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The Dynamic Model of Water Balance in A Sub-Basin

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ABSTRACT

Management of water resources in a river basin requires a new approach. The availability of water is a basic thing that must be considered given the increasing need for water. This study aimed to develop a water balance model in the Upper Bekasi River Sub Basin. In this study water balance model of the Bekasi River Sub Basin was built with several variables that affect water demand and availability, namely population growth rate, public facilities, and efforts to utilize resources. In this research, water supply and demand modelling was carried out using a dynamic system supported by Vensim software. Simulations were carried out from 2012 to 2045. The increase in population growth was directly proportional to the increased in population water needs. This dynamic model simulation used the application of rainwater harvesting and water-saving behaviour. Water demand for the Bekasi River Sub Basin was equal to 156.649.000 m3/year. The availability of surface water was 138.127.680 m3/year and had not been able to meet the water needs. The dynamic model showed that the water balance will be deficit in 2031, namely 51.883.200 m3/year. However, with the application of the water saving scenario, the water balance has a surplus of 258.564.000 m3 / year until the end of the simulation. Water reducing behavior can be used as an efficient method of water utilization.

1. INTRODUCTION

Management of water resources in a watershed (DAS) currently requires a new approach. The need for water is a basic thing that must be considered that the availability of water is decreasing. The imbalance between water demand and availability can lead to competition among water users which have the potential to cause water conflicts (Purwanto, 2014). Potential conflicts can be avoided by providing water according to needs and identifying alternative water sources that can be utilized (Yulistyorini, 2011).

The Upper Bekasi River Sub Basin is an area covering eight sub-districts in Bogor Regency and is currently unable to meet its raw water needs. This region plans to apply the concept of a water sensitive city (WSC), which is a city as a water provider that can meet the water needs of its residents, which includes drinking water and water for other purposes (Wong & Brown, 2009). To apply WSC concept, the water balance analysis of the Upper Bekasi River Sub Basin is needed. The potential flow rate of Bekasi River was 9.16 m^3/s, but with the additional supply from the West Tarum Main Channel of 21.68 m^3/s, the carrying capacity can be up to 2023 (Nurhayati, 2008). Based on this, it is necessary to know the potential flow rate of the Upper Bekasi River Sub Basin as a water provider in Bogor Regency.

The dynamic system model is used to analyze a complex dynamic of policy and to design a more effective policy (Sterman, 2000). In general, the existence of regional policies to issue autonomy related to the development of areas into housing and industry has resulted in an increase of water demand. Utilization of surface runoff from the Upper Bekasi River Sub Basin will affect water availability in Lower Bekasi River Sub Basin. Based on these problems, a water resources management system using water sources other than surface water and groundwater is needed, and a water balance analysis is needed to achieve an even water allocation. This study aimed to develop a water balance model in the Upper Bekasi River Sub Basin. In this study, the focus of the study was directed at watershed-based water balance modeling using the analysis of the water harvesting concept applied in the upstream area. The analysis was carried out by building a dynamic model that described the pattern of water supply and demand in the future.

2. MATERIALS AND METHODS

The research was carried out in the Upper Bekasi River Sub Basin, and is located at 6°1'21.1" – 6° 40' 14.5" S and 106° 49' 54.48" – 107° 11' 30.52" E (Figure 1). The research area had a surface of 38,679.61 ha. The flow of the Upper Bekasi River Sub Basin is going to the administrative area of Bogor Regency. There are 8 districts in Bogor Regency, namely Babakan Madang, Cileungsi, Sukaraja, Citereup, Cibinong, Klapanunggal, Sukamakmur and Gunung Putri. This study used secondary data consisting of daily rainfall, river flow discharge, population statistics, industry, agriculture and government facilities. Data requirements and types of the analysis methods were presented in Table 1. Data analysis was carried out from September 2019 to March 2020.

Table 1. Types, sources and data uses

Data Variables	Data source	Analysis Methods	Uses
Daily rainfall, flow rate	BMKG (2016), BBWS Ciliwung-Cisadane (2019).	The Weibull and Thiessen polygons	1. Estimated river flow rate 2. Formulate a model
Statistical data on population, industry, agriculture, and government facilities	BPS Bogor Regency	Dynamic System	1. Analyze population growth, industry, agriculture, and government facilities 2. Analyze the increase in water requirements 3. Formulate a model

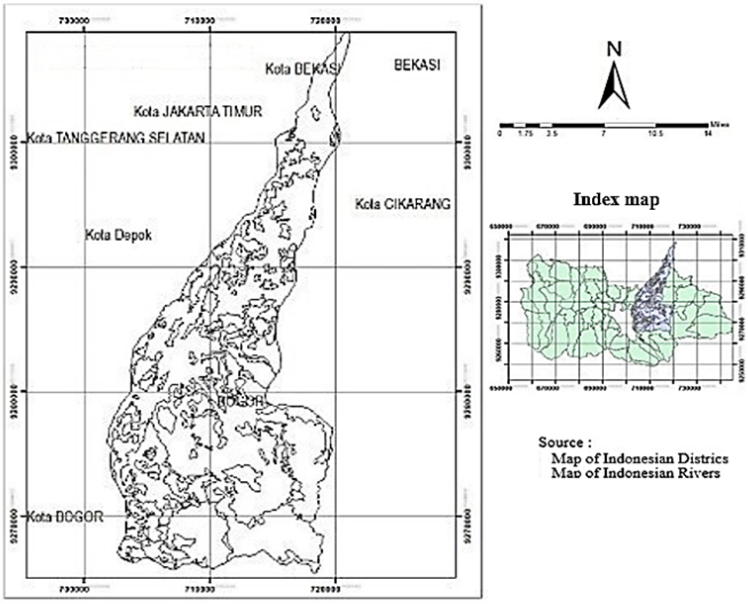

Figure 1. Location of Upper Bekasi River Sub Basin

2.1. Analysis of Water Demand and Water Availability

The calculation of water demand was based on SNI 6728.1: 2015 (BSN, 2015). The equation used in the calculation is Equation (1).

$$\text{Water Demand} = 365 \times N \times Std \tag{1}$$

where *N* is the number of parameters for which water demand will be calculated, and *Std* is the standard for water consumption (m^3/year).

The right informatics data concerning water potential, water quality, water quantity and basin characteristics could be used to analyze water availability of an area to fulfill water demand (Eda & Chen, 2010). Water availability analysis was carried out by calculating the potential availability of surface water, groundwater, and regional rainfall. Surface water was calculated by reliable discharge analysis using a 95% probability. Groundwater potential was calculated by analyzing the volume of groundwater using the Darcy method. The average rainfall was analyzed using the polygon Thiesen method. The analysis used Equations (2), (3) and (4).

$$d = \frac{\sum_1^n A_i d_i}{A} \tag{2}$$

$$P\% = \frac{m}{x+1} \times 100 \tag{3}$$

$$Q = k \times A \times \frac{\partial h}{\partial L} \tag{4}$$

where *d* is the average rainfall (mm/year), *A* is the polygon area (m^2), *n* is the number of climate stations, and *i* is the climate station sequence, *P* is the probability, *m* is the serial number of the data, *x* is the number of rainfall data, *Q* is the flow rate of groundwater (m^3/day), *k* is the hydraulic conductivity (m/day), **∂**h is the difference in the depth of the groundwater level (m),**∂**L is the length of the groundwater path (m).

2.2. Rainwater Harvesting Analysis

Rain harvesting planning used a planned rainfall which was calculated using 80% dependable rainfall (KemenPU, 2013). Furthermore, the storage volume calculation was carried out. The volume of collected rainwater was calculated by Equation (5) (Nurrohman *et al*., 2015).

$$V = R \times L \times C \tag{5}$$

where V is the number of volumes accommodated (m^3), C is the coefficient of runoff, R is the rainfall (m), and L is the catchment area (m^2).

2.3. Dynamic System Analysis

The dynamic model analysis was conducted in 5 stages.

1. Analysis phase: needs analysis and system identification.

At this stage, the identification of variables that have a real effect on the system is carried out. The variables are determined based on the interests of stakeholders (actors) who have an influence on the availability of water in the Upper Bekasi River Sub Basin.

2. Model engineering

This stage was done by making input-output diagram (black-box diagrams) (Figure 2).

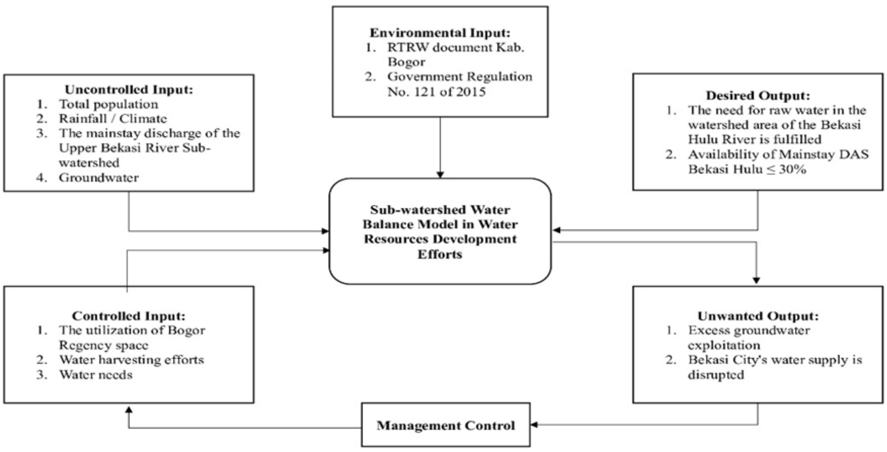

Figure 2. Black-box diagram

3. Computer implementation

This process used computer system tools, and the 2019 Vensim program.

4. Model validation

In this study, two validation tests were carried out, namely the work validation test and the validation test of the model structure, using Equations (6) and (7).

$$AME = \frac{S' - Aa'}{Aa'} \tag{6}$$

$$AVE = \frac{Ss - Sa}{Sa} \tag{7}$$

where *AME* (absolute mean error) is the average deviation value, *S* is the average of the simulation values, *Aa'* is the average of the actual values, *AVE* (absolute variant error) is the value of the variance deviation, *Ss* is the simulation standard deviation value, and *Sa* is the actual standard deviation value. The acceptable deviation limit is a maximum of 10%.

5. Model simulation
Policy analysis using simulations was carried out by applying scenarios. In this study, four scenarios were developed, namely the business-as-usual scenario, groundwater use scenario, rainwater harvesting scenario and water saving scenario. The simulation period was started from 2012 to 2045.

3. RESULTS AND DISCUSSION

The discharge of the Upper Bekasi River Sub Basin reached 11,481.67 m^3/s with rainfall reaching 1,497,636 mm/year. In this study, surface water discharge was calculated using a reliable discharge value with a probability of 95% with the consideration that 95% reliability was operational reliability. This study did not discuss building planning but focused more on calculating water demand and availability (Sari *et al*., 2012). The amount of water supply is based on a 95% probability value of 4.38 m^3/s or 138,128,000 m^3/year (Figure 3). The maximum flow in the 2009-2018 period is 373.14m^3/s and the minimum flow is 1.13 m^3/s.

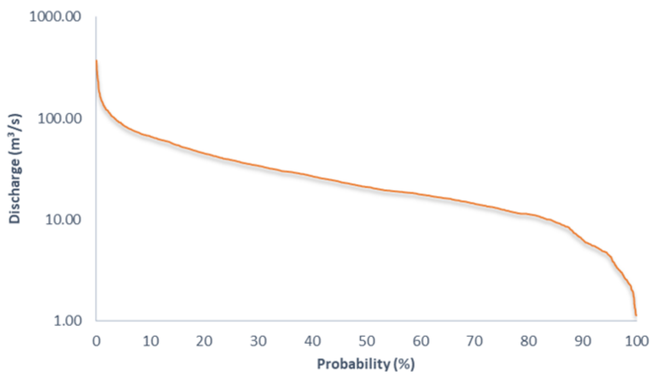

Figure 3. Discharge of the Upper Bekasi River Sub Basin

The groundwater supply in the Upper Bekasi River Sub Basin in the initial year of the simulation was equal to 67 million m^3/year. According to the Ministry of Energy and Mineral Resources (KemenESDM, 2011), it was estimated that 70% of the population's clean water needs come from groundwater. A groundwater deficit can occur if the available volume of groundwater is less than its potential water requirement.

Model simulation starts from 2012 to 2045. Population growth initially will increase exponentially, then it will decrease as the existing land decreases, causing the graph to slope towards equilibrium. Based on the suitability of the applicable theory for the validation test, the model structure in Figure 4 was included in the valid model (Malaka *et al*., 2015).

The results of the model performance validation test based on the population showed that the *AME* value for water needs of residents and residents were 0.5% while the *AVE* values are 5.1% and 4.9% (Table 2). The *AME* deviation limit was <10% which indicated that the model can simulate changes that actually occur in the field (Satrio & Suryani, 2017). Model validation was seen by the suitability of the variables and assumptions used in building the model.

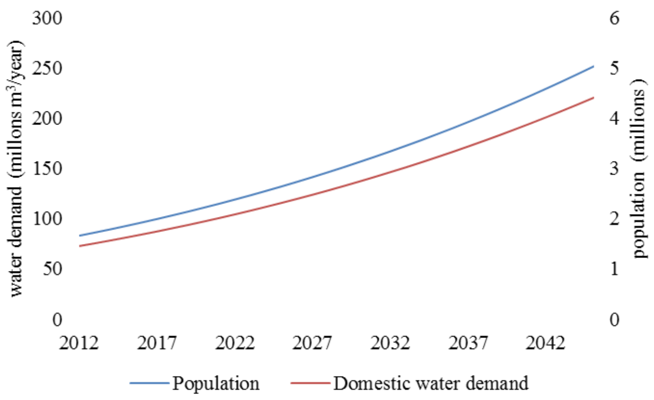

Figure 4. Model structure validation

Table 2. Validation results

Variable	AME (%)	AVE (%)
Population	0.5	5.1
Population Water Needs	0.5	4.9

Input parameters used in this study include raw water capacity, population growth rate, and community water needs in the Upper Bekasi River Sub Basin. The scenario used in this research was to save water and pay attention to the potential for rainwater harvesting in the Upper Bekasi River Sub Basin. Water balance was used to anticipate the risk of water shortages that can occur as an effort to efficiently use water resources. According to Asdak (2007) potential of rainwater harvesting is 30% of rainfall at impervious catchment area and flat field, while at impervious catchment area and slope field is more than 90%.

The framework for making a dynamic model of water balance was built based on the needs of stakeholders in the system (Figure 5). The flow discharge of the Upper Bekasi River Sub Basin and groundwater were the main elements that can affect the system. Unwanted output was a possible negative impact on the system even though the goal had been achieved. The current situation illustrates that there was an over-pumping of groundwater, which had an impact on lowering the groundwater table. The use of groundwater for industry and other commercial businesses in the Bogor CAT tends to increase and causes a decrease in the groundwater level between 0.06 - 5.07 m/year (Rengganis & Harnandi, 2011). Another possibility that could occur was that the utilization of the dependable flow of the Upper Bekasi River Sub Basin will disrupt the water supply in Bekasi City.

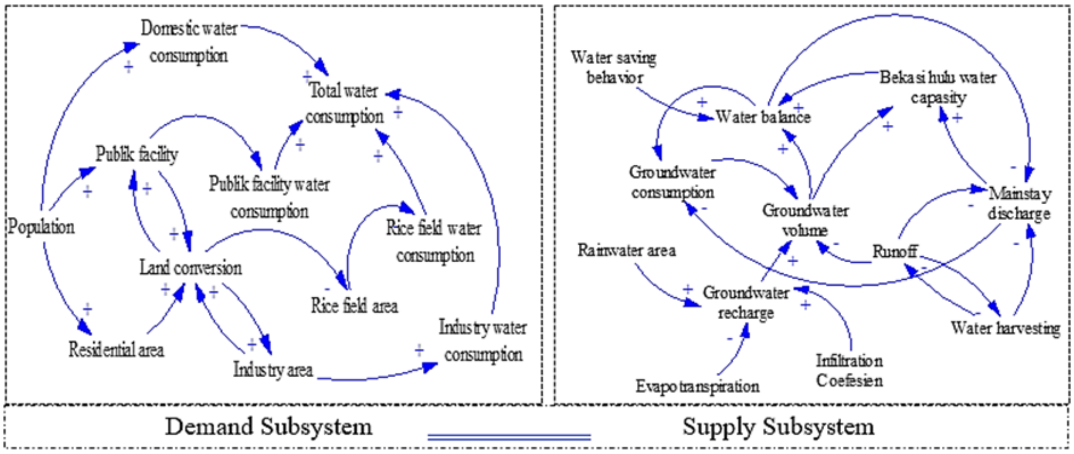

Figure 5. Clausal loop diagram of demand and supply subsystem

3.1. The First Scenario

The water balance in the first scenario (exiting) illustrated the deficit in 2031 of 51,883,200 m^3/year (Table 3). This scenario described the current condition without any system intervention to make efforts to prevent the condition for the variables. The need for water in various sectors continued to increase, and was influenced by population growth which continued to increase.

The total water requirement in 2012 was equal to 156,649,000 m^3/year. It continues to increase until 2045 and the total water demand becomes 352,504,000 m^3/year. Water availability has not been able to meet water needs. The highest proportion of water needs was in the domestic sector (47%), while for agriculture 45%, industry 5% and infrastructure 3%.

3.2. The Second Scenario

The second scenario was designed with a groundwater use policy of 30% and a shallow groundwater utilization of 27% of the total water demand. The population growth rate continues to increase without any efforts to suppress reduction. The assumptions in this scenario aimed to reduce groundwater use. The limit for groundwater exploitation was 40% of the availability of ground water (KementrianESDM, 2011). The total volume of groundwater at the start of the simulation was 67 million m^3/year of deep groundwater and 47 million m^3/year of shallow groundwater. The result of the second scenario was showed in Table 3. In the second scenario, the water balance experiences a deficit starting in 2031, which is 4,883,180 m^3/year.

Table 3. Water balance in the Upper Bekasi River Sub Basin*

Year	Water balance (10^6 m^3/year)								
	Scenario 1	Scenario 2	Scenario 3			Scenario 4			
	Existing	GW 30%	WH 20%	WH 90%	WH 20 + 90%	WR 10% (industry)	WR 10% (industry) + 30% (agric.)	WR 10% (industry) + 30% (domestic)	WR 10% (industry) + 30% (domestic) + 30% (agric.)
2012	47.84	94.84	94.84	94.834	94.84	103.03	233.88	117.61	138.73
2031	-51.88	-4.88	-6.18	-16.14	-41.34	261.22	388.86	678.53	887.85
2035	-398.81	-351.81	-353.68	-366.61	-404.34	-4.00	123.63	536.39	816.55
2037	-613.25	-566.25	-568.41	-582.77	-626.73	-174.50	-46.87	433.62	750.53
2043	-1,436.88	-1,389.88	-1,392.86	-1,411.39	-1,473.54	-852.59	-724.99	-13.93	417.96
2044	-1,602.39	-1,555.39	-1,558.51	-1,577.71	-1,642.80	-991.71	-864.11	-110.34	341.46
045	-1,776.48	-1,729.48	-1,732.73	-1,752.59	-1,820.58	-1,138.75	-1,011.15	-213.36	258.56

*) GW = groundwater shallow; WH = water harvesting; WR = water reduce

Thus, the second scenario is able to reduce the water deficit by 47,000,020 m^3/year. The assumption of 30% groundwater use is expected to prevent a decrease in the groundwater table. Excessive exploitation of groundwater can lead to a decrease in the water table. A drop in the groundwater level can occur if groundwater withdrawal is not balanced by groundwater replenishment. An imbalance between recharge water and groundwater extraction often occurs because water demand is increasing, and surface water has not been able to become the main source of water supply.

3.3. The Third Scenario

The third scenario is by harvesting rainwater at a rate of 20 %, 90 % and 20 % + 90 % (Table 3). The water balance value in the third scenario also starts a deficit in 2031. This scenario is able to reduce the water deficit 10,538,800 m^3/year. Rain harvest assumption is calculated based on the area of settlement. The selection rate of 20 % is based on the 2016-2036 Bogor Regency RDTR document that for the infiltration well area for the yard is 20 % of the area of the detailed building coefficient. The rate of 90 % is assumed for the rainfall falling from the roof of the building. Rainwater harvesting is assumed to not interfere with the production capacity of PDAM Tirta Kahuripan as a raw water supplier in the Upper Bekasi River Sub Basin. The amount of rain harvested will affect the total amount of water flow in the watershed. If the rainfall is harvested 100 %, the infiltration rate is 0 and will cause a low water flow rate that can be utilized. Maximizing rainwater harvesting with existing potential will affect the reliable reduction of the Bekasi River flow (Baskoro *et al*., 2020).

3.4. The Fourth Scenario

The fourth scenario is to implement water saving behavior. Savings of 10 % were chosen based on research by Haug (1998). The research result of Haug showed that the domestic and industrial water used can be reused by 10 %. Savings of 30 % were selected based on Njiru *et al*. (2006). The research result of Njiru *et al*. (2006) showed that the highest use of water in the domestic sector is the need for toiletries, and the use of good equipment can reduce toiletries water needs from 12 l/day to 4 l/day. Savings of 30 % in the agricultural sector were also applied based on SRI agriculture. According to Rizal *et al*. (2014) SRI method can save irrigation water by 35 %. Water saving behavior is one of the efficient methods of water use. In the third scenario for 10 % savings, the water balance will become deficit in 2035. Table 3 also showed that by savings of 10% total water needs and 30 % of the domestic sector, the water balance will become deficit in 2043. In scenarios of saving 10% plus 30 % of domestic sector and 30 % of agriculture sector, the water balance still positive (surplus) until the end of the simulation (Table 3). One way to reduce water demand is by implementing the reduce and reuse water program in various sectors by making savings of 10 % (Malaka *et al*., 2015). The implementation of the application of the selected scenario can be seen in Figure 6.

The water balance model must be adapted to the potential of natural resources and the environment in the area. Based on the scenario analysis of 10% water savings for various sectors added by 30% of the domestic sector and 30% of the agricultural sector is one scenario that experiences a surplus until the end of the simulation of 258,564,000 m^3/year (Figure 6). In this study, groundwater use cannot be considered as a true indication, because the actual use of groundwater in the field is three times greater than the registered groundwater. The true shallow groundwater extraction rate can only be obtained through socio-economic surveys of water consumption and demand.

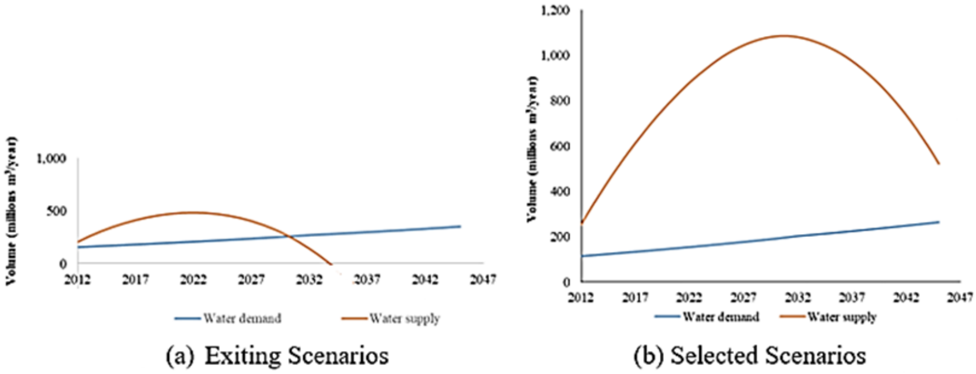

Figure 6. Implementation of model scenario application

In this study, the application of the scenario was chosen to reduce water demand and maintain water availability in order to avoid a deficit. Utilization of other water resources, such as harvesting rainwater, has not been able to reduce the deficit. Rainwater harvesting is estimated to be able to meet the community's domestic water needs, but harvesting rainwater will indirectly limit the supply of groundwater in the area. Meanwhile, a water deficit can occur partly because the volume of groundwater is insufficient to meet potential needs. Based on this research, the application of water-saving behavior can reduce the value of the water deficit in the Upper Bekasi River Sub-watershed. Most of the efforts to save water originate from community behavior. The implementation of a water demand management program requires a regulation because technological developments are still not fully affordable (Njiru *et al*., 2006).

4. CONCLUSIONS

The water balance model of the Upper Bekasi River Sub Basin was built with several variables that affect the need and availability of water, namely population growth rate, public facilities, and efforts to utilize resources. The availability of surface water based on the dependable flow of the Upper Bekasi River Sub Basin was equal to138,127,680 m^3/year and the volume of groundwater was 67,266,288 m^3. The water requirement for the Upper Bekasi River Sub-watershed was equal to 156,649,000 m^3/year. The dynamic model of the water balance showed that there would be a water deficit of 51,883,200 m^3/year in the Upper Bekasi River Sub Basin starting in 2031. Harvesting rainwater has reduced the dependable flow of the Upper Bekasi River Sub Basin and made the water balance remain deficit. The simulation results for each variable indicate a relationship between water use savings and efforts to increase water availability. The application of water-saving scenarios can help maintain the surplus water balance value until the end of the simulation year, especially in the saving variable 10% of the total demand added saving 30% for domestic and 30% for agriculture. Water-saving behavior can be used as an efficient method of water utilization.

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