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Drought analysis in Bedadung Watershed based on a Geographical Information System

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Abstract. Reduced water availability toward water needs is an indicator of the occurrence of a drought. Droughts have received greater attention from the Government of Jember Regency in the form of management directions for drought disaster areas. The location of this research is the Bedadung River Watershed, with 13 rain posts located upstream of the Rowotamtu AWLR Station. Drought analysis used the Palmer Drought Severity Index method in the form of an index that informs the level of drought in an area. The results of the study showed that drought with extreme dry classification occurred from June to October with drought index values ranging from -1.820 (June average) to -14.140 (October average). Patrang, Jelbuk, Arjasa and Panti Sub-Districts are areas that have experienced droughts with a duration of 5 months. The Palmer method meteorological drought index and hydrological drought index (value of AWLR Discharge Standardized Box Cox Transformation (Z)) have a unidirectional relationship and a very significant relationship, with the Pearson correlation coefficient being $r = 0.905$.

Keywords: Meteorological drought index, hydrological drought index, Standardized Box Cox Transformation

1. Introduction

The Government of Jember Regency has a concern for droughts. This is stated in Government of Jember Regency Regional Regulation No. 1 of 2015 on the Regional Spatial Planning of the Government of Jember Regency [1]. In Article 38 Section (1) Letter g, droughts are one of the natural disasters which become the concern of the Government of Jember Regency. The concern is in the form of management directions of drought disaster areas as mentioned in Article 38 Section (15) Letter a, which identifies locations and risk levels of drought. The risk level of a drought in an area can be determined by calculating the drought index, which is then used to detect, monitor, and evaluate the occurrences of drought. The resulting drought index can be used to compile information about droughts in the form of intensity, duration, severity level, and spatial distribution. This can then be used as an anticipatory (mitigation) measure in facing droughts. The drought index is a key component for monitoring drought based on meteorological or hydrological variables [2].

The Palmer Drought Severity Index is one of the methods to calculate the drought index, which was developed by Palmer (1965). In principle, the calculation of the Palmer method is based on the amount of rainfall and the ability of the soil to store water according to the type of soil. The Palmer method uses a two-layer model of soil, the upper and lower layers, based on the Thornthwaite method [3]; each layer has an available capacity, being AWCs (first layer water availability) and AWCu (second layer water availability). Palmer's method is based on the concept of input and output from the
water balance equation, which is also influenced by rainfall and temperature data as well as groundwater availability [4], [5]. One of the reasons why Palmer's Drought Index is used because this index assesses drought from various sources of observation; in addition, this method is standardized for the local climate and thus can be used for all countries to show the relative drought or rainfall conditions.

Meanwhile, hydrological drought analysis can be performed by utilizing available hydrological data in the form of river water levels or AWLR data. River flow/discharge is an indicator of hydrological drought that is easily observed in the field. If the flow of the river is small, this is a symptom of a drought. In addition, according to Loukas A. et al. (2007) the discharge data from the AWLR Station can be normalized using Box Cox transformation and standardized to obtain the hydrological drought index.

The purpose of this study is to provide an overview of the distribution of drought that occurs in the Bedadung Watershed using the Palmer Drought Severity Index method, to find out the hydrological drought conditions, and to find out the relationship between the meteorological drought index and drought conditions based on hydrological data.

![Figure 1. Bedadung Watershed (Upstream of Rowotamtu AWLR Station)](image)

Source: Dept. of Public Works and Water Resources of Jember Regency and Dept. of Public Works and Water Resources of the Province of East Java

2. Materials and Methods

2.1. Research Location

This research takes the location of the Bedadung Watershed, specifically the part of Bedadung watershed upstream of the Rowotamtu AWLR station. The location of this research is hydrologically bordered in the west by the Tanggul Watershed, in the east by the Mayang Watershed, in the north by Bondowoso Regency, and in the south by the part of Bedadung watershed downstream of the Rowotamtu AWLR station. Administratively, the study location is in Jember Regency. The climate in Jember Regency is tropical. Temperature ranges from 24.40-29.10 °C, with the dry season occurring from June to October and the rainy season occurring from November to May. The annual rainfall ranges from 924 mm to 4,915 mm.

Bedadung Watershed upstream of the Rowotamtu AWLR station as the study area has an area of 804.6 km², which covers the 11 sub-districts of Panti, Sukorambi, Patrang, Kaliwates, Jelbuk, Arjasa,
Sumbersari, Sukowono, Kalisat, Pakusari, and Sumberjambe. The type of land cover at the study site consists of forests, shrubs, plantations, agriculture, rice fields, and settlements, while the soil texture at the study site consists of clayey loam, fine sandy loam, clay, and fine sand.

2.2. Location Data

The following are the data that can be collected to conduct the analysis or calculation in this study: (1) Rainfall data from 13 rain stations (2004-2018); (2) Climatological data from 1 weather station, in the form of temperature data (2004-2018); (3) Topographic map; (4) Map of land use; (5) Watershed boundary map; (6) Map of soil type and soil texture; and (7) Discharge data at the outlet of the study area, as the Rowotamtu AWLR post.

3. Analysis Method

3.1. Data Testing

Data testing has the aim to determine the quality and reliability of the data used in the calculation analysis. The quality and reliability of data are closely related to the compatibility of the results of the calculation analysis with the real situation. Data testing for rain data utilized the consistency test of the double curve method, while AWLR discharge data utilized the consistency test of the Rescaled Adjusted Partial Sums (RAPS) method and temperature data utilized the stationarity test.

3.2. Analysis of Rainfall Data

Rainfall data from selected rain stations was utilized to obtain the regional average rainfall using the Thiessen Polygon method. This resulted in the rainfall pattern of the obtained data period.

For the rainfall data from the selected stations, analysis of monthly average rainfall can be performed for each rain station to determine the pattern and variation of the monthly average rainfall. In addition to knowing the patterns and variations in rainfall, using the Mohr method, the months can be differentiated as wet months ($P \geq 100$ mm), dry months ($P \leq 60$ mm), and humid months (60-100 mm).

3.3. Potential Evapotranspiration

Potential evapotranspiration ($EP$) was calculated by the Thornthwaite method. The potential evapotranspiration is based on the monthly average air temperature. The equations are shown below:

$$EP_x = 16 \times \left[\frac{10Tm^{7/4}}{I}\right]$$  \hspace{1cm} (1)

$$EP = f \times EP_x$$  \hspace{1cm} (2)

$$I = \sum_{m=1}^{12} \left(\frac{T}{5}\right)^{1.514}$$  \hspace{1cm} (3)

$$a = (6.75.10^{-7}).I3 - (7.71.10^{-5}).I2 + (1.792.10^{-2}).I + 0.49239$$  \hspace{1cm} (4)

Equations (2) through (5) above include $Tm$ as the average monthly air temperature ($°C$), while the correction coefficient was taken from the adjustment coefficient table according to longitude and month ($f$) and multiplied by the unadjusted potential evapotranspiration. This results in the potential evapotranspiration ($EP$).
3.4. Monthly difference between $P$ and $EP$

Calculation of the difference between the $P$ and $EP$ values has the aim to determine whether the month is considered as a wet or dry month. If $(P-EP) > 0$, the month is wet, and if $(P-EP) < 0$, the month is dry.

3.5. Water Holding Capacity

Estimation of water holding capacity (WHC) was performed indirectly. This method required a soil type (texture) map and a map of land cover as well as the Thornthwaite-Mather conversion table. The method of estimation involved these steps: (1) Depicting the map of Thiessen polygons; (2) Overlaying the maps of rain distribution, soil types (texture), and land cover; (3) Performing area calculations for each type of land use on each polygon by considering the differences in soil texture; and (4) Calculating the value of available water and root length followed by the WHC value with the Available Water Capacity Estimation Table based on a combination of soil and vegetation types. By utilizing a geographical information system (GIS), the water holding capacity (WHC or STO) can be estimated.

3.6. Drought Index

Drought index by the Palmer Drought Severity Index (Palmer) method is one method to identify the severity level of drought contained in a rain data series in an area. To obtain the drought index by the Palmer method, several main parameters are needed. The main parameters are evapotranspiration, soil moisture filling, and loss of soil moisture. To obtain these parameters, the Thornthwaite water balance method can be used. In addition to the main parameters mentioned above, the Thornthwaite water balance method can result in other parameters related to calculations, including potential evapotranspiration, potential replenishment of moisture into the soil, potential surface runoff, and potential soil loss.

The calculation of the water balance of Thornthwaite method involved several steps. (1) The values of the four climate constants, which are the evapotranspiration coefficient ($\alpha$), charging coefficient ($\beta$), runoff coefficient ($\gamma$), water loss coefficient ($\delta$), and climate characteristics ($\kappa$) were determined. (2) The Climatically Appropriate for Existing Conditions (CAFEC) value was determined; this value is the estimation of parameters of evapotranspiration, runoff, recharge, precipitation, and loss that are climatologically in accordance with the conditions of time and place of testing. (3) The period of rain loss ($d$) was determined. (4) The average value of $d$ was obtained to obtain the absolute value ($D$). (5) The value of the second approach to the value of the $K$ factor ($\kappa'$) was obtained. (6) The value of climate character as a weighting factor ($K$) was obtained. (7) The moisture deviation (anomaly) index ($Z$) was calculated. (8) The Palmer method drought index value was obtained.

3.7. Drought Index Mapping

After obtaining the drought index value, the value is then displayed on the drought distribution map. The drought index classification can be seen in Table 1.

<table>
<thead>
<tr>
<th>Drought Index</th>
<th>Nature of Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 4.00$</td>
<td>Extreme Wet</td>
</tr>
<tr>
<td>3.00 – 3.99</td>
<td>Very Wet</td>
</tr>
<tr>
<td>2.00 – 2.99</td>
<td>Rather Wet</td>
</tr>
<tr>
<td>1.00 – 1.99</td>
<td>Slightly Wet</td>
</tr>
<tr>
<td>0.50 – 0.99</td>
<td>Early Interval Wet</td>
</tr>
<tr>
<td>0.49 – (-0.49)</td>
<td>Normal</td>
</tr>
<tr>
<td>-0.50 – (-0.99)</td>
<td>Early Interval Dry</td>
</tr>
<tr>
<td>-1.00 – (-1.99)</td>
<td>Slightly Dry</td>
</tr>
<tr>
<td>-2.00 – (-2.99)</td>
<td>Rather Dry</td>
</tr>
<tr>
<td>-3.00 – (-3.99)</td>
<td>Very Dry</td>
</tr>
<tr>
<td>$\leq -4.00$</td>
<td>Extreme Dry</td>
</tr>
</tbody>
</table>
The depiction of drought distribution map utilized the ArcGIS 10.2 software with the IDW interpolation method.

3.8. Hydrological Drought Analysis

According to Loukas A. et al. (2007) the discharge data from the AWLR Station can be normalized using Box Cox transformation and standardized to obtain the hydrological drought index. Box Cox Transformation \( Y \) values are obtained by the following formula:

\[
Y = \begin{cases} 
\frac{X^\lambda - 1}{\lambda}; & \lambda \neq 0 \\
\ln(X); & \lambda = 0
\end{cases}
\]  

(5)

The value of standardized Box Cox Transformation \( Z \) is obtained with the following formula:

\[
Z = \frac{Y - \bar{Y}}{\sigma_Y}
\]  

(6)

From AWLR discharge data \( X \), with assistance by Minitab 18, the \( \lambda \) value was obtained and used as a coefficient to perform the transformation of AWLR discharge data into the value of \( Y \). Furthermore, the data transformation result was subtracted by the average value of AWLR discharge data transformation \( \bar{Y} \) and divided by the standard deviation of the AWLR discharge data transformation \( \sigma_Y \) to obtain the standardized value \( Z \). This \( Z \) value was used as the hydrological drought index.

3.9. Analysis of the Relationship between Meteorological Drought and Hydrology Indices

Analysis of the relationship between the meteorological drought and hydrology indices was performed using correlation analysis. Correlation analysis is a statistical tool to determine the degree of the linear relationship between one variable and another, to find the direction and strength of the relationship between two variables (Qudratullah, M. F., 2014). Correlation analysis utilized the Pearson product moment correlation coefficient \( r \). In addition to correlation analysis, the relationship between the two drought indices utilized regression analysis by constructing \( xy \) scatter graphs to assess the closeness of the relationship between rain measurements and discharge data.

4. Results and Discussion

4.1. Analysis of Rainfall Data

From the thirteen rain measuring/gauge stations, the monthly regional average rainfall for fifteen years (2004-2018) was obtained, as shown in Figure 2 below.

![Figure 2. Graph of Monthly Regional Average Rainfall in Bedadung Watershed](image-url)
From the selected measured rainfall data, the monthly average rainfall analysis was performed for each rain station. The monthly average rainfall was used to find out patterns and variations of the monthly average, maximum, and minimum rainfall in the study area. This is displayed in Figure 3.

![Figure 3. Monthly Average Rainfall Patterns in Bedadung Watershed](image)

Source: Analysis Results

From Figure 3 it can be concluded that there were 3 dry months from July-September, 2 humid months in June and October, and 7 wet months from November-May.

4.2. Calculation of the monthly difference between P and EP

The amount of rainfall (P) is subtracted by the potential evapotranspiration (EP) value, and the difference was used to determine the value of deficit and surplus in Bedadung Watershed.

![Figure 4. Graph of Rainfall (P) against Potential Evapotranspiration (EP)](image)

Source: Analysis Results

From Figure 4, the average value of the calculated difference between monthly average rainfall and monthly average potential evapotranspiration (P-EP) Bedadung Watershed showed that in the study location there was a water deficit (P-EP < 0) for 6 months from May-October, and from November-April there was a water surplus (P-EP > 0).
4.3. Water Holding Capacity Analysis

The value of excess retained soil or soil moisture at field capacity (STO) is the same as the water storage capacity or Water Holding Capacity (WHC) (Jannah, 2015). Calculation of the value of water holding capacity (WHC) was performed at each rain gauge station in the study area, with the assistance of the ArcGIS 10.2 software. Then, the overlay of the maps of Thiessen polygons, soil texture, and land cover was created (Figure 6). The combined resulting overlay map resulted in the area of land cover against soil texture in the area of each Thiessen polygon. The area is represented as percentage areas. To obtain the WHC value, the percentage area from the overlay result was multiplied by the length of the root zone and the available water to obtain the WHC value at each rain gauge station.

4.4. Drought Index

From Table 2, using the monthly average Palmer drought index value, there were 5 dry months starting from June being Slightly Dry ($IKM_{Palmer} = -1.465$) and ending with October being Extremely Dry ($IKM_{Palmer} = -8.090$). The lowest $IKM_{Palmer}$ value = -14.140 occurred for September.

4.5. Drought Index Mapping

The map of monthly drought index distribution was further overlaid with the sub-district boundaries to find out whether the sub-district area, as stated in Government of Jember Regency Regional Regulation No. 1 of 2015 on Regional Spatial Planning for 2015-2035 Article 38 Section (14) as a drought-prone area, conforms to drought analysis using the Palmer method. The areas of concern are the Patrang, Jelbuk, Arjasa, and Panti Sub-Districts.

Based on the analysis of the drought distribution map (Figure 7), all sub-districts in the study area experienced drought with varying durations. The sub-districts of Panti, Patrang, Jelbuk, and Arjasa had a duration of drought of 5 months. Whereas, the sub-district area within the study location had a drought duration of 4 months.

From the analysis results, the four sub-districts are included as areas that experience drought with a duration of 5 months, the longest duration compared to other sub-districts. Therefore Government of Jember Regency Regional Regulation No. 1 of 2015 appropriately includes Patrang, Jelbuk, Arjasa, and Panti Sub-Districts as drought-prone areas based on Palmer's drought index method.
Table 2. Summary of the Monthly Average Palmer Method Drought Index Value in Bedadung Watershed

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
</table>

|------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|

Source: Analysis Results

4.6. Analysis of the Relationship of AWLR Discharge with Monthly Regional Average Rainfall of the Rainfall Area

Figure 7 shows the relationship between the monthly regional average rainfall processed from data from the Department of Public Works and Water Resources of Jember Regency and the AWLR discharge data obtained from the Rowotamtu water estimation post managed by the Department of Public Works and Water Resources of the Province of East Java.

4.7. Analysis of the Relationship between the Meteorological Drought and Hydrology Indices

To obtain the value of the drought index in the Bedadung watershed, area analysis calculation was then performed by multiplying the drought index value of each rain gauge station from 2004-2018 with the weighted area of Thiessen polygon distribution for each rain gauge station.

The value of AWLR Discharge Standardized Box Cox Transformation (Z) can be used as an index of hydrological drought.
Figure 6. Map of Monthly Average Drought Distribution from 2004 - 2018 for the Sub-District Area

Source: Overlay Results from ArcGIS 10.2
Figure 7. Relationship of Monthly Regional Average Rainfall of the Rainfall Area with AWLR Discharge

Source: Analysis Results
Figure 8. R Value of the Relationship between Hydrology and Meteorology Drought Index  
Source: Analysis Results

Figure 8 shows that the relationship between the meteorology drought and hydrology indices has a value of $R^2 = 0.8184$; this indicates that the two drought indices have a close relationship with each other. In addition to regression analysis, the relationship between the two drought indices can be seen through correlation analysis. The Pearson correlation coefficient indicated a value of $r = 0.905$. The interpretation of this value is that the meteorological drought index by the Palmer method and the hydrological drought index (the value of AWLR Discharge Standardized Box Cox Transformation ($Z$)) have a unidirectional relationship, indicated by the positive correlation sign. The conclusion is that if the meteorological drought index shows a dry month, then the hydrological drought index also tends to show a dry month, or if the meteorological drought index indicates a wet month, then the hydrological drought index also tends to show a wet month. Besides having a unidirectional relationship, the correlation value also shows that the two drought indices have a very strong or significant relationship.

5. Conclusion

From the results of processing, calculation, and analysis, the following conclusions can be drawn:
1. The value of the Palmer method monthly average drought index shows dry months ranging from -1.820 (June average) to -14.140 (September average of). The distribution of the monthly average drought index was found. From the map of the distribution of monthly average drought, it can be seen that the Panti, Patrang, Jelbuk, and Arjasa Sub-Districts have a drought duration of 5 months, from June to October. The sub-districts in the other areas of the study have a drought with a duration of 4 months.
2. From the figure showing the pattern between rainfall and discharge, there is a similarity in that in wet months, the rainfall and discharge have greater values than in dry months.
3. Based on the estimation results of the Pearson correlation coefficient, this resulted in the value of $r = 0.905$. The positive correlation sign indicates that the meteorological drought index of the Palmer method and the hydrological drought index (the value of AWLR Discharge Standardized Box Cox Transformation ($Z$)) have a unidirectional relationship. In addition, the correlation value shows that the two drought indices have a very strong or significant relationship. Regression relationship analysis shows that the value of the relationship between the meteorology drought and hydrology indices is $R^2 = 0.8184$, which indicates that the two drought indices have a close relationship with each other.

To further increase accuracy, further studies are recommended to consider the following:
1. It is necessary to conduct research on different watershed locations to make further real conclusions.

2. To obtain more accurate analysis results, a narrower study area and a greater length of historical rain data are needed.

3. Further research needs to verify the relationship between AWLR discharge and model discharge.

4. Further research needs to look into the relationship among meteorological, hydrological, and agricultural drought.

Significant attention needs to be given on the form of management directions for drought disaster areas, such as the construction of village retention basins in the upstream area of the Bedadung Watershed.

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[1] Regional Regulation of Jember Regency No. 1 of 2015 on the Regional Spatial Planning / Rencana Tata Ruang Wilayah (RTRW) of Jember Regency Government


