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Flooding Management with System Dynamic Approach (Case Study: Citarik Sub Watershed)

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Abstract. Citarik Sub Watershed (Upper Citarum Watershed) is a critical and priority sub watershed indicated by the occurrence of hydrological degradation, the annual flood phenomenon. Floods occur due to runoff increase, influenced by natural and many anthropogenical factors. A necessary study is conducted to model the dynamic system using STELLA related to floods in Citarik Sub Watershed to study the flood phenomenon, its influential components, and their interactions by simulated scenario and become a consideration in determining policies based on the flood discharge. The model shows based on the sensitivity analysis that the low leverage variables include growth and mortality rate, while the high leverage variables include forest conversion rate. According to the case analysis, the RPJMN (26 m^3/s) and river normalization (16.82 m^3/s) policies are considered to be enhanced with other scenario and the most effective scenario based on STELLA running result by maintaining a minimum forest area of 30% of the watershed's total area and reducing the forest conversion rate to zero by making the forest a conservation forest and conducting reforestation, the model predicted that this scenario could avoid flooding occurred (0 m^3/s) in the area for the next 20 years.

Keywords: *Citarik Sub Watershed; flood; land conversion; STELLA; system dynamic.*

1 Introduction

The Citarik Sub-Watershed is one of the parts of the Upper Citarum Watershed, located at an altitude of 700-1,500 meters above sea level with an area of 53,493 hectares, which administratively belongs to the Bandung, Sumedang, and Garut Regencies. The upstream area of the Citarik Sub-Watershed is bordered by Sindulang mountain, which makes its slope very steep and its flow velocity also high, while the downstream area is flat, resulting in low flow velocity Table 1. This makes the downstream area prone to floods, especially in areas where several rivers meet. It is noted that flood disasters occur annually in the downstream area of Citarik and the impact has been increasing every year, particularly in the districts of Rancaekek and Solokanjeruk with a potential impact of 1832, followed by the districts of Majalaya and Baleendah with potential impacts of 966 and 1092 respectively, resulting in floods of 0.5 to 2 meters in depth [1].

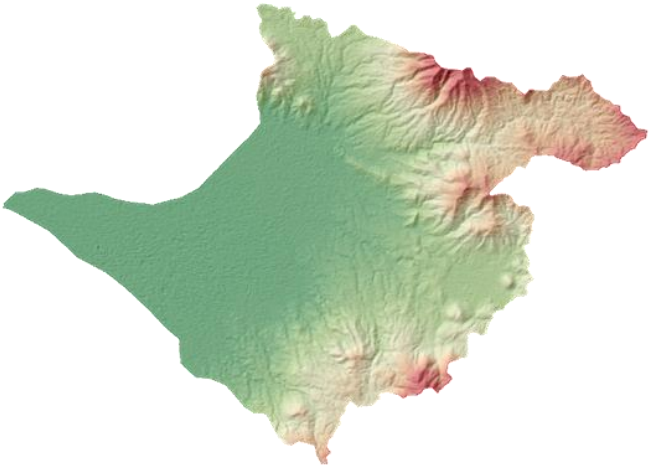


Figure 1 Citarik Sub-Watershed DEM Maps[1]

Table 1 Citarik Sub Watershed slope classification (remote sensing)[2]

Class	Classification	Area (Ha)	%
0% - 8%	Gently Sloping	64.91	50.38
8% - 15%	Moderately Sloping	56.2	43.62
15% - 25%	Moderately Steep	7.63	5.92
25% - 45%	Steep	0.09	0.07
> 45%	Very Steep	0.00	0.00
Total		128.84	100.00

In simple terms, a flood is the overflowing water from a channel that occurs due to an increase runoff discharge. Runoff discharge is influenced by natural factors such as geography and climatology, as well as anthropogenic factors such as land conversion. The natural factors that support flooding in the Sub-DAS Citarik area are geographical and climatological factors. The geographical factor can be seen from the slope Table 1 and soil types. The soil types in this area are mostly Andosol and Latosol, which are the result of volcanic processes, and some are associated soils of Andosol and Latosol [3]. These soil types are potentially eroded and eventually become sediment at the bottom of the river, reducing the river's carrying capacity and supporting flooding, particularly in the downstream area. This is because the flat downstream area and low flow velocity are the most optimal sedimentation areas in the region. The sedimentation in the Sub-DAS Citarik area reaches 63,012 tons per year [3]. Regarding the climatological factors, the Sub-DAS Citarik has a relatively high annual average rainfall ranging from 1500 to 2500 mm per year [4], with the wettest months between November and March, while the dry months occur between April and August [5]. As the main input to the river in the hydrological cycle, the amount of rainfall plays a very important role in runoff discharge and floods.

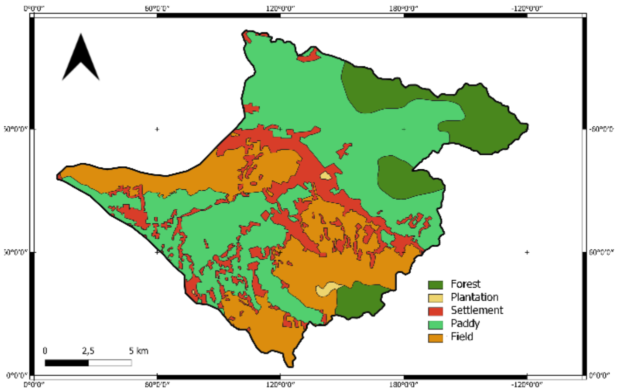


Figure 2 Map of land use in the Citarik sub-watershed [4]

The anthropogenic factor that is the main cause of increased runoff is land conversion. Land conversion is heavily influenced by population growth in the area. Citarik Sub Watershed has experienced quite rapid population growth (Table 2) because in the past this area was sparsely populated, making it a very potential area for settlement and development. From 2012 to 2020, Citarik sub watershed experienced rapid land conversion (Table 2). The use of land in Citarik sub watershed also does not yet meet the RPJMN (National Medium-Term Development Plan) that has been planned until 2027. One of the most important uses of land for a watershed is the use of forest land, where based on Law No.41 of 1999 Article 18 paragraph 2, the minimum forest land availability in a DAS is 30% of the total area, while Citarik sub watershed itself has only 14.48% forest land of its total area [6]. Forests have a very small runoff coefficient, so the extent of land conversion and the shrinking of forest area will increase the value of the runoff coefficient, which represents the amount of water runoff. The most extreme land conversion in the Citarik sub watershed occurred in the period 1993, which changed the coefficient from 0.019 to 0.122, and in the period 1993 to 2002 it became 0.229 [6]. These factors make Citarik sub watershed one of the critical areas that are prioritized in its management (Ekasari in [3]).

Table 2 Citarik Sub Watershed Demografic Data

District	Subdistrict	Population	Area (km^2/sq.km)	Population Density (population/km^2)	Growth Rate 2020 - 2022 (%)
Sumedang	Cimanggung	88940	55.55	2182	1.63
	Pamulihan	63542	50.70	1098	2.55
	Tanjung Sari	87520	44.86	2457	2.23
Bandung	Majalaya	162658	25.36	6365	0.63
	Nagreg	60488	49.30	1204	1.77
	Paseh	139939	51.03	2702	1.36
	Cikancung	100031	40.14	2447	1.70
	Cicalengka	125079	35.99	3430	1.19
	Rancaekek	189801	45.25	4141	1.15
	Solokan Jeruk	88829	24.01	3652	1.17
Total		1106827	**Mean**	2967.8	1.538

Table 3 Citarik Sub Watershed Land Use Data (1)

No.	Land Use	Area (Ha)		
		2012	2013	2020
1	Settlement	16,306.68	17,216.39	18,209.32
2	Plantation	30,748.00	24,337.13	24,285.62
3	Paddy Area	40,983.84	37,420.57	35,947.14
4	Dry Land Farm (DLF)	22,053.77	34,508.21	33,546.65

Table 4 Citarik Sub Watershed Land Use Data (2)

No.	Land Use	Area (Ha)		
		2021	RTRW 2027	RTRW 2036
1	Settlement	25,173.82	31,029.52	33,458.53
2	Plantation	22,782.92	40,750.63	35,449.37
3	Paddy Area	33,910.42	33,655.79	31,046.74

4	Dry Land Farm (DLF)	35,417.11	11,658.51	8,376.22

Therefore, it is necessary to conduct a dynamic system modeling related to floods in the Sub-DAS Citarik to study flood phenomena, influential components, and their interactions so that the best scenarios can be simulated and become considerations in policy-making.

2 Modeling System

Conceptualization in modeling problem is the most important activity in system dynamics model development where many descriptions of model conceptualization have been based on seminal ideas about reference modes and dynamic hypotheses with the development of methods in outlining basic ideas as well as major disagreements being important for each element of the process [1].

2.1 Causal Loop Diagram

Causal loop diagram is a diagram that shows causal relationships and interrelationships between variables. The relationship is expressed in the form of an arrow, if the arrow is positive, then the relationship between the two variables is mutually reinforcing (directly proportional), whereas if the arrow is negative, the relationship between the two related variables is inversely proportional (weakens). In system dynamic modeling, understanding of the system so that problem-solving steps provide feedback to the system. The feedback loop/causal loop is expressed in the concepts of stock and flow. The causal loop diagram states that a situation X affects Y and Y affects X which may go through a chain of causal relationships. Situations of mutual influence between X and Y cannot be studied separately. The concept of stock and flow explains that there are system components that are accumulation in nature, namely stock and there are also those that are flowing, namely flow.

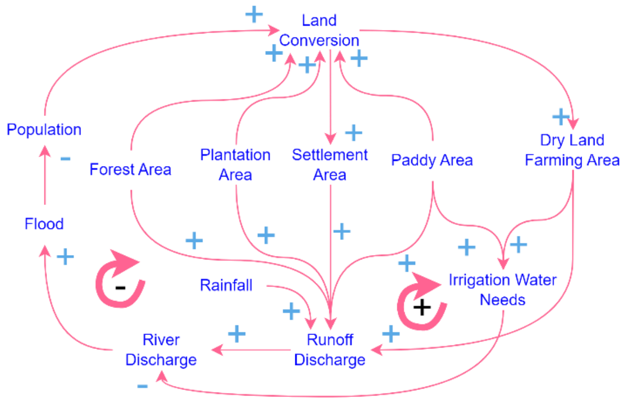


Figure 3 Causal loop diagram for flood

Based on Figure 3, CLD represents the main variables that will be described in the model based on the variables in **Error! Reference source not found.**. Cause-a nd-effect relationships in CLD are depicted with arrows equipped with positive and negative signs. The positive sign indicates a directly proportional relationship between the variable and the variables it influences, such as the relationship between population and land conversion where an increasing population means land conversion will also increase so that the variable relationship is positive. Conversely, arrows marked negative show an inverse relationship, for example, as in the relationship between the variable irrigation needs and river discharge where if irrigation needs increase where irrigation needs are met from the river, the river discharge will decrease because it is distributed by irrigation needs.

2.2 Stock Flow Diagram

The system dynamics tool used in this study to model flooding has four basic building blocks: stock, flow, connectors, and transducers. Stock (level) is used to represent everything that has accumulated. An example of stock is water stored in a reservoir. Flows (rates) represent activities that replenish and deplete inventory. Examples include reservoir drinking water flow or reservoir inflow. Connectors are used to build relationships between variables in a model. These are represented graphically in the software as arrows, with the direction of the arrow indicating the dependency. Transformers transform inputs into outputs. Transformers can accept input in the form of algebraic relationships, graphs, and tables. The concept of storage and flow in SD is very suitable for dealing with the reservoir problem of water resources.

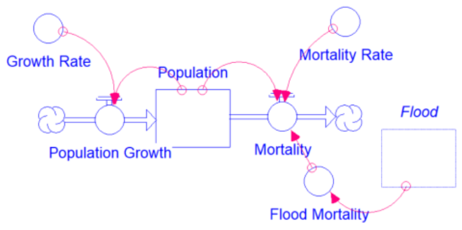


Figure 4 SFD for population

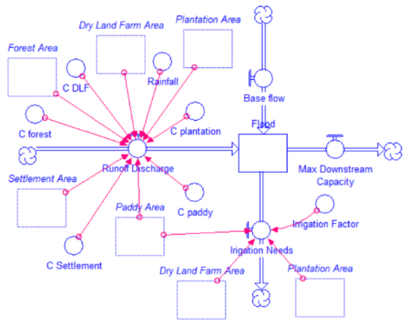


Figure 5 SFD for flood

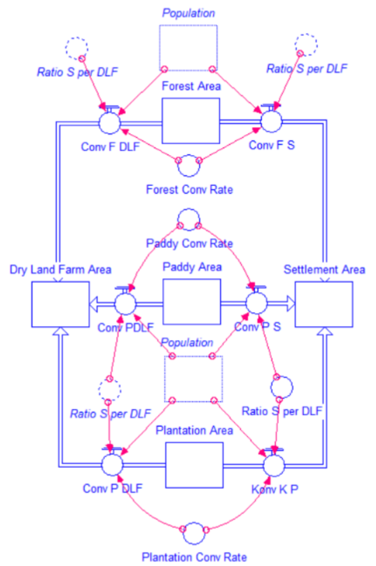


Figure 6 SFD for land use conversion

The dynamic system modeling used several assumptions, including:

- The Garut Regency area is ignored due to its very small proportion.
- The rate of land conversion follows the rate of land conversion in Bandung Regency, which has the largest proportion.
- Based on the data of decreasing forest, plantation, and paddy field areas due to land conversion, it is assumed that they will continue to decrease, and the magnitude of the decrease is obtained from linear regression of the data against the population.

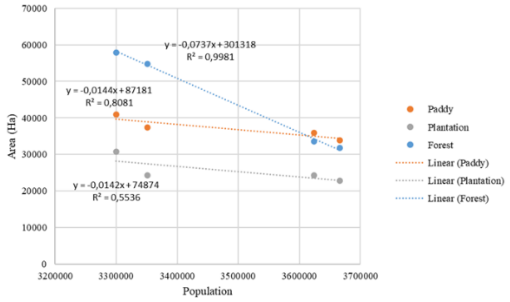


Figure 7 Regression linear relationship between variable

- Based on the data of increasing settlement and dryland agriculture areas due to land conversion, it is assumed that they will continue to increase, and the magnitude of the increase is obtained from linear regression of the data against the population.

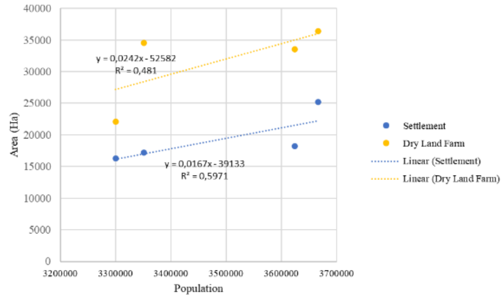


Figure 8 Regression linear relationship in population

- The mortality rate due to flooding follows the mortality rate due to disasters, which is 3.68 per 100,000 population [8].

2.3 System Component

One method commonly used to estimate peak flow rates (flood discharge or design discharge) is the USSCS Rational Method. The Rational method was developed based on the assumption that the rainfall that occurs has a uniform intensity and is evenly distributed throughout the catchment area for at least the same time as the concentration (tc). The Rational Method's mathematical equation is as follows.

$$Q = C \times I \times A \tag{1}$$

Where:

Q = Discharge (m^3/second)

C = runoff coefficient

I = Rainfall intensity during concentration time (mm/hour)

A = Watershed area (Ha)

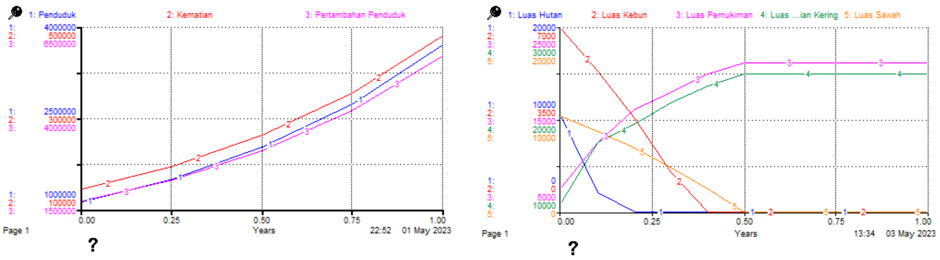
The equation based on Eq. (1) is a fundamental equation used in rain modeling because it can represent the amount of runoff discharge based on land use.

3 Analysis and Result

3.1 Model Validation

Validation is the process of determining whether a conceptual simulation model is an accurate representation of the real system being model. Model validation can also be seen as a step in validating or testing whether a model that has been developed can accurately represent the real system. A model can be considered valid when there is no significant difference between its characteristics and behaviour compared to the real system being observed. In STELLA, validation is done through two processes, namely structural validation and predictive validation.

Structural model validation is the main validation process in systems thinking which aims to see the extent of similarity between the model structure and the structure in reality, which is related to system boundaries, constituent variables, and assumptions regarding interactions that occur within the system. In this case study, structural validation is done by comparing the model results with various literature on system behaviour in theory.



(a) (b)

Figure 9 Population and land use growth graph

As can be seen in Figure 9, the population graph increases exponentially, which is consistent with the logic that population growth is not linear and tends to continue to increase. Because each component has been logically constructed, and all equations make sense, it can be said that the model is structurally valid.

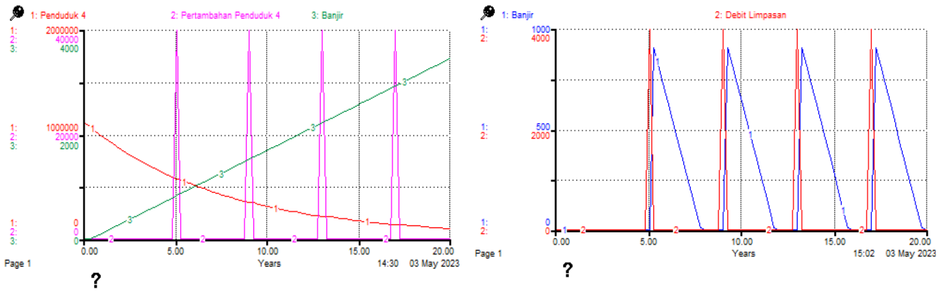
Predictive validation is the process of testing the accuracy of the results obtained from a modeling. This validation is necessary because future predictions will significantly influence decision-making processes. However, due to the limited data, where the modeling results in flood discharge data while the actual field data is only flood height, the model cannot be directly validated predictively. Instead, other approaches are used. The model shows predictive validity if its predictions about the behavior of the system closely mimic the actual system. Running the model with benchmark cases can be used to test predictive validity. The behavior of the system in real life can be predicted from theory or direct observation. The predictive validation shown in Figure 9 provide a case of runaway behavior patterns, where population growth continues to increase and results in a system behavior that is out of control, causing an increasing demand for land conversion. As a result, forest, Plantation, and paddy field areas will be depleted. This tragedy can also be called "the tragedy of the commons."

3.2 Exploratory Analysis

The main goal of exploratory analysis is to use models to develop an understanding of how systems respond or "adjust" to changing stimuli. Through such an understanding, it can determine how policies or technologies can affect system performance. The mode in which the system responds to change is determined by something modelers call system dynamics.

3.2.1 PULSE, RAMP, STEP analysis

The pulse, ramp, and step functions are used to observe the behavior of the system when it is disturbed. Pulse is a type of disturbance that causes the value of the flow or converter to increase and decrease drastically at a certain time. The intervention points used for PULSE analysis are population growth and runoff discharge.



(a) (b)

Figure 10 PULSE on population growth (a) and runoff discharge (b)

Based on Figure 10, PULSE is carried out by giving a population shock of 10,000 residents with a frequency of every 5 years for 4 periods and the resulting graph of the population decreases because there is no significant growth rate, it only increases when given PULSE but the death rate continues to increase, while flooding continues to increase linearly with the population PULSE. This scenario can occur if the construction of a complex or housing is carried out in a short time. The events in the PULSE scenario Figure 10 assume that flash floods occur due to shipments from other areas, so based on the graph the flood graph will increase with a height and then decrease again.

An analysis is carried out by applying the ramp function to the system. Interference with the ramp increases or decreases at a constant speed, starting at a certain time. In this case, a RAMP analysis was carried out on the flow of population growth to see changes in flooding when a constant population increase was carried out.

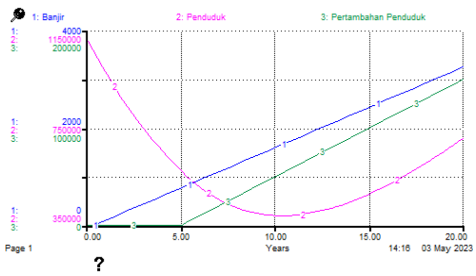
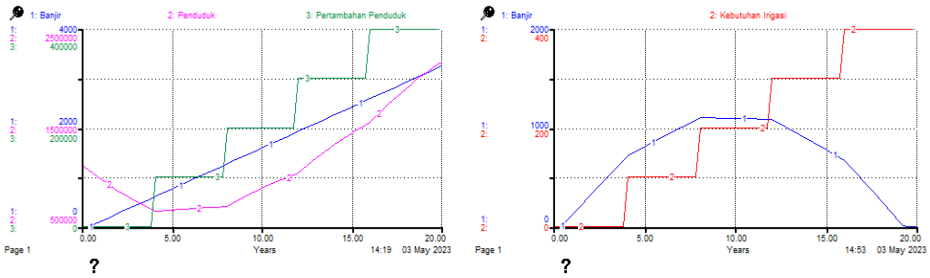


Figure 11 RAMP on population growth

Based on Figure 11, RAMP is inputted in the 5th year where before RAMP existed, population growth experienced a decline, and when RAMP was carried out, growth increased again. In addition, the flood graph shows no change and is still increasing from start to finish. Subsequent analysis is carried out by applying the STEP function to the system where the disturbance is given with a gradual increase every time frequency. In this study, an analysis was carried out on population growth, irrigation needs, and runoff discharge.



(a) (b)

Figure 12 STEP on population growth (a) and irrigation needs (b)

Based on Figure 12, STEP is inputted into population growth with a population increase of 100,000 people for every 4 years it increases. The results graph shows that in the first 4 years, the population decreased, and after STEP was carried out in the 4th year, the population began to increase, while floods continued to increase linearly from the initial year even though changes were made every year. This scenario can be assumed to occur if there is regular migration to the study area. STEP analysis of irrigation needs is carried out with an increase in irrigation needs of 100 m^3/s every 4 years with the assumption that there is a massive conversion of paddy fields, plantations and dryland farming every year and flooding is seen starting to decrease at the first STEP when there is an increase the need for irrigation is 100 m^3/s, and will continue to decrease until there are no floods when the need for irrigation is very high.

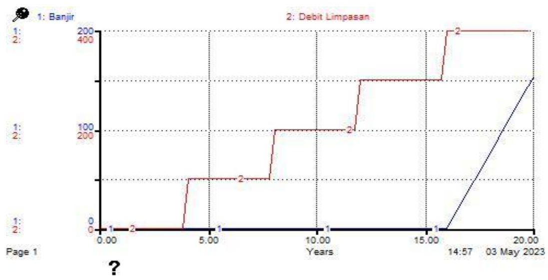


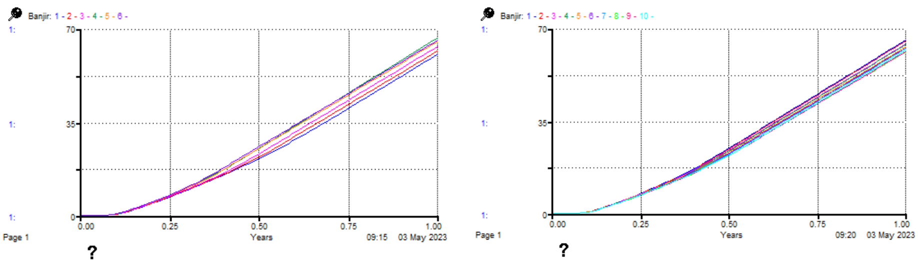
Figure 13 STEP on runoff discharge

Based on the graph in Figure 13, when the runoff discharge increases every 4 years with a total discharge of 100 m^3/s, it can be seen that a new flood occurs in the 16th year because the runoff discharge has exceeded the maximum capacity of the river to carry water flow.

3.2.2 Sensitivity Analysis

Sensitivity analysis helps to identify elements in the system based on their high leverage on system behavior and their minimal or maximal influence on those variables. The elements used in sensitivity testing are exogenous variables, which affect stocks and flows but are not influenced by any other variables, usually in the form of converters and do not have any input arrows. Since the main problem of this system is flooding, the effect of sensitivity analysis is flooding. The target of sensitivity analysis is to identify exogenous variables in the system that fall into the following two categories.

- Low Leverage Sensitivity



(a) (b)

Figure 14 Sensitivity growth rate (a) and mortality rate (b)

- High Leverage Sensitivity

From the sensitivity analysis of exogenous variables, there are several variables that have high leverage characteristics, here are the high leverage variables from the most sensitive to the least sensitive: Rainfall, Forest Conversion Rate, Settlement Ratio/PLK, Paddy Field Conversion Rate, Orchard Conversion Rate, and Irrigation Rate.

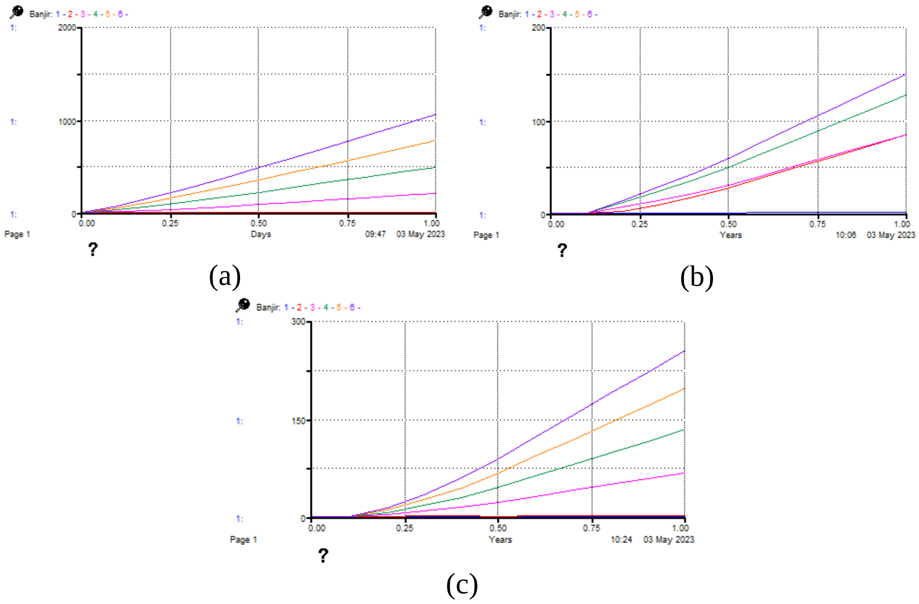


Figure 15 Sensitivity analysis of rainfall (a), forest conversion (b), and S/DLF ratio (c) to flooding

Base flow and maximum downstream capacity variables were not included in the sensitivity analysis because they are clearly defined to have the same unit as floods, so they are equivalent (1:1 ratio).

3.3 Case Analysis

Government Policy Scenarios:

A. Running with RPJMN Scenario

In this scenario, the proportion and area of land use based on RPJMN 2027 [6] were used, and the results obtained are as follows.

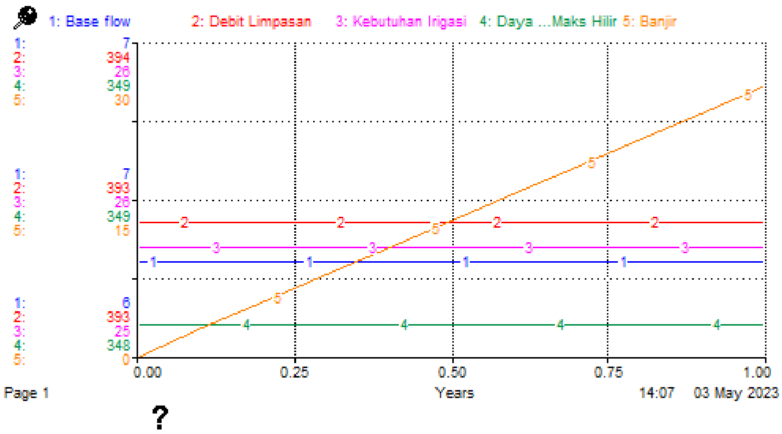


Figure 16 RPJMN running scenario

The result shows that with this scenario, flooding still occurs from the beginning and continues to increase over time. Therefore, it can be said that this policy is not effective in addressing the problem of flooding that occurs.

B. Normalization

Based on the information obtained from the Bandung District Environmental Agency in 2022, one of the efforts to handle floods in the Citarik Sub-Watershed is by conducting normalization in the downstream part of the Citarik Sub-Watershed. Normalization is done by dredging 96,000 m^3 along 5.52 km.

Based on the normalization data, we need to adjust its unit to match the system which is m3/s. To do this, we need data on the river flow velocity where the average velocity of the Citarum River is 9.1 m/s [9]. From the data on the length, velocity, and volume of normalization, we obtain a normalized discharge value of 16.82 m^3/s.

If we combine both government scenarios, the flood caused by RPJMN (26 m^3/s) can be reduced by the normalized discharge (16.82 m^3/s), but the remaining flood is still 9.18 m^3/s.

C. Limitation on Forest Land Area

Referring to Article 18 paragraph 2 of UU No. 41 of 1999 which states that the allocation of forest land area is at least 30% of the total area of the watershed. In this system, the proportion of forest land is only 14.48%. Therefore, the rate of deforestation must be reduced and reforestation should be carried out to achieve the 30% forest land proportion as stipulated by the regulation.

Based on the sensitivity analysis results, forest conversion rate is a high leverage variable **Error! Reference source not found.** If the forest c onversion rate is reduced to zero, then no flood will occur. Moreover, if the rate is reduced even further through the increase of forest area to achieve the 30% forest cover according to the regulation, then the flood will not occur for the next 20 years and even beyond, thus this policy is considered more effective.

4 Conclusion

Based on the result of flood system model in Citarik sub watershed, we can conclude that the existing scenario from the government plan policies still couldn't manage the flood discharge which still remaining 26 m^3/s while the normalized scenario produces 16.82 m^3/s flood, and even with combined scenario between the government scenario and normalization still produce flood with discharge 9.18 m^3/s. As the result of the model by choosing the most sensitive and impactful scenario to reduce the flood discharge, all of the government policies can be combined well with the highest leverage variable input to get the best scenario by maintaining the minimum forest area below 30% of the total watershed area which refer to Law No. 41 1999, even lower is much better. It is proven by the sensitivity analysis result that shows the rate of forest conversion is a high leverage variable and impact the forest function in hydrological degradation significantly. Furthermore, reducing even further through the increase of forest area to achieve the 30% forest cover according to the regulation, the flood is predicted will not occur for the next 20 years and even beyond. It is considered as an effective way to manage the flood in Citarik sub watershed, but needed further research to model the flood management in main watershed (Citarum Watershed) because more data and assumption will be needed.

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