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Rainfall-Runoff Modelling in Tropical River Basin for Water Conservation Planning Using Water Recharge Ponds

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ABSTRACT

Land conversion in river basins poses a threat to future water availability. This research aims to estimate water availability, particularly stream flow for planning of water conservation. Water availability was analyzed using a hydrology tank model. The model was calibrated by using stream flow data measured in a reservoir and then used to estimate water availability in the reservoir's catchment area. The value of model parameters such as wet infiltration coefficient (WIC), dry infiltration coefficient (DIC), soil moisture capacity (SMC), initial soil moisture (ISM), initial groundwater storage (IGWS), groundwater recession constant (k) was determined through the calibration process. The results showed that the model has good accuracy for stream flow calculation indicated by the value of statistical parameters i.e. coefficient of correlation (R) = 0.93, a volume of error (VE) = 0.04, and a coefficient of efficiency (CE) = 1.00. During the wet season, the specific maximum discharge is 0.11 $m^3s^{-1}km^{-2}$. Meanwhile, the minimum specific discharge is 0.030 $m^3s^{-1}km^{-2}$. These differences indicate that optimizing rainwater harvesting during the wet season is required. Rainfall-runoff modeling reveals the potential for surface runoff during the wet season is 1,139 mm. This finding provides an essential reference for water conservation, especially using water recharge ponds.

1. INTRODUCTION

Water demand continues to grow as the population continues to increase. Over the past 30 years, the use of water resources has increased due to rising population and urbanization, climate change, and drought (Ibrahim-Bathis & Ahmed, 2016). Water resources are utilized directly by the community and as an important factor in supporting the agricultural sector. The existence of water resources is influenced by various factors, including land cover characteristics (Nyatuame *et al*., 2023).

Land cover has an important influence on the sustainability of the hydrological cycle components in a basin such as increasing and decreasing surface runoff, evapotranspiration, and interception (Yang *et al*., 2009). Recently, the balance of the hydrological cycle has been disturbed due to excessive agricultural practices, mining, residential development, and others. These conditions lead to sub-optimal groundwater recharge, wet-season flooding, and dry-season drought. This phenomenon necessitates maximising the efficiency of water resources management by forecasting water availability through river flow (Narayanan *et al*., 2013). Watershed conservation planning needs to pay attention the groundwater recharge process as a supply to meet water demand (Ibrahim-Bathis & Ahmed, 2016).

Groundwater recharge is one of the most challenging processes to measure directly in the hydrological cycle (Lentswe & Molwalefhe, 2020). Conventional field-based hydrological investigations require a lot of time, cost, and expertise (Jena *et al*., 2020). The estimation process through model simulation is one option for determining the amount of water availability quickly and cheaply. The water balance model is a commonly used method in the runoff-rainfall modelling process with a relatively simple process and good simulation results (Boyko *et al*., 2021). Mostly, conservation practices specially created by farmers were lack of water availability consideration. In this study, the hydrological model of Mock was used for water availability estimation as the basis for conservation practices by using water recharge ponds.

The hydrological model of Mock is one of the hydrological models developed by FJ Mock and is commonly used in predicting the mainstay discharge in a watershed by applying the concept of water balance (Jayanti *et al*., 2023). The FJ Mock method assumes that rain falling to the earth will be converted into components, namely evapotranspiration, direct runoff, and infiltration (Sunaryo *et al*., 2019). The effect of gravity will cause water to continue to enter the ground until percolation occurs as groundwater. In a relatively long time, groundwater will become the base flow that flows into the river (Tunas, 2007). The combination of direct runoff and base flow becomes an instrument in determining the discharge value of the FJ Mock method. Based on research (Chandrasasi *et al*., 2020), the results of discharge simulations using the Mock model show high correlation and low error rates. This shows the model's reliability in predicting the discharge value at the study site. Therefore, this research aims to predict water availability through hydrological simulations using the FJ mock method in the Upstream Serayu Watershed. The analysis results are used to plan water conservation at the study site using conservation structures (recharge ponds).

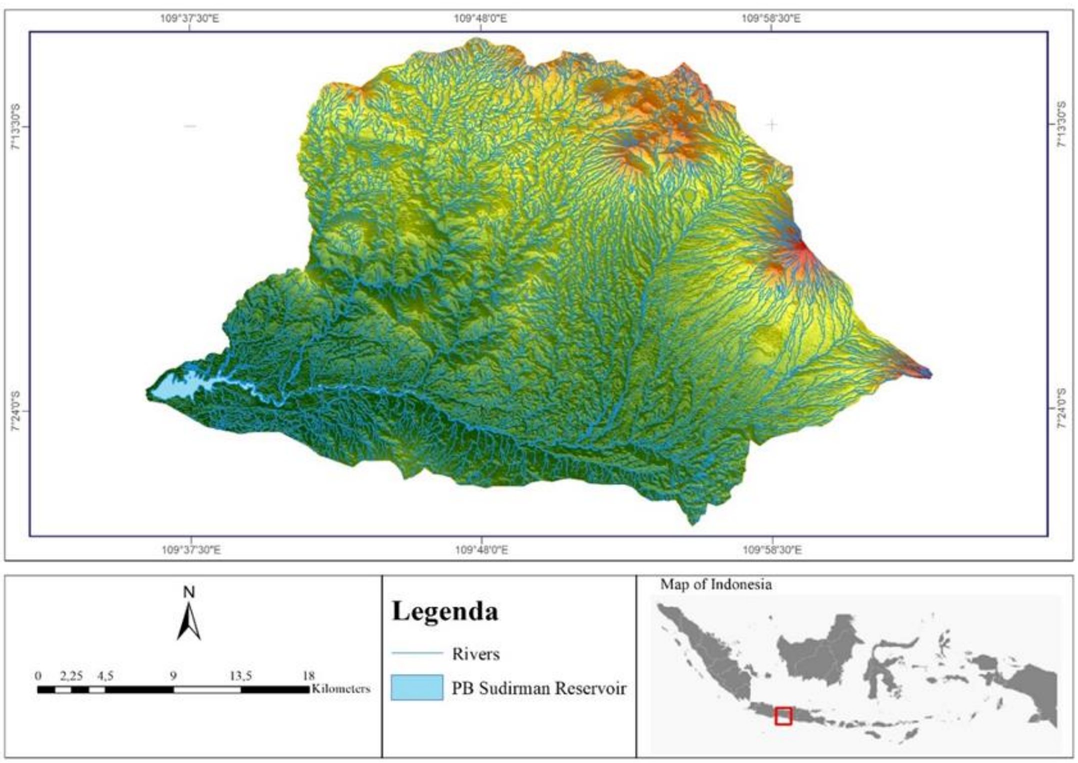

Figure 1. Catchment Area of PB Sudirman Reservoir

2. MATERIAL AND METHODS

2.1. Study Location

This study was conducted in the catchment area of PB Sudirman Reservoir (Upstream of Serayu Watershed) which covers about 1.010 km^2 area. The catchment area of PB Sudirman reservoir covers several sub-watersheds such as Merawu, Tulis, Senggalosang, Preng, Beber, Putih, and Begaluh which are incorporated in the Upstream Serayu Watershed (Figure 1). Administratively, PB Sudirman catchment covers several administrative areas of Central Java

Province such as Wonosobo and Banjarnegara regencies. The overall coordinates of the research location are located at 01°52″ to 07°31′54″ N and 108°50′16″ to 110°04′20″ E (Soewarno & Syariman, 2008). Land use in this watershed is dominated by agricultural land (Susanti *et al*., 2020).

2.2. Data and Material

The research data such as rainfall, climate parameters (air temperature data, wind speed data, humidity data, and sunlight intensity data), and others were obtained from some sources, especially from PT. Indonesia Power, Banjarnegara Branch for the period of 2011-2020. Spatial analysis primarily to determine the catchment area boundary and the total area of study location was performed by using QGIS 3.34.4.

2.3. Data Analysis

2.3.1. Evapotranspiration

Evapotranspiration (ET) is a combination of two different processes, namely the process of converting water on the soil surface into water vapour, plants, and other water sources on the soil surface and the process of transpiration through plant stomata (Pereira, 2015). ET is one of the parameters considered for rainfall-runoff calculation by using the Mock Model. In this study, evapotranspiration was calculated using the modified Penman method (Eq. 1). This method uses some climate data such as air temperature, sunshine duration, wind speed, and relative humidity to estimate the evapotranspiration value.

$$ETo = c[W.Rn + (1 - W)(ea - ed).f(u)] \quad (1)$$

where ET_o is the evapotranspiration potential (mm/day); C is the weather condition adjustment factor due to day and night; W is the weighting factors that influence the temperature and altitude of the place; Rn is the solar radiation (mm/day); f(u) is the wind speed function; ea is the saturated vapour pressure depending on temperature (mbar); ed is the actual vapour pressure (mbar).

2.3.2. Rainfall-Runoff Modelling

The hydrologic tank model of mock (Figure 2) consists of three main parts that express rainfall transformation in the atmosphere, upland, and underground. The model considers six main parameters as the part namely wet infiltration coefficient (WIC), dry infiltration coefficient (DIC), initial soil moisture (ISM), soil moisture capacity (SMC), initial groundwater storage (IGWS), groundwater recession constant (K). The value of model parameter was obtained from the reference value as described in Table 1. The initial value of model parameters was then calibrated and statistically tested to determine the optimum parameter value of the model for predicting monthly discharge.

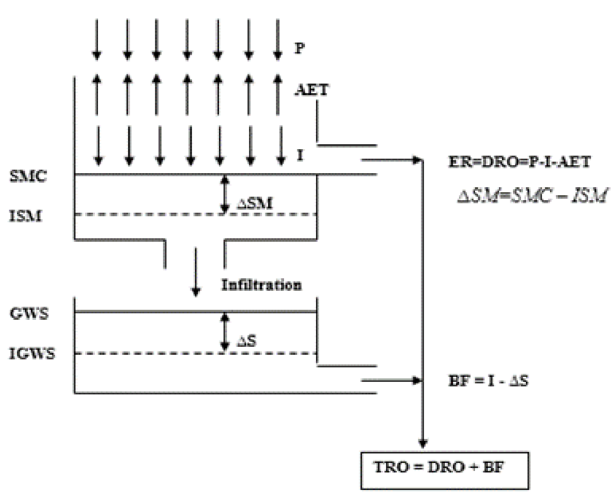

Figure 2. Hydrologic tank model of Mock

Model testing and validation are carried out by calibrating and verifying model output at the River Flow Observation Station (SPAS) located in the Upstream Serayu Watershed of the PB Sudirman Reservoir. The Mock model process was run based on input data and will produce output data based on 6 model parameters, namely: (a) Wet Infiltration Coefficient (WIC) is used to calculate the damp month infiltration coefficient (rain) based on parameters set by BMKG; (b) Dry Infiltration Coefficient (DIC), DIC is used to calculate the dry month infiltration coefficient based on parameters set by BMKG; (c) Initial Soil Moisture (ISM), is the amount of water content in the initial soil per m². Determination of ISM is done by using an options value ranging from 50 - 200 mm; (d) Soil Moisture Capacity (SMC), is the amount of water content in the soil surface layer per m². SMC is calculated by optimising Mock parameters with a value range of 100 - 300 mm; (e) Initial Ground Water Storage (IGWS), is the assumed value of water volume at the beginning of the calculation. The IGWS value is determined by optimising the parameters with a value range of 100 - 2000; and (f) Groundwater Recession Constant (K), is the ratio of the value between the ground flow in the n month to the ground flow at the beginning of the month. In the Mock model, the value of k is obtained from optimising the model parameters with a range of 0 - 1.00.

Next, model validation was performed to determine the level of validity of the resulting output. Model validation is done by comparing the discharge (m³/s) with the discharge in the field. The process of determining validation uses calibration and verification of the model in obtaining optimal parameter values so as to produce model outputs that match the specified criteria. The validation process is one form of effort in determining the level of reliability and accuracy of the model in predicting the output of the model calculation with the output of observations in the field. Determination of the level of reliability and accuracy of the model is done by statistical testing as outlined in the form of a graph. The statistical test criteria used are (Table 1): (a) Coefficient Correlation (R), is a criterion that shows the level of accuracy of the model built. The value of R ranges from 0.0 - 1.00, where the value closer to 1.00 indicates the high correlation of the model with the actual situation (Table 2); (b) Volume of Error (VE), is the difference between the calculated volume and the measured volume. The desired error range in building this model is below 5% (0.05) which indicates high model performance. The Volume of Error (VE) value closer to 0.00 indicates a low level of error in the analysis process and a high level of model accuracy (Table 2); and (c) Coefficient of Efficiency (CE), is a statistical test that shows the efficiency of the calculated discharge with the measured discharge. The desired CE value is >0.75 with a very good category (Table 2).

Table 1. The limit of parameter model value (Data *et al*., 2019)

No	Parameters	Unit	Notation	Limit Values	
				Min	Max
1	Wet Infiltration Coefficient	-	WIC	0.5	1.00 and must ≤ DIC
2	Dry Infiltration Coefficient	-	DIC	0.5	1.00
3	Initial Soil Moisture	mm	ISM	10	100
4	Soil Moisture Capacity	mm	SMC	300	700
5	Initial Groundwater Storage	mm	IGWS	1000	3000
6	Groundwater Recession Constant	-	K	0.5	1.00

2.3.3. Water Conservation Planning

There are three primary sources of water to support the needs of living things, namely (1) groundwater, (2) rainwater (rain, snow, and hail), and (3) surface runoff (rivers, lakes and other surface water sources) (Carrard *et al*., 2020). In the case of the study site, rainwater is one of the water sources that can be utilized in the process of recharging groundwater and surface water. High rainfall coupled with significant land use change in the study area causes the potential for surface runoff to be relatively high. This potential can have a negative impact on the environment if not appropriately managed such as flooding, erosion of the land surface, sedimentation and groundwater recharge that is not optimal. One solution that can be applied to overcome these problems is to conduct water harvesting based on water and soil conservation concepts.

The Kilimanjaro concept is one of the concepts that support sustainable water availability through the formation of local-regional scale networks for rainwater harvesting and storage processes in catchment areas (upland areas) (Qi *et al.,*

Table 2. Model accuracy parameters

Parameter	Range of Value	Criteria	Formula
Coefficient of Correlation (R)	0.7-1.0	High correlation	$R = \sqrt{\frac{\sum_{i=1}^{N}(Qobs - Q)^2 - \sum_{i=1}^{N}(Qobs - Qcal)^2}{\sum_{i=1}^{N}(Qobs - Q)^2}}$
	0.4-0.7	Moderate correlation	
	0.2-0.4	Low correlation	
	0-0.2	Ignored	Q_{obs} = observation discharge (m^3/s) Q_{cal} = calculation discharge (m^3/s) Q = average observation discharge (m^3/s) N = amount of data
Volume of Error (VE)	-5%<VE<5%	High performance	$VE = \left\lvert\frac{\sum_{i=1}^{N} Vcal - \sum_{i=1}^{N} Vobs}{\sum_{i=1}^{N} Vobs}\right\rvert \times 100\%$
	Other than the values above	Low performance	V_{cal} = calculation volume (MCM) V_{obs} = observation volume (MCM)
Coefficient of efficiency (CE)	> 0.75	Very efficient	$CE = 1 - \left[\frac{\sum_{i=1}^{N}(Qobs - Qcal)^2}{\sum_{i=1}^{N}(Qobs - Q)^2}\right]$
	0.36-0.75	Quite efficient	
	< 0.36	Inefficient	

al., 2019). The Kilimanjaro concept is implemented in an effort to achieve two main objectives, namely: (1) long-term environmental conservation (reducing soil erosion) and (2) reducing the impact of potential droughts and floods (increasing water recharge) (Freni & Liuzzo, 2019). This concept can be adapted to rainwater harvesting innovation in the catchment area by creating a network of water recharge ponds.

3. 3. RESULTS AND DISCUSSION

3.1. Hydrological Models

The process of calibration and verification of model variables begins with the optimization of initial parameters. The optimisation results are presented in the form of semi-monthly time series diagrams during 2011-2015 (Figure 3). It shows that the actual water discharge value (Qobservation) is greater than the predicted discharge value (Qprediction) Especially in the wet months (November, December, & January). Meanwhile, adjustments were performed to the parameters of the Mock model to produce optimization results that conform with statistical requirements (Table 2). After conducting statistical tests on the semi-monthly time series graph from 2011 to 2015, the obtained R^2 value of 0.75 indicates that the optimization procedure is performing effectively.

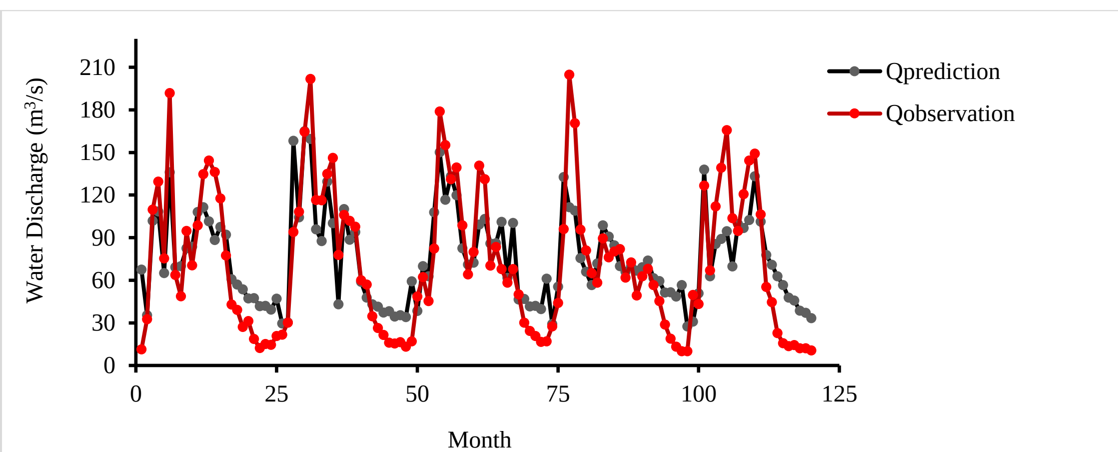

Figure 3. Semi-monthly time series chart Q_{pred} vs. Q_{obs} (2011-2015)

Good watershed conditions will be able to maximize the storage of runoff water into groundwater through the infiltration process during the wet season. Healthy watershed conditions are also able to minimize surface runoff that has an impact on soil erosion and flooding that is harmful to the surrounding environment. This condition is the impetus for modelling surface runoff using the Mock model. In calculations using the Mock model, it is necessary to calibrate the value of each parameter, such as DIC, WIC, ISM, SMC, IGW, and K. The calibration result can be seen in Table 3.

Table 3. Calibration of the Mock Model in Upstream Serayu Watershed

No	Parameters	Unit	Notation	Optimization Results
1	Catchment Area	km^2	A	1010
2	Wet Infiltration Coefficient	-	WIC	0.53
3	Dry Infiltration Coefficient	-	DIC	0.54
4	Initial Soil Moisture	mm	ISM	100
5	Soil Moisture Capacity	mm	SMC	300
6	Initial Groundwater Storage	mm	IGWS	2000
7	Groundwater Recession Constant	-	K	0.96

Source: Data processing

The Mock model in this study showed good calibration and verification results by the specified criteria. The model automation process begins by calibrating and validating the model using measurement data at the PB Sudirman Reservoir from 2011-2020. The model calibration process produces output in the form of discharge data on a semi-monthly average scale in 2011-2015 and for validation used data in 2016-2020. The maximum specific discharge value was found to be 0.11 $m^3s^{-1}km^{-2}$ which indicates that the discharge is in good condition. The minimum specific discharge based on mock modelling was found to be 0.030 $m^3s^{-1}km^{-2}$, classified as moderate. The total discharge was 1.812 m^3/s with an average value of 75.51 m^3/s. The model output calibration results are displayed in graphical form as shown in Figure 4.

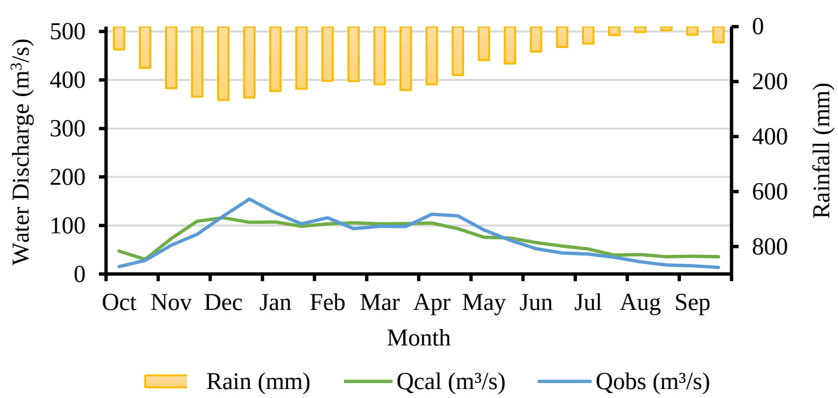

Figure 4. The calibration results of the model

The average water discharge (Q) on a semi-monthly scale (Figure 4) shows that the actual discharge value (Q_{obs}) has a high fluctuation compared to the predicted discharge (Q_{cal}), especially in the wet season. This condition is caused by the high level of rainfall in the catchment area of PB Sudirman Reservoir in the wet season. Mock modelling used in the Upstream Serayu Watershed requires repeated optimization to produce predicted values close to actual conditions. The modelling process resulted in a coefficient of correlation (R) of 0.93, volume of error (VE) of 0.04, and coefficient of efficiency (CE) of 1.00 on a semi-monthly scale which indicates the runoff modelling process has run with good accuracy based on the criteria (Table 2). Meanwhile, based on hydrological modelling, the maximum specific discharge value is about 0.11 $m^3s^{-1}km^{-2}$, which indicates a good discharge value, and the minimum specific discharge is about 0.030 $m^3s^{-1}km^{-2}$, indicating a moderate discharge value. Figure 5 displays the time series graph comparing Q prediction and Q observation on a semi-monthly basis.

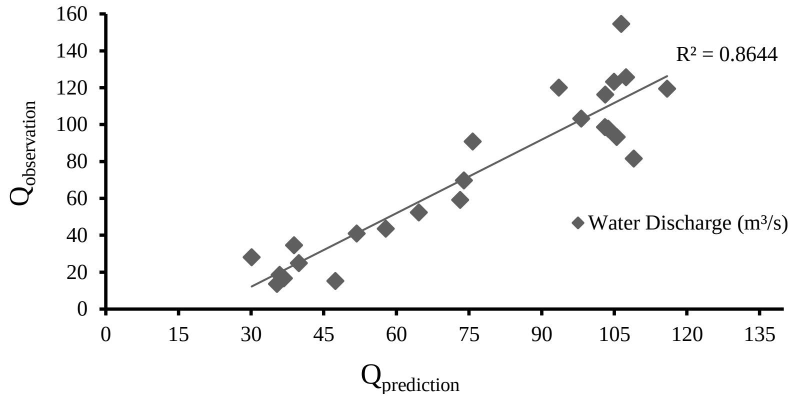

Figure 5. Semi-monthly calibration correlation Q predicted vs Q observed (2011-2015)

3.2. Rainfall-Runoff

The availability of water in the soil is influenced by several factors, one of which is land use on the land surface (da Costa *et al.*, 2019). Significant land use change can affect the water regime and groundwater quality (Junior, *et al.*, 2014). The study of surface and groundwater relationships can provide information that can support the sustainable use and management of water resources (Kalbus *et al.*, 2006). The relationship between surface water and groundwater is related to the hydrological processes that distribute water to the land surface as surface water and partially absorbed into groundwater through the water recharge zone. The groundwater recharge zone is an area of the land surface that allows infiltration and percolation into the soil (Zaidi *et al.*, 2015). Optimization of groundwater recharge is done by utilizing surface runoff that enters the ground through the infiltration process during the wet season. In addition to maximizing groundwater recharge, this process can also minimize excess runoff resulting in flooding, soil erosion, and sedimentation in downstream areas. This condition can be achieved if the watershed is in good condition and the hydrological cycle of the watershed is running correctly.

The rainfall-runoff modelling analysis in the study showed high runoff values during the wet season. Based on the analysis, it is known that the total surface runoff at the research site (Upper Serayu Watershed) in the wet season is 1.098 mm or about 1.109.062.636 m³ (Figure 6). The high potential of surface runoff in the study area is due to wet climate characteristics and significant land use change.

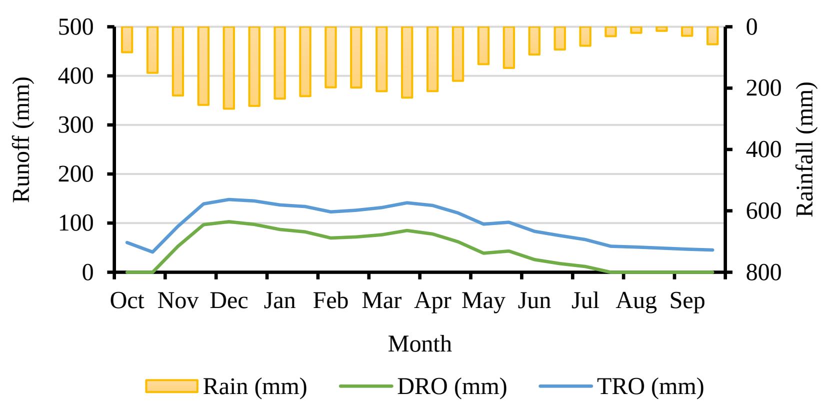

Figure 6. Runoff and rainfall relationships at the study site

This research uses a comparison of DRO, TRO, and rainfall to determine water availability. Direct Runoff (DRO) is the accumulation of rainwater that flows over the surface. Meanwhile, Total Runoff (TRO) is the accumulation of surface water and subsurface water discharge. Runoff and rainfall values (Figure 6) show a significant relationship. Rainfall at the study site in the wet season, which reaches 2.533 mm out of the total rainfall of the study area of 3.552 mm, influences the recharge of river water (TRO). During the dry season, the water discharge comes from the base flow accumulated from the groundwater system. Groundwater recharge is very important to maintain the availability of river water, especially in the dry season (Oktavia *et al*., 2022). High runoff potential can be seen in the wet season, which decreases in the dry season.

3.3. Water Conservation Planning

Based on previous research (Khoirotunnisa *et al*., 2023), which said that the design of water harvesting technology needs to pay attention to social and economic aspects in the research location, the design of small-scale dams (water recharge ponds) with the adaptation of the Kilimanjaro concept is expected to be applied by the surrounding community optimally. Water recharge ponds (WRP) are one of the innovations in rainwater harvesting technology in the form of a network of small-scale dams at the local level. The WRP concept can be applied in 2 schemes, namely surface water storage and subsurface water storage. Both schemes are suitable for areas with relatively high surface runoff, but from both schemes, the surface water storage will be adapted in the Upstream Serayu Watershed area (Figure 7 & Figure 8). The surface water storage scheme (Figure 7) uses a series system with the aim of minimizing surface runoff loss in the catchment area. This design is adapted based on the characteristics of the Upstream Serayu Watershed, which has a relatively high slope with a dominant slope of 8-15 (Christanto *et al*., 2018). Water Recharge Ponds (WRP) is one of the innovations in water harvesting technology in the form of a small-scale square dam with a

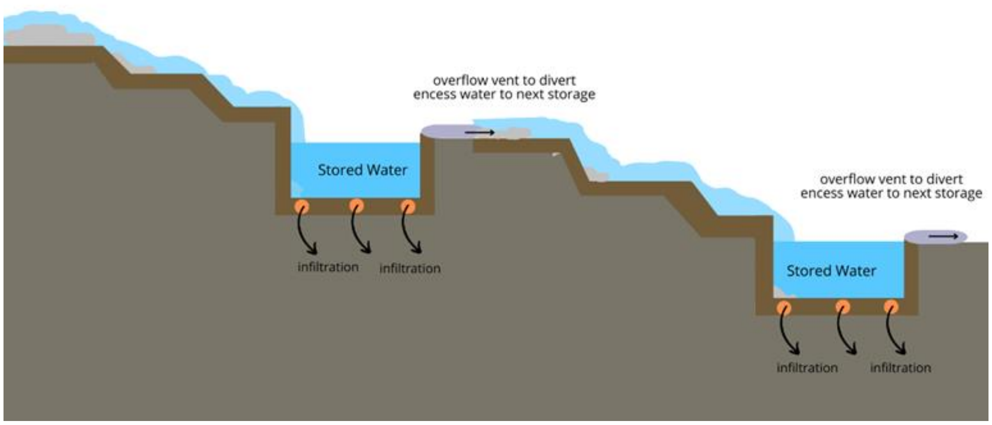

Figure 7. Schematic of surface water recharge ponds

Figure 8. Example of application of WRP in Indonesia

length of 3 meters, a width of 2.5 meters, and a depth of 1.5 meters. The determination of these dimensions considers the ability of the socio-economic aspects of the community and the technical aspects of the application of water harvesting. This WRP will accommodate the surface runoff of the Upstream Serayu Watershed and maximize groundwater recharge through infiltration of the WRP base. The dimensions of this WRP building are predicted to be able to accommodate surface runoff of around 11.25 m³ and be able to pass water into the soil through infiltration averaging 1 m³/day - 5 m³/day depending on the condition of the conservation building (Jódar-Abellán *et al.*, 2017). Technical design studies related to this conservation building need to be carried out further to ensure the effectiveness of the dimensional influence on the water discharge that can be accommodated or absorbed into the soil.

The water harvesting structures can help collect surface runoff and help facilitate the groundwater recharge process in the aquifer zone. The potential surface runoff in the wet season is 1.098 mm or 1.109.062.636 m³ with a catchment area of 739.38 km^2 in the study site. Such a large catchment area and runoff potential requires adequate water conservation structures (Figures 7 & 8) to achieve optimal results of rainwater harvesting. Based on the capacity of WRP (11.25 m^3), approximately 98.583.345 WRPs are needed to accommodate all of the surface runoff in the study area. The number of WRPs is equivalent to 73.21% of the study area. This concept can be combined with a vegetation-based conservation model to optimize the absorption of surface runoff into the soil.

3.4. Economic Analysis of the Water Recharge Ponds

The application of conservation methods needs to pay attention to several factors, one of which is the economic factor. Conservation buildings must have financial benefits. In this study, there are 2 economic analyses used in determining the economic feasibility of WRP, namely the Benefit and Cost (B/C) ratio and Net Present Value (NPV) (Table 4). The values from B/C ratio and NVP must exceed 1 and 0 respectively, to indicate that the WRP is economically profitable.

Table 4. Economic analyses of WRP construction

Component	Benefit (IDR)	Cost (IDR)	B/C Ratio	NPV (IDR)
Construction cost	-	1.687.500		
Groundwater Increasing	6.225.307	-		
Land Productivity Increasing	616.869	-	4.40	5.729.196
Soil Erosion Reduction	564.519	-		
Total	7.416.696	1.687.500		

The construction cost of the conservation building design was adjusted to the standard cost of constructing similar buildings at the study site, which is around IDR 150.000 per m³. Groundwater enhancement was determined based on total direct runoff (DRO) data at the study site through the calculation of base flow coefficient (BF infiltration ratio). BF infiltration ratio is a representation of the ratio between base flow during the dry season (April-September) and total rainfall during the wet season (October-March). Based on the calculation, the BF infiltration value is 0.76. This BF infiltration value is multiplied by the total DRO value during the wet season with a value of 1.098 mm or about 122.01 mm/month. The BF infiltration value and total DRO are then used in determining the amount of water collected in the WRP and become the base flow. WRP with large 3×2.5 meters can increase the base flow by 6.235 liters. The increasing base flow value was multiplied by the latest water price in the study area, namely in Central Java Province (IDR 1.000 per litter), resulting in a water-saving value of IDR 6.235.307.

The increased value of land productivity is estimated by using crops that have high potential during the dry season such as garlic. The productivity of garlic reaches 8.2 tonnes/ha (Septiana *et al*., 2022) with a gross water requirement of around 6.580 m³/ha during the growing season (Ayele *et al*., 2023). Based on calculations that have been carried out, a WRP can provide water for an area of 0.0017 ha and can produce around 14 kg of garlic. With a selling value of around IDR 44.000 per kilogram in January 2024, and with the ability of WRP to provide water to produce 14 kg of garlic, it can be seen that the economic value obtained is around IDR 616.869.

The results of the economic loss analysis due to soil erosion were estimated based on the total area that can be protected by the WRP. The area that can be protected from soil erosion due to surface runoff is calculated using average surface runoff data per month with a value of 122.01 mm and the capacity of the WRP (11.25 m³) with estimated results of about 0.087 ha during the wet season. Based on research by Sutrisno (2013), shows that the economic loss due to soil erosion is IDR 3.300.000 per ha per year. The value of economic savings from soil erosion using WRP is around IDR 564.519 during the wet season. The application of the WRP concept must pay attention to the topography of the region to optimize economic benefits.

The calculation of benefit and cost values in Table 4 shows the Benefit and Cost ratio (B/C ratio) and Net Present Value (NPV) of the WRP conservation building. Based on the calculation results, the B/C ratio value is around 4.40 and the NPV value is around IDR 5.729.196. This value indicates that the construction of the WRP can be economically profitable (Singh & Nandi, 2020).

4. CONCLUSIONS

The potential surface runoff at the study site reaches 1,139 mm or approximately 1.109.062.636 m^3 during the wet season. This potential surface runoff can be utilized as a water source to meet water needs during the dry season through the design of water recharge ponds (WRP) conservation buildings with surface storage schemes. Each WRP can accommodate approximately 11.25 m^3 of surface runoff at the study site. Construction of WRP with a capacity of 11.25 m^3, requires approximately 73.21% of the total area study (1.010 km^2) to accommodate total surface runoff. Based on economic analysis, the construction of WRP showed economically profitable with the value of a B/C ratio of around 4.40, and the Net Present Value (NVP) of around 5.729.196 indicates the WRP can be economically profitable.

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