Thornthwaite-Mather water balance analysis in Tambakbayan watershed, Yogyakarta, Indonesia

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Abstract. Depok sub-district in Yogyakarta is one of the most populous areas, which also develops rapidly. The Tambakbayan watershed, which includes Depok sub-district, has been seen as one crucial watershed in Yogyakarta. This study conducted a Thornthwaite-Mather water balance analysis in the watershed in order to understand its hydrology capability. The result of the study on three stream areas of the watershed (upstream, midstream and downstream) shows that the dry months begins in May-June and ends in September-October. August tends to be the driest month in the year with total deficit value reaches 179.2 mm. Still, the annual rainfall is higher than the annual evapotranspiration. The results also show that the lower area of the watershed has a lower capability to preserve water. However, the watershed still sufficient in providing the domestic water demand in the current state. Comprehensive water management plans suggested to be applied to protect the watershed from overstressing the water resources, especially in the downstream area.

Keywords**:** Thornthwaite-Mather, water balance, watershed, Yogyakarta

1 Introduction

Daerah Istimewa Yogyakarta (Yogyakarta Special Region, DIY) is one of Indonesia rapidly growing provinces. The province capital, Yogyakarta City, has been full of building and there is a little room left for building new housing settlements. Therefore, housing development currently is emerging in the city outskirt. One of the significant outskirt areas in northern DIY is Depok, a sub-district of Sleman Regency. Depok hosts many universities including three major ones. Yogyakarta is indeed nationally well-known as “the city of student” for its high quality and quantity of universities. Depok sub-district and areas north of it are currently seen as some prospective areas to build new housing settlement and small home industries.

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The DIY Province area has two main watersheds and rivers, Opak River in the east after Yogyakarta City and Progo River in the west after Yogyakarta City. Tambakbayan river is one of Opak River's tributary rivers; thus it is a sub-watershed of Opak River. The Tambakbayan watershed is one crucial watershed because it is located in one of the most populous areas in DIY, which is Depok sub-district along with several sub-districts around it. With the great prospect of being rapidly developed, the water balance of Tambakbayan watershed needs to be studied before its water resources can be developed.

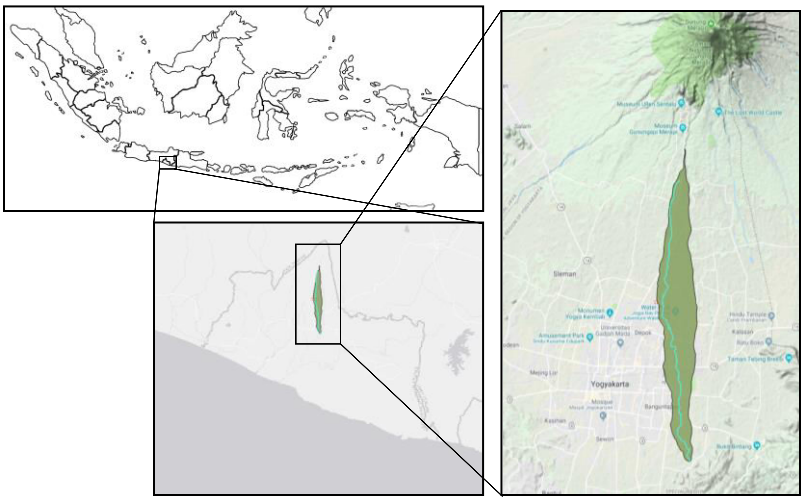

Fig. 1. Location of Tambakbayan Watershed in Yogyakarta, Indonesia.

Water balance can be defined as how much water is preserved in a water catchment area by considering how much water flows in and out of the watershed. Thornthwaite and Mather proposed a method that has become one of the most widely used methods to compute the balance nowadays [1, 2]. Eagleson [3] describes water balance as a quantitative relation among long-term averages of the partition of precipitation and evapotranspiration, which are the most critical parameters. Those parameters are typically computed as average values from a time-series data set.

This study provides a water budget balance for the area of study. Radhika *et al.* [4] stated that Java Island (which Yogyakarta in it) in 2010 had 2,079 m^3/s water demand and 5,005 m^3/s water availability. From their study, it is also known that the Java Island was the only island in Indonesia with "stress conditions" based on scarcity indicator of Falkenmark [5]. According to Widodo *et al.* [6], the water carrying capacity in the Yogyakarta urban area is on a worrying condition in 2013. Hence, for sustainably managing the water resource in Java Island and Yogyakarta area, it is important to identify sound management strategies. This includes updating the condition of water resources in Yogyakarta annually. This study contributes to that task.

2 Methods

This study aimed to investigate the water budget condition in the Tambakbayan watershed, sub-watershed of Opak Watershed, Yogyakarta. A water balance analysis of this study was conducted by using the Thornthwaite-Mather method. This method has been widely used to analyze water balances because it is easy to use and parameters are readily available. It suits the limitation of data parameter of the study area that could be obtained.

2.1 Study Area

The Tambakbayan watershed covers 47.67 km^2 area, and there are six rain gauges in the immediate area surrounding the watershed (Fig. 2). Based upon the investigation of Tambakbayan river streamflow data, there are three monitoring points represent the upstream area, midstream area and downstream area of the watershed. The watershed area shapefile was obtained from Balai Besar Wilayah Sungai Serayu Opak (Central River Region Serayu Opak). In order to compare the water budget and the streamflow discharge among the three areas, the shapefile of the watershed area then was cropped into three parts, representing upper stream (22.1 km^2), middle stream (14 km^2) and lower stream (11.5 km^2) area (Fig. 2).

The upper stream area was linked to precipitation data from three rain gauges (Prumpung, Kemput and Bronggang station in Sleman District), the middle stream area linked to precipitation data from two rain gauges (Santan and Gemawang station in Sleman District) and the lower stream area linked to precipitation data from one rain gauge (Karang Ploso station in Bantul District).

Temperature data was not from the same station with the rain gauges. There are only three stations available that represent temperature data in the three regions, Plunyon, Geofisika Yogyakarta and Barongan station. Due to distance and elevation of the stations with the watershed regions, the representation of data divided as follows. Upstream region temperature data represented by Plunyon station's data. Midstream region temperature data represented by averaging Plunyon station's data and Geofisika Yogyakarta station's data. Last, downstream region temperature data represented by averaging Geofisika Yogyakarta's data and Barongan station's data.

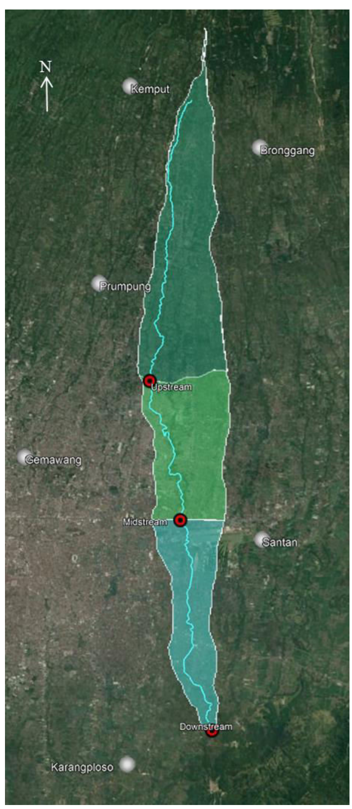

Fig. 2. Watershed cropping and location of rain gauges (grey circles) and stream gauges (red circles).

2.2 Thornthwaite-Mather Water Balance

Thornthwaite-Mather water balance equation uses the soil moisture capacity to estimate water budgets. The parameters needed for using this method include:
1. difference between precipitation and potential evapotranspiration (*P-PE*)
2. accumulated potential water loss (*APWL*)
3. available water capacity (*AWC*)
4. difference between soil moisture storage (ΔST) between month_i and month_{i+1}.
5. actual evapotranspiration (*AE*)
6. deficit and surplus of the water budget
7. runoff estimation

Precipitation (P)
Precipitation data on a monthly basis is required. Missing rainfall data can be estimated first by the arithmetic method or the normal ratio method. If a study area has many rain gauge stations, the mean areal precipitation value shall be determined first. Mean areal precipitation in this study determined by averaging the rainfall data from every region representative rain gauge.

Potential Evapotranspiration (PE)
Potential evapotranspiration means the atmosphere potential that can take out water from the land surface. In the Thornthwaite method, the potential evapotranspiration (*PE*) is computed according to [7]:

1. Calculate the annual value of the heat index (I) based on the monthly heat index (i) and summing all the twelve-month heat indices.
$$i = (T_a/5)^{1.51} \tag{1}$$
$$I = i_1 + i_2 + \dots + i_{12} \tag{2}$$
T_a is the mean monthly temperature.
2. With $a = 67.5\times10^{-8}I^3 - 77.1\times10^{-6}I^2 + 0.0179I + 0.492$, calculate the unadjusted *PE'* (mm) using the following equation (3).
$$PE' = 16(10.\ T_a/I)^{a} \tag{3}$$
3. Adjusting the unadjusted *PE'* by using the average monthly daylight duration (in hour) which is a function of season and latitude. If the daylight duration data is known, the following equation can be used to calculate the adjusted *PE*. Note that *N* is the number of days in a month and *d* is daylight duration (in hour).
$$PE = PE'\ (d/12)\ (N/30) \tag{4}$$

P-PE
The difference value of potential evapotranspiration and precipitation (*P-PE*) is negative when there is a potential water deficit, while positive *P-PE* value represents a potential water surplus. If the *P-PE* value is less than zero, the month called as "dry month" and it is subjected to APWL value. While the *P-PE* value is more than zero, the month called as "wet month" and it is subjected to surplus value.

Accumulated Potential Water Loss (APWL)
The accumulated potential water loss is calculated as the cumulative sum of *P-PE* values during months when *P-PE* is negative. Accumulated potential water loss increases during dry seasons. It is reduced during wet seasons because of soil moisture recharge. The value would be zero when soil moisture equals the soil's available water holding capacity [8].

Available Water Capacity (AWC)

Thornthwaite and Mather have suggested the determination method of *AWC* values by considering land use, soil texture types and rooting depth by providing a water holding capacity (WHC) table [2]. In this study, the *AWC* typical value of each land use assumed to be 150 mm/m, same with the WHC table. The land use types in this study were divided based on the vegetation cover division as in the table: shallow-rooted, moderately rooted, deep-rooted, orchards, and mature forest. The land use areas of each stream region determined by Google Earth and QGIS help. Area of settlement land use is also added assuming that settlements have a small area of vegetation. The rooting depth values for each land use type were following the values in the WHC table, except for the settlements land use. The rooting depth value of settlements land use is assumed 0.1 m, lower than shallow-rooted land use. The *AWC* value was then calculated for upstream, midstream and downstream areas by multiplying the *AWC* typical value with rooting depth and percentage area of land use as shown in Table 1.

Table 1. Available Water Capacity Estimated

Vegetation	% Area	AWC[2] (mm/m)	Rooting Depth[2] (m)	AWC (mm)
Upstream				
Settlements	40.6%	150	0.1	6.09
Shallow-rooted	25.0%	150	0.5	18.75
Moderately rooted	21.6%	150	1	32.40
Deep-rooted	2.0%	150	1	3.00
Orchards	5.0%	150	1.67	12.53
Mature forest	5.8%	150	2	17.40
Total	100%		Σ AWC upstream:	90.20
Midstream				
Settlements	65.2%	150	0.1	9.79
Shallow-rooted	10.0%	150	0.5	7.50
Moderately rooted	13.7%	150	1	20.55
Deep-rooted	2.0%	150	1	3.00
Orchards	4.6%	150	1.67	11.61
Mature forest	4.5%	150	2	13.39
Total	100%		Σ AWC midstream:	65.80
Downstream				
Settlements	42.4%	150	0.1	6.35
Shallow-rooted	20.0%	150	0.5	15.00
Moderately rooted	23.9%	150	1	35.85
Deep-rooted	9.0%	150	1	13.50
Orchards	1.4%	150	1.67	3.51
Mature forest	3.4%	150	2	10.10
Total	100%		Σ AWC downstream:	84.30

Monthly Soil Moisture Storage Difference (ΔST)

The soil-moisture term represents the amount of water held in soil storage. If the value of *P-PE* is positive, then soil moisture storage value is the same as the *AWC*. On the other hand, if the value of *P-PE* is negative, then soil moisture storage is calculated by equation (5). The difference in soil moisture between months (ΔST) then can be calculated by equation (6). A positive value of ΔST means there is enough water to add to the soil moisture storage, while negative value implies that water is removed from the storage because of evapotranspiration [8].

$$ST = AWC.e^{APWL/AWC} \tag{5}$$

$$\Delta ST_{\mathrm{i}} = ST_i - ST_{i-1} \tag{6}$$

Actual Evapotranspiration (AE)

The difference between actual evapotranspiration (*AE*) and potential evapotranspiration (*PE*) is in their relationship with soil moisture storage. The *PE* accounts water removal from land surfaces only by atmospheric potential (heat), while the *AE* accounts changes on soil moisture storage in land surfaces. When the precipitation (*P*) is higher than the *PE*, it means that soil moisture storage still saturated from the excess precipitation. Hence, the *AE* equals the *PE* because there are no changes to the soil moisture storage. When the *P* is lower than the *PE*, it means there are changes in the soil moisture storage. Thus, the *AE* equals the *P* subtracted by the changes in soil moisture storage.

$$P > PE \rightarrow AE = PE \tag{7}$$
$$P < PE \rightarrow AE = P - \Delta ST \tag{8}$$

Deficit (D) and Surplus (S)

Soil-moisture deficit expressed as the difference between actual evapotranspiration and potential evapotranspiration [2]. When soil moisture reaches the maximum soil-moisture capacity, which is *AWC*, any excess precipitation become the surplus value, thus makes surplus value equals to *P-PE* [8].

$$D = PE - AE \tag{9}$$
$$S = P - PE \tag{10}$$

Runoff (R)

Thornthwaite and Mather suggest that there is only 50 percent of the surplus water in the large watersheds which will become runoff in any month. The remaining 50% is assumed to be detained and will become runoff during the next month [2].

$$R_i = 50\%\ R_i + 50\%\ R_{i-1} \tag{11}$$

3 Result and Discussion

Rainfall data over the last ten years (2007-2017) show that the watershed tends to have a dry season in the middle of the year, starting in May. The months of July and August especially become the driest months with monthly precipitation below 50 mm in each stream region. Big rain events tend to occur around the end and beginning of the year, which can reach 300 mm in one month. These conditions are reflecting the typical tropical season in Indonesia.

The temperature data covering the last ten years (2007-2017) also reflect the typical tropical season in Indonesia. The average temperature at Tambakbayan watershed is in between 24°C and 25°C for over a year. It makes no significant fluctuated series of data. However, there is about a 1°C difference in temperature between the stream regions which adjacent to each other. The average temperature of the three regions are 23.6°C, 24.9°C and 25.9°C; upstream, midstream, downstream respectively. The temperature difference suggested is due to the elevation differences of the three stream regions: 200-500 meter above sea mean level (masml) for upstream regions, 120-200 masml for midstream regions, and 65-120 masml for downstream regions.

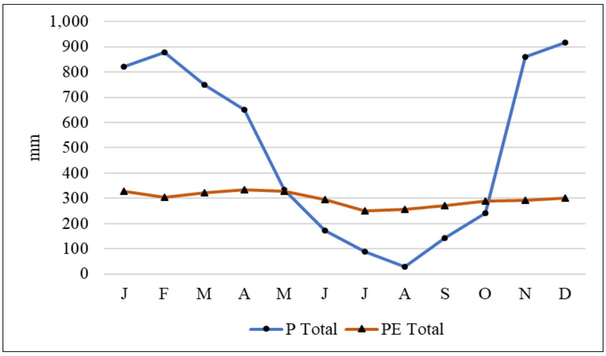

Fig. 3. Monthly precipitation *P* and potential evapotranspiration *PE*.

In many tropical areas with distinct dry seasons, the annual precipitation frequently found to be lower than the annual potential evapotranspiration [9]. However, Tambakbayan watershed has average annual precipitation of 490.8 mm, about 200 mm higher than its average annual potential evapotranspiration, 297.4 mm. On the other side, the average annual actual evapotranspiration in the whole watershed is 253.2 mm, only a bit lower than the average annual potential evapotranspiration.

The difference of the hydrology condition in the upstream and the lower streams can be seen from the calculated accumulated potential water loss (*APWL*) value. The final *APWL* values of the three stream regions are 137.7 mm (September), 204.3 mm (October) and 406.1 mm (October) for upstream, midstream and downstream region, respectively. The values indicate that the upstream area potential for losing water is much lower than in the midstream and downstream area. It means that the northern part of the watershed (upstream), where Plosokuning village up till Pakem village situated, have good water preservation potential, whereas downstream areas, such as Banguntapan village in Bantul, need to manage their water resource more carefully. With the total *APWL* of 748.1 mm, Tambakbayan watershed would potentially lose about 10,572,595 m^3 water each year, with 44% of it occurs in the downstream area.

The estimated available water capacity (*AWC*) value was assumed the same for all months in each of the regions. The analysis shows that the water holding capacity of the soil is higher in the upstream area. This finding is possible, related to the fact that there are more trees and small forests scattered in the upstream region than the lower region. It is also found that the upstream region still has similarly high soil moisture storage (*ST*) value of than the midstream region, even though it is in the middle of the year where the water loss potential should be at its highest. The water utilization by plants represented by ΔST. The highest changes in soil moisture storage are in July, reaching 70.1 mm for all regions.

The surplus water in Thornthwaite-Mather method was assumed as water that becomes runoff. In this study, the upstream region has the most surplus month with only four months (June, July, August, September) of deficit, compared to five (June, July, August, September, October) and six months (May, June, July, August, September, October) in the midstream and downstream, respectively. The water balance analysis shows that the highest surplus value achieved by midstream region, with the peak value of 218.4 mm in December. While the highest deficit value achieved by downstream region with the value of 74 mm in August. The August month noticed as the driest month of the year, with the total of soil moisture deficit reaches 179.2 mm or 1,860,715 m^3. Since September-October is the end of dry months, the soil moisture recharge begins in October-November.

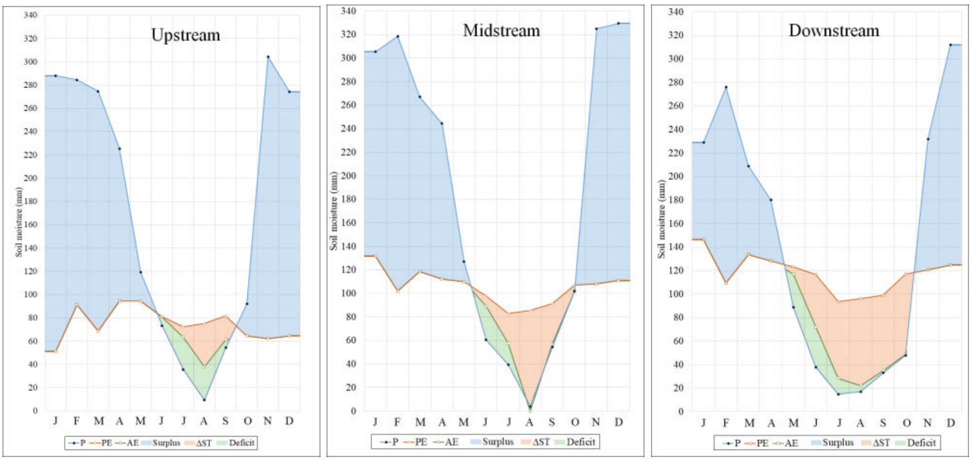

Fig. 4. Water budget in upstream, midstream and downstream region.

Table 2. Water balance in the upstream region.

Param.	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
P	mm	288	284	275	225	119	73	36	9	54	92	304	274	2,035
PE	mm	51.2	91.2	68.6	94.4	94.4	81.1	72.4	75.2	81.6	64.4	62.3	64.5	901
P-PE	mm	236.8	193.1	206.1	130.9	24.9	-7.8	-36.8	-65.9	-27.3	27.6	242.0	209.5	
APWL	mm						-7.8	-44.5	-110.4	-137.7				-137.7
AWC	mm	90.2	90.2	90.2	90.2	90.2	90.2	90.2	90.2	90.2	90.2	90.2	90.2	
ST	mm	90.2	90.2	90.2	90.2	90.2	82.7	55.0	26.5	19.6	90.2	90.2	90.2	
ΔST	mm	0.00	0.00	0.00	0.00	0.00	-7.44	-27.70	-28.52	-6.92	70.57	0.00	0.00	
AE	mm	51.2	91.2	68.6	94.4	94.4	80.8	63.4	37.9	61.3	64.4	62.3	64.5	834
D / S	mm	236.8	193.1	206.1	130.9	24.9	-0.3	-9.1	-37.3	-20.4	27.6	242.0	209.5	

Table 3. Water balance in midstream region.

Param.	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
P	mm	306	319	267	245	127	61	40	4	55	102	325	330	2,178
PE	mm	131.6	102.0	118.5	112.2	110.0	98.0	82.9	85.6	91.2	107.1	108.1	111.1	1,258
P-PE	mm	173.9	216.5	148.5	132.3	17.0	-37.5	-43.4	-81.6	-36.7	-5.1	216.9	218.4	
APWL	mm						-37.5	-80.9	-162.5	-199.2	-204.3			-204.3
AWC	mm	65.8	65.8	65.8	65.8	65.8	65.8	65.8	65.8	65.8	65.8	65.8	65.8	
ST	mm	65.8	65.8	65.8	65.8	65.8	37.3	19.3	5.6	3.2	3.0	65.8	65.8	
ΔST	mm	0.00	0.00	0.00	0.00	0.00	-28.57	-18.00	-13.69	-2.39	-0.24	62.88	0.00	
AE	mm	131.6	102.0	118.5	112.2	110.0	89.1	57.5	-17.7	56.9	102.2	108.1	111.1	1,117
D / S	mm	173.9	216.5	148.5	132.3	17.0	-8.9	-25.4	-67.9	-34.4	-4.8	216.9	218.4	

Table 4. Water balance in the downstream region.

Param.	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
P	mm	229	276	209	180	89	38	15	17	33	48	232	312	1,678
PE	mm	146.3	109.4	133.6	128.3	123.3	116.8	93.5	96.3	99.0	117.2	120.7	124.7	1,409
P-PE	mm	82.7	166.6	75.4	51.7	-34.3	-78.8	-78.5	-79.3	-66.0	-69.2	111.3	187.3	
APWL	mm					-34.3	-113.1	-191.7	-270.9	-337.0	-406.1			-406.1
AWC	mm	84.3	84.3	84.3	84.3	84.3	84.3	84.3	84.3	84.3	84.3	84.3	84.3	
ST	mm	84.3	84.3	84.3	84.3	56.1	22.0	8.7	3.4	1.6	0.7	84.3	84.3	
ΔST	mm	0.00	0.00	0.00	0.00	-28.17	-34.10	-13.36	-5.29	-1.84	-0.87	83.63	0.00	
AE	mm	146.3	109.4	133.6	128.3	117.2	72.1	28.4	22.3	34.8	48.9	120.7	124.7	1,087
D / S	mm	82.7	166.6	75.4	51.7	-6.1	-44.7	-65.2	-74.0	-64.2	-68.3	111.3	187.3	

Table 5. Runoff and streamflow estimation.

Parameter	unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
R ups.	mm	223.2	208.1	207.1	169.0	97.0	48.5	24.2	12.1	6.1	16.8	129.4	169.5	1,311
R mids.	mm	96.1	206.3	177.4	154.8	85.9	43.0	21.5	10.7	5.4	2.7	109.8	164.1	1,178
R downs.	mm	135.0	150.8	113.1	82.4	41.2	20.6	10.3	5.1	2.6	1.3	56.3	121.8	740.4
Total R	mm	554.3	565.2	497.6	406.2	224.1	112.0	56.0	28.0	14.0	20.8	295.5	455.4	3,229
Q ups.	m^3/day	159,090	164,285	147,651	124,509	69,134	35,719	17,284	8,642	4,465	12,009	95,348	120,821	958,958
Q mids.	m^3/day	139,829	162,847	126,466	114,064	61,254	31,648	15,313	7,657	3,956	1,914	80,892	116,999	862,838
Q downs.	m^3/day	96,229	119,001	80,606	60,672	29,358	15,168	7,339	3,670	1,896	917	41,478	86,832	543,167
Total Q	m^3/day	395,148	446,133	354,724	299,245	159,746	82,535	39,936	19,968	10,317	14,840	217,718	324,652	2,364,962

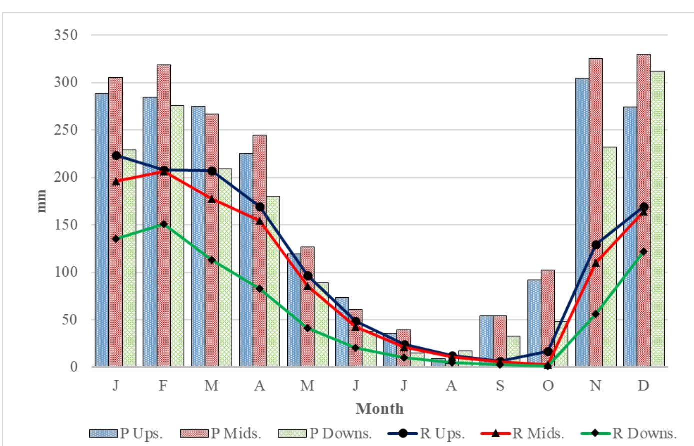

Fig. 5. Monthly runoff *R* estimation compared to the precipitation *P*.

The runoff (*R*) parameter is not a real-time runoff. The *R* in TMWB system is the excess water that not only becomes direct runoff but also indirect runoff (baseflow). The analysis results suggest that the runoff (excess rainfall after subtracted by evapotranspiration and soil moisture change) to the downstream area is less. It happens because of the less water holding capacity and more evapotranspiration in the lower region. The less water holding capacity also suggests that the runoff coefficient in the lower regions is higher than the upper regions. It is reflected by the availability of plants or trees which causes the changes in soil moisture storage. The lower stream area has a fewer green area, thus the water holding capacity lesser than the upper stream area.

The water discharge (*Q)* value which calculated by multiplying *R* with watershed region area can be used to estimate water availability in the watershed. The highest total discharge value estimated in the Tambakbayan watershed is 446,133 m^3/day, which is in February. The lowest total discharge value estimated is 10,317 m^3/day, which is in September. The highest discharge value was achieved by upstream area with the value of 164,285 m^3/day in February, while the lowest discharge value estimated is 917 m^3/day, in October within the downstream area. With the total population of 329,979 in the year 2018, Tambakbayan watershed demands 24,135 m^3/day (with water demand per capita as 100 $^{L}/_{person.day}$). It can be concluded that the current condition of Tambakbayan watershed is still sufficient to provide water for domestic purpose only. Nevertheless, the demands of other variables, such as agricultural demand, livestock demand, industrial demand, public facilities demand and ecological demand, have to be accounted to justify the real water carrying capacity in this watershed.

4 Conclusion

The current condition of water availability in Tambakbayan watershed reflects the typical seasons and monsoon in Indonesia. The annual rainfall is 1.7 and 1.9 times higher than the potential evapotranspiration and actual evapotranspiration, respectively. It makes the potential water availability in the watershed is in a good state.

The analysis of the accumulated potential water loss (*APWL*) showed that the dry months occur around May-June and ends around September-October. The driest month of the year in Tambakbayan watershed is August, with deficit value 179.2 mm. The average annual water loss in Tambakbayan watershed is 249.4 mm with the highest point in the downstream region. The runoff to the downstream area is less due to the higher evapotranspiration and lower water holding capacity.

This study suggests that concern about the hydrologic capacity of the watershed is justified when looking towards more development in the future. The hydrologic capacity of the study area is good, especially the water availability. However, the downstream area needs more attention, since it has six dry months and the lowest water preservation capability. Comprehensive water management and city development plan have to be implemented to protect the watershed from overstressing its water resources.

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