



System dynamics model for sustainable water supply strategy in Sentul City area

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Abstract. *Good management of water resources is a requirement for an area with a high population development. Sentul City, which is an independent city in Bogor Regency which has a high population, is in an area that lacks water. Because of this, Sentul City requires infrastructure and policies that can ensure the availability of water for its residents. One of the paradigms of water management in urban areas is a water-sensitive city. One of the steps in this paradigm is wastewater management and rainwater harvesting. The system dynamics modeling method is used to predict the impact of implementing several policies that will be taken to manage water resources. This study aims to build dynamic models to predict water supply and demand and analyze policies for wastewater management and rainwater harvesting. Sentul City water demand is estimated will reach 122 105 000 m³ and a water crisis will occur in 2027. The wastewater recycle policy can inhibit water crisis until 2030, and the negative water balance will last until 2040. Combining wastewater recycle and rainwater harvesting can increase water availability by 240% and prevent a water crisis.*

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INTRODUCTION

Indonesia in 2000, on the island scale level of water available, showed a degree of scarcity, especially in Java Island. Until 2045, the level of water availability in Java, Bali, West Nusa Tenggara, and Southern Sulawesi was critical (BAPENAS, 2019). High city population growth requires access to facilities and infrastructure to increase land conversion and water needs. Brown (2008) states water is essential for human activities in the city. This condition forces that a city must be able to maintain the quality and quantity of water because water is the center health of the city. Sentul City is an independent city in Bogor Regency designed with the principle of green development with the concept of eco-city. Sentul City is an area developed in water-scarce regions because the texture of the soil is dominated by clay texture.

There are three sources of water supply to fulfill the current needs of Sentul City. PDAM (Local Water Supply Utility) Tirta Kahuripan currently provided 200 l/s, Sentul City water treatment plant 80 l/s, and Sentul City wastewater treatment plant 0.03 l/s. Based on existing sources capacity, Sentul City can fulfill water needs of about 280.03 l/s or 16 130 m³/day (Hermawan *et al.*, 2020). Harahap (2018) predicted that in 2050 Sentul City could only fulfill 59.90% of water needs because of population growth that increases water demand. Sentul City targeted 200 000 people in 2050 and needs 15 492 060 m³/year of water supply, assumed that water supply 5 887 351 m³/year (existing water supply), there will be a water scarcity in Sentul City.

The government of Bogor Regency and Sentul City Management plans for implementing rainwater harvesting that part of the Water Sensitive City (WSC) paradigm for water management sustainability. Water sensitive city is a city that utilizes capabilities holistically in the management of water resources in the city, not flooded in the rainy season and not drought in the dry season. The first two steps of WSC are provided water supply and wastewater water management/water recycle (Brown *et al.*, 2009). The change from each stage is based on city population growth and government policy (Jun *et al.*, 2012). Management of water resources model built to predict the performance of policies implemented by the government.

The system dynamics model in this study serves to simulate the implementation of the policies that have been formulated. This method can help understand the system by exploring the important structure of the mechanism and analyzing the feedback in the system that can be used as a reference for the management of water resources strategies efficiency (Park *et al.*, 2015). Furthermore, the simulation can predict raw water availability and water demand in the Sentul City Region in the next few years and variables that can significantly affect the water balance; thus, system dynamics modeling for water supply management can reference making appropriate water resources management policies. The objective of this study is for built system dynamics to predict the water supply and demand in Sentul City urban area and then to predict the impact of water policies in Sentul City urban area.

METHOD AND MATERIAL

Study Area

The study area is in Sentul City, Bogor Regency, West Java Province, Indonesia, an upstream of Bekasi Watershed. Geographically at $06^{\circ}33'55''$ - $06^{\circ}37'45''$ S and $106^{\circ}50'20''$ - $106^{\circ}57'10''$ E (Figure 1). Sentul City is an integrated area that combines residential, commercial, tourism, and public facilities. The area of Sentul City is 2 905.83 ha and is located in two sub-District, Babakan Madang and Sukaraja.

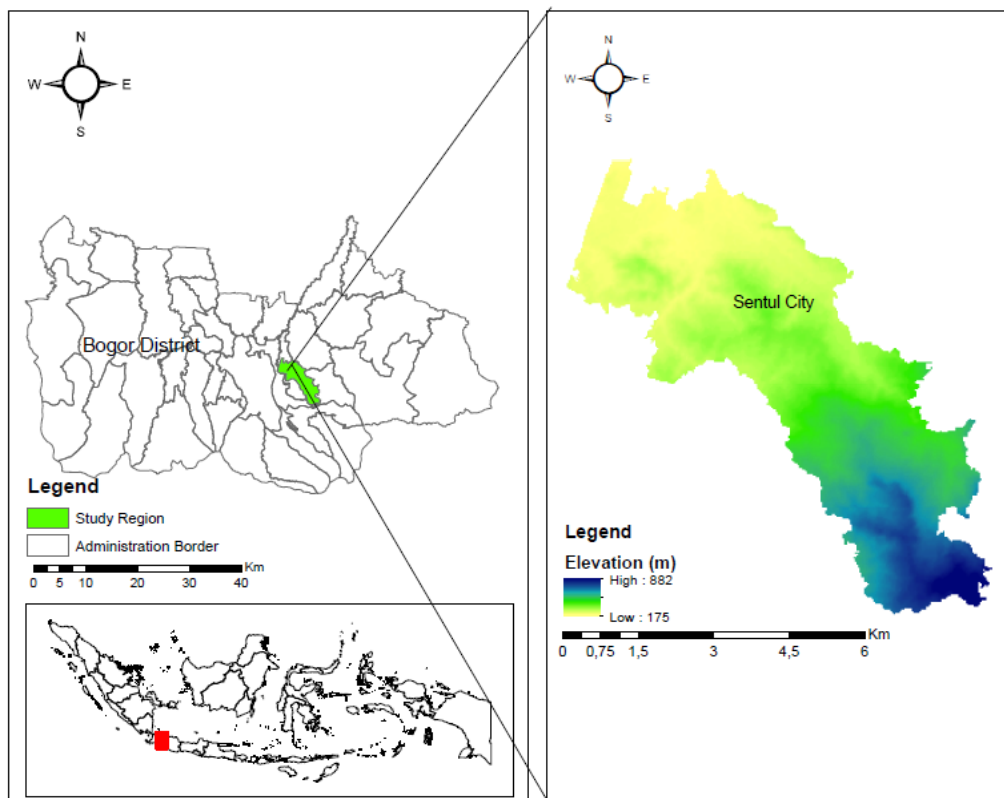


Figure 1 Study area (Sentul City, Bogor District)

Data and Tools

The tools used in this study are ArcGIS 10.4 for spatial analysis and Vensim PLE for building system dynamics. Spatial analysis in this study is for a total determined area of Sentul City and calculate rainfall potential in Sentul City Area. The data for this study rainfall in 2010-2019 period, Sentul City master plan, Sentul City population, and existing water supply.

Population Growth

According to Meyer and Ausubel (1999), population growth is calculated by logistically increasing carrying capacity which is described in equation (1). Logistically increasing carrying capacity method can limit growth with a non-fixed capacity, which means population growth depends on carrying capacity/resources. P_n is population in year n, P_0 is the initial population at the beginning of model simulation, α is population growth rate, K is the initial capacity (estimation maximal population of sentul city, 200 000 people), K_n is reached capacity in year n.

$$P_n = P_0 + \alpha P_0 \left(1 - \left(\frac{K_n}{K} \right) \right) \tag{1}$$

$$DWC_n = 365 P_n SD \tag{2}$$

Baskoro *et al.* (2020) states that domestic water consumption is multiplication and individual standard water consumption (equation 2). Thus, DWC_n is domestic water consumption in year n, P_n is a population in year n, and SD is standard individual water consumption (0.12 m³/day).

Water Consumption

Sentul City water consumption is accumulated by domestic, commercial area, and public facility water consumption necessary for an independent city area (equation 3). Domestic water consumption is water that used for daily activities of Sentul City resident, commercial water consumption is water that used in the economic sector (hotel, department store, office, and traditional market), and public facility water consumption is water that used in basic human need sector (school, hospital, and worship place).

$$\text{Water Consumption} = DWC + CWC + PWC \tag{3}$$

Where DWC is domestic water consumption (m³), CWC is commercial water consumption (m³), and PWC is public water consumption (m³).

Rainwater Harvesting

The potential rainfall in Sentul City was determined using average annual rainfall. Potential rainwater harvesting is calculated by urban water balance that changes along with urban spatial policy of the administrative region (Li, 2010). Rainwater harvesting (equation 4), based on precipitation (P) (m³), administrative area (m²), and runoff coefficient (Q). Runoff coefficient value in rainwater harvesting can be assumed by 0 because there is a government effort to keep rainwater maximally (Baskoro *et al.*, 2020).

$$Wh = P A (1 - Q) \tag{4}$$

System Dynamic Model

The system dynamics model in the analysis process uses Vensim PLE software. Building an understanding of system dynamics model in general, according to Koushali *et al.* (2015), has several stages, namely defining problem in the field, determining significant variables to the system, determining mathematical equation that can describe the behavior of the system, and determining the time period of the simulation. Determining variables that describe the behavior of a system can be done using several criteria:

1. These variables are important and significantly influence system behavior. This depends on the restrictions made by modelers, factors outside the system are considered not important and are not taken into account in making the model.
2. Similar variables must be combined because a few factors will avoid unnecessary complexity.
3. Variables must be precisely defined.

The system dynamics method needs to generalize the pattern of behavior of the system in casuistic after modelers can determine the variable. The system's behavior must be understood in causal relationship/feedback loops that will form a system structure. The system dynamics model that is made consists of a basic model (business as usual/BAU) and a model with a scenario. The basic model of a system dynamics is a system that occurs today without any policy intervention being implemented. The system dynamics simulation uses three scenarios:

1. The BAU scenario is the current system.
2. The scenario of using recycled water from Sentul City's consumption waste is assumed to increase every year based on total water consumption, and the efficiency of the wastewater treatment is 65%.
3. Rainwater harvesting scenarios that are assisted by the use of recycled water as in scenario 2. Assuming rainwater harvest rates increase 5% every year.

RESULT AND DISCUSSION

The fulfilment of Sentul City's raw water can be seen from two subsystems. Two subsystems are the demand subsystem and the supply subsystem. The raw water supply subsystem has several important variables as a source of water utilization: PDAM Tirta Kahuripan and wastewater/wastewater. The variables in the demand subsystem consist of domestic needs, commercial and public services. The variables determined based on the interests of stakeholders (actors) influence consumption (Table 1). Stakeholders are determined based on the influence that can be generated and the role in the system (Glicken, 2000; Mirgani and Savenije, 1995), as well as the parties who are directly affected by the policies made (Jansky *et al.*, 2005).

Table 1 Requirement in Sentul City raw water fulfillment system

No	Actors	Requirement
1	Sentul City residents	1. water needs to be fulfilled 2. consistent water flow
2	PDAM Tirta Kahuripan	1. water needs of Bogor regency to be fulfilled 2. there is no water conflict 3. Additional raw water supply
3	Environmental Agency, Bogor Regency	1. Land conversion control 2. there is no pollution of water sources
4	Highways and Waterworks Agency, Bogor Regency	1. the preservation of water resources 2. availability of water in public facilities
5	Commercial area	1. continuously water supply

PDAM Tirta Kahuripan plays a role as a water supplier for the Sentul City area. Residents of Sentul City, commercial areas are consumers who are affected by the policies implemented. Local governments represented by related agencies influence the policies implemented. The framework for meeting the raw water needs in Sentul City can be described in a black-box diagram. Black box diagrams require input and output, which will be used as feedback as a system improvement (Figure 2).

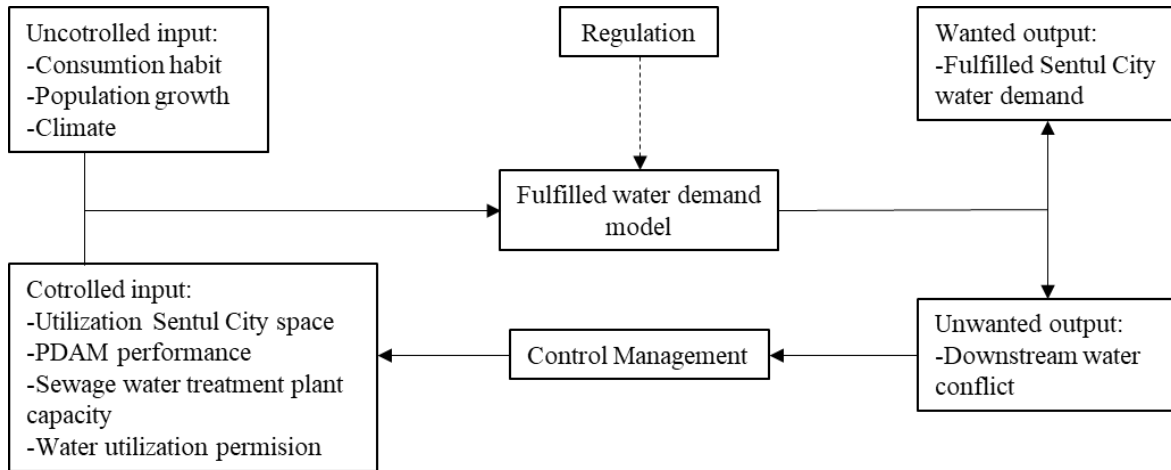


Figure 2 Black-box diagram of Sentul City water fulfillment system

The relationship between variables in the system is depicted in the causal loop diagram. The causal loop diagram is divided into two subsystems. The demand subsystem describes water consumption in Sentul City, and the supply subsystem describes the source of water supply for the Sentul City area (Figure 3 and 4). The water supply from PDAM Tirta Kahuripan and wastewater water treatment is constant base on maximal capacity, and potential rainwater harvesting in the Sentul City area is 27 868 884 m³/year. The water supply subsystem contained some significant variables. The total water supply of Sentul City is affected by water treatment, wastewater treatment, regional water company supply, and rainwater harvesting (in the scenario). A positive sign means, increasing the variable can cause an increased total water supply. In the scenario, the relation between water balance and rainwater harvesting means that if water balance has a positive value, the attempt to harvest rainwater decreases. In scenario 2 assumed that every increasing water supply followed by increased wastewater treatment due to the design of an independent city that must be able to recycle its water according to the capacity of its inhabitants.

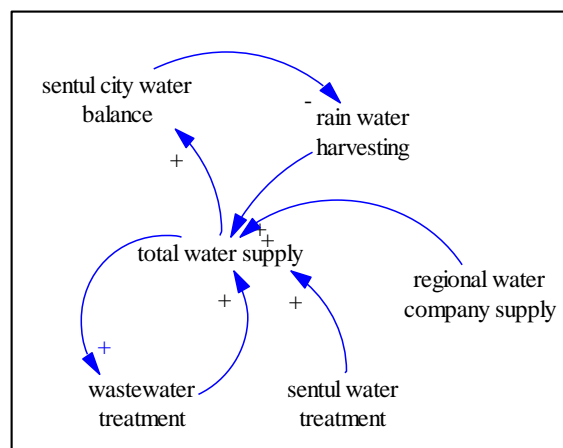


Figure 3 Causal loop diagram of water supply subsystem

The water demand subsystem contained three significant variables, domestic, public facility, and commercial area water consumption—all three variables affected by the Sentul City population. Increasing the city population can reduce potential areas because of housing needs and increased water consumption in all sectors. The total water consumption assumed will continue to increase until the capacity of Sentul City is fulfilled. Therefore, in this model, the total water consumption, in general, depends on Sentul City capacity, in this case is the area.

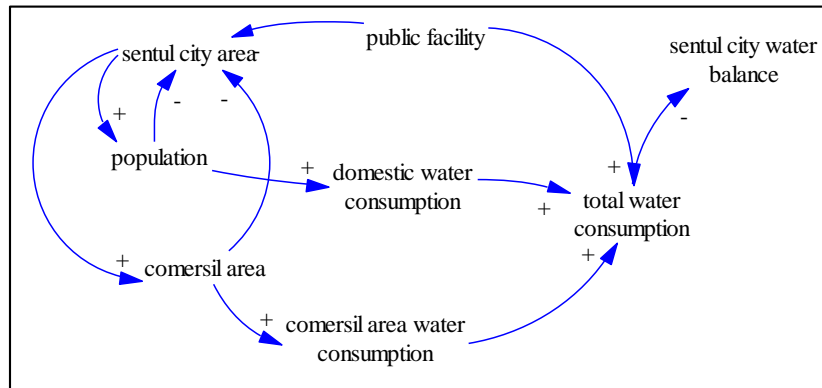


Figure 4 Causal loop diagram of water demand subsystem

The result of system dynamic model simulation, in the base model (BAU scenario), the Sentul City water demand is estimated in 2013 (at the start of simulation) reach to 4 185 420 m³, reaching 122 105 000 m³ in 2050. The assumption in the base model is water supply in Sentul Area is constant base on a water supply capacity 9 268 080 m³/year. The model simulation results show that the increase in water needs is caused by the domestic sector, which increases with the increasing population (Figure 5). However, population growth will be starting a decrease in 2037 due to the reduced capacity of Sentul City.

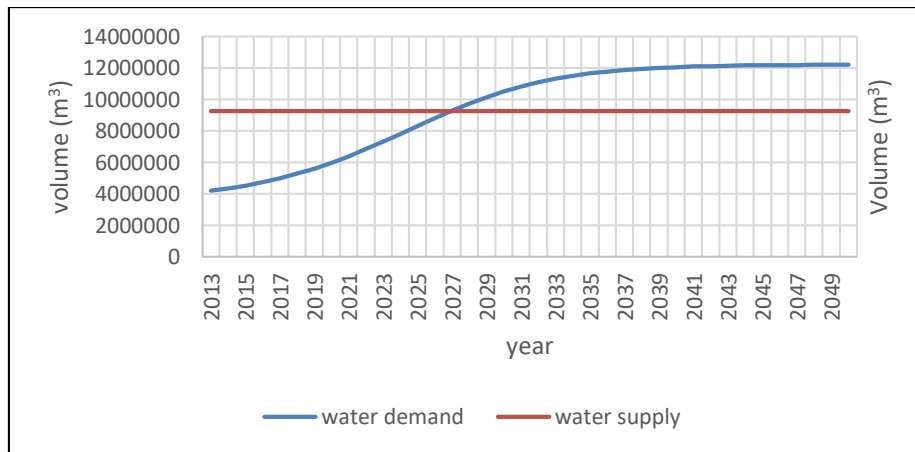


Figure 5 Water supply and demand of Sentul City simulation

Water availability in the simulation model shows a significant increase in scenario 3. Increased water supply through wastewater recycling and rainwater harvesting provide a significant potential for water availability. The diagram below shows that scenario two utilization of wastewater recycling can increase water availability by 150%, and scenario three recycling wastewater and harvesting rainwater can increase water availability by 204% in Sentul City. It is assumed that the rainwater harvesting efforts in scenario three will start in 2025 (Figure 6).

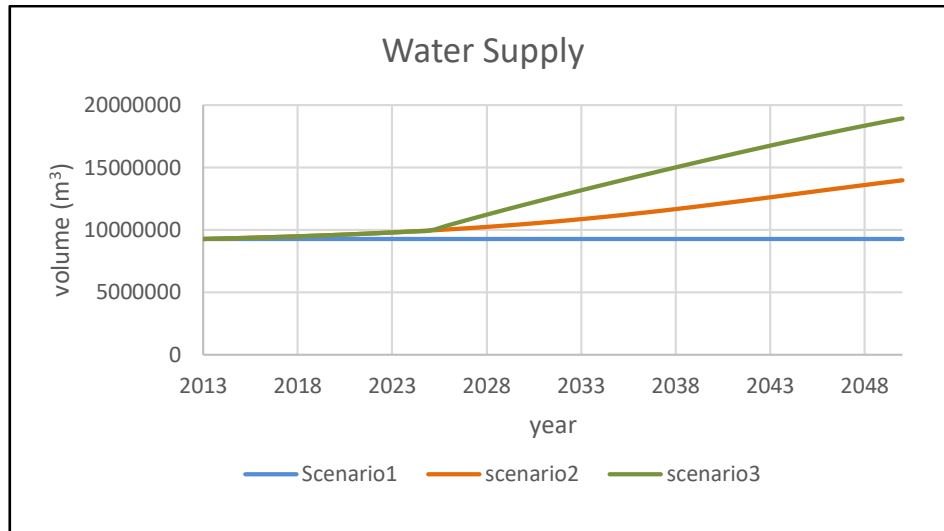


Figure 6 Water supply subsystem simulation

Sentul city water balance estimation in scenario 1 (BAU), shows a potential water crisis in 2027 due to the absence of additional water supply from PDAM or regional wastewater treatment, which causes water demand to be greater than water availability. Scenario 2, the water crisis that will occur in 2027 can be inhibited until 2030. The negative water balance will last until 2040 so that in scenario two, an additional supply of sufficient water is required for up to 10 years. The water balance is predicted to return to a positive value in 2041 due to the addition of the planned wastewater recycling capacity (Figure 7).

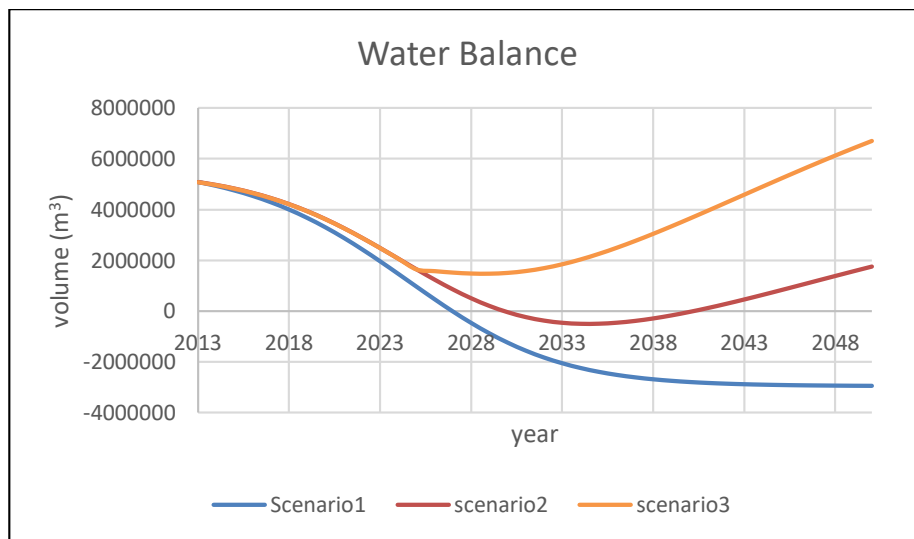


Figure 7 Water balance simulation

The water supply needed to meet water needs in scenario 2, in this simulation model, is obtained from rainwater harvesting used as scenario 3 in the simulation. Scenario 3 shows that in 2025 the water balance will decline insignificantly and tends to slope so that in 2030 the water balance is expected to increase. Harvesting rainwater at a rate of 5% potential rainwater harvesting per year can prevent Sentul City from a water crisis. Scenario 3 in the model shows that the water balance never indicates a negative value until the area's carrying capacity reaches its maximum limit.

CONCLUSION

The Sentul City Water demand will reach 122 105 000 m³ in 2050 that caused a water crisis in 2027. Implementation of wastewater treatment with 65% efficiency can increase water availability by 150% and inhibited water crisis to 2030, then can fulfill water need in 2041. The Sentul City water balance can sustain with rainwater harvesting in 2025 with rate of 5% of potential rainwater harvesting per year.

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