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The Characteristics of the Wala Dam Monthly Inflow and the Relationship between Inflow and Outflow

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ABSTRACT

This study investigates the main features of the Wala dam's monthly inflow and discusses the relationship between the monthly inflow and outflow to improve future reservoir operational practices. The dam's monthly inflow and outflow were obtained from observed daily inflow and outflow data over the period from November 2002 to April 2016. This study finds that monthly water releases generally followed the rise and fall pattern of the monthly inflow and that major water releases were delayed one month after major inflow amounts without consideration for future non-flowing or low-inflow amounts. Regarding non-flowing months, the event of one-month zero inflow usually occurs once every two rainy seasons, while zero-inflow periods of four months or more are rare events. The analysis found that January and February contribute about 50% of the total inflow entering the Wala dam, while most of the water release occurred in February and March every season. Finally, to predict the magnitude of monthly inflow that is associated to a certain recurrence time, normal distribution can be effectively used after applying power transformation to normalize the inflow. Later, the predicted normalized inflow is back-transformed to the original inflow domain.

KEYWORDS: Inflow prediction, Normal distribution, Outflow pattern, Wala dam.

INTRODUCTION

Dams are hydraulic structures built across streams, rivers or estuaries to store water that can be used for human consumption, irrigation and industrial activities and generating hydro-electric power, having an important influence on hydrological conditions of rivers (Nafchi et al., 2021; Altinbilek, 2002). Water is retained in the dam reservoir during times of excess flow and is later released during times when the natural water inflows are insufficient to meet the needs of end users (Altinbilek, 2002). Therefore, dam operators should take into consideration corrective actions to maintain the balance between the amounts of demand and supply in places where rainfall is a major water source (Joshi and Yadav, 2021). Besides retaining water, dams generally moderate the timing of high and low flows and change the timing of the yearly maximum and minimum flows (Graf, 2006).

In Jordan, there are 10 major dams that retain about 332 million cubic meters (MCM) of fresh water per year distributed all over the country. Among the major dams, the Unity dam stores nearly 110MCM, King Talal dam 75MCM, Karama dam 55MCM, Mujib dam 35MCM and Wala dam 25MCM after rising (MWI, 2019). In terms of the total annual precipitation, the 2020/2021 rainy season in Jordan was classified as the lowest among the past 10 rainy seasons. The amount of precipitation received during that season was 70% of the long-term mean of the annual precipitation in Jordan. In that season, the Wala catchment has received about 74% of its long-term mean annual precipitation. Consequently, very low amounts of water flowed into the Wala valley and later entered the dam. Besides the low inflow, the unplanned continuous water release has eventually emptied the Wala reservoir almost totally.

In general, any dam reservoir is considered as a dynamic system that receives natural (stochastic) inflow, while water release is a regulated outflow (Yoshioka, 2022). Since the reservoir inflow is stochastic in nature, its prediction is considered a crucial

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issue for appropriate reservoir management (Amnatsan et al., 2018). Water release decisions including optimal water allocation, flood control, drought mitigation and water need for the downstream environment highly depend on the accuracy of inflow prediction (Noorbeh et al., 2020; Turner et al., 2020; Brown et al., 2015). Although the need for predicting long-term dam inflow is considered the key parameter in the optimal reservoir operation, the accuracy of long-term dam inflow prediction is still a challenging task (Awan and Bae, 2014). The prediction of monthly inflow in the literature was conducted using three ways: stochastic models (Yoshioka, 2022; Noorbeh et al., 2020; Mamman et al., 2017; Valipour et al., 2013; Valipour et al., 2012; Sharma et al., 1997), Artificial Neural Network (ANN) algorithms (Allawi et al., 2021; Mehdizadeh et al., 2019; Amnatsan et al., 2018; Ostad-Ali-Askari et al., 2017; Bae et al., 2007; Awan and Bae, 2014; Jain and Srivastava, 1999) and modeling software (Ijam and Al-Mahamid, 2012). The stochastic model is a probabilistic expression that usually consists of a linear term plus a random component that captures the inflow variability, whereas the ANN model relies on a computer training algorithm that captures the linear and nonlinear components of the inflow (Moeeni et al., 2017). Usually, the ANN model is preferred by researchers when the stochastic model gets complicated.

In order to understand the relationship between the dam inflow, outflow and storage, it is crucial to accurately predict the inflow. The accurate prediction or generation process requires the selection of a proper probability distribution function that fits the dam inflow. The literature cites the gamma and log-normal functions as the most common probability distribution functions used to fit the positively skewed monthly inflow (Wang et al., 2018; Kim et al., 2018; Mamman et al., 2017; Sharma and Panu, 2008; Chebaane et al., 1995; Sim, 1978; Prekopa and Szantai, 1978; Sangal and Biswas, 1970). For example, to predict drought scenarios, Kim et al. (2018) have used the lognormal distribution to fit and simulate the quarterly inflow volumes for the case of the Andong dam in Korea. Similarly, to forecast the monthly river flows in China during dry seasons, Wang et al. (2018) generated monthly inflow for the Yellow river at the Tangnaihai station employing the lognormal distribution for January – November, while gamma distribution was used to model the river inflow for December. To analyze monthly droughts in Canada, Sharma and Panu (2008) found that the use of gamma distribution to fit the monthly flows in the Canadian rivers resulted in the satisfactory prediction of monthly drought statistics. Chebaane et al. (1995) proposed a stochastic model with gamma distribution to generate monthly intermittent flows. Although gamma distribution has been proposed as a candidate distribution to fit monthly precipitation and flow statistically, it has been rejected after transformation of the data to the normal domain to obtain the Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) for the UK catchments (Svensson et al., 2017).

As mentioned previously, after the 2020/2021 dry season, the Wala dam has ended with zero-water storage; consequently, the dam has failed to supply water for agricultural activities and other downstream needs. Since the dam is located in an arid region, it is believed that studying the characteristics of the dam monthly inflow, including non-flowing months, as well as understanding the relationship between the dam inflow and outflow, will improve the dam future operation studies, which indicates the importance of this study. The first objective of this study is to characterize the Wala dam's monthly inflow including the distribution of non-flowing months and their recurrence time. Using the dam monthly inflow and outflow data, the second objective is to investigate the relationship between the inflow and outflow of the Wala dam; i.e., highlighting common dam operation practices. The third objective is to select the best probability distribution function that can be effectively used to predict the Wala monthly inflow magnitude.

STUDY AREA

The upper Wala catchment has an area of 1743 km^2 that extends east of the dam (Figure 1). It forms the northern part of the Mujib drainage basin (6600km^2) and the catchment is drained by the Wala valley flowing from an elevation of around 850 m to 100 m above the mean sea level, where it merges with the Mujib valley before flowing into the Dead Sea. The catchment land cover consists mostly of open rangelands (about 47%), some tree cover, irrigated and non-irrigated agricultural crops (about 38% as wheat and barley) and about 7% of the catchment area is classified as urban (Farhan et al., 2018). The catchment receives an average annual precipitation of about 280 mm during the rainy season ranging between 346 mm at Madaba weather station to about 266 mm at the Wala valley weather station. In the south-east zone of the catchment, the annual precipitation is low; about 100 mm, while the mean annual potential evaporation is relatively high; about 3000 mm. In contrast, the northern zone of the catchment receives an annual precipitation of about 500mm, while the mean annual potential evaporation is low; about 2300 mm, compared to the south-east zone; therefore, most of the Wala valley flow comes from the northern part of the catchment (Margane et al., 2009). Downstream the upper Wala catchment, the Wala dam is located at 31° 34' 5.04"N and 35° 48' 16.5"E, nearly 40 km south of Amman city. The dam retains rainwater flowing into the Wala valley due to seasonal storms over the upper Wala catchment. The stored water is used mainly for irrigation and groundwater recharge. The construction of the Wala dam began in 1999 and ended in 2002. Seasonal waterflow was retained in the dam starting in November 2002. The dam was constructed using Roller Compacted Concrete (RCC) technology with earth abutments (clay core). Initially, the height of the dam above the foundation was 42 m, the dam crest length was 265m and the reservoir total capacity was 9.3 MCM distributed as an active storage of 7.3MCM and a dead storage of 2MCM. Starting in September 2017, the dam was being upgraded such that the initial water level in the reservoir was raised from the elevation of 520m to 535m above mean sea level targeting a new pool storage of about 25MCM instead of the 9.3MCM.

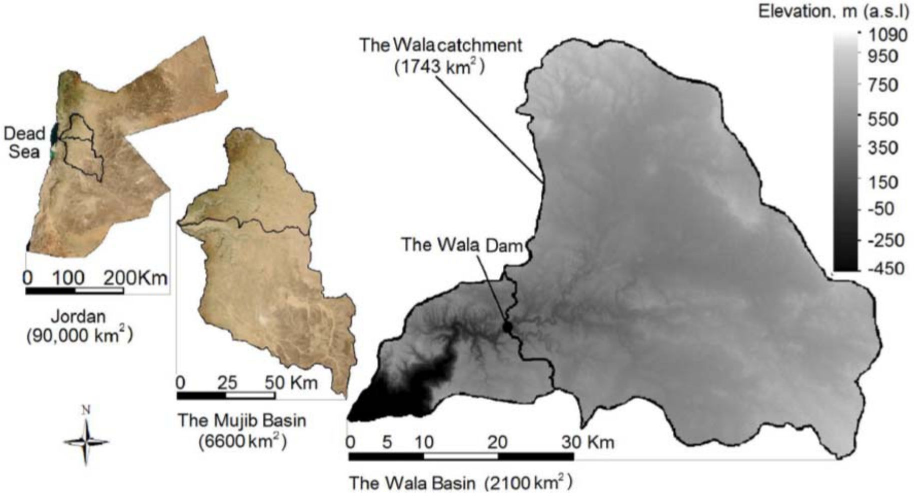

Figure (1): The Wala catchment and the Wala dam (Tarawneh et al., 2016)

DATA AND METHODS

The data available to this study consists of daily natural inflow measured at the dam site during the rainy season. Figure 2 shows the definition of the rainy season adopted by this study. It is the season that spans over the active rainy months; i.e., from November of a given year to April of the next year. The available daily inflow and outflow data starts in November 2002 and ends in April 2016, with no missed data. Before reaching the dam site, the water inflow accumulates in the Wala valley as a result of the catchment surface runoff during an active rainstorm and somehow to a certain time after the storm ends depending on the rainfall-runoff response function of the catchment; i.e., the flow hydrograph. Eventually, after the rainstorm vanishes, the daily inflow returns to zero (non-flowing day); therefore, the time series of the Wala daily inflow has the form of an intermittent series. Based on the registered daily inflow over the study period (November 2002 – April 2016), the inflow in any specific month was obtained by accumulating the daily inflow over that month. Similarly, the monthly outflow was computed given the daily outflow data over the study period. Figure 3 shows the time series of the computed monthly inflow that entered the dam reservoir *versus* the monthly outflow.

In order to explain the relation between the Wala dam monthly inflow and outflow, it could be of much interest to define the storage difference (ΔQ):

$$\Delta Q = Q_{in} - Q_{out} \quad (1)$$

where Q_{in} is the monthly inflow and Q_{out} is the monthly outflow. In this case, a dam storage deficit occurs if $\Delta Q < 0$ and a surplus occurs if $\Delta Q > 0$.

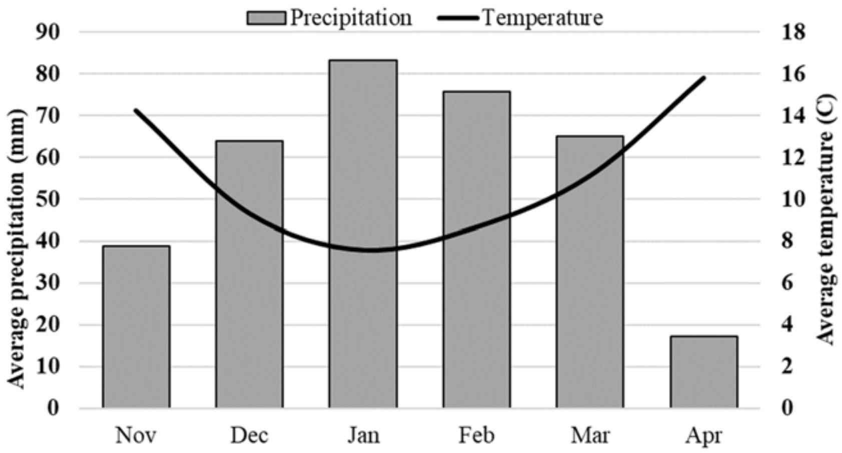

Figure (2): Average monthly precipitation *versus* average monthly temperature for Madaba region

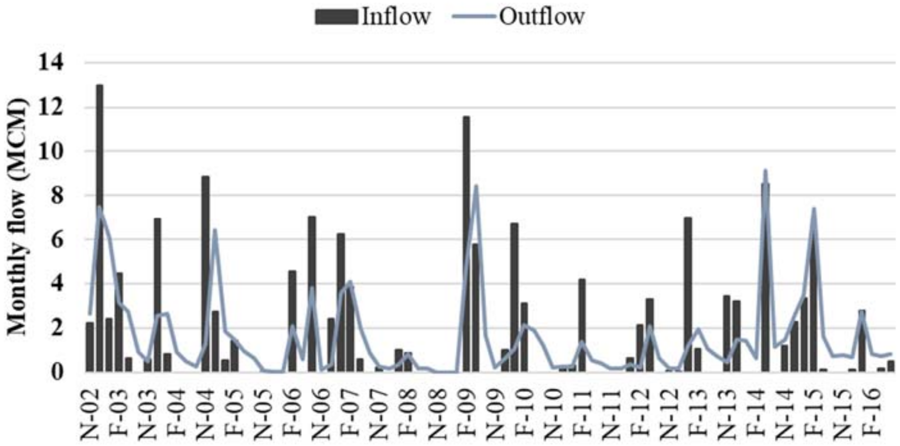

Figure (3): Wala dam monthly inflow versus monthly outflow

Since the Wala dam exists in an arid region, the occurrence of non-flowing months creates an extra burden on the dam storage. For the dam future operation plans, it is important to determine the characteristics of the non-flowing months; i.e., the non-flowing period length and its recurrence time. According to the theory of runs proposed by Yevjevich (1967), a run of non-flowing months is defined as an uninterrupted run (period) of months where the inflow is zero headed and proceeded by at least one month of inflow greater than 0. The probability distribution (frequency), $P\,[L = l]$, of the non-flowing period length is computed as:

$$P[L = l] = \frac{n_l}{N} \quad (2)$$

where l = 1, 2, 3, …months, n_l is the number of periods of length l and N is the total number of non-flowing periods including all values of l. The recurrence time (T) of the non-flowing period of length l is the average waiting time between non-flowing events of the same length computed as:

$$T = \frac{w_1 + w_2 + \cdots + w_n}{n_l} \quad (3)$$

where w is the waiting time between the successive non-flowing periods. The values of w_1, w_2, ….w_n and n_l can be obtained from the observed inflow data. Gamma and lognormal distributions are common models used to predict the monthly inflow magnitude once fitted well. The probability density function of the two parameters of gamma distribution is:

$$f(x) = \frac{\beta^{\alpha} x^{\alpha-1} e^{-\beta x}}{\Gamma(\alpha)} \tag{4}$$

where x is the inflow magnitude, while α and λ are the distribution shape and scale parameters, respectively. The probability density function of the lognormal distribution is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{\ln(x)-\mu}{\sigma}\right)^2\right] \tag{5}$$

where μ and σ are the expected value and standard deviation of the variable ln(x).

RESULTS AND DISCUSSION

The Wala reservoir monthly outflow is obtained after accumulating the reservoir regulated daily outflow released to meet the water needs for downstream users. Because the monthly outflow is a regulated flow, there is no need to discuss its statistical features. On contrast, the monthly inflow exhibits natural variability with random rise and fall pattern including non-flowing months. The mean, standard deviation, coefficient of variation and skewness statistics of the Wala reservoir monthly inflow in MCM are 3.07, 3.14, 1.02 and 1.32, respectively. It can be seen that the Wala monthly inflow is positively skewed; i.e., most of the inflow magnitudes fall below the mean, while little are distributed around the upper tail of the data; thus, the positively skewed marginal distributions like the gamma and lognormal distributions are strong candidates to fit the Wala monthly inflow. Furthermore, the computed coefficient of variation shows a moderate inflow variability; i.e., the higher the coefficient of variation the more the inflow variability.

Since non-flowing months bring no water to the dam, which dramatically affects the dam water release, it is very important to investigate the characteristics of the non-flowing months. Following the theory of runs defined by Yevjevich (1967), Table 1 shows the probability distribution; i.e., the frequency of the Wala non-flowing period length in months computed using Eq. (2) and the associated recurrence time (T) computed using Eq. (3). It can be seen that the non-flowing period of l = 1month is a common event occurring 44% of the time (n_1 = 8 events and N = 18 events) and is expected to recur once nearly every 2 rainy seasons (T = 2 years computed empirically using Eq. 3); thus, it represents the majority of the non-flowing periods. On the other hand, periods of 4 – 5 non-flowing months are rare events happening 6% of the time and are expected to recur once every 14 rainy seasons (T = 14 years). The non-flowing period length distribution and the average recurrence time shown in Table 1 are key statistics that can be used in future water release studies related to the Wala dam.

Table 1. The Wala non-flowing period length probability distribution (frequency) and recurrence time computed using Eq. (2) and Eq. (3), respectively

Period length (month)	Distribution of the period length, $P[L = l]$	Recurrence time (T) (season)
1	0.44	1.75
2	0.33	2.33
3	0.11	7
4	0.06	14
5	0.06	14

Table 2. The goodness-of-fit test statistics for the competing theoretical distributions

Selected distribution	RMSE	Adjusted AD statistics	p-value
Gamma	0.052	0.855	0.028
Lognormal	0.060	1.167	0.003
Normal (transformed inflow)	0.036	0.345	0.485

Figure (3) shows the Wala dam monthly inflow *versus* the outflow over the seasons from2002/2003 to 2015/2016. Figure (3) clearly depicts that the natural rise and fall pattern of the Wala monthly inflow has controlled the pattern of the reservoir monthly water release (outflow). Although regulated, the monthly outflow has responded increasingly to any increase in the monthly inflow and *vice versa*; this result explains the relation between the Wala dam monthly inflow and outflow. The dramatic effect of the Wala monthly inflow on the dam water release can also be presented through the analysis of dry periods. If the dry period is defined as a sequence of continuous months where the inflow is very low or zero, then Figure (3) shows two prolonged dry periods, where the first dry period extended from January 2007 to February 2009 and the second from March 2010 to February 2012. During these dry periods, water amounts released from the dam were kept minimum, because the dam incoming flow was insufficient to fulfill the downstream water needs, which also demonstrates the strong relation between the dam inflow and outflow; i.e., how the inflow magnitude can control the reservoir water release plans.

The relation between the Wala dam inflow and outflow can be investigated further by considering the difference in the dam storage (ΔQ) computed using Eq. (1). Figure (4) shows the time series of the computed storage deficits and surpluses (ΔQ) over the period 2002/2003-2015/2016. The Figure shows that whenever a considerable surplus existed in a given month, a notable storage deficit occurred directly in the next month or subsequent months. For example, a deficit of 3.67 MCM has occurred in January 2003 right after the 5.47 MCM surplus that occurred in December 2002. This storage pattern is evident over several times along the study period (Figure 4). It seems that large surpluses usually encouraged the dam operator to release more water in subsequent months without paying attention to the inflow magnitude during these months, which created a series of deficits that brought the reservoir storage to zero or to very low levels. It seems that the dam was operated depending on the past-month inflow magnitude without considering low-inflow or zero-inflow in subsequent months. Such unplanned water release could be responsible for several continual series of deficits in the Wala dam storage, where the longest started in January 2014 and ended in May 2016 (Figure 4).

For dam-water release arrangements, it could be of much interest to know how much each month contributes inflow to the dam and requires water release during the common rainy season. Figure (5) shows that the majority of the inflow has entered the dam during January and February every season. The two months contribute about 50% of the whole dam's seasonal inflow. Regarding the outflow released to satisfy the dam downstream needs, Figure (5) shows that February and March contribute about 48% of the whole season's water release. This result is expected, since the Wala dam water release pattern depends on the inflow of the past month as mentioned previously; i.e., large monthly outflow quantities are delayed one month after large monthly inflow quantities. Furthermore, Figure (5) indicates the increasing gap between the Wala inflow and outflow during the months of March and April. This is also expected, where the low rainfall amount during March and April generally generates low inflow, while the demand on water for irrigation and other uses increases as the air temperature rises. In general, it can be noted that the distribution of the per month inflow amount is highly associated with the distribution of the rainfall in that month (Figure 2).

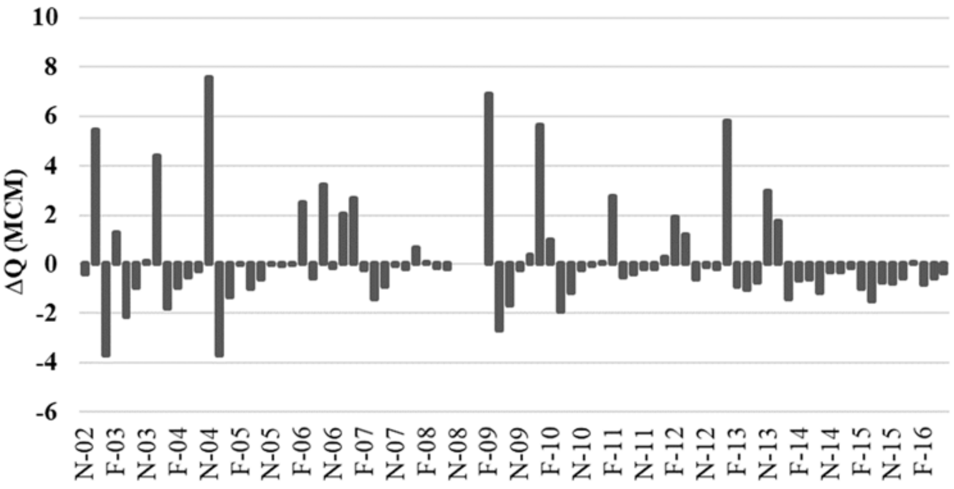

Figure (4): Wala reservoir deficit and surplus time series

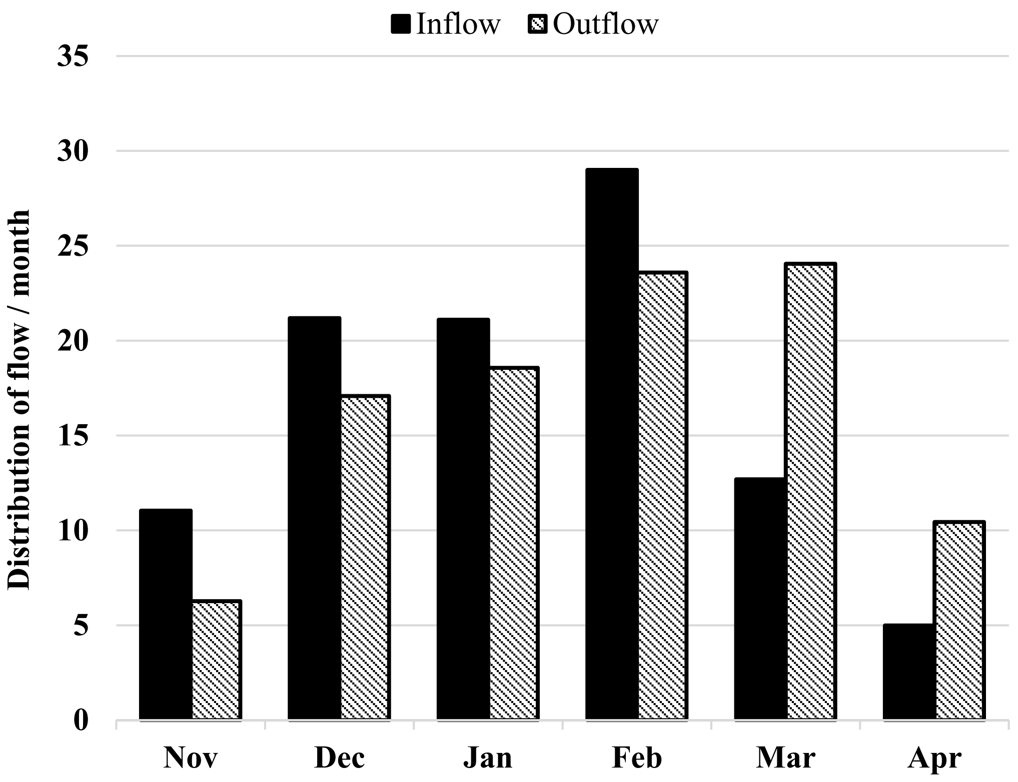

Figure (5): Distribution of the Wala reservoir monthly inflow and outflow

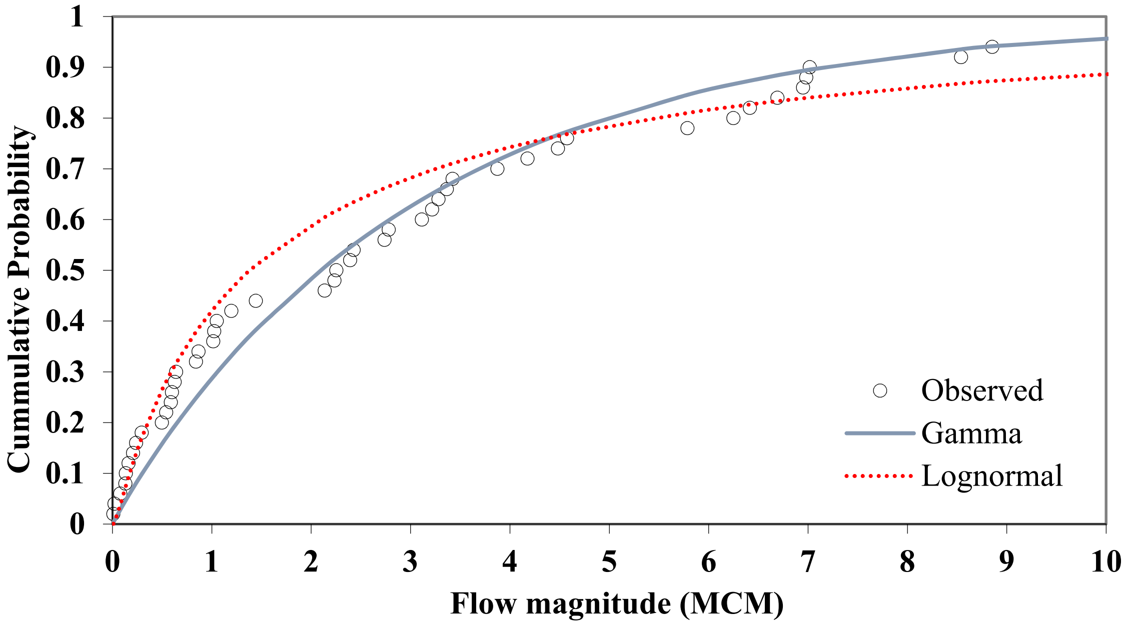

Figure (6): The fitted probability distribution functions for the Wala inflow magnitude

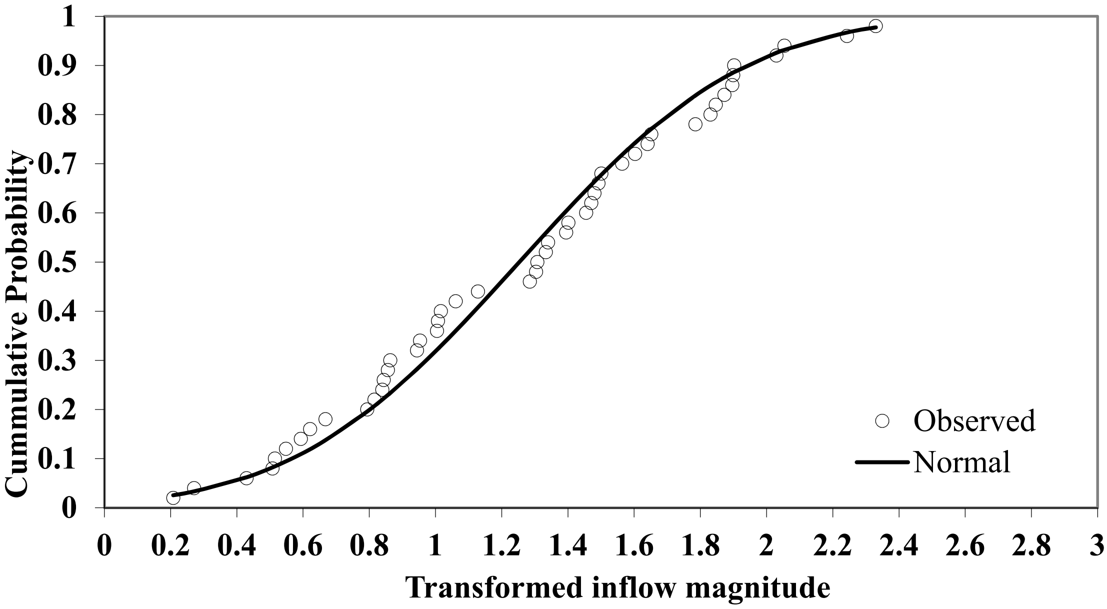

Figure (7): The normal probability distribution function for the Wala transformed inflow magnitude

The prediction of the Wala monthly inflow amount requires the selection of a proper probability distribution function that fits the recorded inflow data. For example, knowing the probability distribution of the inflow facilitates answering the following question: What is the monthly inflow amount that usually occurs once every specific months or seasons? Since the natural monthly inflow data is positively skewed; i.e., skewness coefficient = 1.32, then usually the positively skewed probability density functions, like the gamma (Eq. 4) and lognormal distribution (Eq. 5) functions, are strong candidates to fit the distribution of the Wala monthly inflow. Using the method of moments for both distributions, the gamma distribution shape parameter α = 0.957 and the scale parameter β = 3.212, while for the lognormal distribution, the parameters μ and σ are 0.327 and 1.628, respectively. Figure (6) shows the cumulative probability for the monthly inflow magnitude *versus* the fitted gamma and lognormal distributions. To decide which distribution fits the inflow data, Table 2 shows the goodness-of-fit test statistics for the gamma and lognormal distributions. The computed root mean squared error (RMSE) is 0.052 for the gamma distribution and 0.06 for the lognormal distribution, which initially indicates that the gamma distribution fits the Wala monthly inflow magnitude better than the lognormal distribution. However, the Anderson-Darling goodness-of-fit test results (Table 2) reject the null hypothesis stating that the Wala monthly inflow magnitude is gamma-or lognormally distributed. For gamma distribution, the AD statistic adjusted for the sample size = 0.855 and the computed p-value is 0.028 (less than the 0.05 significance level), while for lognormal distribution, the adjusted AD statistic = 1.167 and the computed p-value is 0.005.

Since the gamma and lognormal distributions do not properly fit the Wala monthly inflow and since the inflow magnitude is positively skewed, then a power transformation can be used to normalize the inflow data, defining the normally distributed variable Y as:

$$Y = X^a \qquad (6)$$

where Y is the normally distributed transformed inflow magnitude, X is the natural monthly inflow magnitude and a is a selected power. Using $a = 0.33$, the transformed inflow variable (Y) has a skewness coefficient of -0.006; therefore, the transformed inflow can be considered normally distributed. Figure (7) shows the transformed inflow magnitude against the fitted normal distribution. The computed RMSE = 0.036, which is less than the RMSE for the gamma and lognormal distributions (Table 2). Also, the computed AD adjusted statistic is 0.345 and the p-value = 0.485, which is greater than the 0.05 significance level; thus, the null hypothesis stating that the Wala transformed monthly inflow is normally distributed cannot be rejected. To predict the Wala inflow magnitude that is associated with a certain recurrence time, normal distribution can be used after the suggested power transformation. For example, if it is required to know the inflow amount that is associated with a recurrence time (T) of 120 months (20 rainy seasons or 20 years), then given that the mean = 1.2528 and the standard deviation = 0.5365 of the transformed inflow (Y), the normally distributed transformed inflow quantile = 1.2528 + 2.39× 0.5365 = 2.535, where the value 2.39 is obtained from the standard normal distribution table at an exceedance probability = 0.5 – (1/T). Now, given the computed transformed inflow value of $Y = 2.535$, the natural inflow amount (X) in its original domain = $(2.535)^{1/0.33}$ = 16.757 MCM.

CONCLUSIONS

The analysis shows that the Wala dam water release is controlled by the rise and fall pattern of the monthly inflow and that the water release in a given month relies on the inflow amount of the past month only, without considering low-flow or non-flowing months in the near future. This study finds that a zero-inflow period of one month is a common happening once every two rainy seasons, while zero-inflow periods of four months or more are rare events. The analysis shows that January and February contribute about 50% of the total inflow entering the dam, while most of water release occurred during February and March each season. To predict the magnitude of the Wala monthly inflow associated with a certain recurrence time, normal distribution can be used effectively after applying a power transformation to normalize the inflow data.

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