Watershed based model for water allocation

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Abstract. The city of Bekasi is located downstream of the Bekasi watershed, which currently cannot reach the target of access to clean water. Access to clean water in Bekasi City according to USAID (2017) only reaches 31.44%, thus it has not yet reached the target of Sustainable Development Goals (SDGs). Moreover, many upstream areas of the watershed have been grown as a satellite city that plans to harvest more water to meet their needs. And also urban and rural areas in the whole watershed have population growth that needs a water supply. Increasing water demand due to population in upstream and downstream areas can cause water conflicts if not managed wisely. A water allocation study by making a model of the Bekasi watershed could explain better water allocation solution. This study's purpose is to make a model for meeting the raw water demand of both urban and rural areas within Bekasi watershed. The more allocation of water in the upstream part of the Bekasi watershed (Sentul City) shows a decrease in the long-term water availability of water supply in the downstream watershed (Bekasi City). The development area of the upper part of Bekasi watershed should be evaluated properly and policy settings for water allocation can be analyzed using the dynamic model built.

1. Introduction

Indonesian water resources management has not been able to provide water services to the resident. Distribution of the population in upstream and downstream areas can cause water conflict, if not managed wisely. For this reason, the management of water resources is a need for integrated clean water service (involve upstream and downstream areas). Access to clean water in Bekasi City according to [1,2] only reaches 30% (has not reached the target of Sustainable Development Goals). Meanwhile supply in the upstream area which is in the Bogor Regency area has also not been able to provide clean water [1] and upstream plan to harvest water to meet the needs. Bekasi City has two main sources of raw water supply such as Kali Malang (West Tarum Canal) and Bekasi River. Raw water supply originating from Bekasi River is threatened to decrease because of discharge ratio increases [3]. Another thing that becomes a problem in the utilization of raw water is the limitation of the Kali Malang due to distribution to fulfill the City of Jakarta's needs. Kali Malang is the source of raw water for Karawang Regency, Bekasi Regency, Bekasi City dan Jakarta City, therefore the portion of water that can be utilized by the area it passes through tends to be insufficient to meet needs. Another problem that reduces raw water supply of Bekasi City is an application of the Bogor Regency policy on rainwater harvesting in the Sentul City area that applies a zero-runoff concept. The zero runoff can result in no runoff towards the river, which causes a decrease in the flow rate of the Bekasi River. The performance of Regional Water Company in supplying water in Bekasi City also has a problem in increasing efficiency and capacity.
2. Research Method

2.1. Study area

The scope of this research is divided into two parts, that is Bekasi City and Bekasi upstream watershed which has a border with Bekasi DAM (Figure 1). In this study, Bekasi City is considered as downstream area which can be impacted by the upstream water resources management policy. Indicator of the impact from the upstream water resources management policy is the water supply of Bekasi River. Bekasi upstream watershed has 38,679.61 ha which includes several districts in Bogor Regency Administrative Region. The area that can be a pilot project to water sensitive city implementation is Sentul City (an integrated township in Bogor Regency) and five districts (Cileungsi, Cibinong, Gunungputri, Citeureup, and Babakanmadang) that have significant development in the industrial and commercial sector. The area of Sentul City is 2,905.83 ha and the total area of five districts is 24,353.86 ha with potential annual rainfall 3,115.97 mm. Bekasi City has two local water companies, Tirta Patriot and Tirta Bhagasasi. Total Capacity of clean water production Bekasi City is 2.09 m³/s.

![Figure 1. Map of the Study Area](image_url)

2.2. Dependable flow

The dependable flow of Bekasi River was analyzed with the Weibull plotting position in Flow Duration Frequency Curves (FDC) and the data was generated from daily recording gauge at the Bekasi Dam. The data input for the Weibull method in this research is 7 years period (2010-2016) of daily mean streamflow. Probability streamflow Q90%-Q100% (low flow) was the input for the system dynamics model. The Weibull plotting position constructed by using the equation:
\[ P\% = \frac{m}{(n + 1)} \times 100 \]  

(1)

Where \( P \) is the exceedance or equaled probability, \( m \) is the rank number daily mean flow, \( n \) is the total data. The slope of FDC was indicating the dominancy of the base flow. Slope value is based on the ratio of Q90% to Q50% and the steep slow curve is interpreted as the direct flow in other hands low slope indicated base flow dominance [4,5].

2.3. Groundwater and rain harvesting

Groundwater estimation in Bekasi City based on [6] research required aquifer thickness, aquifer area, and specific yield. Groundwater potential estimated by static approach equation:

\[ V_{gw} = Sy \times A \times l \]  

(2)

Where \( V_{gw} \) is groundwater volume (m³), \( Sy \) is percentage water that can be used (specific yield), \( A \) is a cross-section of aquifer and \( l \) is aquifer thickness. Groundwater recharge/water harvesting estimated by urban water balance that changes along with an urban spacial policy of administrative region [7]. An equation to estimated water balance is:

\[ \Delta S = P - Q - E \]  

(3)

Where \( \Delta S \) is water ground recharge (m³/year), \( P \) is precipitation (m³), \( Q \) is runoff (m³/year) and \( E \) is evapotranspiration (m³). The impact of land use causes an increase or decrease in water infiltration that can affect the water ground recharge and runoff value in the rainfall harvesting method is 0 (4) because all precipitation assumed can behold in the area. The value of runoff replaced by base flow index/ratio between Q90% and Q50% in FDC. The value of the runoff coefficient in a large area depend on landcover, that has more than one landcover. Composted runoff coefficient estimated by area-weighted average equation (5).

\[ Wh = P \times A \times (1 - Q) \]  

(4)

\[ Ct = \frac{\sum C_i A_i}{\sum A_i} \]  

(5)

Where \( C \) is runoff coefficient, \( Ct \) is a composite runoff coefficient, \( A \) is area (m²) and \( i \) is kind of landcover that has different runoff coefficient [8]. The range of coefficient runoff is 0 to 1 which is the value that closes to 1 means high runoff and less infiltration. The Value of coefficient runoff in this research change during the time because of land-use change in the urban area.

2.4. Water consumption

The water consumption in the system dynamics model commonly has three components to include population, industry, water stock and arable land/agriculture [9]. Population growth calculated by logistically increasing carrying capacity equation (6). Logistically increasing carrying capacity method can make limitation growth with a non-fixed capacity which means population growth depends on carrying capacity/resources [10]. The domestic water consumption is multiplication population and individual standard water (7).

\[ P_n = P_0 + \alpha P_0 \left( 1 - \frac{K_p}{K} \right) \]  

(6)

\[ DWC_n = 365 \times P_n \times SD \]  

(7)
Where \( P_n \) is population in year \( n \), \( P_0 \) is the initial population at the beginning of model simulation, \( \alpha \) is population growth rate, \( K \) is the initial capacity (potential development land). DWC\( n \) is domestic water consumption in year \( n \) and SD is standard individual consumption 60 liters/person/day. The agricultural and industrial water consumption calculate based on the area (8)(9).

\[
AWC_n = 365 \ A_n \ SA
\]

\[
IWC_n = 365 \ A_n \ SI
\]

Where AWC\( n \) is agriculture water consumption from irrigation channel, IWC\( n \) is industrial water consumption, \( A_n \) is an area in year \( n \), SA is standard consumption for agriculture/paddy field 86.4 \( m^3/\text{day} \), that value is similar with industrial standard consumption (SI). The stock water of Bekasi City is the sum of dependable flow (Bekasi River), static groundwater and available water in West Tarum Canal (WTC).

2.5. System dynamics model

The identified problem in the Bekasi City water supply is poor water quality and sometimes lack raw water in the dry season. This model boundary is a concern only in water supply without regard to water quality and socio-economic of the community to get access to clean water. The relation between variables describes a common conceptual framework named causal loop diagram (CLDs). CLDs in this research divided into two subsystems, the demand subsystem describes water consumption in Bekasi City and supply subsystem describes the source of raw water stock supply for Bekasi City (Figure 2&3). Water supply from WTC is constant, based on Tirta Bhagasasi production capacity and water supply from Bekasi River based on dependable flow.
3. Result and discussion

The potential water supply from Bekasi River represented by dependable flow in probability exceeds 95%. The Q95% of the Bekasi River flow is 4.38 m³/s that value equal to 138,127,680 m³/year. The slope that showed in FDCs (Figure 4) is steep slope which means the dominant contribution comes from the direct flow. The base flow contribution in Bekasi Hulu Watershed is 30.32%, that value base on ratio Q90% to Q50% (Welderufael and Woyessa 2010). The minimum flow in the 2009-2016 period is 1.13 m³/s in August and the maximum flow is 373.14 m³/s in April.

![Flow duration curve of Bekasi River](image)
The input system in this research is the Bekasi City local water company’s capacity, WTC allocation of raw water, Bekasi River dependable flow, population, and consumption behavior. The desired output from the system is fulfilled water needs in Bekasi City. The system does not consider about over-exploitation of groundwater and idle capacity in local water company production. The potential water supply from the Bekasi River cannot be used maximally because of the lack of a local water company’s water production capacity (Tirta Patriot). The water production (Tirta Patriot) can only process as much 22,075,200 m³/year. This causes the deficit water balance at the beginning of the simulation (Figure 6). The water deficit in this simulation is following the existing situation (Figure 6). The deficit of water supply fulfilled by groundwater. The system dynamics simulation is carried out with three Scenarios. The first Scenario is business as usual, second is rain harvesting in Sentul city area, third is rain harvesting in the pilot project district. The structure of the system dynamics can be seen in Figure 5.

**Figure 5.** Stock and flow diagram of Bekasi City water balance

In common term, water balance is the balance of the water input and output in a region at a certain period that can be used to determine the amount of water surplus or water deficit [11]. Bekasi water balance in this context is the amount of water that produce by Bekasi City local water company. The local water company supply sourced from TB production capacity (22,075,200 m³/year) and WTC potential raw water (43,835,000 m³/year), total is 65,910,200 m³/year.
The potential water balance is all potential water supply, given by nature (Bekasi River, WTB and groundwater), reduce by Bekasi water demand that ignoring local water company production. The potential water balance represented the carrying capacity of water in Bekasi City. The simulation showed the limit of water supply reached in 2066 (Scenario 1 and 2) and 2063 (Scenario 3) (Figure 7). The highest sector for water consumption is in the domestic sector. The arable water consumption has decreased every year, that is because of land conversion for housing and industrial area. Total industrial area increases from 629 ha to 861.9 ha based on city development plant in the 2011-2031 period. The groundwater recharge is not sufficient to recover groundwater volume. The land cover of Bekasi City according to Suwarli (2012) consists mostly of 56.64% building area, 9.84% arable land, 3.76% green open space, therefor the runoff coefficient of Bekasi City is 0.81.
Table 1. Bekasi City water supply scenario

| Time (Year) | Bekasi Demand (m³) | Local Water Company Supply (m³) | Water Balance (m³) | Potential Water Balance (m³) |
|-------------|-------------------|---------------------------------|-------------------|-----------------------------|
|             | Scenario 3        | Scenario 2                      | Scenario 1        |
| 2010        | 105,622,000       | 65,910,200                      | -39,712,100       | 2,176,340,000               |
|             |                   |                                 |                   | 2,176,340,000               |
| 2020        | 119,926,000       | 65,910,200                      | -54,015,500       | 2,169,210,000               |
|             |                   |                                 |                   | 2,169,210,000               |
| 2030        | 135,500,000       | 65,910,200                      | -69,590,000       | 1,867,020,000               |
|             |                   |                                 |                   | 1,939,510,000               |
| 2040        | 152,527,000       | 65,910,200                      | -91,703,200       | 1,550,460,000               |
|             |                   |                                 |                   | 1,665,570,000               |
| 2050        | 170,994,000       | 65,910,200                      | -110,170,000      | 1,000,880,000               |
|             |                   |                                 |                   | 1,165,660,000               |
| 2060        | 190,837,000       | 65,910,200                      | -130,013,000      | 259,000,000                 |
|             |                   |                                 |                   | 474,402,000                 |
| 2066        | 203,358,000       | 65,910,200                      | -142,535,000      | -283,974,000                |
|             |                   |                                 |                   | -38,090,700                 |

In the simulation of scenario 1 (business as usual), there is no rain harvesting in the upstream watershed area that means the dependable flow in Bekasi City can be utilized maximally (Table 1). Rain harvesting in Sentul City (second scenario) have potential water harvesting 27,868,884 m³/year with realization rate 0.2/year (20%) can be sustained because of the rain harvesting relatively does not influence local water company production. The district rain harvesting (third scenario) has potential water harvesting 236,449,740 m³/year with realization 0.05/year (5%). Rain harvesting in the district pilot project does not sustain because of rain harvesting can cause decreasing Bekasi City local water company production, in another word there will be water management conflict such as in Euphrates-Tigris Watershed [12] and Pong Watershed [13].

Table 2. Impact of rain harvesting in upstream area

| Time (Year) | Water Harvesting (m³/year) | Bekasi River Dependable Flow (m³/year) | Water Demand (m³/year) | Water Balance (m³/year) |
|-------------|-----------------------------|---------------------------------------|------------------------|-------------------------|
|             | Scenario 3 | Scenario 2 | Scenario 3 | Scenario 2 | Scenario 3 | Scenario 2 |
| 2010        | 0          | 0          | 138,128,000 | 138,128,000 | 105,622,000 | -39,712,100 | -39,712,100 |
| 2036        | 121,139,000 | 25,434,400 | 16,988,800 | 113,123,000 | 145,541,000 | -84,717,600 | -79,631,100 |
| 2046        | 121,139,000 | 27,389,600 | 16,988,800 | 110,823,000 | 163,437,000 | -102,614,000 | -97,527,300 |
| 2056        | 121,139,000 | 27,774,500 | 16,988,800 | 110,370,000 | 182,741,000 | -121,917,000 | -116,830,000 |

Figure 8. Upper stream water harvesting period
The system dynamic model in this study limits the rain harvesting to not reduce the production of Bekasi City local water company. In scenario 3, rain harvesting can be applied up to 2035 assuming an annual realization 5% with potential rain harvesting 236,449,740 m³/year, maximal rain water that can be harvested reach 121,139,000 m³/year or 9.33% (Tabel 2). This is different from scenario 2 which can maximize rain harvesting to existing potential (Figure 8). These conditions happened because of differences in large catchment area, so that the larger the catchment of rain in the upstream area more influential on decreasing dependable water flow of Bekasi River.

4. Conclusion

The water supply from a local water company insufficient for Bekasi City water demand and the dominant water supply comes from groundwater. The land cover in Bekasi City does not support to recharge groundwater there is shown in coefficient runoff Bekasi City area. Rain harvesting in Sentul city can be sustained otherwise harvesting water projects in the district can cause water management conflict. The limit of the district rain harvesting is 9.33%.

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