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Evaluation of Groundwater Availability for Rice during Period 2018-2022 in Tuban Regency, East Java

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Research has been conducted on the deficit, surplus, percentage of groundwater availability, and classification of Oldeman climate type in Tuban Regency, East Java in 2018-2022 to increase rice crop productivity in Tuban Regency, East Java. This process begins with the collection of data, namely rainfall, air temperature, coordinates and height of rain posts, and soil physical data which is then calculated ETC (Plant Evapotranspiration) rice, deficit, surplus, and ATS using the Thornthwaite and Mather methods. The results of data analysis obtained the smallest deficit value of 0.1 mm which occurred in Medalem in June and the largest deficit occurred in Ngimbang in November of 279.6 mm. The smallest surplus of 0.9 mm occurred in Sumurgung in April and the

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largest surplus of 313 mm occurred in Jenu in January, with 100% groundwater availability which generally occurs in November-April and 0% ATS which occurs in June-September and Oldeman Climate type in Tuban Regency consecutively C3, D3, D4, and E3.

Keywords: Rainfall; groundwater availability; water balance; thornthwaite and mather methods; deficit and surplus.

1. INTRODUCTION

Most of the Indonesian population works in the agricultural sector, which is why Indonesia is referred to as an agrarian country. The agricultural sector serves as the largest support for the economy in Indonesia. A crucial component of the agricultural sector is a water management system. With the existence of a water management system, efforts can be made to avoid water scarcity in agricultural land. This water management system can be determined by analyzing groundwater availability [1]. The condition of groundwater availability in agricultural land can be known by using water balance analysis. To calculate the water balance, a simple equation can be used, such as the Thornthwaite method, which requires inputs like rainfall. In this method, the groundwater storage capacity in a specific region with certain crop conditions is used to determine the level of groundwater, surplus, and deficit. The data used in this method include precipitation or rainfall (CH), potential evapotranspiration (ETP), actual evapotranspiration (ETA), groundwater content (KAT), surplus, and deficit [2].

Java Island represents the largest distribution for the agricultural sector in Indonesia, including Tuban Regency in East Java. Tuban Regency is an agricultural center that heavily relies on rainfall, also known as rainfed agriculture. According to the Central Statistics Agency (BPS) of Tuban Regency, East Java, rice production in the period 2018-2019 in 20 sub-districts showed that 11 sub-districts experienced an increase in production, while 9 sub-districts experienced a decrease in production. For example, the sub-district of Jatirogo had a 1.5% increase in production, while the sub-district of Rengel experienced a significant decrease of 26.7% in rice production [3].

1.1 Groundwater Availability

Groundwater availability is the volume of water per unit of time estimated to be available in a place within a certain period [4]. Groundwater availability (ATS) or the percentage of groundwater availability is divided into five categories as shown in Table 1.

Table 1. Percentage of groundwater availability

Groundwater availability (ATS)	Percentage (%)
Very Low	< 10
Low	10 ≤ ATS < 40
Moderate	40 ≤ ATS < 60
Sufficient	60 ≤ ATS < 90
Abudant	90 ATS < 100

1.2 Water Balance

Water balance is a breakdown of all the inputs, outputs, and changes in water storage found on land to determine the amount of water contained in the soil. [5]. Water balance is divided into three models:

a. General Water Balance This model utilizes climatological data and is useful for determining the occurrence of wet months or the amount of rainfall exceeding the water loss due to evaporation from the soil surface, as well as evaporation from the plant system (transpiration), and their combination (evapotranspiration) [6].
b. Land Water Balance This model combines climatological data with soil data, especially data on the field capacity (KL), the wilting point (TLP), and available water [6].
c. Crop Water Balance Crop water balance is a model that combines climatological data, soil data, and crop data. This water balance is specifically designed for certain types of crops. The crop data used includes the crop coefficient in the output component of the water balance [6].

1.3 Water Balance Components

The components of the water balance are as follows:

1.3.1 Precipitation

Rainfall is the amount of water that falls on the ground surface during a certain period. A rainfall height of 1 mm means that 1 liter of rainwater falls on a 1 m^2 area [5].

1.3.2 Temperature

Temperature variation in the Indonesian archipelago depends on the altitude or elevation. Temperature decreases with increasing altitude from sea level, with a decrease of approximately 0.6 ºC per 100-meter increase in elevation. In the absence of temperature observation data, estimation can be done by considering the elevation factor from the nearest weather station using the following formula [1].

$$\mathrm{Th} = \mathrm{Th}_0 - 0,6\left(\frac{\mathrm{h}_1 - \mathrm{h}_0}{100}\right) \tag{1}$$

Explanation:

Th : Temperature at a height of h m above sea level (°C)
Tho : Temperature at sea level (0 m) (°C)
h0 : Reference point elevation (m)
h1 : Elevation of the location (m)

1.3.3 Evapotranspiration

Evapotranspiration is the combined evaporation of soil and plants [7].

1.3.4 Soil moisture content

Soil moisture content refers to the amount of water present in the soil, which serves as a supporting system for plants to regulate their water balance. In determining soil moisture content, there are several terms that need to be understood:

a. Field capacity

Field capacity is the state of the soil in saturated conditions, which shows the maximum amount of water that the soil can hold [8].

b. Permanent wilting point

The permanent wilting point is the lower limit of water availability in the soil for plants, at which point plant roots cannot absorb water for growth [8].

c. Available water

Available water refers to the water in the soil that falls within the range between field capacity and permanent wilting point [8].

1.4 Thornthwaite Method

Thornhwaite in 1948, in "The Evapotranspiration in Climate Classification" by Cunha and Schoffel [9], proposed the calculation of water balance using monthly average air temperature, precipitation, and soil water storage capacity. The assumption was made that the soil acts as a reservoir, and all available water in the soil undergoes evapotranspiration. To monitor the variation in water storage throughout the year, considering groundwater supply from precipitation, potential evapotranspiration, available water capacity, estimates of actual evapotranspiration, deficit, surplus, and soil water content were obtained. Thortnhwaite and Mather further developed the water balance calculation for each month in 1955. If there is no available data for potential evapotranspiration (ETP) in a specific region, ETP estimation can be done using monthly average temperature data. The following calculation can be used to obtain ETP using this method [10]:

1. Calculate the monthly heat index (i):

$$\mathrm{i} = \left(\frac{\mathrm{t}}{5}\right)^{1,514} \tag{2}$$

Where t: air mean temperature (^{o}C) dan i: heat indeks (^{o}C)

2. Then add up the total i for a year with the formula

$$\mathrm{I} = \sum_{\mathrm{i}=1}^{12} \mathrm{i}\left(\frac{\mathrm{t}}{5}\right)^{1,514} \tag{3}$$

3. Calculate $ETP_{standard}$ using formula:

$$ETP_{Standard} = 1,6\left(10\frac{t}{I}\right)^{a} \tag{4}$$

Where a equals to 0,000000675 I^3 – 0,0000771 I^2 + 0,01792 I + 0,49239

4. Considering the location is at the equator (latitude 0), it is necessary to correct the standard ETP by using the daylight hours (for

latitude 0, 1 day = 12.1 daylight hours) and the number of days per month = 30 days. Therefore:

$$ETP = \left(\frac{X}{30}\right)\left(\frac{Y}{12.1}\right)ETP_{Standard} \quad (5)$$

Where

X: Total days of the month
Y: days in hours

5. The conversion of evapotranspiration to millimeters (mm) can be calculated using the following formula:

$$\text{ETP (mm)} = \text{ETP (cm)} \times 10 \quad (6)$$

6. For the plant water balance, the evapotranspiration used is crop evapotranspiration (ETC), which represents the amount of water evaporation that occurs in the plants according to their age and crop type during the growth period. Therefore [7]:

$$\text{ETC} = \text{ETP} \times \text{kc} \quad (7)$$

kc is the crop coefficient, which depends on the type of crop. In this study, rice is the crop being used, and the value of kc for rice is 1.13.

Next, calculations are performed for the plant water balance, which includes APWL (Accumulated Potential Water Loss), KAT (Soil Water Content), ETA (Actual Evapotranspiration), and ATS (Available Groundwater). The calculation steps and data processing are as follows:

a. Accumulated potential water loss for evaporation:

Accumulated potential water loss is necessary to determine the potential water loss during dry months. When CH > ETC, APWL = 0 as there is no water deficit. Conversely, if CH < ETC, APWL can be calculated using the following formula:

APWL = Previous month's APWL + (CH - ETC)

b. Soil Water Content (KAT):

To calculate KAT for the current month, APWL can be determined using the following formula.

Please note that the above information is a translation of the provided text and may require further context or clarification for accurate interpretation.

$$KAT = TLP + \left(1{,}00041 - \left(\frac{1{,}07381}{AT}\right)\right)^{|APWL|} \times AT \quad (8)$$

Where:

TLP : Permanent wilting point (mm) (TLP Tuban Regency: 210 mm)

KL : Field capacity (mm) (KL Tuban Regency: 350 mm)

AT : Available water (mm), calculated as AT = KL – TLP

|APWL| : Absolute value of APWL

Then, for months where APWL does not occur, KAT is calculated using the following formula.

Please provide the specific formula for calculating KAT in order to assist you further.

$$\text{KAT} = \text{KAT final} + \text{CH} - \text{ETP} \quad (9)$$

c. Changes in groundwater level (dKAT)

Changes in groundwater level can be determined using the following formula:

dKAT = dKAT of that month – dKAT the month before (10)

Positive values indicate changes in groundwater content that occur when CH > ETC (rainy season). If dKAT = 0, it means that KL is reached. Conversely, if CH < ETC or dKAT is negative, then the entire CH and dKAT will be evaporated.

d. Actual evapotranspiration (ETA)

If CH > ETC, ETA = ETC because ETA reaches its maximum value. However, if CH < ETC, ETA = CH + |dKAT| because the entire CH and dKAT will be evaporated.

e. Deficit (D)

Deficit refers to the reduction in water available for evapotranspiration, so D = ETC - ETA, which occurs during the dry season.

f. Surplus (S)

Surplus refers to the excess water when CH > ETC, so S = CH - ETC - dKAT, which occurs during the rainy season.

Table 2. Oldeman climate type classification

Oldeman climate type	Sub type	Number of WM	Number of DM
A	A1	> 9	< 2
	A2	> 9	2 ≤ DM ≤ 3
B	B1	7 ≤ WM ≤ 9	> 2
	B2	7 ≤ WM ≤ 9	2 ≤ DM ≤ 3
C	C1	5 ≤ WM ≤ 6	< 2
	C2	5 ≤ WM ≤ 6	2 ≤ DM ≤ 3
	C3	5 ≤ WM ≤ 6	4 ≤ DM ≤ 6
	C4	5 ≤ WM ≤ 6	7
D	D1	3 ≤ WM ≤ 4	< 2
	D2	5 ≤ WM ≤ 6	2 ≤ DM ≤ 3
	D3	5 ≤ WM ≤ 6	4 ≤ DM ≤ 6
	D4	5 ≤ WM ≤ 6	7 ≤ DM ≤ 9
E	E1	< 3	< 2
	E2	< 3	2 ≤ DM ≤ 3
	E3	< 3	4 ≤ DM ≤ 6
	E4	< 3	> 6

g. Available groundwater (ATS)

$$ATS = \frac{KAT - TLP}{KL - TLP} \times 100\%$$

Explanation:

KAT : Groundwater content (mm)
TLP : Permanent wilting point (mm)
KL : Field capacity (mm)

1.5 Oldeman Climate Classification

The classification criteria of the Oldeman climate type are based on the number of consecutive Wet Months (WM) and Dry Months (DM) within a year, taking into account rainfall probability, effective rainfall, and plant water requirements. The categories for Wet Months and Dry Months in the Oldeman climate type are as follows:

a. Wet Months (WM): Months with an average rainfall of > 200 mm.
b. Dry Months (DM): Months with an average rainfall of < 100 mm.

Based on these values, Oldeman established 5 types of climate: A, B, C, D, and E, depending on the number of consecutive Wet Months and Dry Months that occur within a year [11]. The classification of Oldeman climate types is shown in Table 2.

2. METHODS

This research was conducted at the BMKG Class III Meteorological Station in Tuban, East Java. The map of the research area is shown in the Fig. 1.

2.1 Data Collection Method

The following data were collected for this research:

a. Rainfall data: The rainfall data used in this study were obtained from 28 rain gauge stations in the Tuban Regency, East Java, for the period of 2018-2022.
b. Temperature data: Monthly temperature data were collected from the Meteorology Station III in Tuban, East Java, which has observation data. For rain gauge stations without temperature observation data, estimates were made based on the nearest station, using temperature calculation formulas based on the altitude of the location according to.
c. Soil physical data: Field capacity (FC) and permanent wilting point (PWP) data for Tuban Regency, East Java, were obtained from secondary data in the book "Pemanfaatan Sumberdaya Air" [12].
d. Coordinate and elevation data: Coordinate and elevation data for the 28 BMKG rain gauge stations in Tuban Regency were obtained from the BMKG Meteorology Station Class III in Tuban, East Java.

Fig. 1. Rainfall station map of tuban regency

2.2 Data Processing Method

The data were processed as follows:

a. Determination of Oldeman climate types: The determination of Oldeman climate types in Tuban Regency, East Java, was based on the average monthly rainfall data from the rain gauge stations and BMKG stations, considering the number of wet months (WM) and dry months (DM) in sequence. The number of wet months and dry months is classified based on the Oldeman climate types.

b. Calculation of deficit, surplus, and groundwater availability levels were processed using Microsoft Excel with the Thorntwaite method.The ATS (Available Groundwater) results were divided into 5 classes representing the percentage of groundwater availability.

2.3 Analysis Method

Analysis of the results of data processing using descriptive analysis method, namely describing data in the form of Oldeman climate type classification results, calculation of the percentage of groundwater availability or ATS, and surplus and deficit to determine the planting schedule in Tuban Regency, East Java.

2.4 Thinking Framework

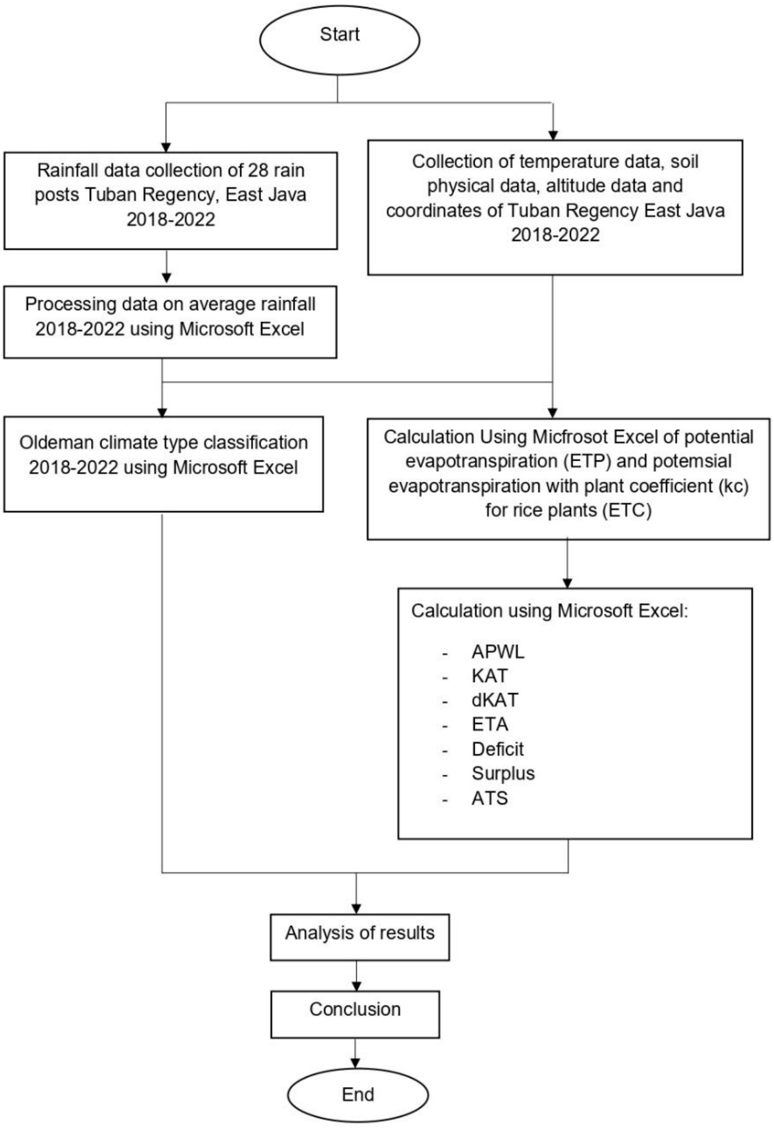

Fig. 2. Research flow chart

3. RESULTS AND DISCUSSION

3.1 Rainfall Analysis

Based on rainfall data obtained from Meteorological Station Class III Tuban, it can be seen that Tuban Regency has a monsoonal rainfall pattern. The monsoonal rainfall type is a type that has a clear difference in the rainy season and dry season, where this monsoonal rainfall type is influenced by the west monsoon or Asian winds which cause the rainy season in Tuban Regency to occur around November-March and the dry season which is influenced by the east monsoon or Australian winds occurs around June-September. The following is an example of a graph of average rainfall at one of the rain posts in Tuban Regency.

3.2 Oldeman Climate Type Analysis

Tuban Regency has Oldeman climate types C3, D3, D4, and E3 respectively which are presented in the following Table 3.

Table 3. Climate type oldeman Tuban regency

No.	Climate Type	Rain Station
1	C3	Mundri, Laju Kidul, Sendang, Jojogan, medalem, Ngabongan, Kerek, Tegalrejo, widang
2	D3	Bangilan, Kejuron, Montong, Sumurgung, Kebonharjo, Kepet, Bogorejo, Soko, Rengel, Maibit, Klotok, Parengan
3	D4	Jenu
4	E3	Belikanget, Simo, Tuban, Silowo, Palang, Ngimbang

Table 4. ATS in Tuban regency, east Java 2018-2022

Rain Statiom	ATS (%)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bangilan	100	100	100	100	58	30	24	13	0	100	100	100
Mundri	100	100	100	100	37	0	0	0	0	100	100	100
Kejuron	100	100	100	100	36	1	0	0	0	0	100	100
Laju Kidul	100	100	100	100	61	0	0	0	0	0	100	100
Sendang	100	100	100	100	34	0	0	0	0	0	100	100
Jojogan	100	100	100	100	63	11	0	0	0	0	100	100
Montong	100	100	100	100	68	15	0	0	0	0	100	100
Sumurgung	100	100	100	100	38	0	0	0	0	0	100	100
Banyu Urip	100	100	100	100	46	46	8	0	0	0	100	100
Ngabongan	100	100	100	76	100	49	5	0	0	0	100	100
Kebonharjo	100	100	96	100	49	8	0	0	0	0	100	100
Belikanget	100	100	100	100	49	0	0	0	0	0	0	100
Kerek	100	100	100	100	60	0	0	0	0	0	100	100
Simo	100	100	86	100	25	0	0	0	0	0	0	100
Kepet	100	100	100	92	21	0	0	0	0	0	100	100
Tuban	100	100	100	88	7	0	0	0	0	0	100	97
Bogorejo	100	100	100	100	100	100	100	100	100	100	100	100
Tegalrejo	100	100	100	100	15	0	0	0	0	0	0	100
Silowo	100	100	100	100	22	0	0	0	0	0	100	100
Jenu	100	100	100	100	35	0	0	0	0	0	0	0
Soko	100	100	100	85	44	0	0	0	0	0	100	100
Rangel	100	100	100	100	30	0	0	0	0	0	100	100
Maibit	100	100	100	91	23	0	0	0	0	0	100	100
Klotok	100	100	100	88	16	0	0	0	0	0	100	100
Widang	100	100	100	100	37	0	0	0	0	0	100	100
Palang	100	100	78	34	0	0	0	0	0	0	0	0
Ngimbang	100	100	89	76	9	0	0	0	0	0	100	100
Parengan	100	100	100	69	44	0	0	0	0	0	100	100

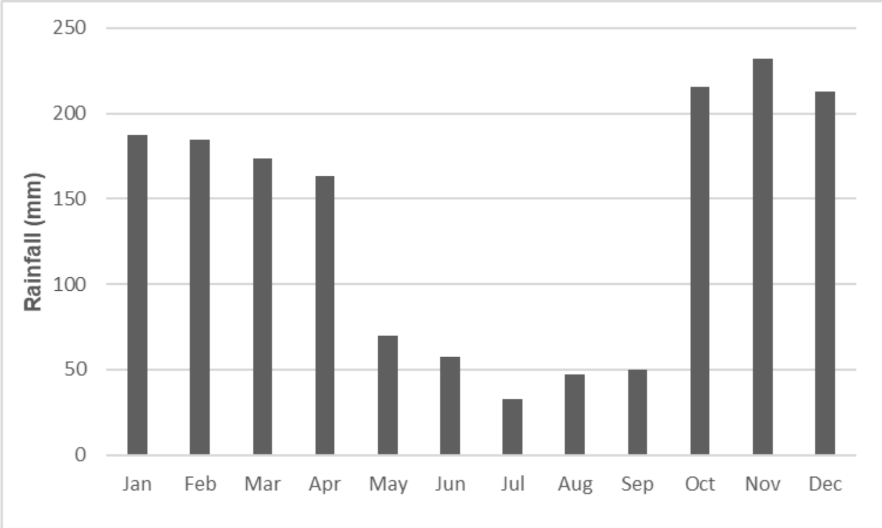

Fig. 3. Mundri rainfall 2018-2022

The C3 Oldeman climate type occurs in the Mundri, Laju Kidul, Sendang, Jojogan, Medalem, Ngabongan, Kerek, Tegalrejo, and Widang regions, indicating that these areas can only have one rice planting season per year based on the agroclimate zone. The D3 Oldeman climate type is found in the Bangilan, Kejuron, Montong, Sumurgung, Kebonharjo, Kepet, Bogorejo, Soko, Rengel, Maibit, Klotok, and Parengan regions, indicating that these areas can have one rice planting season depending on the availability of irrigation water. The D4 Oldeman climate type occurs in the Jenu region, indicating that in Jenu, only one rice planting season is possible per year depending on the availability of irrigation water, with a dry period of 7-9 months. The E3 Oldeman climate type occurs in the Belikanget, Simo, Tuban, Silowo, Palang, and Ngimbang regions, indicating that these areas are generally too dry for rice cultivation, but they can have one planting season for other crops depending on rainfall availability.

3.3 Analysis of Groundwater Availability

The availability of groundwater in Tuban Regency generally reaches the maximum value in November-April where the KAT value is the same as KL, which is 350 mm, which means that in that month there is a rainy season so the water obtained is abundant and there is a surplus.

Based on Table 4 and Fig. 4 as an example, Tuban District, East Java generally has very sufficient groundwater availability with a percentage of 100% in November-April, which also indicates that in that month Tuban District experiences the rainy season so the rainfall that occurs is greater than the evapotranspiration of rice plants. Whereas in June-October, in general, Tuban Regency has a very low percentage of groundwater availability, which is 0%, indicating that in June-October Tuban regency experiences a dry season, so the availability of groundwater for rice plants is very less and even experiences drought, which means that rainfall in June-October is also smaller than the evapotranspiration of rice plants. Whereas in May, Tuban Regency has moderate groundwater availability, which indicates that this month is a transitional season, namely from the rainy season to the dry season. Jenu has 0% ATS in June-December and Palang in May-December. BY looking at the percentage of ATS, where the availability of groundwater is very sufficient in Tuban Regency generally occurs in November-April, it can be determined the appropriate initial rice planting schedule in Tuban Regency, namely the beginning of rice planting can be done in November with a rice planting period of 4 months including the harvest period. As for the Bogorejo area in Fig. 5 because the percentage of ATS is 100% throughout the year, then rice planting can be done 3 times with a planting period of 4 months including the planting period and rice harvesting process. From the calculation of groundwater availability, it can also be known for deficits and surpluses in the Regency which shows that when the Tuban Regency Experiences a deficit, the surplus will be 0 MM, otherwise, if there is a surplus, the deficit will be 0 MM, this shows that the value of deficits and surpluses is influenced by rainfall when rainfall is low or there is a dry month, there will be a deficit, otherwise if rainfall is high or wet months, there will be a surplus, besides being influenced by rainfall, deficits, and surpluses are also influenced by evapotranspiration because when rainfall is lower than evapotranspiration, there will be a deficit in Tuban Regency. The smallest deficit in Tuban Regency is 0.1 mm which occurred in Medalem in June and the largest deficit occurred in Ngimbang in November amounting to 279.6 mm, this shows that in Ngimbang in November there was a drought because the deficit value was 279.6 mm, which means that the greater the deficit value obtained, the higher the level of drought or soil conditions lacking water that occurs. Meanwhile, the smallest surplus is 0.9 mm which occurred in Sumurgung in April and the largest surplus is 313 mm which occurred in Jenu in January.

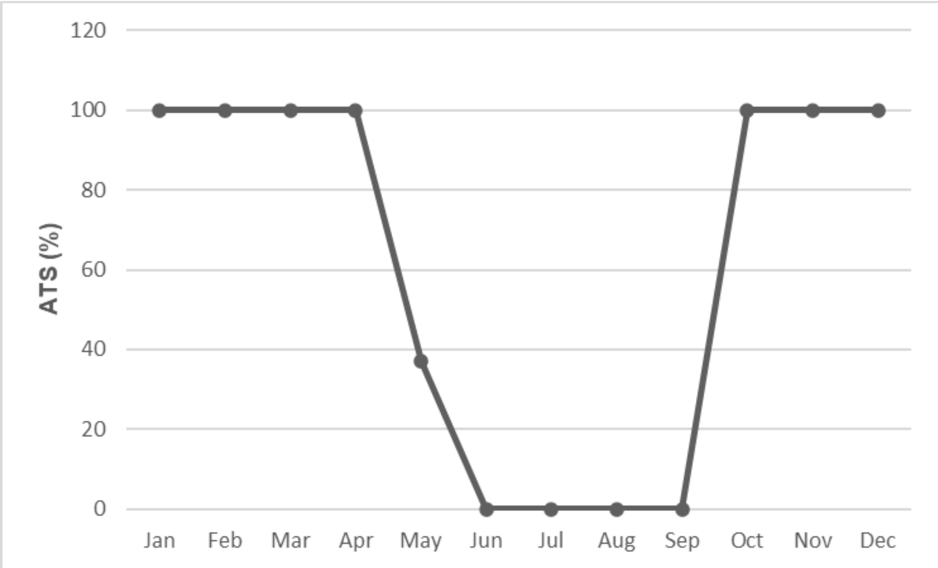

Fig. 4. Groundwater availability in Mundri

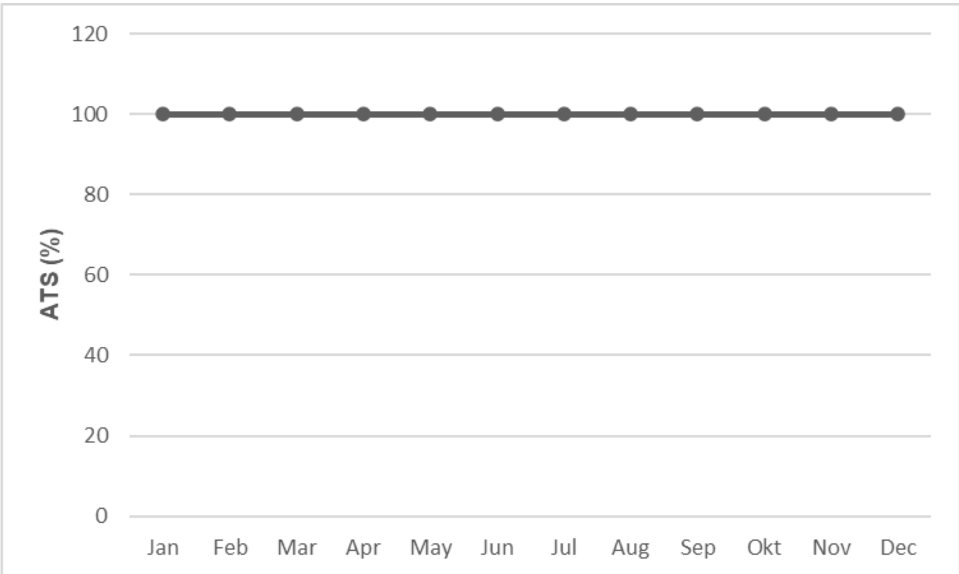

Fig. 5. Groundwater availability in Bogorejo

4. CONCLUSION

Based on the discussion, the conclusions that can be drawn are as follows:

a. ATS (Available Soil Moisture) in Tuban Regency, East Java, has a value of 100% which generally occurs during the months of November-April, and ATS 0% which indicates very low availability of soil moisture, typically happening during the months of June-September. The Oldeman Climate Types in Tuban Regency are C3, D3, D4, and E3 in sequential order.
b. The smallest deficit value is 0.1 mm, occurring in Medalem during the month of June, while the largest deficit occurs in Ngimbang in November, amounting to 279.6 mm. As for the smallest surplus, it is 0.9 mm, occurring in Sumurgung in April, and the largest surplus is 313 mm, occurring in Jenu in January.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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