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RESEARCH ARTICLE

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Hydrological Modeling in the Capluk Watershed, Rembang Regency for Evaluation of Spatial Patterns

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ABSTRACT

Rembang Regency has little annual rainfall, ranging from 1,000 to 2,000 mm. The Capluk Watershed in Rembang is the only one with a discharge station. The average rainfall of the watershed in 2011 to 2020 is relatively low (1,877 mm/year). Moors are the dominant land use in the watershed, so the watershed is prone to drought. This study aims to assess the water balance and land use planning to reduce water deficits. The FJ Mock modeling method is used to understand hydrological phenomena, where the results can help manage water resources by regulating land use by utilizing the exposed surface parameters in the model. The results show that the demand for water in the watershed for the 2011 to 2020 period reaches an average of 49,151,012 m^3/year, while the availability of water is 132,512,172 m^3/year. This condition shows that the total water balance experiences an average surplus of 83,361,160 m^3/year but experiences a deficit in the dry season, an average of 3,452,278 m^3/year. For land use planning, scenario 5 (a combination of regional spatial plan maps, forest area maps, general plan for forest and land rehabilitation maps, and land use in 2020) is the best in reducing the water deficit by 20,383,274 m^3 or can lower the water deficit to 4,957,173 m^3.

Introduction

Rembang Regency is one of the regencies on the north coast of Central Java Province, which borders East Java Province, so the area is a strategic node on the northern coast of Java Island. The rainfall in the Regency is relatively small, with an average rainfall of 30 years (1981–2010) ranging from 1,000 to 2,000 mm [1]. In 2019, 61 of 287 villages in Rembang experienced drought [2]. Deficiency causes sub-districts in coastal areas to become areas prone to seawater intrusion due to excessive groundwater use and population pressure. Intrusion symptoms such as these are also supported by geological conditions such as alluvial material, geohydrological requirements with moderate aquifer productivity, and pond land use [3]. The current increase in the demand for land in Rembang could potentially increase the critical land area. Critical land has decreased land capacity and hydrological function, so it has an impact on the occurrence of floods (during the rainy season) and drought (during the dry season) as disasters [4].

Therefore, it is necessary to increase the environment's carrying capacity by managing the water resources [5]. Water resource management is a conservation effort to maintain, rehabilitate, maintain, and utilize water resources effectively and efficiently for society's welfare [6]. Water resources such as these can be managed based on the management of watersheds to realize the availability of sustainable water resources. Environmentally based places or hydrological containers for economic activity are described as watersheds [7-8]. Karanggeneng River is one of the rivers in Rembang Regency, and the community widely uses it for various community activities such as household activities, fishing boat traffic, and fish washing activities. Utilization, such as a decrease in river water quality because the waste generated from these activities flows directly into the Karanggeneng River [9]. Siltation also occurs at the mouth of the river owing to silt deposition

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carried by river currents from the upstream area, thus disrupting fishing boat traffic [10]. The Karanggeneng River is part of the Capluk Watershed; therefore, it can be concluded that the condition of the Capluk Watershed is unhealthy. The watershed problem is an ecological balance problem related to the carrying capacity of the environment and its constituent components in the area as a boundary of economic activity, which affects the development of life [11].

The condition of the Capluk Watershed runoff, based on the 2015 runoff hazard map (curve number) of the Ministry of Environment and Forestry, shows that almost 20% of the Capluk Watershed area has high surface runoff. The magnitude of runoff is closely related to human activity in the choice of dominant land use in an area [12]. Land use in the Capluk Watershed is dominated by rice fields (68%). Meanwhile, plantation forests account for 18% of the total population, and settlements account for 13%. Such conditions cause the watershed area to have the potential to experience drought. Therefore, good environmental management for the watershed is necessary to maintain its sustainability through land use planning [13]. Simplification of hydrological phenomena is needed to describe the biophysical conditions of a watershed in a hydrological model [14]. Based on the problems above, this research aims to analyze the balance between the supply and demand of water in the Capluk Watershed in 2011 to 2020 and to plan land use based on water resources in the Capluk Watershed.

Materials and Methods

Research Area

The research was conducted in the Capluk Watershed, which is located at 111°18'28.13"–111°24'27.19" E and 6°42'3.46"–6°53'32.09" S, with an area of 13,154.96 ha which is administratively located in four sub-districts, namely Rembang District, Kaliori District, Sulang District, and Bulu District. The largest sub-district included in the Capluk Watershed is Sulang District, which covers 74% of the total area of the Capluk Watershed. The Capluk Watershed is the only Rembang district with a river discharge observation post. A map of the research locations is shown in Figure 1.

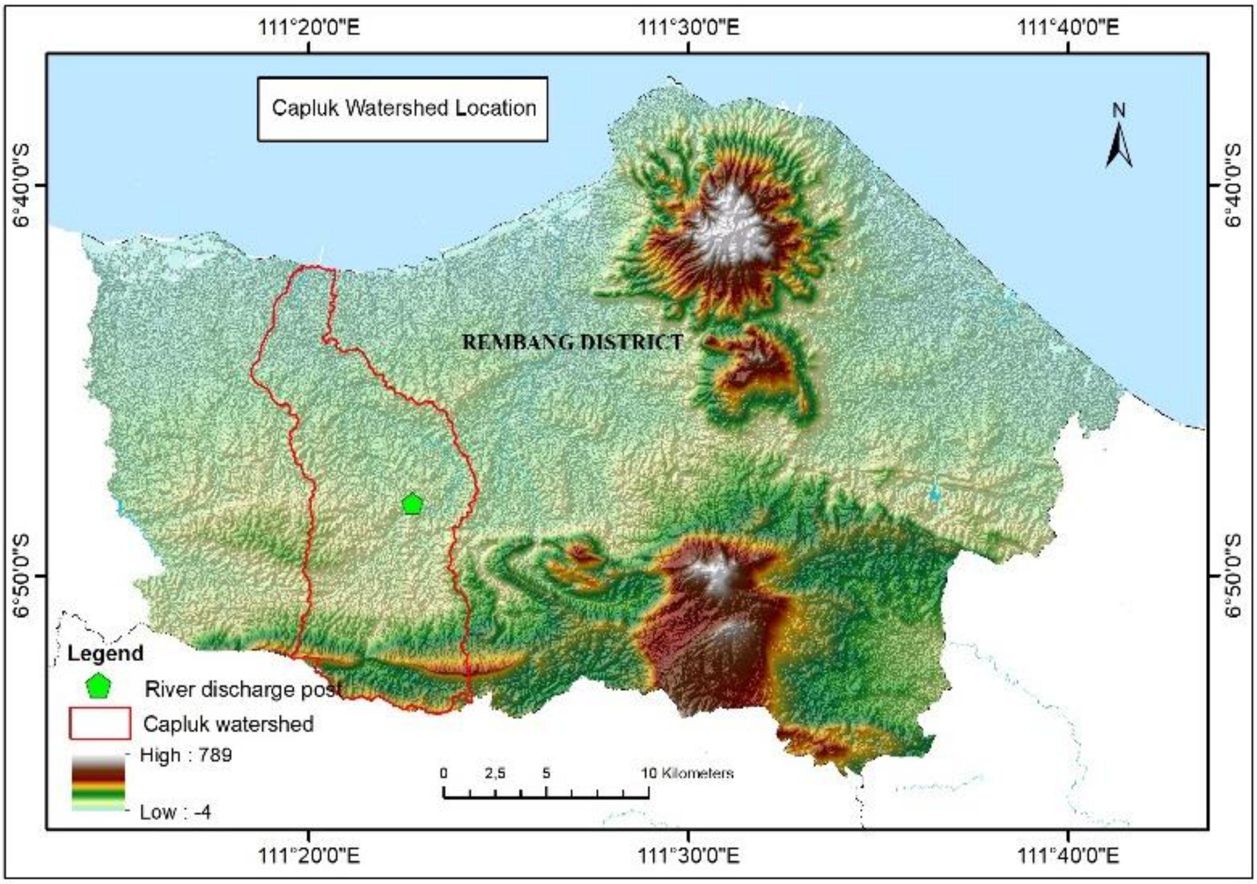

Figure 1. Research location in Capluk Watershed.

Data Collection

This study used primary data collected from the field and secondary data collected from related sources obtained from the *Badan Pusat Statistik* (BPS), Rembang Regency Industry Service, Rembang Regency Agriculture Service, Rembang Regency Fisheries Service, Rembang Regency Animal Husbandry Service, Regency Public Works, and Spatial Planning Office Rembang, Public Works Service, Water Resources and Spatial Planning of Central Java Province, *Badan Perencanaan Pembangunan Daerah* (BAPPEDA), *Lembaga Penerbangan dan Antariksa Nasional* (LAPAN), *Badan Meteorologi, Klimatologi, dan Geofisika* (BMKG), *Badan Informasi Geospasial* (BIG), *Balai Besar Pengujian Standar Instrumen Sumber Daya Lahan Pertanian* (BBPSISDLP), and *Kementerian Lingkungan Hidup dan Kehutanan* (KLHK).

The materials used in this study were SPOT IMAGES 4,5,6,7 for 2011 to 2020, data on domestic water needs, industry, irrigation, fisheries, livestock, rainfall data, climate, river discharge data for 2011 to 2020, watershed maps, administrative maps, topographical maps, soil type maps, 2015 land use maps, maps of the *Rencana Tata Ruang Wilayah* (RTRW) of Central Java Province (2009–2029), maps of the *Rencana Umum Rehabilitasi Hutan dan Lahan* (RURHL), and maps of forest areas. The tools used in the research were a set of computers equipped with ArcGIS 10.8 software, Windows Office, CROPWAT 8.0, Global Positioning System (GPS), and writing instruments.

Data Analysis

Water Needs

Water demand analysis in this study was calculated based on the sum of the analysis of domestic, non-domestic, livestock, industrial, irrigation, fishery, and river maintenance needs for 2011 to 2020 based on the preparation of a water resource balance according to SNI 19-6728.1-2002 [15] and SNI 6728.1-2015 [16]. The data used is the percentage of regional administrative areas included in the Capluk Watershed area. The number of days and working days in a year impact the amount of water needed in the Capluk Watershed, so leap years tend to have a greater amount of water required.

Water Availability

Rainfall level is among the most influential parameters in water availability analysis. The rainfall analysis used in this study was based on the Thiessen polygon, with five rainfall stations: Bulu, Kaliori, Rembang, Sulang, and Tunjungan. This graphical technique calculates station precipitation weights based on the relative area of each measuring station in a Thiessen polygon [17]. The amount of rainfall affects the water balance in a watershed, where the water balance describes the relationship between the inflow and outflow in an area during a specific period. The water balance, according to the FJ Mock Method, explains that rain that falls in an area will come out as evapotranspiration; on the surface, it becomes runoff and below the ground surface, after which it becomes groundwater storage, where some is stored and some flows. The flow on and below the ground surface corresponds to the total runoff. The general form of the water balance is expressed in Equation 1.

$$P = ET + TRO + \Delta GS \quad (1)$$

Information:

P = precipitation

ET = evapotranspiration

ΔGS = changes in groundwater storage

TRO = total runoff

The total runoff is a component of river discharge, which can be calculated based on the sum of the base, surface, and instantaneous rain runoff [18] using equation 2.

$$QTotal = Qbase + Qdirect + Qstrom \quad (2)$$

Information:

QTotal = total runoff (mm/month)

Qbase = base runoff (mm/month)

Qdirect = surface runoff (mm/month)

Qstrom = instantaneous rain runoff (mm/month)

The total runoff analysis results were then converted into debit, which is the water available in the watershed, using using equation 3.

$$Q=\frac{QTotal}{n}\times\frac{A}{24\ hours/day}\times\frac{1000}{3600\ seconds/hour} \quad (3)$$

Information :

Q = debit (m^3/second)

QTotal = total runoff (mm/month)

A = watershed area (m^2)

n = number of days (day)

Model validation was carried out to test the consistency and accuracy of the river discharge prediction model compared with discharge results from observations in the field for ten years in the Capluk Watershed. The model validation used in this study used the Nash–Sutcliffe model efficiency coefficient (NSE) [19]. The Nash–Sutcliffe model efficiency coefficient (NSE) assessment criteria for model validation in this study are as follows [20]: NSE > 0.75, considered good, 0.36 ≤ NSE ≤ 0.75, considered satisfactory; and NSE < 0.36 is considered unsatisfactory. According to the Mock method, other essential parameters in water availability are the proportion of land surface not covered by vegetation (exposed surface), soil moisture capacity (SMC), infiltration factor, and runoff [21]. This study uses the exposed surface for various land-use planning scenarios based on water resource conservation. The value of the exposed surface based on the Mock Model is shown in Table 1.

Table 1. Proportion of land surface not covered by vegetation.

No	Exposed surface (%)	Area
1	0–10	Primary forest
2	10–30	Eroded area
3	30–50	Agricultural field area

The exposed surface values were obtained by visual interpretation of the corrected SPOT images from 2011 and 2020, with detailed 2015 land use maps resulting from digitization of high resolution satellite imagery. Visual image classification produces better accuracy than digital classification in differentiating or separating land cover [22]. The verification process was carried out by taking ground checkpoints using the stratified random sampling method, taking stratification points randomly based on the proportion of the area of each land use class. The validation process was analyzed by performing an overall accuracy test and kappa accuracy test based on the misclassification matrix presented in Table 2.

Table 2. Confusion matrix.

Reference data	Interpreted land use					Sum
	1	2	3	4	5	
1	X_{11}					X_{1+}
2		X_{22}				X_{2+}
3			X_{33}			X_{3+}
4				X_{44}		X_{4+}
5					X_{55}	X_{5+}
Sum	X_{+1}	X_{+2}	X_{+3}	X_{+4}	X_{+5}	N
User's accuracy	X_{11}/X_{+1}	X_{11}/X_{+2}	X_{11}/X_{+3}	X_{11}/X_{+4}	X_{11}/X_{+5}	

Note: N: The total number of field checkpoints; X_{+i} : Total land use in column i; X_{i+} : Total land use in row-i.

A kappa value of 1 (one) indicates that the classification result obtains perfect approval. In contrast, a kappa value of 0 (zero) indicates that the classification results cannot be approved (no agreement). A kappa coefficient ranging from 0.61 to 0.80 falls into the large category, while a kappa coefficient of 0.81 to 1 falls into the almost perfect category [23].

$$\text{Kappa coefficient (K)} = \frac{N\sum_i^r X_{ii} - \sum_i^r (X_{i+}\ X_{+i})}{N^2 - \sum_i^n (X_{i+}\ X_{+i})} \times 100\% \quad (4)$$

Water Balance

The water balance of a watershed is the balance between the inflow and outflow of a watershed area for a certain period of water circulation. The water balance in the Capluk Watershed during 2011 to 2020 was generated by reducing the amount of water available and the water needed in the Capluk Watershed during 2011 to 2020. Results from this water balance can determine the condition of the Capluk Watershed water resources for 10 years whether there is a surplus or deficit in the year.

Land Use Planning Scenario

Land use planning is needed to determine the best recommendations for the continuity of soil and water conservation, which has an impact on watershed sustainability with the characteristics of decreasing land degradation, increasing infiltration, and decreasing runoff, thus affecting water availability, especially during the dry season in the Capluk Watershed. Soil and water conservation techniques and land vegetation improvement can improve watershed hydrological conditions [24–25]. Watershed management can be described spatially in spatial planning based on ecological concepts [26–27]. This land use planning is performed using the Mock Model. The scenarios used are Scenario 1: application of land use according to conditions in 2020; Scenario 2: land use by the RTRW; Scenario 3: land use according to the forest area map; Scenario 4: land use according to the RURHL Map; Scenario 5: land use by combining the 2020 land use scenario, RTRW, forest area, and RURHL.

Results and Discussion

Water Needs

Water needs in the Capluk Watershed for 2011 to 2020 were calculated based on secondary data analysis from several related agencies, including domestic, non-domestic, livestock, industrial, irrigation, fisheries, and river maintenance needs. The data used were the percentage of regional administrative areas included in the Capluk Watershed area. Water demand fluctuates with a tendency to increase in line with fluctuations in the number of parameters for each type of water demand. Water demand in the Capluk Watershed has increased accordingly with a graph of water needs in the Capluk Watershed for 2011 to 2020 which is presented in Figure 2.

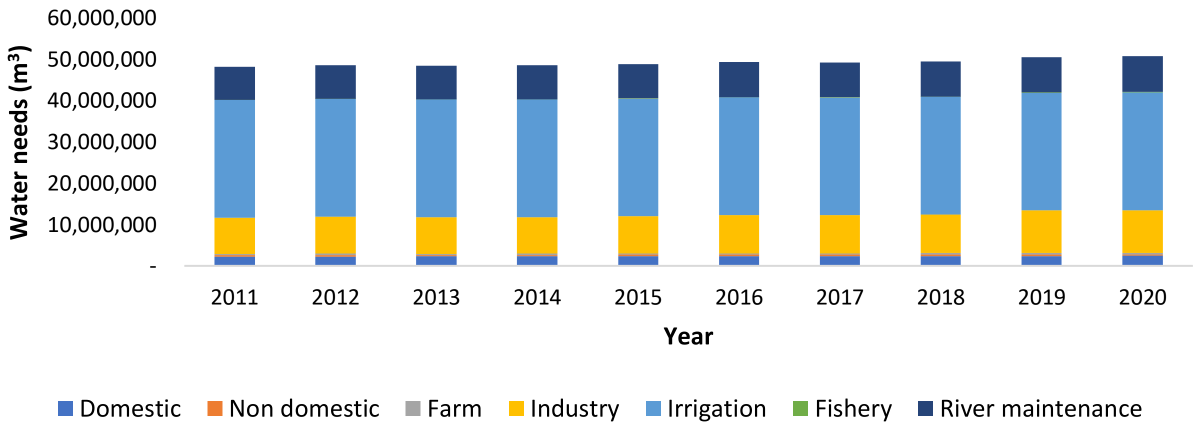

Figure 2. Graph of water needs in the Capluk Watershed in 2011–2020.

The analysis shows that irrigation is the largest water requirement, with an average of 28,463,006 m^3, or 58% of the total water requirement per year. The smallest water need is fisheries water need, with an average of 56,062 m^3, or 0.11% of the total water need per year. The total water demand in the Capluk Watershed fluctuated. In 2011 to 2012, there was an increase, but in 2013, there was a decrease of 42,252 m^3 due to the reduced water needs for livestock, irrigation, and fisheries. The total water demand increased again in 2014 by 92,998 m^3, and continued to increase until 2016. In 2017, the total water demand decreased again by 82,929 m^3 due to reduced water needed for irrigation, industry, and livestock. In 2018, total water demand continued to increase until 2020. This continuing increase in water demand requires the availability of sufficient water to meet water needs. Therefore, maximum efforts must be made to provide water to the Capluk Watershed.

Water Availability

Rain is the main source of water that supplies water to an area. In this case, the low annual rainfall impacts water availability in the Capluk Watershed. The rainfall in the Capluk Watershed in 2011 to 2020 was relatively low, with an average rainfall of 1,877 mm/year. The most considerable rainfall during 2011 to 2020 occurred in 2016, that is, 2,455 mm, where rain occurred throughout the year, increasing water availability in the Capluk Watershed. Based on the interpretation results, the land-use types in the Capluk Watershed consist of reservoirs, forests, industries, mixed gardens, moors, cemeteries, settlements, livestock, rice fields, and bodies of water. The land use map for 2020 was tested for accuracy through field checks at 150 points. An overall accuracy of 94.00% and a kappa coefficient of 92.64% were obtained. Considering that the overall accuracy value is > 85% [28] and the Kappa coefficient is > 80%, the land-use map can be used for further analysis.

This type of land use affects the value of the exposed surface. Based on the digitization results of the SPOT Image for 2011 to 2020, the exposed surface increased, although not significantly, with an average value of 29%. This land use is dominated by moors, with an average value of 46% of the Capluk Watershed area. In addition to the exposed surface value, the SMC value is another parameter used. The SMC value in the Capluk Watershed in 2011 was 184.89 mm and then increased in 2016 to 184.98 mm due to forest and land rehabilitation activities that grew the forest area. Forest land cover, in this case, plays a significant role in regulating the watershed system [29]. The forest area 2017 decreased again until 2020, impacting the SMC value, which decreased to 182.89 mm due to changes in land use types from vegetation to non-vegetation. Thus, a decrease in the vegetated land area can reduce the environment's carrying capacity for the water system, which also functions as a water conservation area in the watershed [30]. The conversion of forests into agricultural land decreases the function of forests in regulating water systems and preventing floods, landslides, and erosion [31–32]; thus, land degradation can change the hydrological characteristics of the watershed [33].

The discharge value of the analysis results was then used for data validation, where this process aims to describe the level of uncertainty of a model in predicting hydrological processes [34]. Validation was carried out by comparing the observed discharge with the simulated discharge of the model in 2011 to 2020 in the Kali Sulang sub-watershed, which is a sub-watershed of the Capluk Watershed with an average NSE value of 0.55 and a coefficient of determination (R^2) of 94%, which means that the model is acceptable and accurate enough to be used [20]. The discharge graph for the analysis of water availability and the effects of observations are shown in Table 3.

Table 3. Average discharge value from simulation and observation results (m^3/s).

Discharge type	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Simulated	4.33	2.95	2.49	2.40	1.52	1.25	0.93	0.82	0.69	0.54	1.98	2.41
Observation	4.13	3.01	2.62	2.54	1.83	1.16	1.01	0.50	0.47	0.44	1.78	2.02

Water Balance

The water balance was calculated based on the reduction between the available water and the water needed in the Capluk Watershed from 2011 to 2020. The amount of water available, water demand, and water balance in the Capluk Watershed for 2011 to 2020 are presented in Table 4. Over the past ten years, there have been fluctuations in the availability and demand sectors of water, thus affecting the water balance level in the Capluk Watershed. These results show that there were several years (2012, 2015, 2017, 2018, and 2019) when water availability decreased while demand increased, resulting in reduced water balance in the Capluk Watershed. Water availability has decreased due to decreased rainfall (2012, 2015, 2017, and 2018) and decreased vegetated land due to reduced forest area (2018 and 2019), so less rain infiltrated the soil. The most significant decrease in water availability occurred in 2015, namely, a decrease of 94,796,861 m^3, whereas the most significant increase occurred in 2016, increasing by 86,454,598 m^3. The level of water demand also fluctuated, and in 2013 and 2017, it decreased, which was influenced by the number of working days and livestock that fell in that year.

The most significant decrease in water demand occurred in 2017, that is, a decrease of 82,928 m^3, whereas the most significant increase in water demand occurred in 2019, increasing by 1,001,236 m^3. Fluctuations in water availability and demand affect the water balance in the Capluk Watershed. The water balance experienced the largest increase in 2016, increasing by 86,002,461 m^3, whereas the largest decrease occurred in 2015, where the water balance decreased by 95,038,565 m^3. The results of the monthly water balance can determine the condition of the Capluk Watershed water resources for ten years, whether they experienced a surplus or deficit, the results of which are shown in Figure 3. The results of the water balance analysis show that over the last ten years the Capluk Watershed has experienced a total surplus, but in the dry season, there has been a fairly large water deficit. The longest dry season occurred in 2015, lasting seven months, resulting in the largest water deficit of 10,014,197 m^3. The water deficit during the dry season in the Capluk Watershed can be overcome by implementing several land-use planning scenarios.

Table 4. Water balance in the Capluk Watershed 2011–2020.

Year	Water availability (m^3)	Water demand (m^3)	Surplus/deficit (m^3)
2011	118,312,094	48,143,483	70,168,611
2012	115,555,959	48,510,677	67,045,282
2013	164,407,289	48,468,425	115,938,864
2014	181,416,271	48,561,423	132,854,847
2015	86,619,409	48,803,127	37,816,282
2016	173,074,007	49,255,264	123,818,744
2017	167,933,358	49,172,335	118,761,024
2018	109,368,208	49,460,470	59,907,739
2019	96,404,341	50,461,706	45,942,635
2020	112,030,785	50,673,211	61,357,574
Average	132,512,172	49,151,012	83,361,160

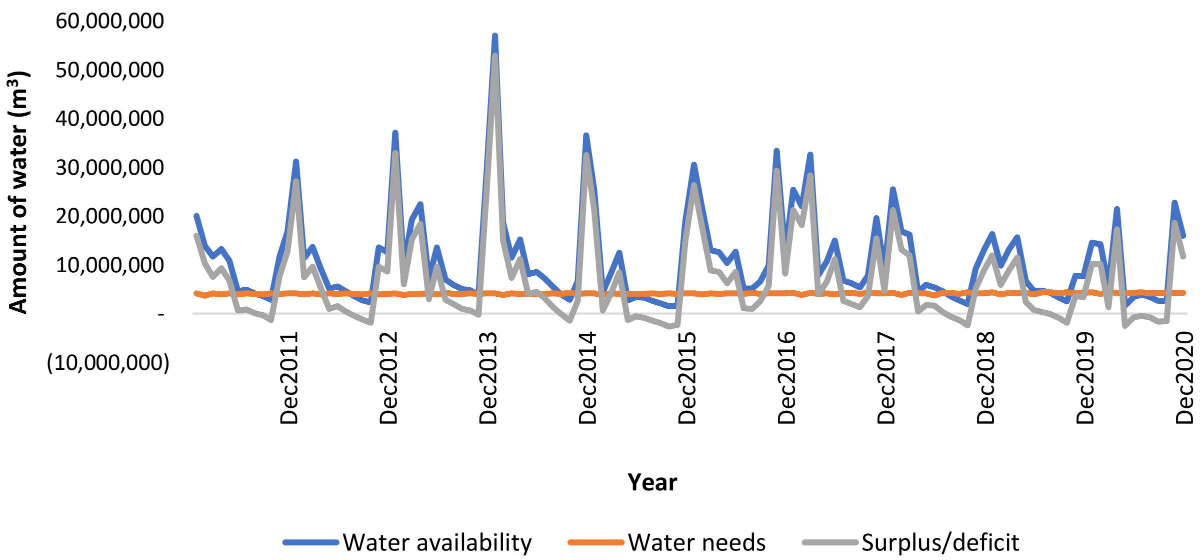

Figure 3. Graph of the water balance in the Capluk Watershed in 2011–2020.

Land Use Planning Scenario

Changes in land use can change the function of watershed land from absorbing water (into the ground) to less/not drinking water into the soil. This condition can increase surface runoff during the rainy season and cause water shortages during the dry season [35]. Thus, planning land use within a watershed is necessary to optimize water resources. Land use planning for optimizing and conserving water resources in the Capluk Watershed uses the mock method, which can predict surface runoff levels. The land use scenario was based on various regulations related to land use, including RTRW, forest area, RURHL, a combination of land use in 2020, and RTRW, forest area, and RURHL compared to land use in 2020. Mock parameter values related to land use in the application of these various scenarios were the proportion of land surface not covered by vegetation, actual evapotranspiration, infiltration coefficient, and soil moisture capacity, the results of which are shown in Table 5.

Table 5. Comparison of changes in hydrological parameters of the Mock Model based on various land-use scenarios.

No	Parameter	Land use scenario				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
1	*Exposed surface* (%)	28.90	28.39	27.39	28.14	26.12
2	Ea (mm/year)	1,284	1,288	1,296	1,290	1,306
3	IF	0.40	0.45	0.45	0.41	0.48
4	SMC (mm)	182.89	189.06	195.00	170.36	207.67

The condition of the exposed surface value has decreased significantly relative to the land use conditions in 2020, which was 28.90% and fell to 26.12% in the combined scenario. This condition also impacts the value of actual evapotranspiration because a decrease in the exposed surface decreases the difference between the potential and limited evapotranspiration. The actual evapotranspiration, initially valued at 1,284 mm/year, increased to 1,306 mm/year in scenario 5. The increase in vegetated land in applying the combined scenario also increases the infiltration coefficient because more vegetation roots can infiltrate rainfall falling into the soil. The infiltration coefficient increased from 0.40 to 0.48. The increase in water entered into the ground by vegetation roots from the application of the land use scenario has an impact on increasing SMC, which was initially 182.89 mm and rose to 207.67 mm. The increase in infiltration and soil moisture capacity in this scenario reduced the direct runoff and increased the base flow. Direct runoff decreased from 486.97 to 419.21 mm, and base flow increased from 324.65 to 386.96 mm. An increase in the infiltration rate reduces surface runoff so that the volume of water in the rainy season decreases and that in the dry season increases [36], as shown in Table 6.

Table 6. Comparison of the results of applying land use scenarios based on the Mock model in the Capluk Watershed.

No	Scenario	Annual volume of water (m^3)	Dry month water supply (m^3)	Dry month water balance (m^3)
1	Scenario 1	112,030,785	17,555,407	−7,785,040
2	Scenario 2	111,898,020	19,406,931	−5,933,517
3	Scenario 3	111,640,345	19,344,145	−5,996,303
4	Scenario 4	111,835,564	17,888,820	−7,451,627
5	Scenario 5	113,327,996	20,383,274	−4,957,173

The results of the analysis of the application of land-use scenarios showed that the water supply increased during the dry season. The largest water supply during the dry season occurred when scenario five was implemented (20,383,274 m^3). This water supply reduced the dry season's water deficit to 4,957,173 m^3. This water deficit occurred from May to October, as shown in Figure 4, which displays the distribution of the water balance by applying various land-use scenarios in the Capluk Watershed.

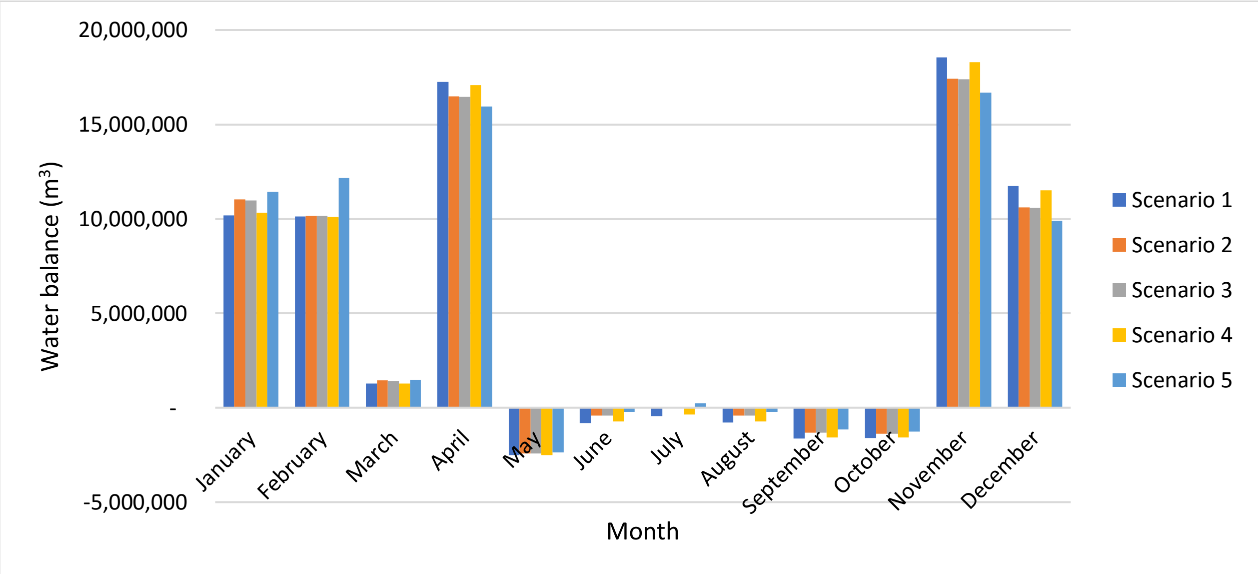

Figure 4. Water balance with the application of various land use scenarios in the Capluk Watershed.

Conclusions

Water demand in the Capluk Watershed in 2011 to 2020 averaged 49,151,012 m^3/year, whereas water availability was 132,512,172 m^3/year. The total water balance experienced a surplus with an average of 83,361,160 m^3/year but a deficit, especially during the dry season, of 3,452,278 m^3/year. Hydrological modeling with the application of Scenario 5, namely, a combined scenario of land use by the RTRW, forest area, RURHL, and land use in 2020, can provide the most significant water supply during the dry season among the other scenarios, namely 20,383,274 m^3, which can reduce the water deficit to 4,957,173 m^3.

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Conflicts of interest

There are no conflicts to declare.

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