e-ISSN: 2655-8777 http://journals.itb.ac.id/index.php/3bio

Analysis and Prediction of Water Balance Using Dynamic Modelling to Solve Water Scarcity in Cimahi

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Received: 2022-03-29
Accepted for publication: 2022-09-22

Abstract

Cimahi is one of the most populated, fast-growing cities in Indonesia. Consequently, various environmental problems appear, primarily related to the sustainability of water resources. Exploitation and pollution of water, especially groundwater, are not accompanied by a good water conservation system that ensures proper water infiltration into the soil, causing several locations in the city to experience water deficits. The city may suffer a severe water shortage if this problem is unsolved. This study aims to predict and analyze the need and availability of water in Cimahi in the next few years to determine the right solution to deal with this problem. Analysis and prediction of water availability/needs were carried out by building a dynamic model using STELLA software for simulating the conditions in the next ten years. The results of the model were combined with the applicable spatial policies to formulate possible solutions. Results showed that Cimahi will experience a water crisis starting from 2029 with a total water deficit of 8.22 million M³. The model also predicted South Cimahi District is the area with the worst conditions where the water crisis has occurred since 2022 and peaked in 2029 with water sufficiency of only 59.83%. Based on local spatial planning laws and policies, the city's government is advised to improve its catchment area to protect its water resources. The vegetation cover area surrounding the catchment area can be improved, and water absorption capacity can be increased through civil technical actions such as building absorption wells. The model results showed that a proper solution could be done by expanding 142.8 Ha of green/vegetation cover, building 1576 units of absorption wells, and increasing the PDAM supply by 100 l/second.

Keywords: *water resources; dynamic model; vegetation cover; absorption wells*

1. Introduction

Water resources are one of the basic needs for human viability. Generally, a higher standard of living accompanies a more increased water need. But on the other hand, there is less than 0.5% of water on the earth's surface that humans can use directly [1]. Therefore, this valuable resource needs to be managed to ensure its utilization will continue sustainably used by humans.

In many large cities in Indonesia, such as Jakarta, Bandung, Surabaya, and others, hard-building construction is increasing rapidly, and a high population growth rate accompanies this. As a result, a significant amount of vegetation cover, especially in catchment areas, is continuously decreasing. It results in less water returning to the ground, plus the amount of water use and pollution continues to rise [2].

Cimahi City is one of the areas experiencing these problems. For the past few years, this city has suffered a significant loss of clean water supply [3]. Cimahi is predicted to have water supply resources of 46.71 million m³ per year, consisting of 33.10 million m³ of surface water and 13.61 million m³ of groundwater. However, the condition of groundwater utilization in Cimahi itself has been dominated by prone, critical to damaged zones, which cover 50.6% of the total area of groundwater utilization zones [3]. As a result, a water crisis occurred in several areas of Cimahi, e.g., Melong, Cibeureum, and Leuwigajah sub-districts. Furthermore, it is predicted that the city will experience a water crisis in 2030 if environmental issues cannot be appropriately managed [3].

Hence, this study aims to analyze factors affecting the availability and the needs of water (i.e., water balance) to predict its condition in the next few years with dynamic modeling as the basis for decision-making in preventing this water crisis disaster in Cimahi.

DOI: 10.5614/3bio.2022.4.2.3

2. Methodology

2.1. Study Area and Period

This study was conducted from February 2021 to December 2021 in three districts of Cimahi City, West Java, i.e., North Cimahi, Central Cimahi, and South Cimahi. Geographically, the study site location is at 6º50'-6º56' SL and 107º30'-107º34' EL.

2.2. Tools and Materials

This study utilized ArcMap 10.4 to analyze the land cover of Cimahi City, STELLA 9.0.2 to build and simulate a dynamic water availability/needs model, and Microsoft Excel 2019 to quantify and calculate all the variables needed. Secondary data used were climate data, water source and supply, biophysical conditions, socio-economic conditions, and satellite images obtained from the respective relevant institutions. See the complete list of data used in Table 1.

Table 1 Research Material and Data

Materials and Data	Source
Stakeholders Perspective	Dinas Lingkungan Hidup Kota Cimahi Dinas Perumahan dan Kawasan Permukiman Kota Cimahi Badan Pengelolaan dan Perencanaan Daerah Kota Cimahi
Precipitation Temperature Humidity Evapotranspiration	Badan Meteorologi Klimatologi dan Geofisika
Satellite Imagery	earthexplorer.usgs.gov
Land Slope Map	tanahair.indonesia.go.id/demnas
Soil Type Distribution Map	fao.org/land-water
Water Supply Capacity From Local Water Company (PDAM)	PDAM Tirta Raharja
River Discharge	Dinas Perumahan dan Kawasan Permukiman Kota Cimahi
Population Denseness Total Population Population Growth	Dinas Kependudukan dan Pencatatan Sipil Kota Cimahi
Economic Growth Number of Industries	Cimahi Dalam Angka Tahun 2021 (Badan Pusat Statistik)
Local Spatial Regulation and Policies	Perda Kota Cimahi No. 4 Tahun 2013 Tentang Rencana Tata Ruang Wilayah Kota Cimahi

2.3. Model Prediction of Water Availability and Water Needs

First, a preliminary analysis involving the prediction of actual land cover conditions in Cimahi was done to calculate the total water absorption potential of Cimahi City as one of the variables in the following model. Land cover analysis was carried out by interpreting satellite images of Cimahi City (year 2021) using ArcMap 10.4. Satellite images were interpreted by color patterns, e.g., the hue, textures, pattern size, shape, shadow, and object location compared to other objects [4]. Land cover types were classified based on SNI-7465-2010 (Classification of Land Cover & Land Use at a scale of 1:50,000). To simplify the process and variables included in the model, land cover classification was reduced to three classes: built-up land, open land, and vegetated land.

The next step is calculating the potential water absorption in Cimahi City area. The analysis of the water absorption potential of Cimahi City was calculated based on the water absorption formula developed by Ffolliot with the following Eq. (1) [5];

$$R = (P - Et)\ x\ Ai(Ca) \quad (1)$$

Where :

R = Volume of absorbed water (m^3/year)

P = Annual precipitation (mm)

Et = Annual evapotranspiration (mm)

Ai = Area of each land cover (m^2)

Ca = Absorption coefficient of each land cover types (Ca = 1 – surface run-off coefficient)

Table 2 shows the surface runoff coefficient, which is used as a reference to find the absorption coefficient value in each type of land cover.

DOI: 10.5614/3bio.2022.4.2.3

Table 2 Coefficient of Surface Runoff for Different Types of Land Cover

Land Cover	C Value (%)
Tropical Forest	<3
Production Forest	5
Shrubs	7
Paddy Fields	15
Fields	40
Settlement	70
Roadway	95
Dense Building	70-90
Scattered Building	30-70
Roof	70-90
Dirt Road	13-50
Parks or Yard	5-25
Open Land	10-30
Other Plantation	0-20

Two models were constructed to predict the need and availability of water in Cimahi for the next ten years. Each model covered each sub-district in Cimahi based on biophysical and socio-economic conditions, resulting in a total of 6 models. In general, water availability is influenced by several factors, e.g., water absorption potential, groundwater potential, river discharge, type of land cover, and supply capacity of local water companies (namely PDAM). Meanwhile, water needs are influenced by the number of industries, economic growth, population, water use per capita, and population growth rate. A causal-loop diagram was formulated for the model prediction (Figure 1).

2.4. Assumption and Research Limitations

The assumptions used to limit the scope of the model include the following:

1. The system is assumed to be closed. Cimahi residents obtain water from their territory; the surplus water remains and is used by the city.
2. All vegetation is assumed to have the same ability of water absorption.
3. There is no flood when the water is exceptionally surplus because only the minimum discharge is used in the model.
4. There are no differences in the amount of precipitation during the rainy or dry season as the model used an annual rainfall.
5. Bottled water supply is not included in the model.
6. The entire population uses the same amount of water every year.
7. There is no (or minor) change in land cover in the city for the next ten years.

2.5. Formulating the Solution for Water Scarcity in Cimahi

In formulating solutions to water shortages in the coming year, a descriptive analysis was carried out by considering, i.e., prediction results of water availability and water needs, perception of relevant stakeholders, and every policy related to the applicable spatial management in Cimahi City.

3. Results and Discussion

3.1. Land Cover Conditions

Land cover analysis of Cimahi in 2021 showed that Cimahi was mostly covered by built-up land (3179.3 Ha), followed by open-spaced land (386.7 Ha), and vegetated land (386.52) Ha. A complete land cover map and detailed information on the area of each land cover are presented in Figure 2 and Table 3.

DOI: 10.5614/3bio.2022.4.2.3

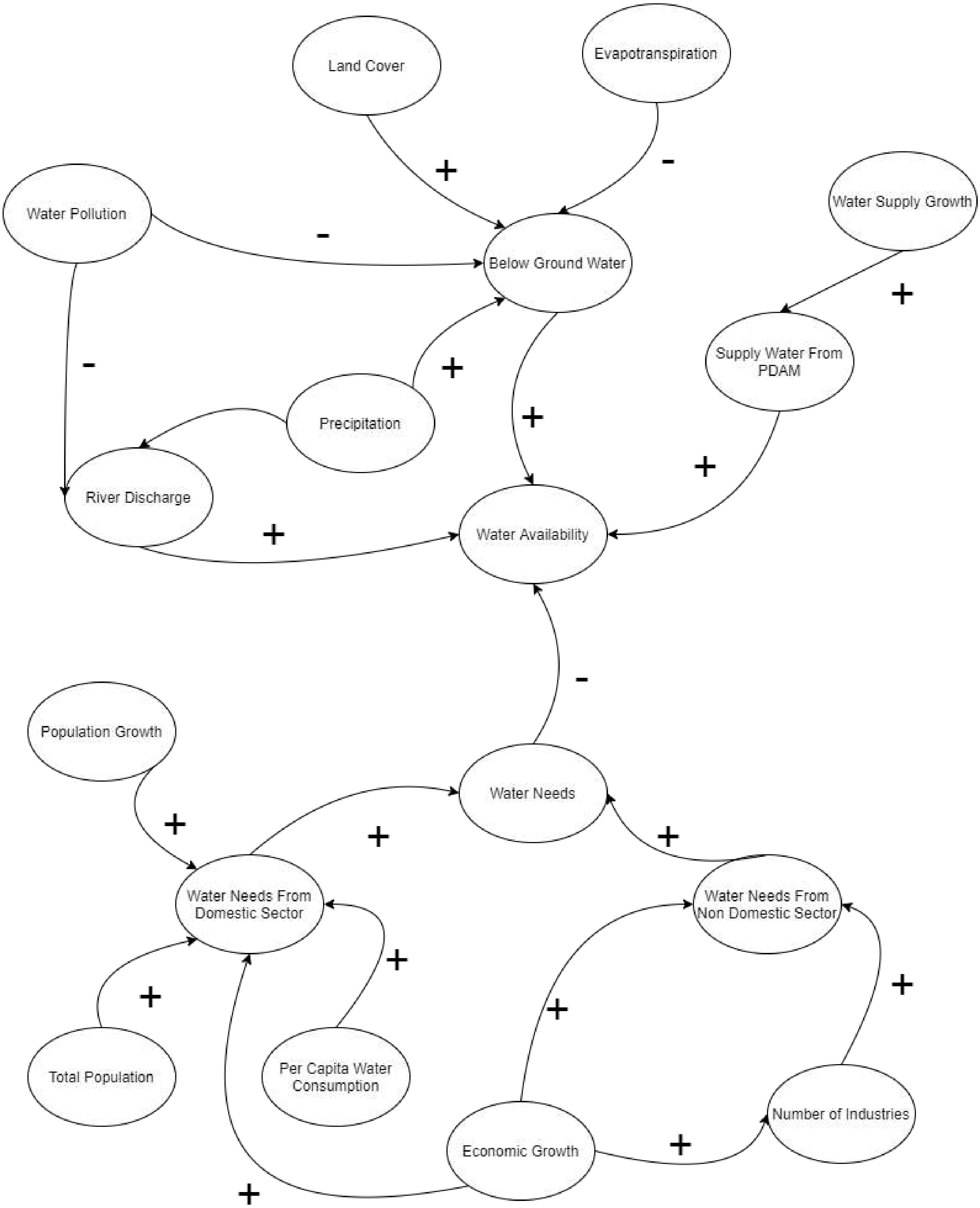

Figure 1 Causal-loop Diagram of Model Prediction of Water Needs and Availability

DOI: 10.5614/3bio.2022.4.2.3

Table 3 Area of Each Land Cover in Cimahi in 2021

District	Land Cover	Total Area (Ha)
North Cimahi	Vegetated Land	179.61
	Open Land	224.15
	Build-up Land	952.34
Central Cimahi	Vegetated Land	34.52
	Open Land	89.80
	Build-up Land	964.99
South Cimahi	Vegetated Land	124.68
	Open Land	146.17
	Build-up Land	1,326.69

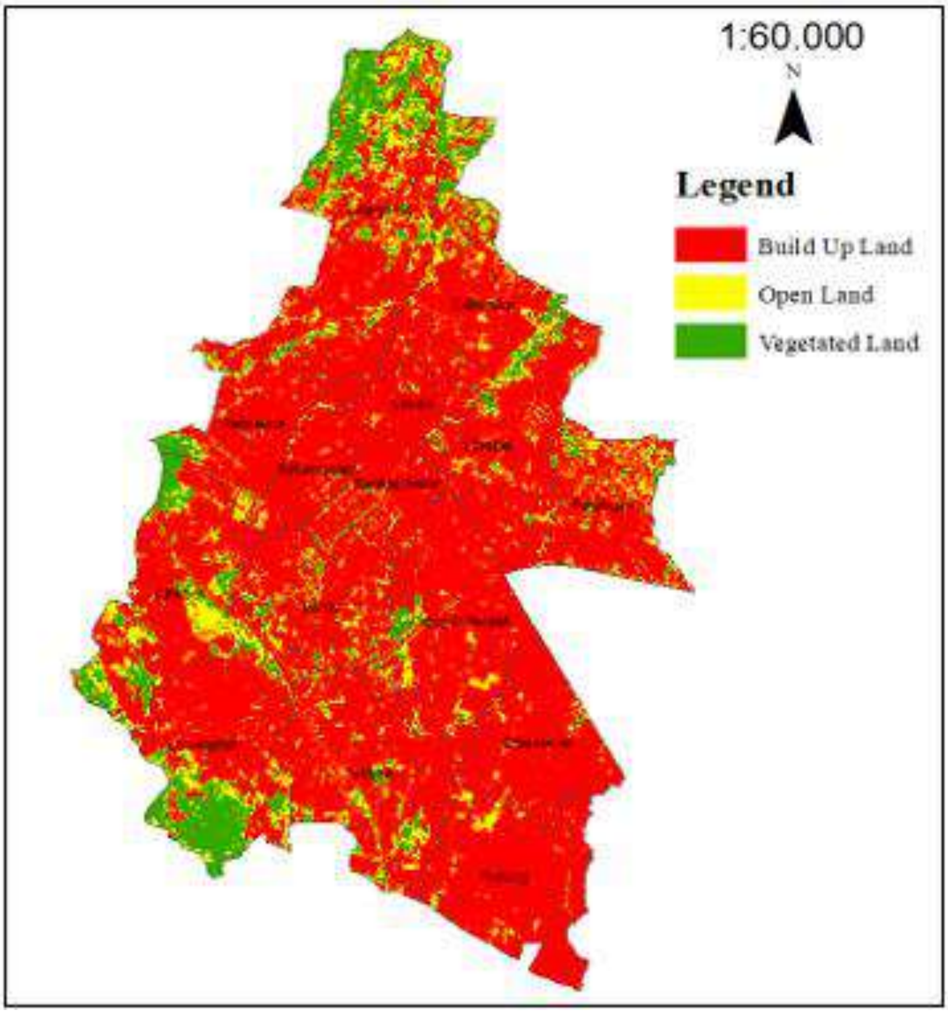

Figure 2 Land Cover of Cimahi City in 2021

Although this city seems to have been mainly occupied with built-up land, the increment rate of built-up land is relatively slow (5.78% in the last four years) compared to land cover conditions in 2017. A possible explanation is that Cimahi City used to be filled with buildings even since this area was not confirmed as a separate city in 2001 by Indonesia's government. However, the increment of built-up land is currently underway and threatens other land covers, especially vegetated land. The highest increment rate of built-up land from 2017-2021 occurred in South Cimahi District (2.83%), followed by Central Cimahi (1.15%), and North Cimahi (0.044%). Several factors cause the development of

DOI: 10.5614/3bio.2022.4.2.3

the built-up land area, e.g., population growth rate, land slope, and land availability surrounding roads and settlements [6].

The vegetated land area in Cimahi City is dominated by agricultural areas, such as fields, rice fields, shrubs, and other plantations. There is no forest in this city since there is no particular area appointed and stipulated as a forest area by the Indonesian Government (KLHK) in this city [7]. Compared with land cover conditions in 2017, the development of vegetated land in Cimahi City has generally decreased, even in small amounts. The reduction of Cimahi vegetated area occurred by 1.54% within four years. In contrast, there was an increase in vegetated land area in South Cimahi District (15.13%) and Central Cimahi District (3.68%). The main driver of overall vegetation land reduction in Cimahi is the area reduction in North Cimahi District (20.34%); thus, this district requires more attention concerning the problem.

On open land in Cimahi, the land cover has decreased in the area from 2017-2021. The reduction occurred in Central Cimahi by 3.24% and South Cimahi by 26.45%. In contrast, North Cimahi experienced an increment of its open land area by 9.53%. The loss of vegetated land cover into open land will undoubtedly affect the response to rain, such as increasing runoff and reducing the amount of water absorbed [8]. The results of this land cover analysis will become one of the input variables in the prediction model of water demand and availability. Simulation results will be discussed in the next point.

3.2. Model Simulation

North Cimahi District has water availability that is constantly above its needs (Figure 3). Thus, this area has always fulfilled its water needs, at least until the predicted year (2031). Even though the water needs in North Cimahi water increased annually, the rate is relatively insignificant. The water needs in 2021 were 10.07 million cubic meters and grew to 10.55 million cubic meters in 2031, meaning that the water demand will only increase by around 4.5% in ten years. This relatively low increment rate is probably since most water users in North Cimahi are from the domestic sector, such as household needs, irrigation, agriculture, or plantations. Meanwhile, water demand from the non-domestic sector only slightly affects the overall water needs. Indeed there are only a small number of medium to large industries in this sub-district since the designated land use is a catchment area and a low-density residential center [9].

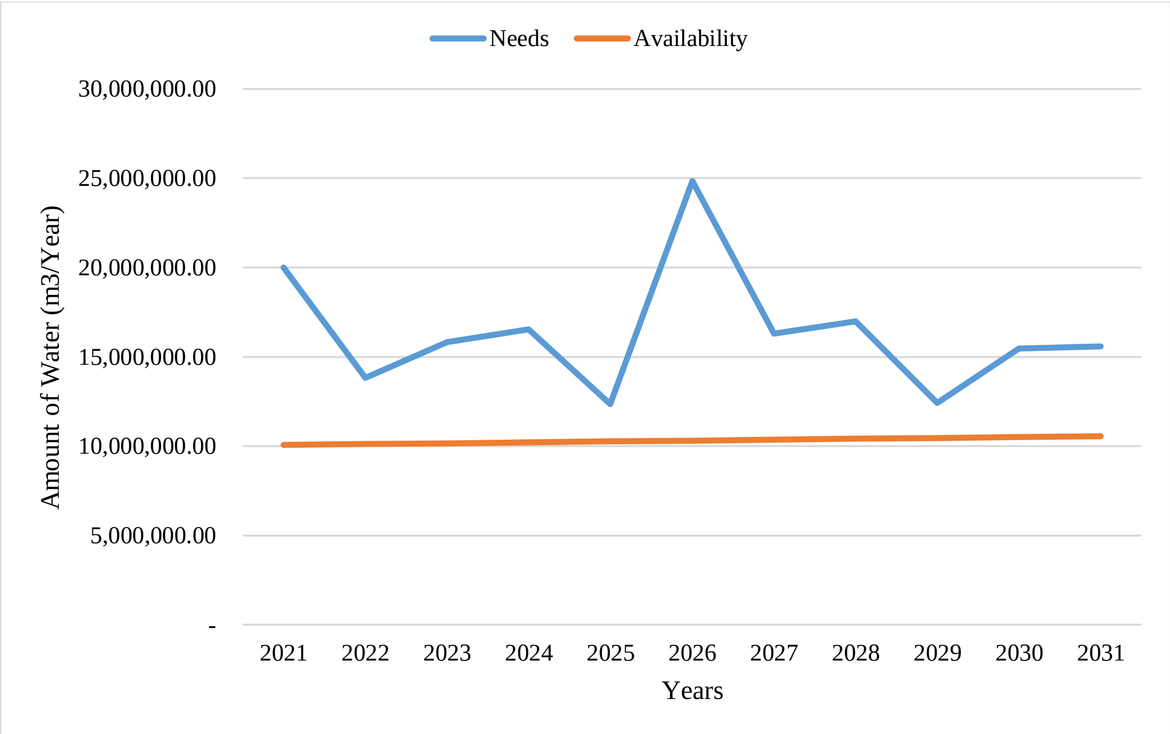

Figure 3 Graph of Water Needs and Availability in North Cimahi in 2021-2031

In contrast to the water needs, water availability in North Cimahi tend to fluctuate. The total water supply reaches 19.98 million cubic meters, or about 98% more than its needs in 2021. The water supply continues to increase and reaches its peak in 2026 with 24.84 million cubic meters, a surplus of up to 141% of the water needed. The fluctuation in the value of water availability in North Cimahi is greatly influenced by the water supply from river discharge sources. Factors that affect the river discharge amount include land slope, soil type, land cover, and rainfall [10]. The surplus in water availability in

DOI: 10.5614/3bio.2022.4.2.3

North Cimahi is logical since it functions as an area that supplies water for others surrounding it at a lower altitude [11].

The simulation result showed that water demand in Central Cimahi sub-district is similar to that of North Cimahi (Figure 4). However, the increase in the water needs rate in this district is not significant. In 2021, the water demand in Central Cimahi will reach 12.11 million cubic meters and will only increase by 1.8% until 2031 or by 12.34 million cubic meters. Its densely populated settlements and buildings in this area possibly contribute to the low increase. Indeed based on secondary data gathered, there were only a few medium to large industries and agricultural land/fields in this area, meaning that the household demand mainly influences the water demand. Fortunately, the water availability in Central Cimahi is sufficient, at least until 2028. However, water shortage is predicted to occur starting from 2029, when water sufficiency is only around 83-89%. One of the reasons for this lack of water availability is the increasing pressure on vegetated areas that can absorb water. The Central Cimahi area is densely populated with many settlements, buildings and a lack of vegetated areas. Do note that the water available here is limited to the ones obtained from the Central Cimahi area. Therefore, should a water shortage happen, the problem can be solved by securing water supplies from North Cimahi.

The model prediction showed a significant increase in water demand in the South Cimahi district (Figure 5) compared to the other districts. The water demand in 2021 reaches 20.37 million cubic meters and will increase by 10.5% to 22.78 million cubic meters in the next ten years. The large amount of water demand in South Cimahi is influenced by the needs of the domestic and non-domestic sectors. This district has the highest population and medium to large industrial numbers in Cimahi City. Unfortunately, the high water demand is not accompanied by the availability of adequate water. Based on the model, this area is predicted to experience a water shortage from 2022, reaching its peak in 2029 with only 13.32 million cubic meters available (60% of the water needs). But in 2026-2028, the model predicts that this region will still experience a little water surplus (2-10%). The insufficient water supply in this area is caused primarily by increasingly critical and damaged catchment areas. In addition, most industrial activities utilize excessive groundwater in this area, making the water supply more critical.

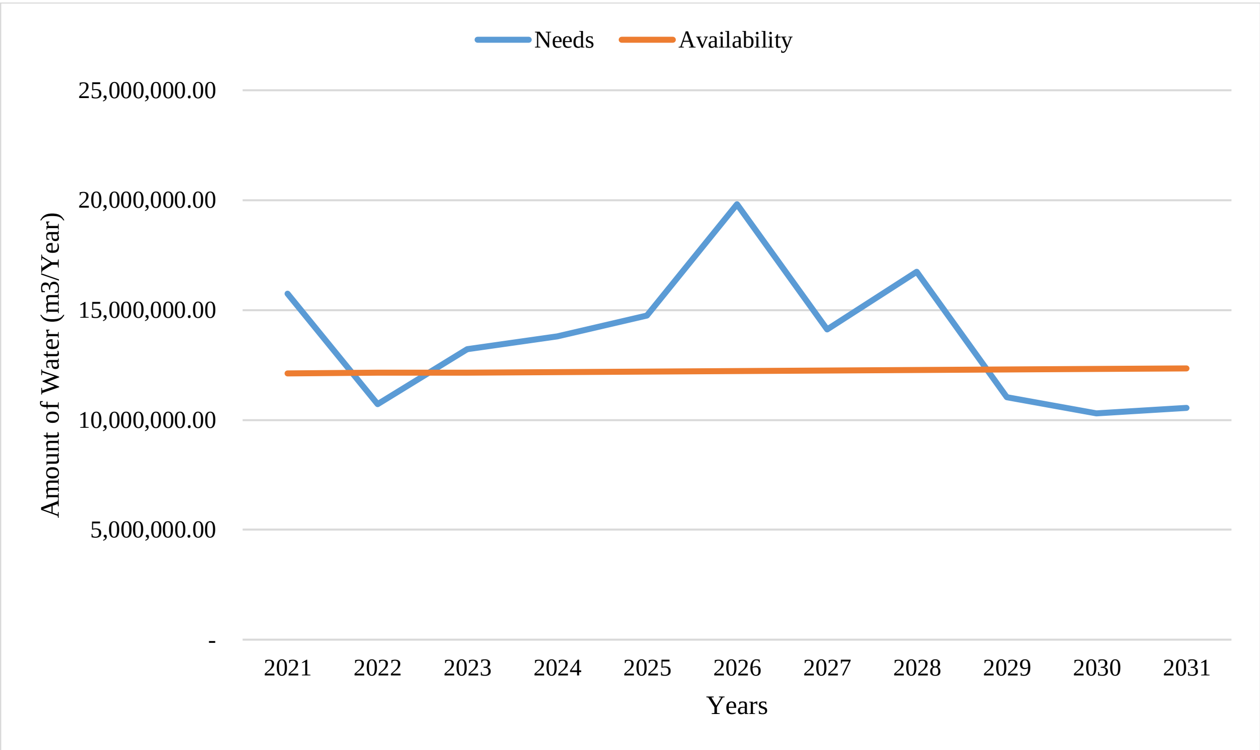

Figure 4 Graph of Water Needs and Availability in Central Cimahi in 2021-2031

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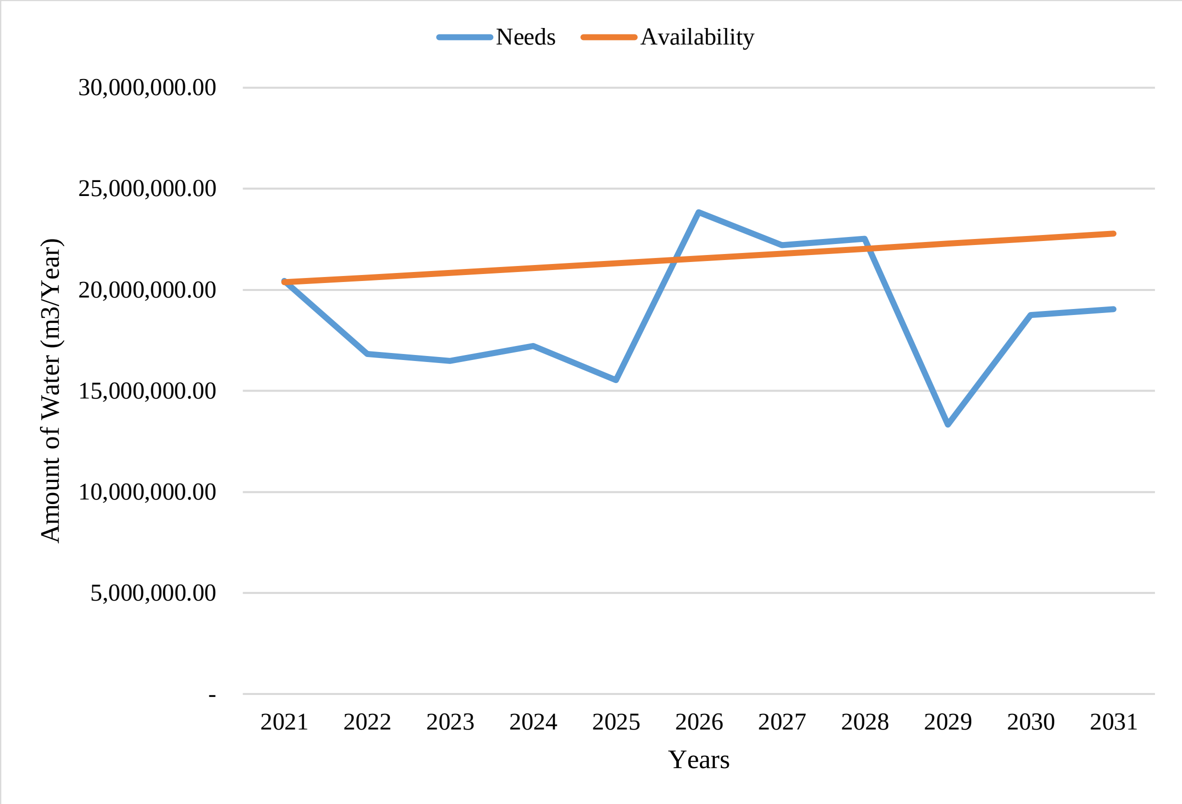

Figure 5 Graph of Water Needs and Availability in South Cimahi in 2021-2031

The previous explanation discusses the water availability and demand condition in each district without considering the input of excess water from certain districts. Figure 6 shows the accumulation and the difference between water demand and availability in Cimahi when excess water in each district is distributed to other areas lacking water. The model predicted that Cimahi will experience a water shortage in 2022, 2025, and from 2029 onwards, with a maximum need of 8.22 million cubic meters in 2029. Meanwhile, the maximum excess water will occur in 2026, up to 24.4 million cubic meters. The duration of surplus years is relatively longer than deficit years. Although not extreme, the predicted water shortage should be the government's primary concern because, without proper handling, these shortages will continue to occur in the following years.

3.3. Problem Solution

The predicted water shortages in the future are strongly influenced by the decrease in vegetation, damaging the catchment area. For this reason, improving the catchment area is a top priority in solving this water shortage. The vegetated areas of Cimahi need to be increased to maintain hydrological functions [8]. Based on regulations and policies related to spatial management in Cimahi, the improvement of this catchment area is prioritized by revitalizing or reforesting the catchment area in the North and South Cimahi districts. However, adding vegetated areas is not always feasible since the space available is limited. Therefore, improving the catchment area condition in Cimahi needs to be considered as an alternative solution to fulfill water needs in this city. From the perspective of the relevant stakeholders, another available solution is to create a rainwater infiltration system by artificially facilitating rainfall to enter the ground, for example, through absorption wells. This method can be prioritized for residential areas due to its high efficiency and minimal adverse impact without relocating the residents' settlements [12]. In addition, increasing the water supply from local water companies (PDAM) can also be considered a short-term solution.

The model simulation results found that the maximum water shortage in Cimahi occurred in 2029 with an 8.22 million cubic meters deficit. The amount of required vegetation area suggested by the model is 355 hectares. Unfortunately, only 142.8 Ha of land is available for planting vegetation in Cimahi, covering most of the North and South Cimahi areas [3]. Likely, water shortages will still occur if we only rely on this solution. Interviews with several relevant stakeholders reveal that the additional water supply provided by the water company cannot cover the predicted water shortage. The reason being the potential for additional water supply is only 100 l/second, which can only provide 7.78% of water needs in 2021. Thus, the application of absorption well

DOI: 10.5614/3bio.2022.4.2.3

as an alternative solution is crucial. An absorption well with a depth of 2.1 meters and a diameter of 1 meter has an average water absorption capacity of 2.43 m³/day [12]. With this assumption, 1576 units of absorption wells will be needed to fulfill the target.

The comparison of simulation before and after implementing the solutions above showed a positive outcome where water availability will be sufficient for Cimahi City until 2031 (Figure 7). By implementing the solution, annual water availability can be increased by up to 34.2%.

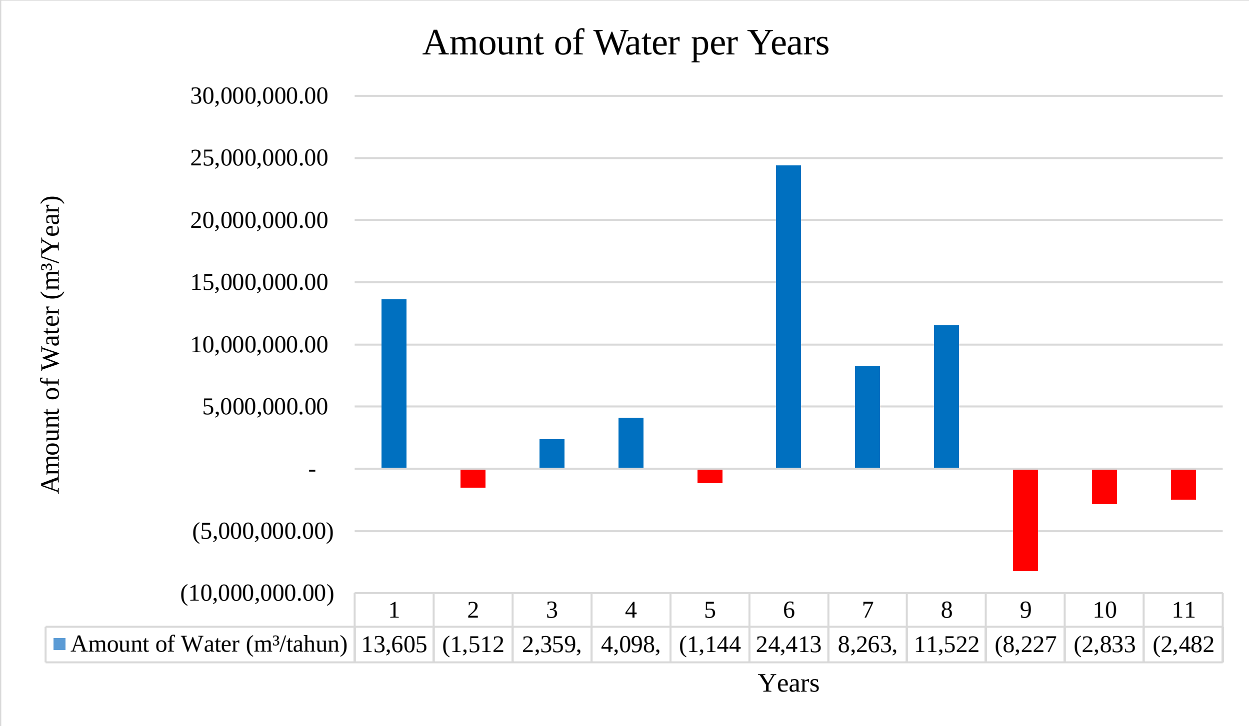

Figure 6 Graph of The Accumulation and The Difference Between the Water Needs and Availability in Cimahi 2021-2031

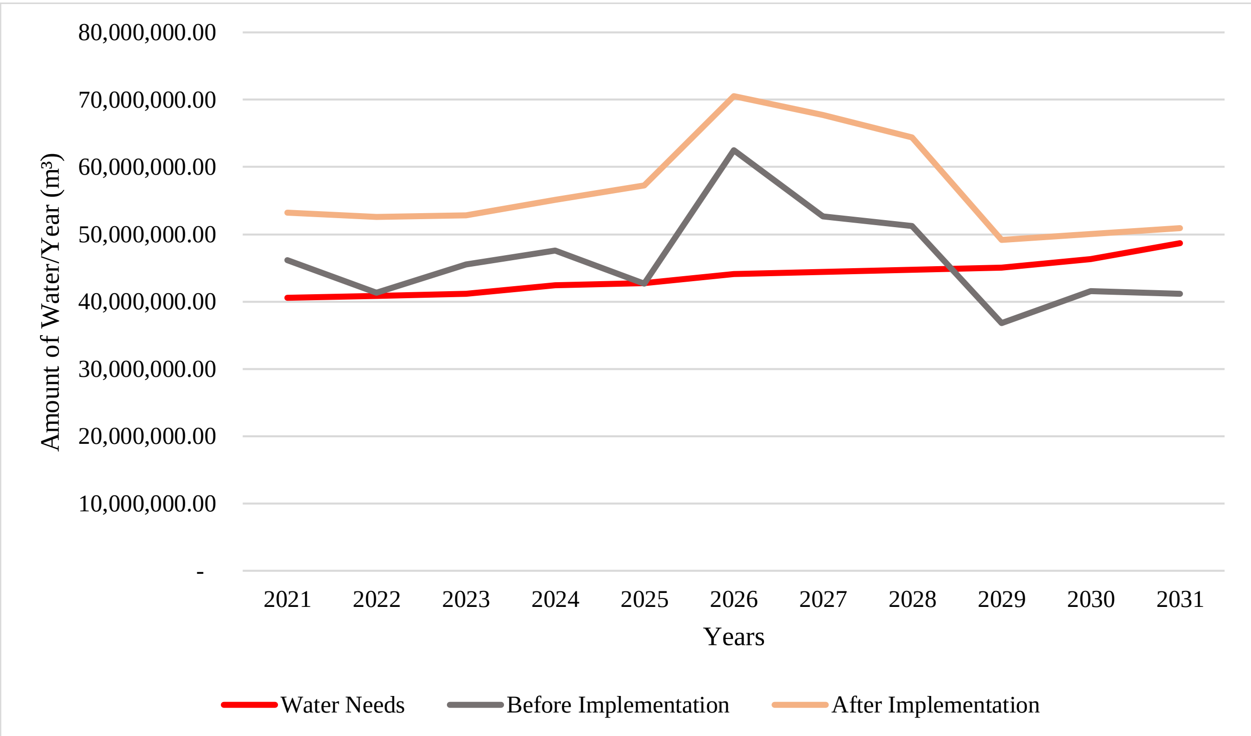

Figure 7 Comparison of The Simulation Results Before and After The Implementation of The Solutions

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4. Conclusions

Based on the results of this study, several conclusions can be drawn, i.e.,

1. The simulation results show that Cimahi will experience water scarcity starting in 2029, with the highest water shortage reaching 8.22 million m³. The worst water scarcity occurs in South Cimahi District, where water shortages start in 2022, with an average water sufficiency of only 60%. This shortage is caused by the increasingly critical catchment area exacerbated by excessive groundwater exploitation. In contrast, conditions in North Cimahi are the most ideal, where there is no water shortage, at least until 2031.
2. The solutions proposed to fulfill the water needs in Cimahi until 2031 are by adding 142.8 hectares of vegetated areas of in North and South Cimahi, increasing the number of absorption wells by 1576 units, and increasing the water supply capacity of regional water companies by 100 liters/second.

Acknowledgements

The authors thanked the stakeholders, including the speakers from Dinas Lingkungan Hidup Kota Cimahi, Dinas Perumahan dan Kawasan Permukiman Kota Cimahi, and Badan Perencanaan dan Pembangunan Daerah Kota Cimahi along with related field technical personnel, that have contributed to the survey and collection of data.

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DOI: 10.5614/3bio.2022.4.2.3