Identification of hydroclimatic patterns and trends in the new capital of Indonesia

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Abstract. The Indonesian government has recently begun massive construction of a new capital city, e.g., Ibu Kota Nusantara (IKN) in East Kalimantan province. IKN will become a futuristic city combining modern infrastructures covered with green environments with a vision of achieving low, or even zero, carbon emission by 2023. It is crucial to identify and obtain available data from any nearby sources prior initiating to set-up environmental monitoring systems for the land-water-air on the site. The objective of this study is to find hydroclimatic patterns and aim to produce trends of climatic parameters, patterns of wet and dry seasons, occurrences of rainstorms risks causing floodings, and fluctuations of dryness index. The parametric linear model and non-parametric Mann-Kendall (MK) test will be used to evaluate and judge the significant trends in the annual climatic parameters. The water balance equation making up the daily rainfall and evapotranspiration will be applied to mark a transition date between wet and dry season. Furthermore, the Gumbel model will be used to uncover occurrent probability of rainstorms, and rainfall deficit will be referred to describe dryness index. The result of the study will provide valuable information on managing environments by revealing patterns and trends of the parameters.

1. Introduction

Indonesia Government has launched a new capital namely Ibu Kota Nusantara (IKN) in East Kalimantan province in which a massive construction is currently underway. IKN will become a futuristic city combining modern infrastructures covered with green environments and purposely would result in low, or even reach net zero, carbon emission from 2023. IKN then will be covered by at least 70% of intact forests and green landscapes in the city. Approximately 256,142 ha have been allocated for the IKN, with 56,180 ha designated for the central government area and 199,962 ha set aside for development [1].

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For this, IKN needs to check environmental entities to watch how the pursued targets perform and to decide what actions are to be done when there are unexpected deviations.

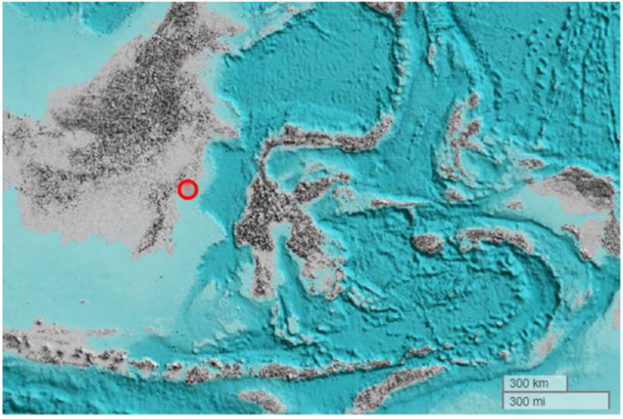
East Kalimantan Province was selected by the government as the location for IKN was based on various considerations. The government cited several reasons, including low disaster risk, a central location within Indonesia, and comprehensive infrastructure. The United States Geological Survey (USGS) reports that East Kalimantan experiences a low frequency of earthquake [1]. Furthermore, the IKN site is located relatively far from active volcanoes, reducing the risk of seismic disasters. However, the potential for hydroclimatic disasters has not been thoroughly examined.

Knowing that as a new developed area, IKN has limited data of the environmental conditions, it is necessary to search and collect the available data from any nearby sources while starting to set-up environmental monitoring systems for the land, the water and the air in the site. Environmental parameters cover the nexus of land, water and air. This data ought to be analysed using proper methods to obtain specific pictures of the environmental status in the site and its neighbouring areas. The analysis shall supply patterns and trends of the parameters as valuable information on managing environments.

This research will find hydroclimatic patterns and aim to produce: 1) trends of climatic parameters, 2) patterns of wet dan dry seasons, 3) occurrences of rainstorms risks causing floodings, and 5) fluctuations of dryness index. Understanding detailed hydroclimatic patterns in IKN will enhance urban planning quality, thereby helping to minimize the potential impact of future hydrometeorological disasters.

2. Methodology

The most represented weather station for IKN is Balikpapan station (Figure 1). We noticed the closest BMKG climate station in Balikpapan has been recording daily data of relative humidity (RH), minimum, average and maximum temperature (Tn, Ta, and Tx), rainfall (R), wind velocity (U) and sunshine duration since 1982 to the present (41 years). The data will be applied to calculate ET (Potential Evapotranspiration) using the most correct ET model confirmed with ET data measured by a specific weather station.



Sumber Peta: Map Service BMKG - Peta Rupa Bumi Indonesia skala 1:50.000

Fig. 1. Location of the Balikpapan weather station

Herewith, the parametric linear model and non-parametric Mann-Kendall (MK) test will be used to evaluate and judge whether there are significant trends of the annual climatic parameters. The linear model will result in the slope (S) and correlation coefficient (R). The linear model to identify climate trends is written as follows:

$$y = a\,x + b \tag{1}$$
$$a = \frac{\Sigma(x-\bar{x})(y-\bar{y})}{\Sigma(y-\bar{y})^2} \tag{2}$$
$$b = \bar{y} - a\,\bar{x} \tag{3}$$
$$r \ = \frac{\Sigma(x-\bar{x})(y-\bar{y})}{\sqrt{\Sigma(x-\bar{x})^2 \Sigma(y-\bar{y})^2}} \tag{4}$$

Where y is annual climatic variable, x is time (year), a is slope, b is intercept, and r is the coefficient of correlation. A positive trend is when S and R have positive signs or else the trend is negative. While the Mann-Kendal test will decide whether this trend is significant subjected to a set confidence limit (CL, say 95%) of the normal distribution (ND). The trend is significant when the absolute score of MK is higher than the score of ND. The Mann-Kendal method for justify climate trend analysis can be written as follows:

For time series $X = \{x_1, x_2, \dots x_n\}$, test statistics are as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} a_{ij} \tag{5}$$

$$a_{ij} = sign(x_j - x_i) = sign(R_j - R_i) = \begin{Bmatrix} 1 \ if\ x_j - x_i \ > \ 0 \\ 0 \ if\ x_j - x_i \ = \ 0 \\ -1 \ if\ x_j - x_i \ < \ 0 \end{Bmatrix} \tag{6}$$

In which, R_i and R_j are the order of observations x_i and x_j from the time series. Sign function whose value is 1, 0 or -1 and whose value depends on whether $(x_j - x_i)$ is positive, zero or negative. A positive S-value indicates an increasing trend, if the S-value = 0 there is no trend, and a negative S-value indicates a decreasing trend. The distribution of the S values can use the normal distribution approach with mean $E(S)$ and variance $Var(S)$ as follows.

$$E(S) = 0 \tag{7}$$

Where n is the amount of data. The presence of bound sequences in the data reduces the variance of S to:

$$Var(S) = n(n-1)(2n+5)/18 - \sum_{j=1}^{m} t_j(t_j - 1)\,(2t_j + 5)/18 \tag{8}$$

Where m is the number of bound sequence groups, each with one observation t_j. The hypothesis is tested using the Z-test, as follows:

$$Z = \begin{Bmatrix} \frac{(S-1)}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{(S+1)}{\sqrt{Var(S)}} & if\ S < 0 \end{Bmatrix} \tag{9}$$

Where Z is the standard value of the normal distribution and α is the confidence level (α=90%).

The water balance equation making up the daily rainfall and potential evapotranspiration (ET) will be applied to mark a transition date between wet and dry season. Here, Hargreaves model was used to estimate ET. The formulation of ET according to the Hargreaves model is following equations:

$$ET = 0.000939\ (Ta\ +\ 17.8)\ (Tx - Tn)0.5\ Ra \tag{10}$$

ET is potential evapotranspiration (mm d^{-1}), Ra is the extraterrestrial radiation (MJ m^{-2} d^{-1}), Tx is the maximum daily temperature (°C), Tn is the minimum daily temperature (°C), and Ta is the average daily temperature (°C). The value of Ra is obtained from the following equations:

$$Ra = 37.6\, dr\, [\omega s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega s)] \tag{11}$$

$$dr = 1 + 0.033 \cos(0.0172J) \tag{12}$$

$$\omega s = \arccos[-\tan(\varphi) \tan(\delta)] \tag{13}$$

$$\varphi = \frac{\pi L}{180} \tag{14}$$

$$\delta = 0.409 \sin(0.0172J - 1.39) \tag{15}$$

In this context, J represents the day number in the Julian calendar, L denotes the latitude (positive for north and negative for south), dr is the relative distance between the Earth and the Sun, ωs signifies the sundial angle, φ is the latitude in radians, and δ is the solar declination angle.

The transition date is determined when the net daily rate of rainfall and evapotranspiration (ET) equals zero. Furthermore, the wet season occurs as the net value is positive while the dry season happens as the net value is negative. Here, the daily rate is the first derivative of a continuous interpolation equation standing for accumulated daily data in a year. The available rainwater in each season can be calculated from the difference between accumulated rainfall and ET. Furthermore, the Gumbel model will be used to uncover occurrent probability of rainstorms. The Gumbel method is written as follows:

$$y = e^{-e^{-(x-m)/a}} \tag{16}$$

$$y' = \frac{dy}{dx} = -\frac{1}{a} y u \tag{17}$$

$$y'' = \frac{d^2y}{dx^2} = -\frac{1}{a}\left[y'u - \frac{1}{a}u^2 y\right] \tag{18}$$

$$u = -e^{v} \tag{19}$$

$$v = -\left(\frac{x-m}{a}\right) \tag{20}$$

Where y is Cumulative Distribution Function (CDF) of the daily rainfall (x), y' is Probability Density Function (PDF), y'' is inflection point, and m and a are fitted parameters. The rainfall deficit will be referred to describe dryness index.

3. Results

3.1 Climate

Figure 2 shows the annual climate data of Balikpapan from 1982 to 2023 and their trends. The results shows that the air is getting hotter with a 41-year increase in minimum, maximum and mean temperature of 2.70 °C, 0.50 °C and 0.80 °C, respectively, with a decrease in RH of 0.03%.

Climate change can also result in more variable rainfall patterns [5,6] and an increase in extreme weather events [7]. The annual rainfall in IKN ranges from 2,584.0 mm y^{-1} to 2,925.2 mm y^{-1} [8], showing an increasing trend over the past twenty years. Over a period of 41 years, R increased with time by 11.95 mm y^{-1} and ET decreased with time by 0.43 mm y^{-1}. The water balance (WB) varied between surplus and deficit, but it showed an upward trend over time of 12.38 mm per year, suggesting that the air is becoming more humid. Consequently, flooding and inundation are more common, especially in central cities with impervious surfaces, leading to pluvial flash floods followed by prolonged dry periods [9].

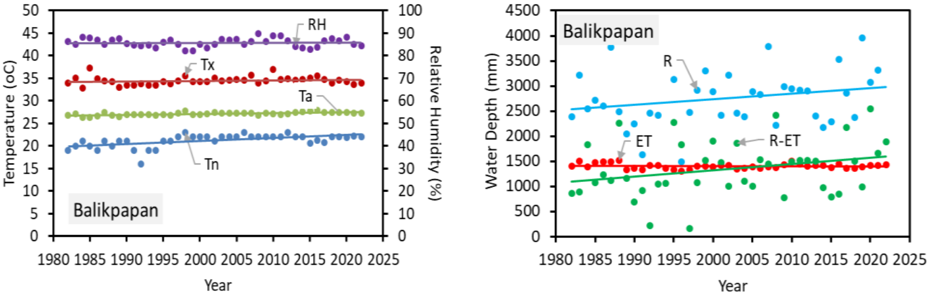


Fig. 2. Climate trends and changes in Balikpapan from 1982-2022. Tn is the minimum temperature. Ta is the average temperature, Tx is the maximum temperature, RH is the relative humidity, R is rainfall, ET is evapotranspiration, and R-ET is water balance which is rainfall minus evapotranspiration.

3.2 Monthly Water Balance

Figure 3 shows the monthly averages of R, ET, and WB (R-ET) in Balikpapan from 1982 to the present. Over the 41-year period, the average WB value is positive, indicating surplus rainwater throughout the year. However, there is a deficit in the standard deviation value during September, October, and November, which marks the peak of the dry season. The minimum annual rainfall occurs in September, measuring 177±116 mm, while the ET value for the same month is 115±7 mm, resulting in a WB surplus of 62±116 mm. The maximum surplus water depth for the year is in June, with a value of 178±154 mm, derived from R of 281±152 mm and ET of 103±5 mm.

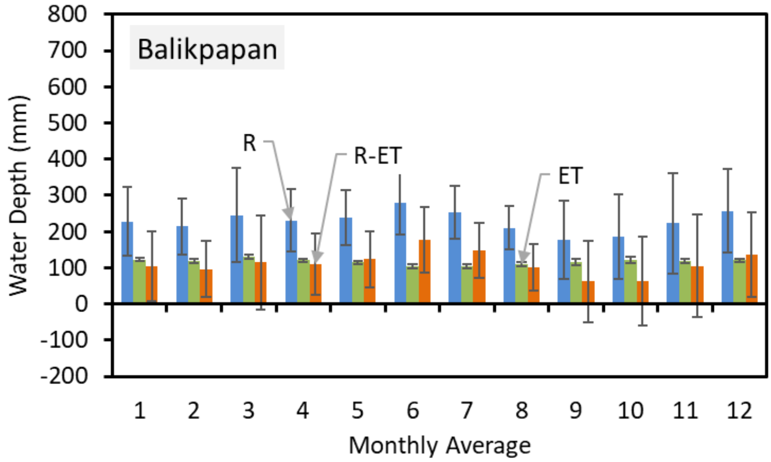


Fig. 3. The average of monthly water balance in Balikpapan from 1982-2022. R is monthly rainfall, ET is monthly evapotranspiration, and R-ET is monthly water balance which is rainfall minus evapotranspiration.

3.3 Rainstorm

Based on 41 years of climate data for Balikpapan, the maximum, minimum, and mean of average daily rainfall (Rx) are 223 mm, 67 mm, and 126.6±38.7 mm, respectively. This extensive dataset enables the calculation of relevant return periods (up to 5-10 years) with minimal statistical uncertainty. Supporting climate data, such as daily rainfall, can reduce errors in analysis and modelling [10]. Figure 4 illustrates the cumulative distribution (CD) of mean daily rainfall (Rx) data using the Gumbel distribution and the return period (RP) of mean daily rainfall. From Figure 3, it is evident that the mode of daily rainfall in Balikpapan is 110 mm, with a return period of 1.6 years.

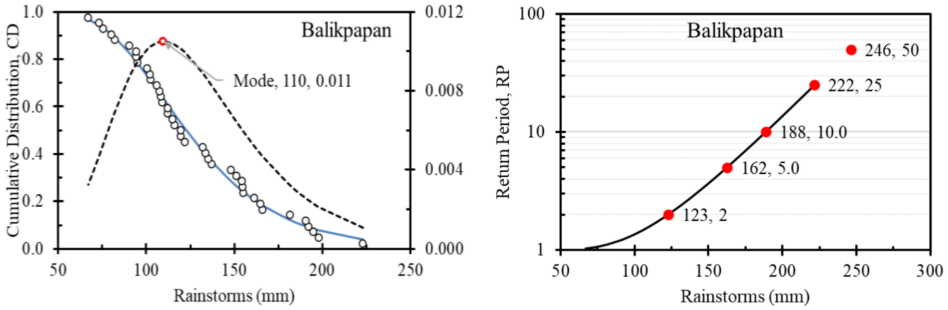


Fig. 4. The maximum daily rainstorm probability and their return periods

Figure 4 also includes analyses of rainstorm values for various return periods. In Balikpapan, the rainstorm returns periods for 2, 5, 10, 25, and 50 years are 123 mm, 162 mm, 188 mm, 222 mm, and 246 mm, respectively. The R80 most expected rainfall in this study was found to be 93 mm, with a return period of 1.25 years.

3.4 Season Calendar

Figure 5 illustrates the annual pattern of dry season (DS) and wet season (WS) periods in Balikpapan. Located in the equatorial region, Balikpapan experiences one DS and one WS each year. Previously, it was difficult to clearly identify the DS in such equatorial region [11]. This research has successfully addressed that challenge. The WS spans from the end of the year to the first half of the following year, approximately from November to May. The DS occurs from the middle to the end of the year, around May to November.

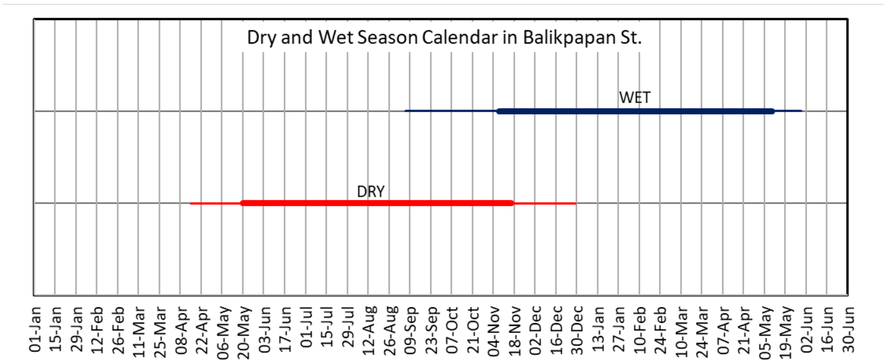


Fig. 5. Wet and dry period in Balikpapan for a year

3.5 Dry Season and Dryness Index

The cumulative distribution function (CDF) for the start, peak, and end of the DS over 41 years in Balikpapan was determined based on the probability of the specific days these events may occur. The probability that the start, peak, and end of the DS will be less than or equal to the largest possible value is one. The R^2 value for all CDFs exceeds 0.99, indicating that the model is reliable. A probability density function (PDF) derived from the CDF illustrates the probability of the start, peak, and end of the DS occurring on specific days. Figure 6 highlights the days with the highest probability for the start, peak, and end of the DS in Balikpapan.

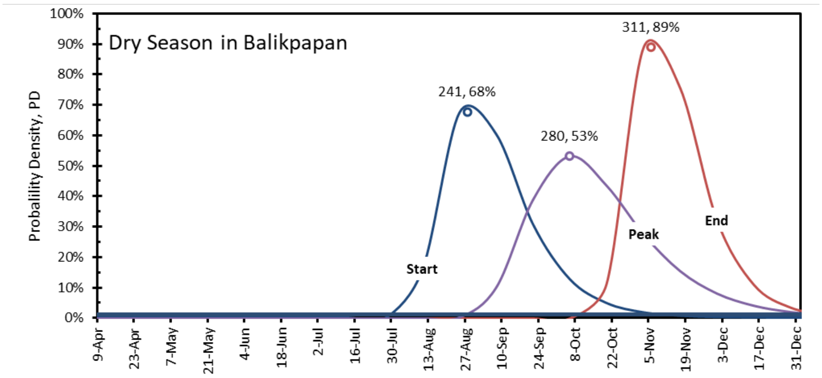


Fig. 6. The peak and the highest probability of the start, peak, and end of the dry season in Balikpapan

From Figure 6, it is evident that the peak start of the DS in Balikpapan occurs on the 241st day of the year, around August 28th, with a 68% probability. The peak of the DS itself is on the 280th day, approximately October 7th, with a 53% probability. The peak end of the DS falls on the 311th day, around November 7th, with an 89% probability.

Figure 7 depicts the fluctuations in the dryness index for Balikpapan over a span of 41 years. The results indicate that the peak of dry period consistently occurs from the middle to the end of the year. This dryness index supports the findings illustrated in Figure 5 and Figure 6 in this study.

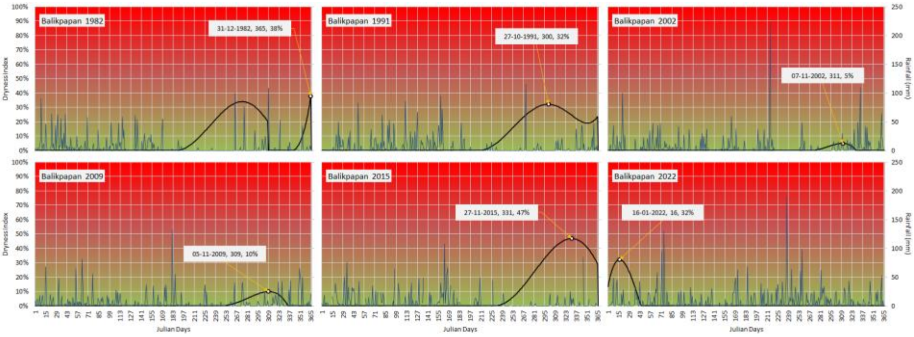


Fig. 7. The fluctuations of dryness index of Balikpapan from 1982-2022

4. Discussions

Rising temperatures have led to seasonal changes and surface soil drying. Among meteorological factors, the maximum air temperature is most strongly correlated with drought and the number of hotspots, more so than mean air temperature, minimum air temperature, and relative humidity [2]. However, the mean air temperature also influences the heat component in the air, contributing to the number of hotspots [3,4].

The combination of increasing temperatures and decreasing precipitation has shifted seasons and dried the soil surface. Daily rainfall, daily maximum air temperature, and daily mean air temperature are key triggers for forest and land fires [12]. Rainfall indirectly affects drought by influencing fuel moisture [13]. Maximum air temperature has a higher correlation with drought and hotspots compared to other meteorological parameters [9], but the relationship between mean air temperature and the number of hotspots can have a positive effect on increasing the heat component in the air [10,11]. On the other hand, climate change could also lead to more variable rainfall patterns [2,3] with an increasing number of extreme events [4]. As a result, flooding and inundation are occurring, particularly in central cities with impervious surfaces. These events, known as pluvial flash floods, are followed by long dry spells [6].

Another study by [14] indicates that climate change can raise air and surface temperatures, as well as the intensity and duration of rainfall. This study's findings show that the IKN region has experienced climate change, evidenced by altered rainfall patterns, changes in the number of rainy days, and a trend of decreasing annual rainfall and its distribution. These findings align with those of studies [15] and [16] which observed that several regions in Indonesia are experiencing climate change. In some areas, there are signs of rising air temperatures, shifts in monthly and annual rainfall distribution patterns, and changes in seasonal classification.

The monthly water balance results of this study align with the findings of [17]. December and April, which have low frequency of occurrence, experience high monthly rainfall (>200 mm/month) across all domains in IKN. Conversely, the months with the highest frequency of drought events vary between domains. This indicates that the distribution pattern of droughts and hotspots in IKN is closely related to atmospheric conditions and climate events in the area. Climate change is expected to bring more wet days and higher temperatures, impacting the water balance by increasing evapotranspiration [18].

Currently, the land in IKN is largely covered by green vegetation, though some areas have been cleared for construction. During the dry season, this vegetation is highly susceptible to fire, while the constructed areas are prone to flooding during the rainy season. Drought reduces the moisture content of vegetation, making it more flammable [19], while pavement reduces water infiltration, leading to flooding. Data from the Indonesian National Board for Disaster Management (BNPB) indicates that forest and peatland fires are most intense and frequent during the peak dry season from June to October (BNPB, 2019). These findings support this study, suggesting that the seasonal calendar pattern shown in Figure 5 can serve as an early warning for forest fires and flooding. Previous studies have developed tools and communication systems for early warning, prevention, control, and post-fire and flooding management. [20–23].

5. Conclusions

The mean temperature increased by 0.02 °C y^{-1} in Balikpapan, and from 1982 to 2023 the mean temperature increased by 0.8 °C. R increased by 11.95 mm y^{-1} and ET decreased by 0.43 mm y^{-1}. The most frequent rainstorm in these provinces was 110 mm with a return period of less than 2 years. There are 1 dry season in a year, occurring from May to November with the highest probability of 89%. The dryness index indicate that the dry period consistently occurs from the middle to the end of the year. These results provide valuable information on managing environments, especially to anticipate extreme wet and dry seasons.

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