Assessment of Surface Runoff Potency under Tropical Environment for Soil and Water Conservation Planning

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Abstract. Water is essential for living organisms, including crops. Its presence is a crucial factor for agriculture. Soil and water conservation is an effort to sustainably maintain the availability of water, thereby meeting the water needs of crops in the agricultural sector. This research aims to estimate the potency of surface runoff as a hydrological indicator of watershed critically for soil and water conservation purposes. A hydrological tank model was used to estimate surface runoff. The results showed a potential for surface runoff of approximately 133.82 mm/month, occurring primarily during the peak rainy season from December to April. Soil and water conservation (SWC) technology using water harvesting ponds (WHP) on farmland was proposed to store surface runoff. Data analysis indicates that the use of WHP provides significant benefits from environmental and economic aspects. Based on an average WHP storage capacity of 10 m^3, approximately 40% of the total watershed area is required for constructing water harvesting structures to accommodate all surface runoff. Harvesting all surface runoffs increases the base flow during the dry season by 225.14 mm. This study serves as a valuable reference for soil and water conservation planning, particularly in tropical watersheds.

1 Introduction

Water is an important factor for crops. Hence, water availability has become a crucial thing for food security [1]. As a tropical country, Indonesia has a reliable potency for water resources. However, the monthly water availability varies climatically every year. A good management of water resources is required to ensure water availability at all times. The primary source of water comes from rainfall that occurs during the wet season. Meanwhile, the water requirements remain consistent year-round, including during the dry season, so water reserves are needed to meet these needs.

Optimizing rainwater harvesting is crucial to ensure secure water availability. To optimize rain harvesting during the wet season, soil and water conservation technology should be applied to store water in the soil, groundwater systems, or on the earth's surface, including reservoirs in the rivers and water storage structures on farmland [2]. The natural water storage system in the soil, in the form of soil moisture and groundwater, can store significant amounts of water and channeling it as base flow during the dry season. The natural water storage function is suboptimal due to damage to the watershed. Many human activities, such as agriculture, mining, and others, can cause damage to watersheds when conservation principles are not implemented.

Landscape changes, particularly in the form of reduced vegetation and increased impervious surfaces, which occur in many watersheds in Indonesia [3], lead to decrease groundwater storage due to the disruption of the infiltration process. This condition increases surface runoff or overland flow and increases the potential for soil erosion and sedimentation in the rivers. Sediment deposition downstream leads to the shallowing of reservoirs and irrigation canals. The use of artificial soil and water conservation technology provides a solution for optimizing rainwater harvesting.

Soil and water conservation technology for rainwater harvesting is developed based on the potential water availability. The calculation of rainfall-runoff transformation is essential for estimating the potential for surface runoff harvesting. In this study, the potency of surface runoff harvesting was estimated as the basis for soil and water conservation development, especially through the construction of WHP on farmland. This engineering conservation building is cost-effective, environmentally friendly, easy to construct, and well-recognized by the community in the study area. From both social and economic perspectives, it meets the requirements.

Surface runoff is the focus of study in this study because it is one of the triggers for problems on land (soil erosion) and downstream areas (sediment deposit and flood). Surface runoff harvesting will reduce the potential for land damage, sedimentation and flooding and increase infiltration, soil moisture and groundwater reserves.

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2 Method

2.1. Study Area

This study was performed in Kalirukem Watershed which occupies about 24 km^2 area (Figure 1). Administratively, the watershed is located in Wonosobo Regency, Central Java Province of Indonesia and a part of the Wadalintang Reservoir catchment area. Climatology Station of Wadaslintang near the study area recorded an average annual rainfall of 3680 mm from 2011-2020, while the average humidity and temperature were about 82% and 26^{0}C respectively [4].

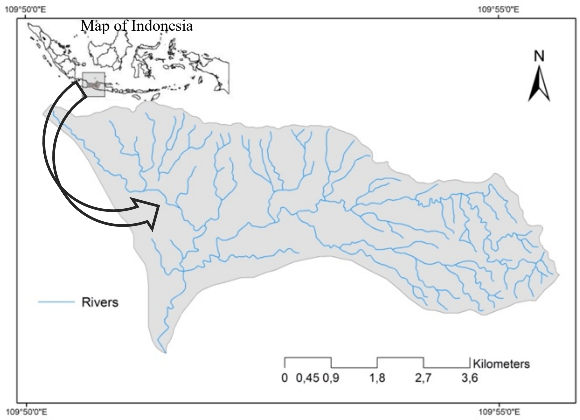
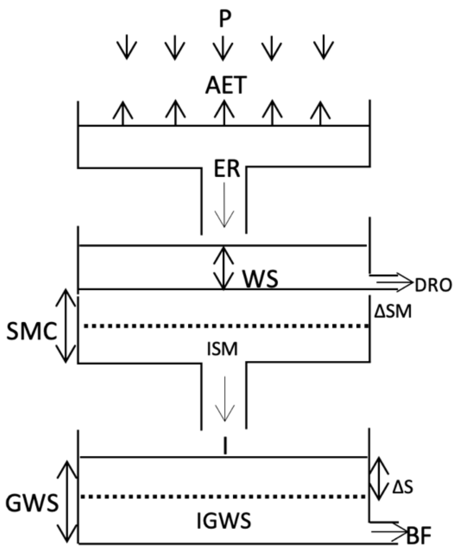


Fig. 1. Map of the study area

The watershed is covered by latosolic red-yellow soil, with an average land slope greater than 15%, and is predominantly dominated by farmland [5].

2.2. Hydrological Model

The tank hydrological model was used to identify the process of rainfall flow transformation and estimate surface runoff values. This model consists of three main components that describe the hydrological cycle in the atmosphere, land surface, and groundwater as shown in Figure 2 [6,7].



ER	=	P-AET	IGWS	=	GWS_{I-1}
WS	=	ER-ΔSM	DRO	=	WS-I
ΔSM	=	SMC-ISM	BF	=	I-ΔS
ISM	=	SM_{I-1}	ΔS	=	GWS – IGWS
I	=	Ci x WS	Q_{TOT}	=	DRO + BF
GWS	=	0.5 (1+K) I + K x IGWS			

P	=	precipitation	I	=	infiltration
AET	=	actual evapotranspiration	WS	=	water surplus
ER	=	excess rainfall	BF	=	base flow
DRO	=	direct runoff	Ci	=	infiltration coeficient
ΔSM	=	change of soil moisture	SMC	=	soil moisture capacity
ISM	=	initial soil moisture	K	=	recession constant
ΔS	=	change of ground water volume	Q_{TOT}	=	total discharge
GWS	=	ground water storage			
IGWS	=	initial ground water storage			

Fig. 2. Structure of hydrological model of Mock

This model has been validated through calibration and verification using observed discharge data from the Wadaslintang River in 1999-2001, downstream of the Kalirukem Watershed. Observed river discharge data was calculated using the calibration curve, which establishes the relationship between reservoir water level downstream of the watershed and water discharge. It's important to note that discharge data after 2001 is not recommended for model validation due to reservoir shallowing, which compromises the validity of the calibration curve. The result of the hydrological model calibration is presented in Table 1.

Table 1. Optimization result of model calibration

Parameter	Symbol	Unit	Value
1. Area of watershed	A	km^2	192.53
2. Wet Infiltr. Coeff.	WIC	-	0.50
3. Dry Infiltr. Coeff.	DIC	-	0.65
4. Initial soil moisture	ISM	(mm)	100
5. Soil moisture capacity	SMC	(mm)	400
6. Initial groundwater storage	IGWS	(mm)	1000
7. Groundwater reces.constant	K	-	0.85

The model calibration showed a correlation coefficient of 0.91, an error volume of 0.01, and an efficiency coefficient of 0.93 (see. Figure 3), indicating high accuracy of the model for runoff calculation [7,8].

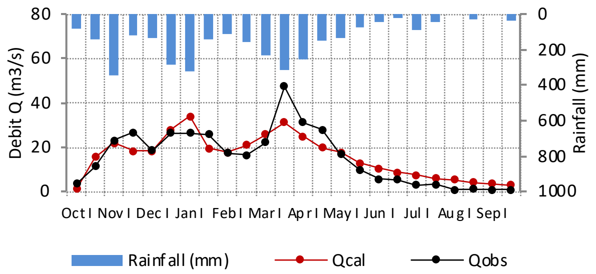


Fig. 3. The result of model calibration

The optimized model parameter values (Table 1) obtained through calibration were then used to calculate the value of direct runoff (DRO) or surface runoff, based flow (BF) and total runoff (TRO) using rainfall and climate data from 2011 to 2020.

The surface runoff value was obtained from the results of direct runoff (DRO) calculations, which is the difference between rainfall and excess rainfall (ER). TRO is the sum of DRO and BF. DRO only occurs during the rainy season with high monthly rainfall, so that during the dry season, river water discharge (TRO) only comes from BF [9]. The formula for calculating DRO, BF, and TRO are presented in Figure 2.

3 Result and Discussions

3.1. Rainfall-Runoff

The rain-runoff transformation reflects the distribution process of rainwater, transforming into evaporation, runoff (including surface runoff, interflow, and river discharge), and infiltration into the soil, ultimately becoming groundwater (base flow).

A watershed in good condition will be able to optimize groundwater recharge through infiltration during the rainy (wet) season and minimize surface runoff which causes soil erosion upstream, flooding and sedimentation downstream. Changes in the watershed landscape, especially the reduction in vegetation, have disrupted the hydrological function of the watersheds. An increase in surface runoff indicates disruption of the hydrological function of the watershed.

The rainfall-runoff modelling in this study shows a significant amount of surface runoff that occurs during the wet season as shown in Figure 4. Total surface runoff reached 802.95 mm or equal to 19,270,722.2 m³ at the study area (Kalirukem Watershed). The potency for surface runoff is high because the study area is located under a tropical climate region. Low vegetation cover and high farmland cover increase the potency of surface runoff [10].

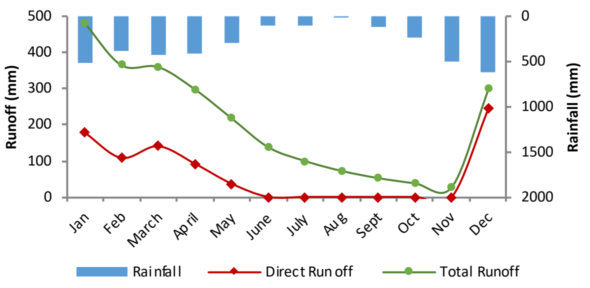


Fig. 4. Rainfall-Runoff Correlation in Study Area

The average annual rainfall of 3680 mm can sustain a consistent river water discharge throughout both the wet and dry seasons. The availability of river water discharge (TRO) follows the monthly rainfall patterns, with river water discharge tending to be high during the rainy season [11]. During the dry season, the water in the river comes from base flow which originates from the groundwater storage system. Groundwater recharge is very important to ensure the availability of river water discharge (based flow), especially during the dry season [9]. Soil and water conservation must be focused on efforts to optimize rain harvesting so that groundwater can be fully replenished.

This study also calculates the surface runoff coefficient (Cs), which represents the ratio between surface runoff or direct runoff (DRO) and rainfall (P) in monthly units. The value of Cs between 0-0.1 indicates good watershed conditions with low potential for surface runoff [12]. In this study, the Cs value during the wet season at the study location ranged from 0.12 to 0.39, with an average value of 0.28. The highest C value occurs in the month with the highest rainfall (P) reaching 625.0 mm/month as shown in Table 2. The surface runoff coefficient (Cs) value is smaller than the total runoff coefficient (C) which can reach 0.50-0.70, due to the additional base flow [13].

Table 2. Surface runoff coefficient (Cs) in the study area

Month	P (mm)	DRO (mm)	TRO (mm)	BF (mm)	Cs
Jan	510.9	178.9	483.2	304.3	0.35
Feb	378.6	108.3	365.9	257.6	0.29
March	424.1	140.6	360.8	220.2	0.33
April	417.3	92.4	298.9	206.5	0.22
May	295.1	36.7	218.5	181.8	0.12
June	108.0	0.0	138.0	138.0	-
July	102.9	0.0	99.7	99.7	-
Aug	12.3	0.0	72.0	72.0	-
Sept	119.7	0.0	52.0	52.0	-
Oct	230.9	0.0	37.6	37.6	-
Nov	505.5	0.0	27.2	27.2	-
Dec	625.0	246.0	299.6	53.6	0.39

The average value of Cs indicates that around 28% of rainfall that occurred in the study area is transformed into surface runoff. This value reveals a potential problem in the watershed [14]. Surface runoff usually occurs shortly after rain therefore, it is also called direct runoff (DRO). Generally, the DRO value shows a linear correlation with the rainfall value. However, the Cs value, representing the ratio of DRO to P, varies and does not always have a similar value. It indicates the influence of other factors in the rainfall-flow transformation, particularly related to environmental characteristics [15]. Table 2 also shows the value of base flow, which constitutes the primary water source in rivers during the dry season. Base flow comes from rainfall in previous months.

3.2. SWC Development

The potential for surface runoff in the study area is quite high. If not controlled, surface runoff can result in soil erosion, sedimentation, and floods. This condition also inhibits groundwater recharge, and triggers drought during the dry season. Appropriate strategies are needed to control surface runoff. Harvesting surface runoff by using soil and water conservation (SWC) technology is the most appropriate way to overcome this problem.

The technical, social, and economic aspects need to be considered in selecting the appropriate surface runoff harvesting technology, as most of the study area is dominated by farmland where local community activity in farmland is high. These three factors are important to ensure the sustainability of conservation based on community participation.

Water harvesting ponds (WHP) on agricultural land are the most suitable technology. This conservation structures collect surface runoff from farmland and optimize infiltration for groundwater recharge [16]. Additionally, these structures can be constructed permanently, allowing them to store water for irrigation or other uses during the dry season. This structure is a square, rectangular, or circular-shaped pool which is easy to construct at a low cost. From a social perspective, this structure is well-known among people in Indonesia and has been implemented in many dry farming areas [17].

WHP is relatively easy to maintain with small to medium scale. In this study, a WHP with dimensions of 2.5 meters in length, 2 meters in width, and 2 meters in depth is used to calculate surface runoff capture potential. This dimension of WHP allows it to hold 10 m^3 of water or surface runoff. This dimension is the most found in the study area. Figure 5 shows a typical example of a WHP commonly found around the study area.

Fig. 5. Example of a WHP applied in the farmland of Indonesia

Considering the potential surface runoff in the research area, which reaches 802.95 mm or 19,270,722.2 m^3, while the average Water Harvesting Pond (WHP) storage capacity is around 10 m^3, approximately 1.9 million WHPs are needed to accommodate all the runoff. This number of WHPs is equivalent to 40% of the study area required to accommodate all surface runoff. Another alternative type of structure that can be used is a long water storage system. Combining engineering and vegetative SWC methods (such as re-greening barren areas, contour strip cropping, and crop residue application), maximizes efforts to control surface runoff [2].

3.3. Economic Engineering Value of SWC

In addition to its environmental benefits, the SWC program must also be economically profitable. In this study, two simple economic analyses i.e. the Benefit-Cost (B/C) ratio and Net Present Value were carried out to assess the economic feasibility of a WHP construction (Table 3). The B/C ratio and NPV values must be more than 1 and 0 respectively, to indicate that the WHP is economically feasible to construct.

Table 3. Economic benefit and cost of a WHP construction

Component	Benefit	Cost
Construction Cost	-	1.500.000
Ground Water Increasing	1.690.000	-
Land Prod. Increasing	750.000	-
Soil Erosion Red.	900.000	-
Total	3.340.000	1.500.000

The calculation of revenue and costs in Table 3 shows that the B/C ratio and NPV value were 2.23 and IDR 1,840,000 respectively. These values indicate that WHP construction is economically profitable as reported by Singh in 2015 [18].

Construction costs are assumed to be approximately IDR 150,000 per m^3, following the applicable standard prices in the study area. This cost may be lower if the WHP construction is undertaken independently by the community, without labor assistance. The increase of groundwater was estimated based on the total surface runoff (direct runoff) that occurs in the study area as provided in Table 2 (802.95 mm), which is then multiplied by the base flow coefficient (Bc). Bc represents the ratio between baseflow during the dry season (April- September) and the total rainfall during the wet season (October- March).

The Bc value in this study was obtained at 0.28. This value was then multiplied by the total surface runoff that occurred during the six months of the wet season, with a total value of 802.95 mm (equal to 133.83 mm/month). By using the Bc value and the total surface runoff, we estimated the amount of runoff that was collected and became base flow. For one WHP with a dimension of 2 x 2.5 meters, the increase in base flow was calculated to be 1,125.68 liter, which was then multiplied by the current price of clean water, (approximately IDR 1,500 per liter in the study area, Central Java Province), resulting in a savings value of IDR 1,690,000.

The increase in land productivity was estimated for dry season farming in shallot crops. This plant has a high economic value and is widely planted during the dry season. The productivity of shallot planting land reaches 10 tons/ha, with water requirements around 400 ml (equal to 4000 m^3/ha) for a planting season [19]. Hence, a WHP can provide water for 0.0025 ha of farmland and produces around 25 kg of shallots. The selling price reaches IDR 30,000 per kilogram in 2021-2023 so that a WHP can provide water to produce around 25 kg of shallots with an economic value of approximately IDR 750,000.

Meanwhile, the economic value of soil erosion reduction was estimated based on the total protected area by a WHP. Based on an average surface runoff value of 133.82 mm per month, one WHP (with a capacity of 10 m^3) can protect about 74.72 m^2 (equal to 0.007472 ha) area from the risk of soil erosion caused by surface runoff. A study by Sutrisno et.al. (2012) [20] noted that economic loss due to soil erosion (loss of soil and nutrients) was about IDR 3,300,000 per ha per year.

Hence, the estimated economic saving value of soil erosion due to a WHP construction was about IDR 150,000 per month or equal to IDR 900,000 during the wet season (six months) when surface runoff is occurred.

The construction of a WHP must adhere to conservation principles to maximize economic benefits. Several important aspects that need to be considered in WHP construction include the topography of the area and the presence of water catchment areas in each location where the WHP is constructed.

4 Conclusions

Surface runoff in the study area occurred during the peak of the wet season, especially when monthly rainfall was high, typically from December to May, with an average value reaching 133.82 mm/month. Based on the potential value of surface runoff, soil and water conservation technologies using engineering methods with the construction of water harvesting ponds (WHP) on farmland offer a viable way to reduce surface runoff and increase groundwater recharge. Engineering economic analysis showed that WHP construction is economically profitable. By using WHPs with a capacity of 10 m^3 (large is 5 m^2) for one structure, approximately 40% of the total area was required to accommodate all surface runoff.

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