Characteristics and return period of hydrological drought base on reservoir capacity reliability: case study of Mamak Dam in Sumbawa Island, West Nusa Tenggara, Indonesia

I Wayan Yasa*

Civil Engineering Department,
University of Mataram,
Jl. Majapahit No. 62, 83125 Mataram, Lombok, Indonesia
Email: yasaiwayan68@unram.ac.id
*Corresponding author

Mohammad Bisri, Moch Sholichin and Ussy Andawayanti

Water Resources Engineering Department,
Brawijaya University,
Jl. MT Haryono No. 167 Malang 65145, Indonesia
Email: mbisri@ub.ac.id
Email: mochsholichin67@ub.ac.id
Email: uandawayanti@ub.ac.id

Abstract: The analysis of hydrological drought indices by using the reservoir will obtain an actual and real drought indefinite and have a clear physical meaning. In this research, we use daily data of the water level of reservoir, inflow and outflow. The research method used to obtain the hydrological drought index (HDI) is the water balance method in the reservoir. Based on selected distribution, for the estimation of drought in a certain return period using the log Pearson type III. The results showed that the extreme drought on Sumbawa Island took place on average for 265 days with a maximum deficit of $35,378 \times 10^3$ m^3 from the effective storage. The hydrological drought index (HDI) ranges from –1.31 to –0.01 with very severe drought criteria to weak drought. The hydrologic drought in the return period of 1, 2, 5, 10, 25, 50, 100 and 200 years, i.e., respectively –0.01, –0.54, –0.90, –1.04 and –1.12.

Keywords: drought; reservoir; El Niño; inflow; outflow; reliability; Indonesia.

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Biographical notes: I Wayan Yasa is working as an Associate Professor in the Department of Civil Engineering at Mataram University, West Nusa Tenggara, Indonesia. He completed his Doctor (Dr) in the Civil Engineering Department, Brawijaya University, Malang, Indonesia, in 2018. He is teaching the subjects of hydrology, irrigation and water resources development. He has also been actively involved with various researches on water resources management, hydrology, water allocation and drought analysis. He is a reviewer/editorial board member of SCOPUS indexed journals.

Mohammad Bisri is a Professor at the Water Resources Engineering Department, Brawijaya University, Malang, Indonesia He was involved in national and international collaborative research activities during his 30 years of professional career. His research interest includes research on ground water study, water resources management and hydrology modelling. He has some publications in SCOPUS indexed high impact journals and conferences.

Moch Sholichin is working as an Associate Professor in the Water Resources Engineering Department, Brawijaya University, Malang, Indonesia. He completed his PhD in the Malaya University (UM), Malaysia. After his PhD, he is teaching the subjects water quality, hydrology and water resources management. He has also been actively involved with various researches on water quality, hydrology modelling and rainfall forecasting.

Ussy Andawayanti is working as an Associate Professor in the Water Resources Engineering Department, Brawijaya University, Malang, Indonesia. She completed her Doctor (Dr) in the Brawijaya University, Malang, Indonesia. She is teaching the subjects of hydrology, irrigation, drainage and water resources management. She has also been actively involved with various researches on, hydrology modelling, rainfall forecasting and urban drainage.

1 Introduction

Climate is the average quantity of whether physical phenomena, which is the extreme variation of seasons that take place locally, regionally or globally. In a certain area, the weather can change rapidly from day to day even from hour to hour. Streamflow alteration is the most climate effects (Mishra et al., 2009). The drought phenomenon is one of many natural disasters occurring on around the world, as it is caused by reduced distribution and depth of rain for long periods of time (Bazrafshan et al., 2017; Haro et al., 2014; Niu et al., 2015), and at the time of the drought, there is very low rainfall variability, so that water resources management fails.

Hydrological drought is defined as a decrease in the quantity of water in all water bodies especially in rivers, reservoirs and subsurface water (Ma et al., 2015; Goyal et al., 2017). The impact of the hydrological drought event will be greatly influenced by the severity, duration of drought, and the flow capacity deficit or storage (Loon, 2015) and for the future drought severity will increase with climate change phenomenon (Bates et al., 2008; Fischer et al., 2013; Romm, 2011). The introduction of signs of drought needs to be identified early so that anticipated impacts can be minimised. The drought analysis approach is adapted to each region because it has different characters (Dracup et al., 1980; Loon and Laaha, 2015).

The occurrence of long rainfall deficits leads to a decrease in surface water/runoff which can then be indicated as an indicator of hydrological drought (Loon, 2015; Wang et al., 2016). Indicators of hydrological drought also refer to river flow, lake storage, reservoirs, and the presence of subsurface water. Some of the hydrological drought indices already applied in some countries are: streamflow percentile, standardised runoff index (SRI), surface water supply index (SWSI), or groundwater resource index (GRI) (Medicino et al., 2008; Shafer and Dezman, 1982; Shukla and Wood, 2008; Ma et al., 2015). Drought can also be monitored with several other indices such as: normalised difference vegetation index (NDVI), normalised difference water index (NDWI), or normalised multiband drought index (NMDI) (Basu et al., 2017).

The increase in a drought that occurs not only due to global warming but can be by other factors more intense (Trenberth et al., 2014). Quantification of the hydrological drought index (HDI) value with surface water has a very important role in the development and management of water resources (Lanen et al., 2013; Weng et al., 2015). This is so because most of the multi-sector water supply comes from surface water (Santos et al., 2011).

The hydrological drought is characterised by significant changes in the frequency, severity, duration and drought-affected areas (Hisdal et al., 2004). The duration of the hydrological drought is the accumulation of the duration of the drought deficit from the start to the end of the drought (Hisdal et al., 2004; Loon et al., 2014). According to Tallaksen and Hisdal (1997), the distribution and duration of drought is influenced by climate but capacity changes are more influenced by the characteristics of the catchment area. Pandey et al. (2008) defines that the severity of drought is a function of the ratio of the capacity of flow deficit to the required capacity. The drought index can be used to determine the severity of the drought area (Dai, 2011; Tate and Gustard, 2000; Smakhtin, 2001; Tallaksen and van Lanen, 2004; Yevjevich, 1967).

Reservoir is a very important facility in the water supply system and has many functions to hold water during the rainy season. The reservoir function is not only limited to the physical side such as capacity and flow but also depends on the needs and operating patterns. Further, noted that reservoir is an important facility in multi-sector water supply system with the main function is to regulate the fluctuating surface water flow (Shiau, 2003). There are still many mechanisms that can be done to identify drought as using surface water, subsurface water, evapotranspiration and water use for various sectors (Sun et al., 2011; Wong et al., 2013). Reservoirs have the advantage of being able to directly identify the severity of drought. The severity of drought based on capacity reservoirs is weak, medium, strong and very strong drought depending on the decrease in capacity of the reservoir (Yasa et al., 2018).

This study aims to obtain characteristics and return periods of drought events based on the reliability of the reservoir capacity. The benefits obtained are for monitoring drought events in the future that are beneficial in regulating and allocating water, especially in the event of El Niño. The limitation of the study is that the analysis study was carried out only based on the year of El Niño events, so the results of the analysis illustrate the real conditions of the severity of the drought that occurred.

2 Methodology

2.1 Study area

The study was conducted at Mamak Dam located in Sumbawa Island, West Nusa Tenggara Province, Indonesia. As one of the islands in Eastern Indonesia, Sumbawa Island is an island with an area dominated by a very wide dry land. The very low intensity of rain and the limited water source to make Sumbawa Island very difficult to increase agricultural production especially rice. The development and improvement of the people's economy in Sumbawa Island is currently more in the field of plantation and livestock.

Sumbawa Island is included in tropical climate area which tends to be humid, however, this area is drier when compared with other regions in Indonesia except East Nusa Tenggara. Maximum temperature ranges from 30°C–33°C and minimum temperature ranges from 20°C–25°C and humidity is between 40%–100%. There are two seasons that are influenced by the monsoon wind which is of course influenced by the relative position of the sun against the Earth. The dry Southeast monsoon wind results in the dry season (generally from May to October) and the wet North West wetlands causing the rainy season (generally from November to April) with the nature of rain generally below normal. Average annual rainfall in NTB is between 1,500 mm to 2,000 mm, smaller than the average annual rainfall of Indonesia which is about 3,000 mm.

Figure 1 Location map of the study area (see online version for colours)

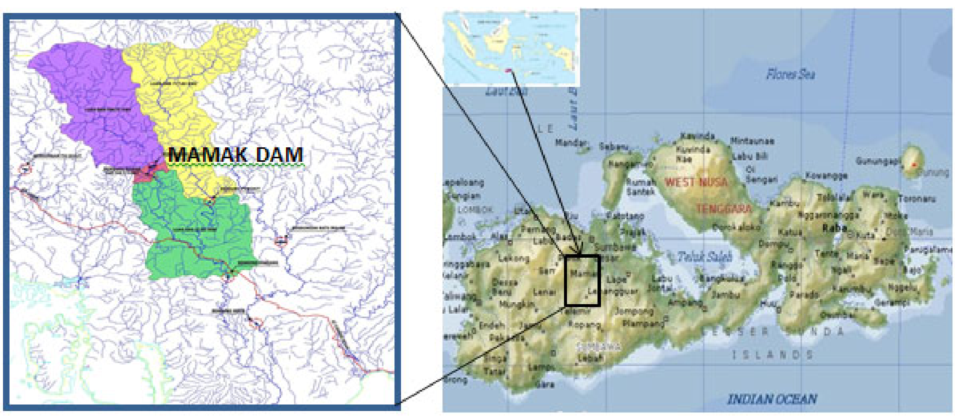


Table 1 Hydrometeorological data on Sumbawa Island

Hydrometeorological parameter	*Rainy season*	*Dry season*	*Annual average*
Maxsimum air temperature (°C)	28.0–29.2	27.6–30.4	28.8
Minimum air temperature (°C)	23.8–24.6	23.1–5.2	24.2
Maximum air humidity (%)	83.9–89.7	69.0–81.0	81.4
Minimum air humidity (%)	72.6–79.3	55.5–69.5	68.7
Average air pressure (mbar)	1.006, 0–1.007, 2	1.008, 7–.010, 8	1.008, 5
Solar irradiance (%)	55.2–79.8	79.6–94.2	80.5
Wind direction (°)	90–330	120–310	090/E
Speed wind (km/hour)	9.5–10.8	12.7–16.7	12.8
Rainfall (mm/month)/(mm/yr)	64–156.5	3–55.5	1.365
Annual rainfall (day/yr)	6–10	1–5	9

Source: Meteorology Climatology and Geophysics Council, West Nusa Tenggara Province

The Mamak Dam was built in 1992 located in Sumbawa Regency, West Nusa Tenggara Province is about 40 km towards east from Sumbawa city which is at coordinate 117°35’00" BT and 08°41’44" LS (Figure 1). Mamak irrigation network area includes several sub-districts of Lape, Lopok, Moyo Hilir and Moyo Utara. The location of the Mamak Dam is on the Mamak River with a total area of 107 km^2. The gross reservoir capacity is 41,143 × 10^6 m^3 and the effective capacity is 36,378 × 10^6 m^3. In addition to providing irrigation water, Mamak Dam is also used to serve the water needs for ponds, tourism areas and freshwater cultivation.

2.2 Methods

2.2.1 Decreasing and increasing lines of reservoir capacity

At the time of El Niño events, there is an imbalance between inflow and outflow, where the outflow is bigger than the inflow so that the reservoir capacity will decrease. This imbalance occurs in a very long period of time so that the reservoir capacity becomes the deficit. The filling of the reservoir capacity will occur when the El Niño event begins to end. Reduction and refill of reservoir water will form a line showing the line of decreasing and increasing of reservoir capacity.

2.2.2 Drought threshold

The threshold is an analysis that can be used to identify drought characteristics. A threshold can have a constant threshold and varying threshold. Constant thresholds are used throughout the year of the review whereas the varying thresholds have different values throughout the year such as daily variations. The setting of threshold values is used to determine:

a Threshold (Xo), which is the limit value determined based on analytical requirements.

b Xo which is Q50 is Qnormal with a probability of 0.5.

The red line in Figure 4 shows the specified threshold capacity. Furthermore, throughout the recording period, the capacity of the existing reservoir is statistically identified as the value of the discharge that falls below the threshold. The recording period in which the reservoir capacity is below the threshold, is expressed as a discharge deficit condition.

2.2.3 Hydrological drought index

The drought hydrological index is one of the common drought parameters used to determine the severity of the drought. The HDI is a deficit of the water capacity of the reservoir under normal water reservoir conditions.

$$I - O = \pm \Delta S \tag{1}$$

where

I reservoir inflow (m^3)

O reservoir outflow (m^3)

ΔS change in storage (m^3).

$$RDI = \frac{Vd}{Ve} \tag{2}$$

where

RDI reservoir drought index

Vd reservoir deficit (m^3)

Ve reservoir effective (m^3).

2.2.4 Distribusi frekuensi

In the analysis of the possibility of occurrence of a hydrologic event in future, statistical analysis is an important tool that can be used. Statistical analysis has the advantage of using measurable hydrological data, therefore it is still considered to have good validity. Some common frequency distribution equation used in hydrology includes normal distribution, normal logs, Gumbel, Pearson and log Pearson type III.

- mean

$$\overline{X} = \frac{1}{n\sum_{i=1}^{i} X_i} \tag{3}$$

- standard deviation

$$S = \frac{\sum_{i=1}^{i} X_i^2 \left\{\left(\sum_{i=1}^{i} X_i\right)/n\right\}}{(n-1)} \tag{4}$$

- coefficient of variation

$$C_v = \frac{S}{\overline{X}} \tag{5}$$

- skewness

$$C_s = \frac{n}{(n-1)(n-2)S^3}\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^3 \tag{6}$$

- kurtosis

$$C_s = \frac{n}{(n-1)(n-2)(n-3)S^4}\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^4 \tag{7}$$

Furthermore, the magnitude of the reliable value of a hydrological even can be determined using the following equation:

$$P = \frac{m}{n+1} \tag{8}$$

where

P probability

n amount of data

m serial number of data.

The following equations are used to calculate the design deficit capacity by the log Pearson type III method:

$$\log X = \overline{\text{Log } X} + k \times S_{\log x} \tag{9}$$

$$\overline{\text{Log } X} = \frac{1}{N} \sum_{i=1}^{n} \text{Log } X \tag{10}$$

$$S_{\log x} = \sqrt{\frac{\sum_{i=1}^{n} \left(\text{Log } X - \overline{\text{Log } X}\right)^2}{N-1}} \tag{11}$$

$$Cs = \frac{N \sum_{i=1}^{n} \left(\text{Log } X - \overline{\text{Log } X}\right)^3}{(N-1)(N-2)\left(S_{\log x}\right)^3} \tag{12}$$

where

$\text{Log } X$ logarithm of data

$\overline{\text{Log } X}$ the mean logarithm of data

$S_{\log x}$ standard deviation from the data logarithm

Cs coefficient of skewness

k frequency factor.

3 Data

3.1 Evaporation

At the time of the events of El Niño evaporation in the Mamak Dam is very high. The location of the reservoirs in dry land areas is also caused by the high sun exposure at the time of El Niño. The amount of evaporation causes the water loss from the reservoir to be high in addition to losses from seepage. The average daily evaporation occurring at the time of El Niño is 0.0045×10^6 m^3/day, maximum evaporation of 0.0074×10^6 m^3/day and minimum evaporation of 0.0020×10^6 m^3/day. The amount of evaporation occurring in the Mamak Dam is shown as in Figure 2.

Figure 2 Average evaporation of the reservoir at the time of El Niño (see online version for colours)

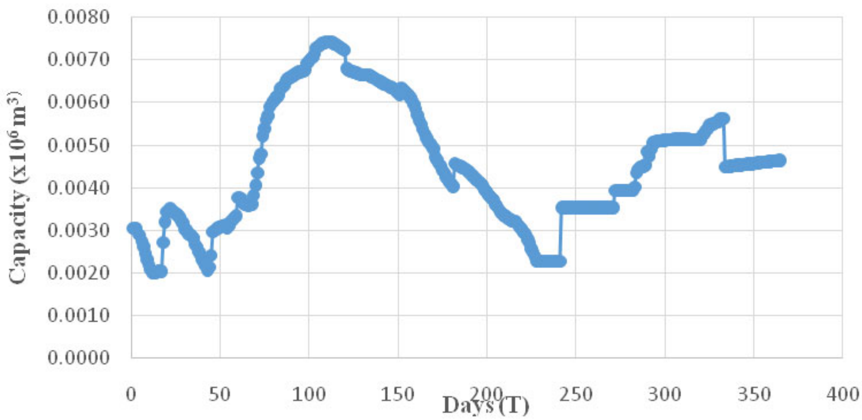
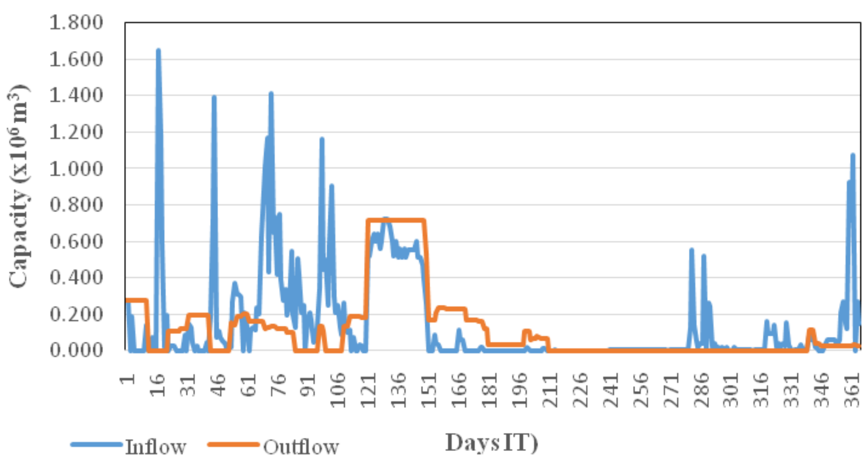


Figure 3 The average inflow and outflow of the reservoir at the time of El Niño (see online version for colours)



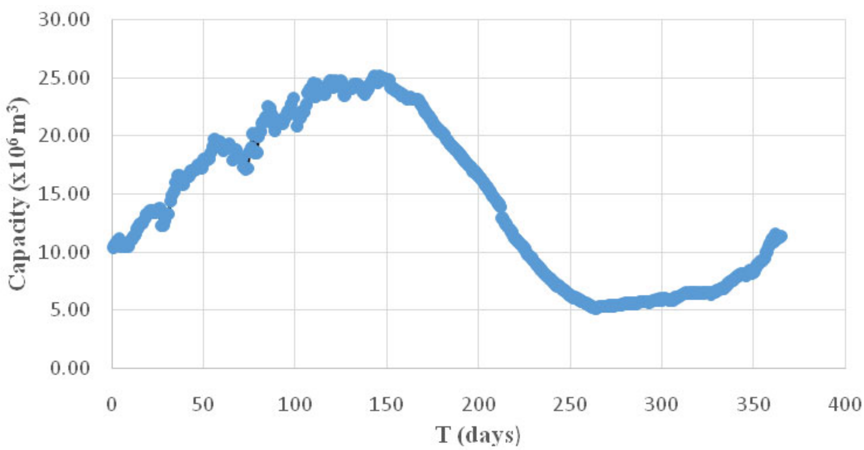
3.2 *Inflow and outflow*

Inflow of Mamak Dam is influenced by the amount of rainfall and flow from the river. While the outflow is affected by the loss of water due to evaporation, seepage and water coming out of the intake for irrigation water needs. At the time of El Niño, there was an imbalance between inflow and outflow of the reservoir. The water requirement at the time of El Niño is very high especially for irrigation water while the water entering the reservoir is very small especially during peak El Niño. The average data of inflow and outflow from the reservoir is obtained from the measurement directly and the result is shown as in Figure 3.

3.3 Reservoir capacity

The data collected were daily data such as reservoir inflow, water level, capacity, and outflow from 1995 to 2016. In the analysis of the HDI using the average data of reservoir capacity in the event of El Niño. The average of the Mamak reservoir capacity at the time of the El Niño event is shown as in Figure 4. From the picture shows that in the event of El Niño the decrease of reservoir capacity is very extreme under the effective capacity. The maximum reduction reached 35,378 mcm from the effective reservoir of 36,378 $\times 10^6$ m^3. The duration of the deficit of the reservoir capacity lasts for a very long period of one year and may last longer if the El Niño event is still going in the following year. In these conditions, the reservoir becomes very dry which affects the scarcity of water availability

Figure 4 The average capacity of the reservoir at the time of El Niño (see online version for colours)



4 Results

4.1 Decreasing and increasing lines of reservoir capacity

The reservoir capacity changes depending on the inflow and outflow at any given period. At the beginning of the El Niño event, an imbalance between inflow and outflow begins, where the outflow component is larger than the outflow. On average, El Niño decreases the capacity of the reservoir for ten months and can be more when El Niño continues until the following month. Figure 3 shows the curve of the reservoir capacity deficit at El Niño. The decrease in reservoir capacity is very extreme, so the available capacity is well below the effective storage. The most extreme reservoir deficit condition is the available water capacity of only 1.74 $\times 10^6$ m^3.

The decreasing line of the reservoir capacity takes place very quickly following the polynomial function. The condition can be more severe when the El Niño event continues until the following year. Figure 4 indicates the recharge line of the reservoir capacity. The charging line is so slow that to reach the effective storage takes a very long time.

Figure 5 Decreasing line of reservoir capacity (see online version for colours)

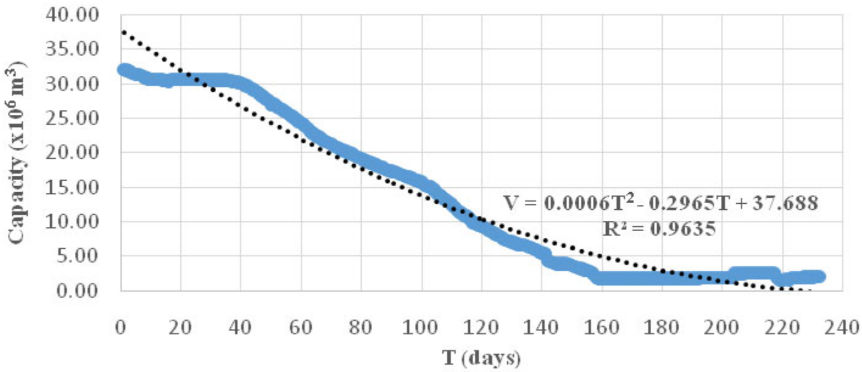


Figure 6 Increasing line of reservoir capacity (see online version for colours)

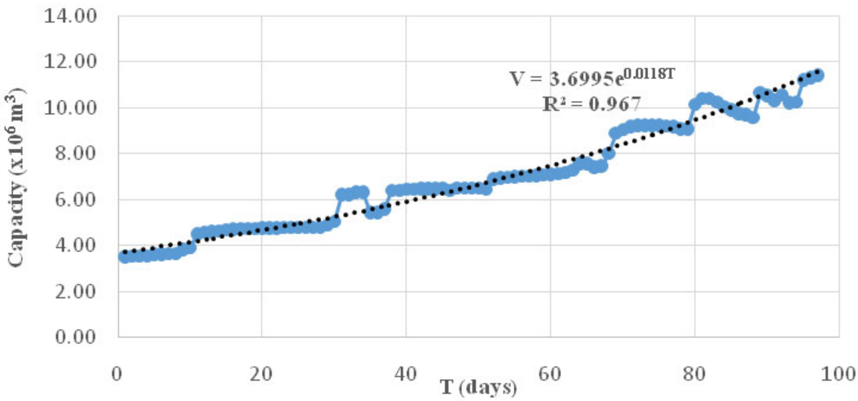
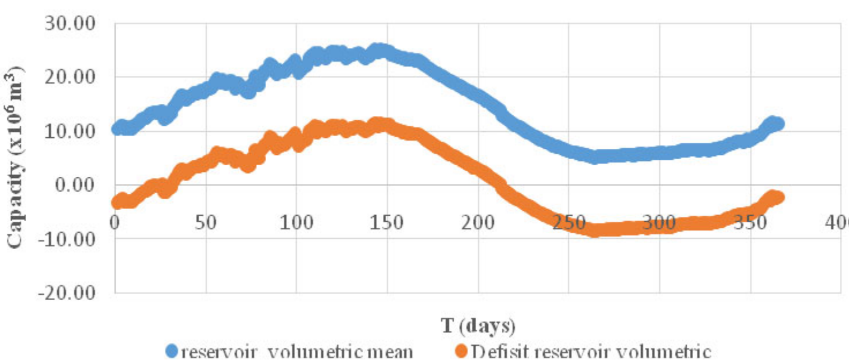


Figure 7 Average reservoir and deficit capacity of Mamak reservoirs at El Niño (see online version for colours)



4.2 Duration and deficit of hydrological drought

Duration of drought is the length of the process of decreasing the capacity of the reservoir up to recharge. While the drought deficit is a decrease in the capacity of the reservoir below the set threshold. Dry conditions if the capacity of the reservoir is smaller than the 50% normal reservoir threshold of 13.62×10^6 m^3. Based on the reservoir deficit duration curve, the maximum hydrological deficit is –8.46 mcm from 50% reservoir condition. The duration of the drought at El Niño lasts an average of 265 days.

4.3 Hydrological drought index

The threshold of reservoir capacity using the capacity of 50%. Dependable 50% is expected that at that capacity the availability of reservoir water is still able to the water requirement for crops. Based on the capacity of reservoirs, 50% capacity of the Mamak Dam is 13.62×10^6 m^3. Based on this, it shows that the hydrological drought condition of the Mamak reservoir is in wet, weak to very severe drought conditions. The drought conditions occur at the water level elevation of the reservoir below 84 m above SWL. Very severe HDI of –1.65 at an elevation of water level +77.40 m above sea level with a reservoir capacity of 5.14×10^6 m^3. While the weak drought indication of –0.05 on the water level of reservoir elevation +83.62 metre on sea level with a reservoir capacity of 11.16×10^6 m^3. Description of the HDI with capacity changes from the Mamak reservoir is as in Table 2.

Table 2 Criteria of drought based on reservoirs capacity

Reservoirs capacity (× 10^3 m^3)	*Hydrological drought index (HDI)*	*Drought description*
V ≥ 13.46	HDI ≥ 0.00	Wet
9.35 ≤ V < 13.46	–0.31 ≤ HDI < –0.01	Weak drought
5.88 ≤ V < 9.35	–0.96 ≤ HDI < –0.31	Moderate drought
4.69 ≤ H < 5.88	–1.31 ≤ HDI < –0.97	Severity drought
V < 4.69	HDI < –1.31	Very severity drought

When compared with the results of the study (Weng et al., 2015), it shows that the amount of the drought index is almost the same, namely: non-drought: HDI ≥ 0.00, mild drought: –1.00 ≤ HDI < 0.00, moderate drought: –1.50 ≤ HDI < –1.00, severity drought: HDI < –2.00 and extreme drought: HDI < –2.00.

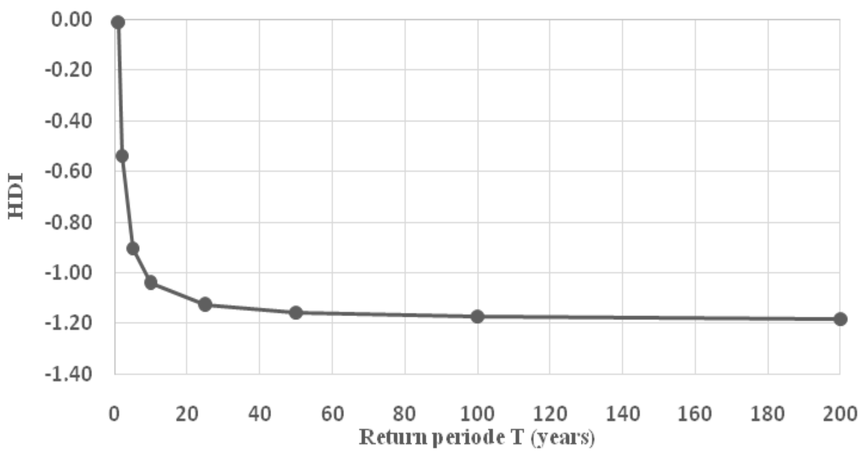
4.4 Return period of HDI

Log Pearson type III distribution is one method for estimating hydrological quantities in the future. In this study, the hydrologic drought index value was predicted in return periods of 2, 5, 10, 15, 25, 50, 100 and 200 years using equation (9). The statistical parameters of the Mamak reservoir HDI include standard deviation (sd) = 0.456, coefficient of variation (cv) = 0.280 and skewness coefficient (cs) = –1.912. The magnitude of the hydrologic drought index value for each return period is shown as in Table 3. Drought characteristic in each period is one year period of weak drought, 2 and 5 years period of moderate drought, return period 10, 25, 50, 100 and 200 years that is severe drought.

Table 3 Return period of HDI

Return period	*K*	*HDI*
1	–3.553	–0.01
2	0.294	–0.54
5	0.788	–0.90
10	0.920	–1.04
25	0.996	–1.12
50	1.023	–1.16
100	1.037	–1.17
200	1.044	–1.18

Figure 8 The relationship between return periods with the HDI



5 Conclusions

Based on the analysis of characteristics and return drought periods in the Mamak reservoir, it was shown that at the time of the El Niño phenomenon, the reservoir had a very extreme accommodation deficit of 35.378 mcm from the reservoir's effective reservoir. The drought period of the reservoir at the time of El Niño is almost 265 days within a year. The HDI of the Mamak reservoir ranged from –0.01 to –1.65 with the criteria of drought weak to very severe. Return periods of drought are successive one-year return periods of weak drought, return periods of 2, five years of moderate drought, return periods of 10, 25, 50, 100, and 200 years of severe drought.

The results of this study are very well applied in the management of water resources specifically to predict the return period of the severity of drought, and to make decisions in monitoring, navigating and anticipating droughts.

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