infiltration capacity change maps, and land cover change maps.

Hypothesis Testing

Hypothesis tests were carried out on the model as a whole with H0: the NbS modeling free variable had a significant effect on flood mitigation and the improvement of Kupang City watershed ecosystem services, and H1: the NbS modeling free variable had no significant effect. The test was performed with the F test and the T test at a 95% confidence level ($\alpha = 0.05$) using multiple linear regression analysis on SPSS.

RESULTS AND DISCUSSION

This research was conducted on watersheds (watersheds) located in the Kupang City area, including the Oesapa Besar watershed, Pasir Panjang watershed, Dendeng watershed, Osmo watershed, Salak watershed, and Baumata watershed. The discussion included the results of the analysis of watershed characteristics, flood mitigation with the application of Nature-Based Solutions (NbS), and the improvement of the resulting ecosystem services.

Characteristics of the Kupang City Watershed Area

The results of modeling using ArcGIS 10.5 on DEMNAS data resulted in 6 watersheds in the administrative area of Kupang City. The watershed with the longest main river is the Oesapa Besar watershed (21.35 km), followed by the Pasir Panjang watershed (17.51 km). The complete characteristics of the six watersheds are shown in Table 4.

Table 4. Watershed Characteristics in the Kupang City Area

No.	Watershed Name	Watershed area (km2)	Overall River Length (km)	Main River Length (km)	Slope of the Main River (%)
1	Oesapa Besar Watershed	56,36	126,76	21,35	2,22
2	Pasir Panjang Watershed	32,40	49,02	17,51	2,14
3	Jerky Watershed	48,89	107,26	16,58	2,34
4	DAS Osmo	14,15	27,72	7,53	1,49
5	Salak Watershed	19,71	42,37	11,44	1,64
6	Baumata Watershed	26,85	67,63	16,67	2,44

Source: Analysis Results, 2026

As a representative example, the spatial characteristics of the Oesapa Besar watershed, which are the focus of the detailed discussion of flood discharge and NbS modeling in the following section, are shown in Figure 2.

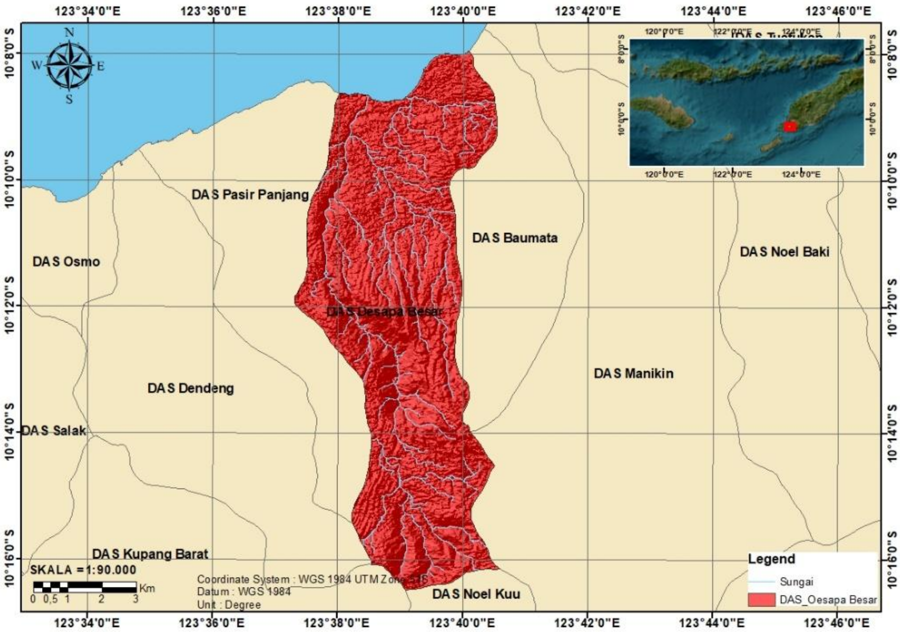

Figure 2. Map of the Great Oesapa Watershed

Source: Analysis Results, 2026

3.2 Availability of Rainfall Data

Ground station rainfall data was obtained from BMKG with an average length of 12 years of data. The details of the rainfall stations used in each watershed are shown in Table 5, while the distribution of satellite rainfall data grids is shown in Table 6.

Table 5. Details of Watershed, Rainfall, and Rainfall Toll Data Length

No.	Watershed Name	Rain Post	Data Length (Years)	Time Period
1	Oesapa Besar Watershed	Eltari, Lasiana, Oepoi, Sikumana/Bello	25 / 25 / 12 / 12	2000–2024 / 2008–2019
2	Pasir Panjang Watershed	Eltari, Oepoi, Mapoli, Sikumana/Bello	25 / 12 / 12 / 12	2000–2024 / 2003–2019
3	Jerky Watershed	Napoli, Mapoli, Sikumana/Bello, Wine	7 / 12 / 12 / 5	2008–2014 / 2021–2025
4	DAS Osmo	Naioni, Mapoli, Wine	7 / 12 / 5	2008–2014 / 2021–2025
5	Salak Watershed	Mapoli, Naioni, Wine	12 / 7 / 5	2003–2014 / 2021–2025
6	Baumata Watershed	Eltari, Lasiana, Sikumana/Bello	25 / 25 / 12	2000–2024 / 2008–2019

Source: Analysis Results, 2026

Table 6. Details of Watershed, GPM Grid, and Satellite Rainfall Data Length

No.	Watershed Name	Grid/GPM	Data Source	Data Length (Years)	Time Period
1	Oesapa Besar Watershed	Grid 1	NASA Giovanni	21	2005–2025
2	Pasir Panjang Watershed	Grid 1	NASA Giovanni	21	2005–2025
3	Jerky Watershed	Grid 2	NASA Giovanni	21	2005–2025
4	DAS Osmo	Grid 3	NASA Giovanni	21	2005–2025
5	Salak Watershed	Grid 4	NASA Giovanni	21	2005–2025
6	Baumata Watershed	Grid 1	NASA Giovanni	21	2005–2025

Source: Analysis Results, 2026

Rainfall Data Feasibility Testing

Rain data testing was carried out through trend absence tests (Spearman method), stationary tests (F-test and T-test), persistence tests (Spearman method), and outlier tests at 5% confidence.

The test results showed that the Sikumana/Bello and Oepoi rainposts showed a trend at a 5% confidence level, so they were not used as the main data in the follow-up analysis. All rain data tested had a stable average and variance (stationary test), were random or had no interperiod dependency (persistence test), no data outside the threshold limit (outlier test), and were consistent based on the Rescaled Adjusted Partial Sums/RAPS method (consistency test). Overall, the rain data used met the statistical requirements for hydrological analysis, design rain, HEC-HMS simulation, and integrated NbS modeling.

Ground Station and Satellite Rain Data Correction

Correction of GPM satellite rain data was carried out on ground station data with the highest correlation value to obtain the accuracy of rainfall data readings (Krisnayanti et al., 2020).

The highest correlation was obtained in the Lasiana Rainpost (R = 0.86) which was in the very strong category, while the lowest correlation was in the Naioni Rainfall of the Dendeng Watershed (R = 0.55) which was in the medium category. The smallest RMSE value was at the Lasiana Rainpost (21.68 mm) and the largest at the Naioni Rainfall (44.11 mm). The highest NSE score was at the Lasiana Rainfall Post (0.73, good category) and lowest at the Naioni Rainfall (0.26, poor category). In general, GPM satellite rainfall data has a strong to very strong relationship with observation data, with a dominant correlation value above 0.60.

The correction to the Daily Maximum Rainfall (HHMH) lowered the error range from 0.02–0.08 to 0.01–0.04 for all rain posts. The correction of the Annual Maximum Daily Rainfall (HHMT) also showed a decrease in errors in most locations, for example the Eltari Rainfall Post from 0.18 to 0.04 and the Mapoli Pasir Panjang Watershed

Rainfall from 0.23 to 0.06, although in some locations such as the Oepoi Rainpost the error actually increased from 0.44 to 0.78.

Overall, the corrected GPM satellite rain data has a better level of accuracy and is suitable for use as input for rain analysis design, HEC-HMS modeling, and NbS modeling.

Rain Analysis Plan

Analysis of the design rain using the Generalized Extreme Value (GEV) distribution with the help of the Hydrognomon 4 software resulted in the design rainfall values for repeat periods 2, 5, 10, 25, 50, 100, 500, and 1000 years in the six watersheds. The distribution match test using the Chi Square and Smirnov Kolmogorov methods showed good compatibility in all analyzed rain stations, in line with previous research that showed the difference between the rainfall results of the Hydrognomon 4 software design and manual calculations only ranging from 0.004%–0.193%.

Flood Discharge Analysis of the Oesapa Besar Watershed Design (Representative Case)

The analysis of the draft flood discharge is discussed in detail in the Oesapa Besar watershed as a representative case, because it has the largest area and length of the main river among the six watersheds of Kupang City.

Land Cover Classification and Soil Type

The results of the land cover analysis of the Oesapa Besar watershed using ArcGIS 10.5 show nine types of land cover. The land cover of Bush/Bushes has the largest area (25.68%), followed by Settlements (14.77%), Plantations (4.94%), Savannas (9.40%), Dryland and Shrub Agriculture (1.77%), Primary Dryland Forests (1.28%), Rice Fields (0.16%), Mangroves (0.19%), and Water Port (0.05%), as shown in Table 10 and Figure 3.

Table 10. Percentage of Land Cover of the Great Oesapa Watershed

No.	Land Cover	Area (km2)	Present (%)
1	Air Port	0,08	0,05
2	Primary Dryland Forests	2,20	1,28
3	Settlement	25,37	14,77
4	Plantations	8,48	4,94
5	Dryland Agriculture + Shrubs	3,04	1,77
6	Savannah	16,14	9,40
7	Rice Fields	0,27	0,16
8	Bush/Bushes	44,11	25,68
9	Mangrove	0,32	0,19

Source: Analysis Results, 2026

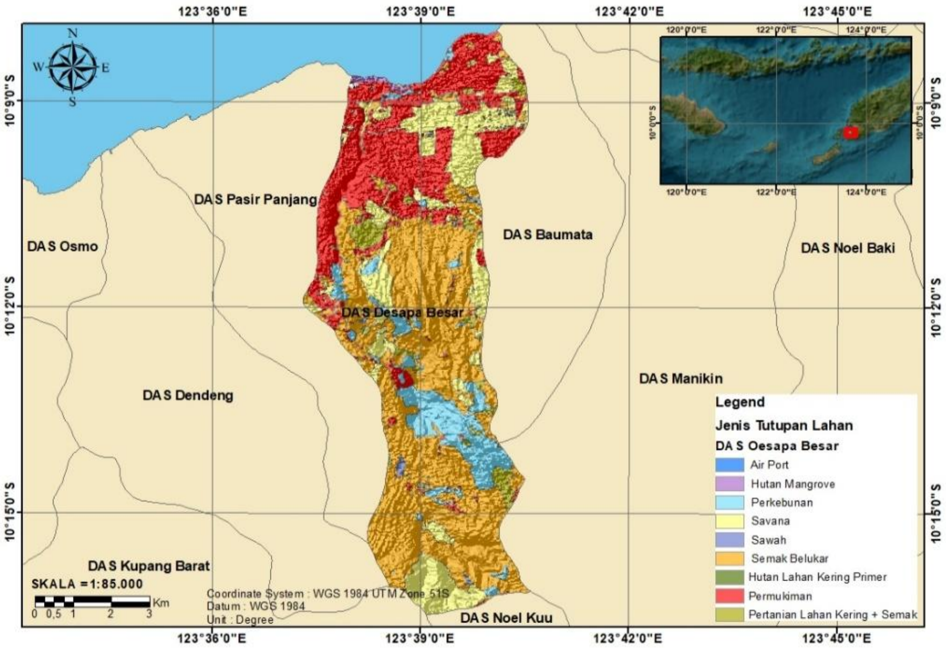

Figure 3. Map of the Greater Oesapa Watershed Land Cover

Source: Visualization Results with ArcGIS 10.5, 2026

The classification of hydrological soil types (Hydrologic Soil Group / HSG) is obtained from the Indonesian Hydrogeological Map on a scale of 1:250,000. The Oesapa Besar watershed is divided into 5 types of lithology with permeability varying from medium to high to low to very low, as shown in Table 11 and Figure 4.

Table 11. Hydrologic Soil Group (HSG) Oesapa Besar Watershed

No.	Lithology	Permeability	HSG	Area (km2)	Weight (%)
1	Alluvium and coastal sediments (gravel, sand, clay)	Medium–high	C	0,87	1,53
2	Napal sands interspersed with sandstone, conglomerates, tufa dasit	Low–medium	C	4,89	8,68
3	Coral limestone, locally karstted	Medium	D	27,27	48,38
4	Coral limestone, locally karstted	Medium–high	D	17,77	31,53
5	Clay contains other rock blocks	Low–very low	D	5,56	9,87

Source: Analysis Results, 2026

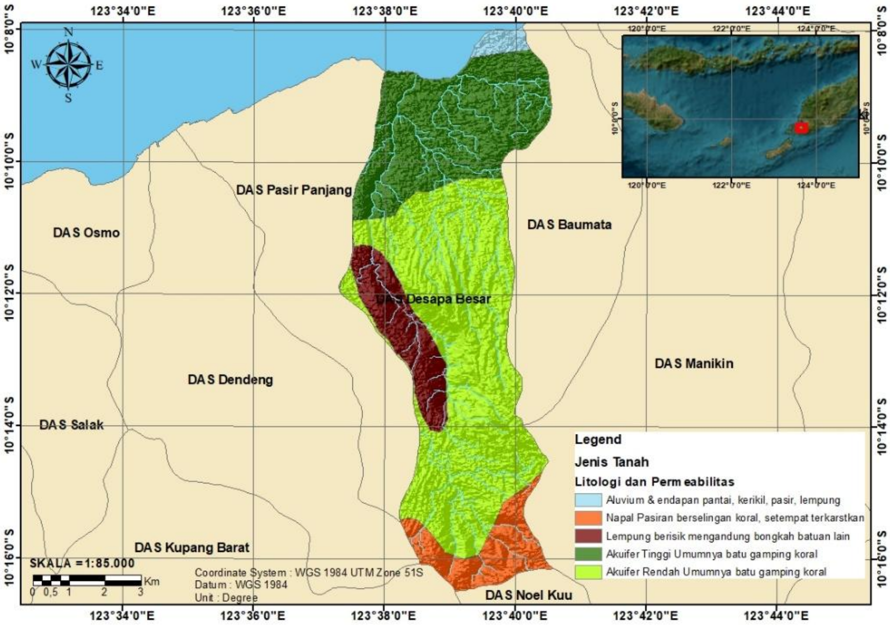

Figure 4. Hydrogeological Map of the Great Oesapa Watershed
Source: Visualization Results with ArcGIS 10.5, 2026

The Oesapa Besar watershed as a whole is dominated by HSG D soil type (very low water absorption potential) with a percentage of 89.78%, while the HSG C soil type is only 10.22% as shown in Table 12, indicating that this watershed has relatively low permeability.

Table 12. The Percentage of HSG Weight of the Oesapa Watershed is Large

No.	HSG	Area (km2)	Percentage (%)
1	C	5,76	10,22
2	D	50,60	89,78
	Total	56,36	100,00

Source: Analysis Results, 2026

Determination of Curve Number (CN) Value

The value of the Curve Number (CN) is obtained from the results of the land cover overlay and HSG as shown in Table 13. The results of the analysis showed that the CN value of the Oesapa Besar watershed was 79.27, with a CN value range of 74–100. The highest CN values (91–100) were found in port water land cover, settlements, and mangroves, while the lowest CN values (74–78) were found in forest land cover, savannas, shrubs, rice fields, and dryland agriculture. The combination of land cover and rock lithology shows that the Oesapa Besar watershed has low permeability with a potential low infiltration rate and a fairly high potential for runoff, thus having a major effect on the resulting flood discharge.

Table 13. Determination of Curve Number (CN) of the Great Oesapa Watershed

No.	Land Cover	Area (m2)	Present (%)	HSG	CN
1	Air Port	46,00	0,08	D	92,00
2	Primary Dryland Forests	1.278,00	2,27	D	77,00
3	Settlement	12.912,00	22,91	C/D	91,00
4	Plantations	4.938,00	8,76	C/D	80,00
5	Dryland Agriculture + Shrubs	1.768,00	3,14	C/D	78,00
6	Savannah	9.397,00	16,67	C/D	75,00
7	Rice Fields	156,00	0,28	C	76,00
8	Bushes	25.679,00	45,56	C/D	74,00
9	Mangrove	189,00	0,34	D	100,00

Source: Analysis Results, 2026. CN weighted by the Oesapa Besar watershed = 79.27

Hydrographic Transformation and Basin Model Parameters

The lag time value of the Oesapa Besar watershed from the HEC-GeoHMS analysis in ArcGIS is 6.09 hours. Other model basin parameters used as HEC-HMS inputs for the design flood discharge simulation are shown in Table 14.

Table 14. Basin Parameters of Large Oesapa Watershed Model

Area (Ha)	Area (km2)	CN	C1	Ct	River Length (m)	River Length (km)	Lc (km)	Time Lag (hours)	S (mm)	Per (mm)	Impervious (%)
5.636,300	56,363	78,89	0,75	1,80	21.350,00	21,350	7,117	6,093	67,98	13,60	20,00

Source: HMS Geo Analysis Results, 2026

Flood Discharge Analysis with HEC-HMS

The model of the Great Oesapa watershed in HEC-HMS is shown in Figure 5, with reservoir SB 1 as the central point emphasizing the outlet point (sink 1).

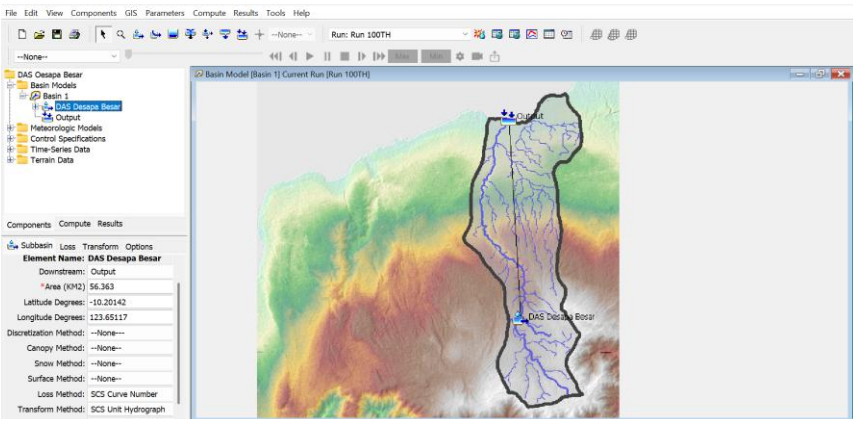

Figure 5. Large HEC-HMS DAS Oesapa Model Basin
Source: Modeling Results with HEC-HMS 4.2.1, 2026

The results of the simulation of the projected flood discharge at various times are shown in Table 15 and Figure 6. The peak discharge increased from 116.40 m3/s at the 2-year replay to 438.30 m3/s at the 1000-year replay, with a consistent peak time at 06.00.

Table 15. Recapitulation of Flood Discharge Results of HEC-HMS DAS Oesapa Besar

No.	Birthday (Year)	Peak Time	Flow (m3/s)
1	2	06:00	116,40
2	5	06:00	171,10
3	10	06:00	209,00
4	25	06:00	256,30
5	50	06:00	291,30
6	100	06:00	325,80
7	200	06:00	360,00
8	500	06:00	404,80
9	1000	06:00	438,30

Source: Modeling Results with HEC-HMS 4.2.1, 2026

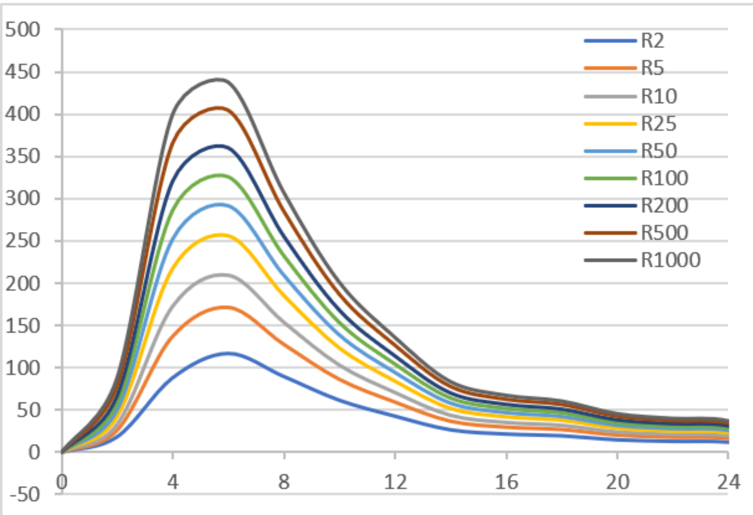

Figure 6. Hydrograph of Flood Reconstruction of the Great Oesapa Watershed
Source: HEC-HMS Analysis Results, 2026

Flood Discharge Calibration with Snyder HSS

The results of the watershed map overlay on the Harmonized World Soil Database (HWSD) map show that the Great Oesapa watershed is dominated by Chromic Luvisol lithology and sandy clay textured Pellic Vertisols, with physical parameters of suction 239 mm, hydraulic conductivity 0.6, and porosity 0.321. The calibration of the peaking coefficient of 0.6 resulted in a peak discharge at the 1000-year replay of 2,263.1 m3/second which is close to the peak discharge value of HSS SCS-CN, while at the 100-year re-discharge of the HSS Snyder peak discharge was 1,694.3 m3/second. The proximity of the results of these two methods shows that the results of the flood discharge analysis of the Oesapa Besar watershed design are quite valid, as shown in Figure 7.

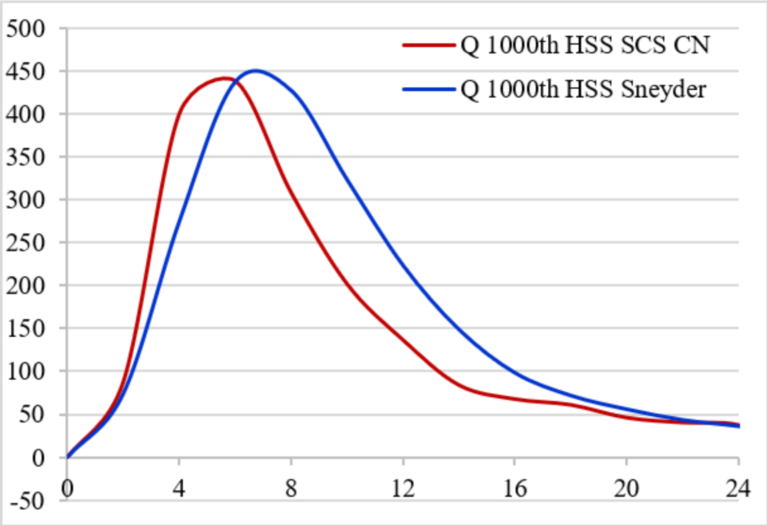

Figure 7. Hydrographic Calibration of Floods on the 1000th Anniversary of the Great Oesapa Watershed

Source: HEC-HMS Analysis Results, 2026

Modeling of Nature-Based Solutions (NbS) of the Great Oesapa Watershed

Population growth is one of the main factors influencing land-use change and increased risk of hydrological disasters through increased demand for residential land, impermeable surfaces, and surface runoff. The projected population component of the Oesapa Besar watershed is shown in Table 16, with an average birth rate of 1.78%, death rate of 0.50%, immigration of 0.35%, and emigration of 0.08% per year.

Table 16. Data Projection of the Population Component of the Oesapa Besar Watershed

Year	Population	Births (%)	Deaths (%)	Immigration (%)	Emigration (%)
2015	111.520	2,11	0,42	0,32	0,11
2018	120.914	2,04	0,57	0,36	0,07
2021	130.057	1,51	0,59	0,30	0,10
2023	133.134	1,70	0,64	0,35	0,07
2025	116.575	1,77	0,54	0,43	0,09
Average	124.471	1,78	0,50	0,35	0,08

Source: BPS Data Analysis Results, 2026

The changes in land cover of the Oesapa Besar watershed for the period 2015–2025 are shown in Table 17. The area of settlements increased by an average of 9.73% per period, while the cover of agricultural land, rice fields, shrubs, and mangroves tended to decrease.

The Causal Loop Diagram (CLD) in Figure 8 shows that population growth drives an increase in settlement area, changes land use, and increases the value of the Curve Number (CN), thereby decreasing infiltration capacity and increasing surface runoff. Rainfall and CN values are the main factors in the amount of runoff, while the application of NbS through vegetation intervention and grey infrastructure plays a role in reducing runoff and flood risk.

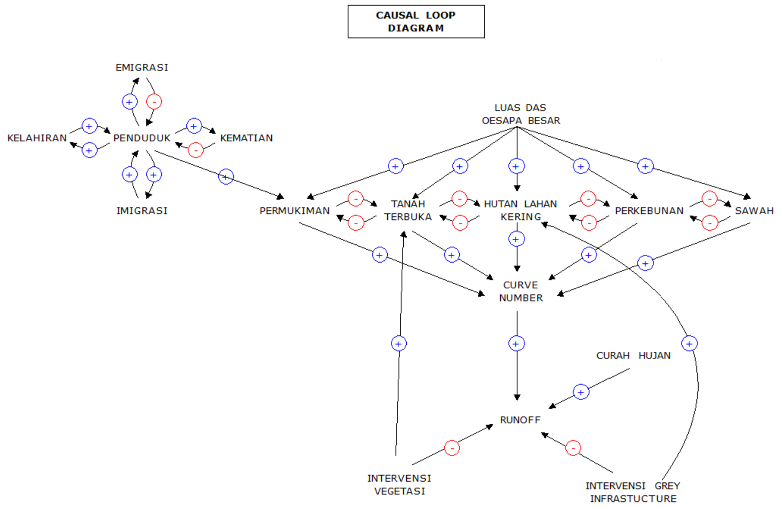

Figure 8. Causal Loop Diagram of the Great Oesapa Watershed

Source: Powersim Studio Analysis Results, 2026

The Stock Flow Diagram in Figure 9 develops the CLD quantitatively, illustrating the accumulation of groundwater storage, changes in land use, the area of NbS application, and changes in flood discharge over time.

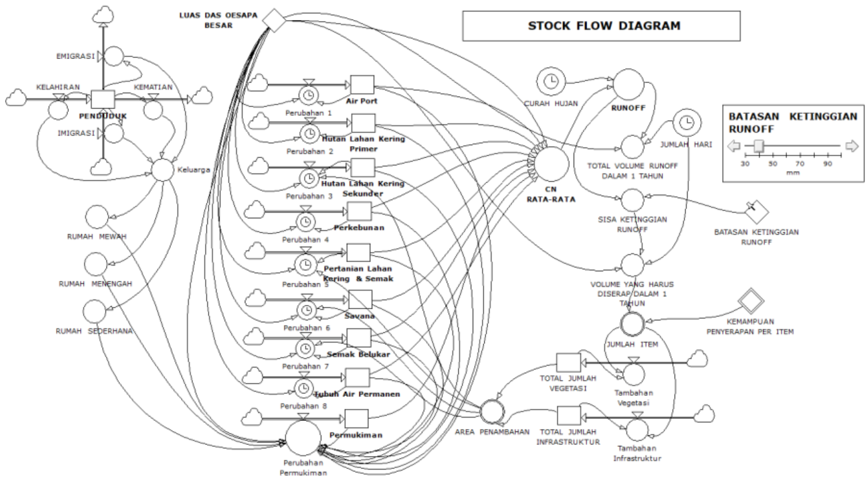

Figure 9. Stock Flow Diagram Oesapa Large Watershed

Source: Powersim Studio Analysis Results, 2026

The simulation results show that the intervention of adding vegetation, green infrastructure, and retention ponds is able to gradually reduce the CN value and surface runoff volume as shown in Table 18. The CN value decreased from 79.27 in 2015 to 76.60 in 2050, while the runoff volume decreased from 71.95 mm to 71.45 mm. The application of NbS in the Oesapa Besar watershed has proven to be effective in reducing the CN value and runoff volume, while maintaining the sustainability of water availability in the dry season so that the hydrological function of the watershed becomes more stable. The effectiveness of NbS increases if its implementation is carried out consistently in the long term, so watershed management strategies need to integrate land rehabilitation, vegetation conservation, spatial control, and sustainable green infrastructure development.

3.8 Analysis of Ecosystem Service Improvement with InVEST Model

The Annual Water Yield analysis shows that the distribution of annual water yield of watersheds is greatly influenced by land cover, soil texture, topography, and climatic conditions. Areas with dense vegetation have high infiltration so that they are able to store a larger amount of water before it is drained as a base stream, while built-up areas produce high surface runoff with a relatively small contribution to groundwater storage. The application of NbS provides a more stable Annual Water Yield value compared to existing conditions, showing an improvement in the hydrological function of the watershed which is important for Kupang City with semi-arid climatic characteristics and uneven distribution of rainfall throughout the year. In addition to increasing water availability, the increase in Annual Water Yield also contributes to reducing the risk of drought in the dry season.

Urban Flood Risk Mitigation analysis shows that the NbS implementation scenario results in a significant decrease in surface runoff compared to existing conditions, due to increased soil infiltration capacity, increased vegetation area, and increased watershed's ability to retain and store rainwater before it is discharged into rivers. The implementation of green open space, river border restoration, upstream area rehabilitation, and the construction of catchment areas contribute to the reduction of peak flood discharge and flow concentration time, so it is important for the urban area of Kupang City which continues to experience an increase in the area of built-up areas.

Overall, the results of the study show that the implementation of NbS is an effective approach in supporting urban flood mitigation, improving ecosystem services, improving environmental quality, strengthening watershed resilience to climate change, and supporting the sustainable development of Kupang City. The integration of dynamic system modeling results using Powersim Studio with spatial analysis using InVEST provides a strong scientific basis in the formulation of ecosystem-based watershed management policies in Kupang City.

CONCLUSION

The integrated modeling study of Nature-based Solutions (NbS) in the Kupang City watershed concluded that the HEC-HMS simulation using the SCS Curve Number (SCS-CN) method in the Oesapa Besar watershed produced a peak discharge of 325.80 m^3/s for the 100-year return period. Meanwhile, calibration using the Snyder Synthetic Unit Hydrograph (SUH) combined with the Green-Ampt infiltration method produced a peak discharge of 2,263.1 m³/s for the 1,000-year return period. These results supported the reliability of the design flood-discharge analysis in the study area. NbS scenario modeling using Powersim Studio 10 was effective in reducing flood risk, as indicated by a decrease in the Curve Number (CN) of the Oesapa Besar watershed from 79.27 in 2015 to 76.60 in 2050, accompanied by a reduction in surface runoff from 71.95 mm to 71.45 mm. These improvements resulted from interventions involving increased vegetation cover, green infrastructure, and retention ponds. The implementation of NbS also enhanced watershed ecosystem services based on the InVEST model analysis, as indicated by a more stable Annual Water Yield and reduced urban flood risk through increased infiltration capacity and water retention by vegetation. Based on these findings, the Kupang City Government is recommended to integrate NbS into regional spatial planning and watershed management policies through riparian-zone rehabilitation, upstream-area conservation, the expansion of green open spaces, and the sustainable development of green infrastructure to strengthen long-term flood-mitigation effectiveness. Further research should apply similar modeling to the other watersheds in Kupang City in greater detail and examine the integration of NbS with structural or gray infrastructure to develop a more comprehensive and climate-adaptive flood-management strategy.

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