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ENHANCING THE SUSTAINABILITY OF WATER RESOURCES IN THE ARID REGION OF JORDAN

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Abstract

This article uses tree-ring reconstructed precipitation, began in 1743, to characterize consistent dry and wet periods for further enhancements to the existed water resources in the arid region of Jordan. With the exemption of the 1958 – 1963 dry period, the analysis of the historical precipitation (1940 – 2010) showed the occurrence of short dry and wet events ranging between 1 – 4 years, mostly 1 – 2 years. On other hand, the analysis of the 239 years of reconstructed precipitation succeeded to capture the occurrence of several long dry and wet events, i.e. the 6-year dry event (1785 – 1763), of 391mm total precipitation deficit, and the 7-year wet event (1817 – 1823) of 551mm total precipitation surplus that is 120% greater than the magnitude of the historical greatest wet period (454mm). Furthermore, this article presents generic theoretical models to compute the return period and the expected number of any dry or wet event that may emerge during the operation life of the surface water resource. Using the models, the obtained theoretical results were compared with analytical results attained from the analysis of the historical and reconstructed precipitation. The proposed models successfully modeled the historical dry and wet events in Madaba region, therefore can be used in water resources studies.

Keywords: *reconstructed precipitation, dry period, wet period, arid region*

Introduction

The arid climate of Jordan usually limits the water resources leading to less water availability to end-users even during wet seasons. The climate pattern in the arid region of Jordan generally brings an extreme dry hot season during the months May – October, followed by a moderate wet season that usually begins in November. Figure 1 shows the average monthly precipitation and temperature for Madaba region, which represents the average climate pattern of the Western highlands in Jordan. Figure 1 illustrates the existence of temporal variation in the precipitation, which in general follows the climate pattern of the East Mediterranean Sea region. Besides the temporal variation, the precipitation over Jordan varies spatially, which is attributed to difference in the elevation and the geographic location of the various regions in Jordan.

Recently, the water supply to end-users has decreased dramatically in Jordan due many factors like the high population growth rate and the sudden refugees influx

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from unstable neighboring countries in the region. Recent statistics provided by the Ministry of Water and Irrigation (MWI, 2015) indicates that the per capita water share in Jordan is nearly 140m^3/year, which is very low compared to the international standards. During the short winter season, the rain water is considered as the main recharge to the limited surface and groundwater sources in Jordan. However, nearly 92% of the annual rainfall finally evaporates leaving around 610 Million cubic meters (Mm^3) of fresh water as a potential recharge for the surface and groundwater resources in Jordan (Abu-Sharar et al., 2012). Therefore, over the past few decades, the government of Jordan put a huge effort to construct rainwater harvesting projects all over the country. In addition to groundwater recharge estimated as 418Mm^3, the surface water storage is used to supply fresh water to municipal, agricultural, and industrial sectors. Unfortunately, the surface water storage in Jordan is continually subjected to a huge stress to fulfill the water needs for all competing sectors (De Laat and Nonner, 2012; Sharadqah, 2014). Table 1 shows the storage capacity and purpose of selected rainwater harvesting projects in Jordan.

Table 1
Storage capacity and purpose of selected rainwater harvesting projects in Jordan.

Project name	Capacity (Mm^3)	Purpose
Mujib dam reservoir	31.2	Supply fresh water to agriculture and industrial activities
Wala dam reservoir	9.0	Supply fresh water to agriculture and recharge of ground water
Qutrana dam reservoir	4.2	Supply fresh water to agriculture.

Investigating long dry and wet periods, considering hydrological or meteorological records, is a critical issue to water resources planning and management (Fischer et al., 2013). For such purpose, short hydrological or meteorological historical records can be used, however, the resulted dry or wet period statistics may not be consistent due to data shortness (Salas et al., 2005; Caloiero et al., 2016). To avoid inconsistency problem, stochastic simulation models are usually employed to generate long synthetic precipitation or flow records, however, synthetic records are not unique (Salas et al., 2005). As an alternative to synthetic records, actual past climatic dry or wet scenarios printed in specific trees can be easily extracted, processed, verified and used to extend the length of flow or precipitation records in the region where the trees exist. These specific trees assimilate into their growing rings the past variation in climate (Meko et al., 1995). In Jordan, long records of annual tree-ring indices were established and used as predictor variables to extend short precipitation records in Southern Jordan for extreme dry periods analysis (Touchan et al., 1999). Processed tree-ring indices for Jordan are now available from the International Tree Ring Data Bank (ITRDB). They were used to reconstruct the annual precipitation at two sites, Madaba and Raba regions, in Central Jordan for characterizing extreme dry periods (Tarawneh and Hadadin 2009). In literature, the reconstructed hydrological or meteorological records were employed generally to achieve several goals including the detection of past climate changes in a particular region (Gou et al., 2007; Lara et al., 2008; Davi et al., 2009), the characterization of extreme dry events (Touchan et al., 1999; Gonzales and Valdes, 2003; Woodhouse et al., 2009; Fang et al., 2010; Yang et al., 2014). However, previous studies rarely considered the complete characterization of wet periods that may have magnitude of water surplus greater than the magnitude of wet periods detected from the analysis of the short historical records.

Despite the fact that water resources in Jordan are limited, climate change may create an extra burden to the Jordanian water resources. In literature, few studies have investigated the existence and the influence of climate change in Jordan on the precipitation trend and amount. In conclusion, a downward trend in the annual precipitation in Jordan has been detected (Smadi and Zghoul, 2006; Rahman et al., 2015). An overall reduction of 0.41mm/year in the rainfall of Jordan was observed after the year 1995 (Rahman et al., 2015). Another study, (Al-Houri, 2014), indicated the existence of a decreasing trend in the duration of the wet season associated with a decrease in the number of the rainy days. In Jordan where water resources are limited and exhausted, a slight decrease in the rainfall amount due to the climate change ultimately reduces the water supply to end-users.

The first objective of this article is to derive consistent dry and wet period characteristics for Madaba region in Jordan where several agricultural activities take place. Precisely, the greatest magnitude and longest duration of dry and wet periods will be examined benefiting of 239 years of tree-ring reconstructed precipitation for further enhancement to existed water resources in Madaba region, i.e. targeting the potential increase of the water supply in the study region. The second objective is to introduce generic theoretical models that provide reliable knowledge about the return period of dry or wet periods and estimate the expected number of dry or wet events that may occur during the operation period of the surface water resources in any region. It is believed that, providing potential numbers of dry or wet events that may happen during the operation period of the water resource will improve water release studies in any region.

Materials and methods

In order to derive consistent statistics of the dry and wet periods in Madaba region including the greatest magnitude, the longest dry and wet events and the return period of specific events, monthly historical precipitation data, obtained from the Meteorological Department of Jordan, was used. The monthly precipitation record began in 1940 and ended in 2010 with no missed data. The visual inspection of the precipitation data shows that the rainy season mainly begins in October and ends in May with no precipitation events after May until the next October (Figure 1).

The monthly precipitations the over the months October – May were summed to obtain the annual rainy season precipitation for Madaba. The mean, standard deviation and skewness coefficients of the annual rainy season precipitation are 345.9mm, 125.4mm and 0.6 respectively.

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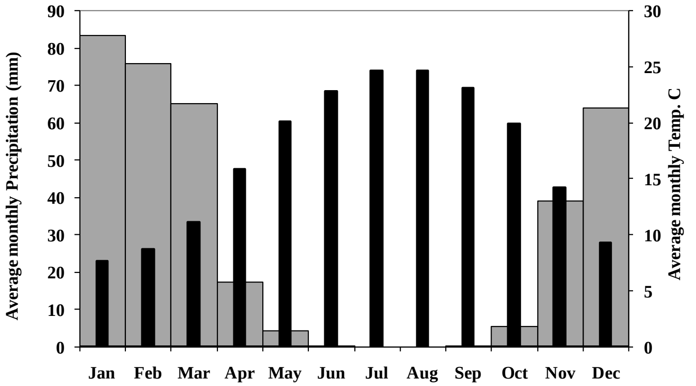

Figure 1 *Average monthly precipitation (grey bar) and temperature (black bar) for Madaba.*

The serial (temporal) autocorrelation of the historical annual precipitation was tested against the lag time in years. The test result (not shown) indicated an insignificant temporal correlation, therefore the annual precipitation series is considered serially independent. Figure 2 shows the bar plot of the annual rainy season precipitation for Madaba over the period 1940 – 2010 truncated at the level of the long-term mean. The truncation level was used to label dry periods (precipitation above the level) and wet periods (precipitation below the level).

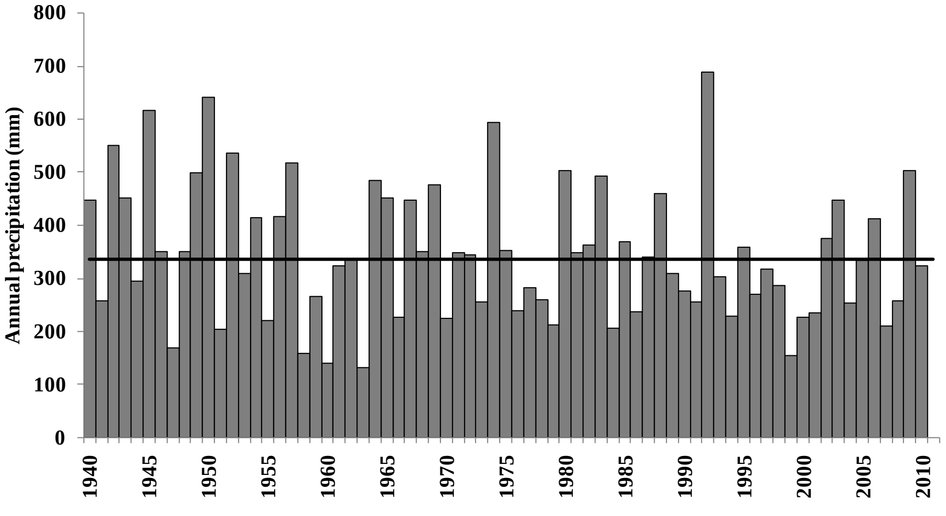

Figure 2. *Historical rainy season precipitation (bars) for Madaba truncated at the level of the long-term mean(solid line).*

Tree-ring indices for two sites in Jordan (Dana Reserve, and Tor Al-Iraq) and two sites in Cyprus (Ceadar Valley – Trocken, and Plano Platres – Feucht), available from the ITRDB, were used in a previous study (Tarawneh and Hadadin, 2009) to reconstruct the annual rainy season precipitation for two regions in Jordan (Madaba, and Raba). Starting from 1743, the reconstructions were made using Multivariate Regression model. The correlation between the rainy season precipitation in Madaba and the tree-ring indices was tested and found significant for the purpose of precipitation reconstruction. The regression model over the calibration period (1953 – 1981) indicated a significant power to reconstruct the precipitation in Madaba using the selected tree-ring indices (R^2 and R^2 adjusted for the lost degrees of freedom were 0.56 and 0.53 respectively). The validation statistic RE that shows how well the reconstruction model predicts the precipitation compared to precipitation not used in the calibration was calculated. The computed statistic RE was 0.48, which indicates a sufficient skill of the regression model to reconstruct the precipitation (Woodhouse, 2003). Furthermore, the sign test was used to track the direction of change from year to year in the historical and the reconstructed precipitation over the calibration period with a result (22+/7-) that exceeded the 95% confidence level (Tarawneh and Hadadin, 2009). Figure 3 shows the reconstructed annual rainy season precipitation for Madaba over the period 1743 – 1981 clipped at the level of the series long-term mean.

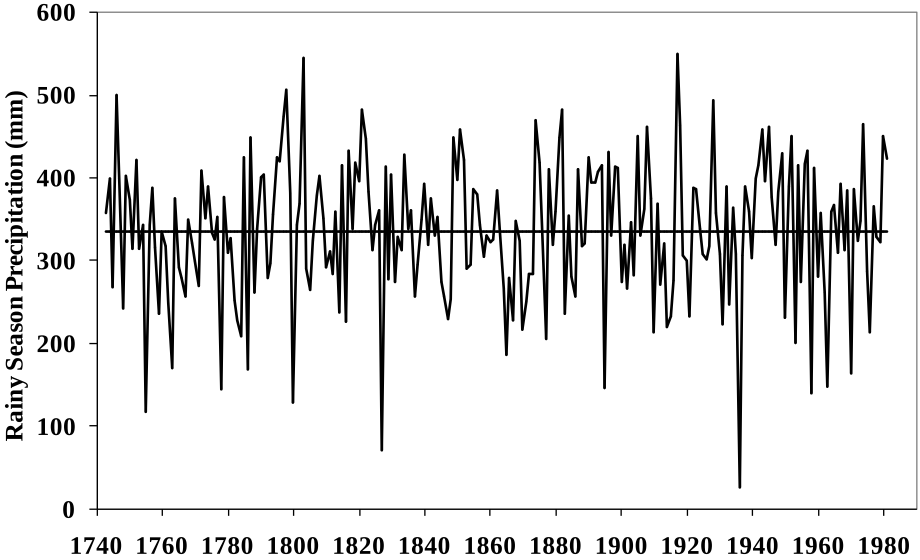

Figure 3. *Reconstructed rainy season precipitation for Madaba truncated at the level of the long-term mean.*

Dry and wet periods achieved after clipping the annual rainy season precipitation can be allocated and counted according to their lengths. The expected number of the dry and wet periods that could happen during the operation period of the surface water storage is an important statistic upon which water release polices may rely on especially in arid regions. After clipping an annual precipitation series, the resulted states are: dry state, when the precipitation is less than the clipping level,

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and wet state otherwise. Each dry or wet period is associated with a magnitude and run length. Generally, the dry and wet states alternate along the clipped series in similar manner as long as the series is stationary (Salas et al., 2005). The geometric distribution is usually used to model the dry period run length distribution (Shiau and Shen, 2001; Salas et al., 2005). Since both of dry and wet periods emerging similarly and fluctuating evenly around the truncation level (mean), then it can be urged that the probability distribution of the wet period run length is also geometric. In general, the probability distribution function of the state (i) *l*-year event, noting that the state (i) is either dry or wet according to the requested analysis, is:

$$P[L_i = l] = p_{ij}\,(1 - p_{ij})^{l-1} \qquad [1]$$

where and p_{ij} is the conditional probability of observing the state (j) given that the past state is (i). In this case, the sequence of the two states (i and j) is assumed stationary process.

After truncating the annual precipitation series, if the total number of the *l*-year events made of state (i) is N_l (*l* could be 1 year, 2 years, …etc.), and if the total number of state (i) events is N regardless to their run lengths, then the empirical probability distribution of the *l*-year state (i) event is estimated as:

$$P[L_i = l] = \frac{N_l}{N} \qquad [2]$$

Given the state (i) events run length distribution (Equation [1]), then the expected run length ($E[L_i]$) of the emerged events is computed as:

$$E[L_i] = \Sigma_{l=1}^{\infty}\; l \text{ x } P[L_i = l] = 1/p_{ij} \qquad [3]$$

Assuming that the discrete random variables the specific number of events N_l and total number of events N are independents, then the expected number the state (i) events of run length *l* ($E[N_l]$) can be derived from Equation [2] as follows:

$$E[N_l] = E[N] \text{ x } P[Li = l] \qquad [4]$$

Given the unconditional probability of observing the state (i) is p_i, and assuming that the discrete random variables of N and L (the total number and the duration of events made of state (i) respectively) are independents, then it can be shown that E[N] is:

$$E[N] = \frac{p_i \text{ x } M}{E[L_i]} \qquad [5]$$

where M in this case is the precipitation record length.

Substituting Equation [3] into [5], then the expected number (Equation [4]) of the *l*-year state (i) event that may happen during a fixed water resource operation period (M) is:

$$E[N_l] = p_i \text{ x } M \text{ x } p_{ij}^2 \text{ x } (1- pij)^{l-1} \qquad [6]$$

Equation [6] is a general model that can be used to predict the number of any dry or wet events of particular length that may emerge during the operation period of the surface water storage. Equation [6] is flexible to consider any desirable planning period, for example M could be 1, 2, 3, 4, …., years.

The return period (T) of the *l*-year state (i) event is defined as average waiting time (E[W]) between events of the same kind (Salas et al., 2005). Given precipitation record of M years, it can be shown that the average waiting time is estimated as E[W] = M / E[N$_l$]. Substituting Equation [6] in the last term of E[W], then the return period (T) is computed as:

$$T = E[W] = \frac{M}{E[N_l]} = \frac{1}{p_i \text{ x } p_{ij}^2 (1-p_{ij})^{l-1}} \qquad [7]$$

Equations [6] and [7] are general theoretical expressions that can be used to model dry or wet periods of any duration. Furthermore, both expressions can be modified to model monthly planning periods considering the periodic features of the monthly precipitation series.

Results and discussion

Dry and wet period analysis

For design purposes, the determination of the surface water storage size relies on the length and the magnitude of the dry and wet periods occurred in the region where the surface storage will be built. Usually, the analysis of the short historical flow or precipitation records may not capture the utmost magnitude or the longest duration of all dry and wet events ever happened, while long records like tree-ring reconstructions may provide more reliable results. Table (2) shows the number, run length and greatest magnitude of dry and wet periods occurred in Madaba region after analyzing the 71 years of historical precipitation against the 239 years of reconstructed precipitation.

Table 2 *Number of dry and wet events and largest magnitude (mm) attained from the analysis of the historical and reconstructed precipitation for Madaba.*

Run length	Historical precipitation				Reconstructed precipitation			
	Number of events		Largest magnitude (mm)		Number of wet events		Largest magnitude (mm)	
Years	dry	wet	dry	wet	dry	wet	dry	wet
1	9	10	175	344	33	31	256	115
2	5	6	222	312	11	18	263	341
3	2	2	194	454	9	9	367	284
4	1	1	388	327	3	1	384	384
5	--	--	--	--	3	1	356	358
6	1	--	711	--	1	2	391	551
7	--	--	--	--	--	1	--	548

After clipping both precipitation series at the level of the long-term mean of each, the analysis showed the occurrence of 19 historical dry periods compared to 62 dry periods detected from the analysis of the reconstructed precipitation.

With exemption of the 6-year dry period occurred in 1958 – 1963, mostly dry events of 1 – 2 years are dominant noting that no events of 5 years duration were detected (Table 2). The magnitude of the longest historical dry event, i.e. the 6 years event, is 711mm of precipitation deficit. The analysis of the reconstructed precipitation gave a proper distribution of dry events, i.e. events of duration 1 – 6 years existed. The magnitude of the longest dry event detected from reconstructions, i.e. the 6-year event occurred in 1758 – 1763, is about 391mm of precipitation deficit that is less than the 711mm of precipitation deficit registered during the 6 years historical dry event that was the most severe dry period ever happened over the period 1743 – 2010. Regarding the single year dry event, the analysis of the historical precipitation showed a magnitude of 115mm of precipitation deficit that is less than the 256mm of precipitation deficit detected after analyzing the reconstructed precipitation. Similar results were found in relation to the magnitude of dry events of 2 and 3 years duration, which could be a privilege of using the reconstructed precipitation to analyze dry periods.

Table 2 shows 19 historical wet events ranging between 1 – 4 years at most, while the analysis of the 239 years of tree-ring reconstructed precipitation indicated the occurrence of 63 wet events, i.e. 3 times larger than the result obtained from the analysis of the historical precipitation, with run length ranging between 1 to 7 years. The principal magnitude of the historical single year wet period was 344mm of precipitation surplus recorded in 1992. The greatest magnitude of the single year wet event resulted after truncating the reconstructed precipitation occurred in 1905 with surplus precipitation of 115mm, i.e. less than the 344mm of historical precipitation surplus. The reconstructed precipitation was not able to capture the magnitude of the extreme single year historical wet event because tree growth was limited by other factors like nutrients even when water was plentiful (Woodhouse, 2003). Generally, while the longest historical wet periods was 4 years, the analysis of the reconstructed precipitation showed the occurrence of several wet periods longer than 4 years, for example the two 6-year wet events occurred in 1794 – 1799 and 1941 – 1946, and the 7-year wet event that occurred during the season of 1817 – 1823 (Figure 3). In conclusion, the analysis of the reconstructed precipitation was more informative than the analysis of the short historical precipitation for two reasons, the first it gives proper distribution of dry and wet events in Madaba, the second it was able to predict dry and wet period magnitudes larger than the magnitude of the historical dry and wet periods. For example, refer to the magnitude of the 1 – 3 years dry periods and the magnitude of the 2 – 7 years wet periods (Table 2).

Investigating the run length probability distribution of dry and wet periods detected from reconstructed precipitation gives a clue of how powerful the reconstructed precipitation represented the past occurrence of the region climate. Table (3) shows the probability distribution of the dry and wet periods run length obtained after analyzing the historical and reconstructed precipitation using Equation [2] versus the theoretical distribution computed using Equation [1] noting that the probability $p_{ij} = p_{dw} = 0.45$ for the dry state, and the probability $p_{ij} = p_{wd} = 0.55$ for the wet state.

Table 3
Run length probability distribution of dry and wet periods detected from historical, reconstructed precipitation versus theoretical values using Equation [1].

Run length (Years)	Probability distribution for					
	Dry run length			Wet run length		
	Hist.	Reconst'd	Theor.	Hist.	Reconst'd	Theor.
1	0.47	0.53	0.45	0.53	0.49	0.55
2	0.26	0.21	0.25	0.32	0.29	0.25
3	0.11	0.15	0.14	0.11	0.14	0.14
4	0.05	0.05	0.07	0.05	0.02	0.07
5	--	0.05	0.04	--	0.02	0.04
6	0.06	0.02	0.02	--	0.03	0.02
7	--	--	--	--	0.02	--

In general, the results shown in Table (3) clearly indicate the geometric decay, the occurrence probability reduction, of the dry and wet periods as their length increase. This result matches with the theoretical result obtained using the well-known probability distribution model (Equation [1]). The geometric distribution of the dry or wet period run length was observed by other studies (Shaiu and Shen, 2001; Salas et al., 2005; Biondi et al., 2005; Ratan and Venugopal, 2013). The general match between results in Table (3) indicate the ability of the tree-ring reconstructed precipitation to replace the short historical precipitation for dry and wet period analysis. For water resources management and planning studies, it could of high importance to give a knowledge about the expected length of dry and wet periods that may evolve in the region where the resources exist. The expected length of any dry period estimated from the historical and reconstructed precipitation is 2.16 and 2 years respectively, compared to the theoretical value of 2.2 years attained using Equation [3]. In general, it is expected to witness usual dry periods in Madaba region of length of around 2 years. Such result is expected since the probability distribution of the short dry periods (1 – 2 years) is high as shown in Table (3). For wet periods in Madaba, the average run length estimated from the truncated historical and reconstructed precipitation is 1.68 and 1.93 years respectively, compared to 1.81 years estimated using Equation [3]. The differences between the estimates of the expected wet events length obtained from the analysis of the historical and reconstructed precipitation is attributed to the past occurrence of long wet periods detected after the analysis of the tree-ring reconstructions (the events of 6 and 7 years duration). In summary, the average wet period run length that may occur in Madaba region is nearly 2 years.

Although useful to water resources management studies, the computation of the average dry or wet period run length may not provide specific details about the average waiting time of the next event, i.e. the return period of a specific event upon which a water supply failure is expected. Table (4) shows the return period of dry and wet events versus the run length for events detected using the clipped historical, reconstructed precipitation and computed theoretically using Equation [7]. In general, results shown in Table (4) indicate that as the dry or wet period run length increases, the event return period increases, i.e. the dry or wet events become rare events as the run length increases.

Table 4
Return period of dry and wet events detected from historical, recontructed precipitation versus theoretical values using Equation [7].

Run length (Years)	Return period for					
	Dry events			Wet events		
	Hist.	Reconst	Theor.	Hist.	Reconst	Theor.
1	7.1	7.3	8.9	7.1	7.7	7.3
2	14.2	21.7	16.3	11.8	13.3	16.3
3	71	26.6	29.7	35.5	26.6	36.3
4	71	80	53.9	71	239	81
5	--	80	98	--	239	179
6	71	239	178	--	120	318
7	--	--	--	--	--	--

While the analysis of the historical precipitation failed generally to estimate the return period for dry or wet events of duration more than 4 years, the analysis of the reconstructed precipitation was able to estimate the return period of 6 and 7 years dry and wet events. For dry or wet events of more than 2 years, there are some differences between empirical results from the historical data and theoretical results obtained using Equation [7]. These differences are attributed to the limited number of historical dry or wet events detected. For dry periods in Madaba, the results indicate that events of short duration like 1 – 2 years are the most frequent events. The average waiting time for the single dry year is 7 – 9 years and for the 2 years event is nearly 15 – 20 years. Similarly, wet events of short duration (1 – 2 years) are also dominant in Madaba. The average waiting time for any single wet year is 7 – 8 years, while 12 – 16 years for any 2 years wet event. Dry periods of duration 3 years or more are less frequent with return period of 30 years or more, i.e. could happen once during the operation life of the surface water resource. Also, wet periods of 3 years or more with return period of 35 years or more are less expected to occur during the operation life of the resource system. In Madaba, for surface water system failure, i.e. not to satisfy the consumers water need during the dry period, then the waiting time of 7 – 9 years for the single dry year and the waiting time of 3.8 years for any dry period regardless of its duration, should be considered in surface water sizing studies. On the other hand, water release studies in Madaba region should consider the average waiting time for the most dominant wet events (the single year wet event) of nearly 7 years, and 3.8 years as waiting time for any wet period (regardless of the length) to reoccur. The average waiting time (3.8 years) for any dry period or any wet period, regardless of the run length, was computed empirically using historical and reconstructed precipitation.

Expected number of dry and wet periods

The estimation of the expected number of dry and wet events that may occur during the operation period of the water resource is important to the resource management studies. For example, the following question may arise: how many 2 years dry events may evolve during a planning period of 15 years or any period (M)?. To answer such or similar questions, Equation [6] developed here, can be used. Equation [6] computes the expected number of dry or wet events that may arise during a specified period (M). Table 5 shows the estimated number of dry and wet events of specific length versus the actual number of events happened in Madaba through the historical precipitation period, i.e. M = 71 years.

Table 5 *Historical (actual) versus estimated number of dry or wet events in Madaba at different run lengths.*

Run length (Years)	Number of event estimated			
	Using historical precipitation		Using Equation [6]	
	dry events	wet events	dry events	wet events
1	9	10	7.91	9.68
2	5	6	4.35	4.36
3	2	2	2.39	1.97
4	1	1	1.31	0.89
5	0	0	0.72	0.40
6	1	0	0.40	0.18
7	0	0	0.21	0.08

Comparing numbers, the actual against the estimated using Equation [6] for both dry and wet periods, the results in Table 5 tell that Equation [6] succeeded to estimate the actual number of dry and wet events occurred during the historical record (period M = 71 years). Therefore, Equation [6] can be used simply to predict the number of dry or wet events of any desired length. Furthermore, Equation [6] is able to consider any planning period. For example, if the plan is to operate the surface water resource for 10 years (M = 10) and it is required to predict the number of the 1-year and the 2-year wet events, then Equation [6] calculates $E[N_{l=1}]$ as 1.36 and $E[N_{l=2}]$ as 0.61. The results are explained as follows, it is expected that 1 event (highly likely) to 2 events (less likely) of 1-year duration will occur during the 10 years period, also, probably one wet event of 2 years duration ($E[N_{l=2}] = 0.61$) will occur in Madaba during the 10 years operation period.

Enhancing surface water storage and climate challenge

Over the past few decades, several surface water storage projects were constructed targeting the harvest of abundant surface runoff from winter floods. However, studies related to surface water storage projects probably relied on runoff computed using the long-term average of the historical precipitation (Hagan, 2008). The analysis of wet periods presented in this study benefiting of the reconstructed precipitation indicates the occurrence of wet periods of magnitude larger than magnitude of any historical wet period ever recorded. Precisely, the magnitude of the 7 years wet period (longest wet event) detected from the analysis of the reconstructed precipitation is 548mm of surplus compared to the longest historical wet event of 327mm of surplus, i.e. about 167% larger. Similar result appears even though the comparison

is made between events of the same duration, i.e. there is 384mm of surplus precipitation in the 4 years wet event detected from the analysis of the reconstructed precipitation compared to the historical 4 years wet event of 327mm precipitation surplus (120% larger). In general, such result should be considered in future surface water storage design studies for the purpose of collecting more of rainwater. Similar finding was achieved after the analysis of the Mujib valley annual flowing water that feeds the Mujib dam near Madaba that was placed in service in 2004.
Figure 4 shows the reservoir annual inflow versus the reservoir storage capacity (31.2Mm^3) over the operation period 2004 – 2010. As can be seen from the Figure 4, the annual inflow for the year 2006 was 66.8Mm^3, i.e. 2.14 times larger than the dam storage capacity. The water volume difference (35.6Mm^3) during the year 2006 was spilled away to the Jordan valley and eventually evaporated.

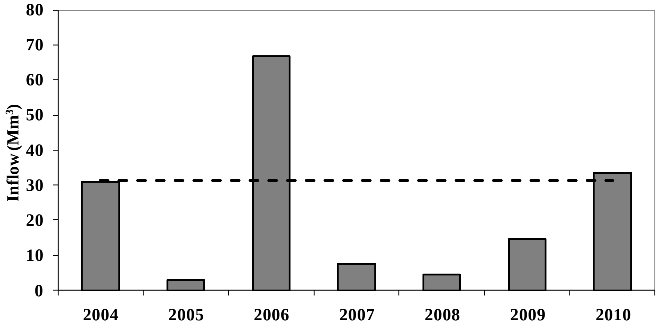

Figure 4
Mujib dam annual inflow (grey bar) in Mm^3 versus the 31.2 Mm^3 storage capacity (dashed line) over years 2004 – 2010.

As further enhancements to the existed water storage, an extra few micro dams can be built downstream the major dam benefiting of the extra water that may flood during such wet year. Furthermore, the governments of countries in arid regions should consider the construction of more surface water storage projects to harvest the utmost possible amount of the precious water.

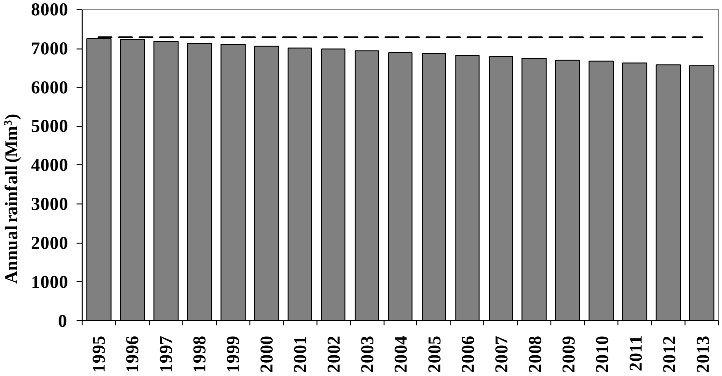

Figure 5
Total rainfall reduction (bars) after 1995 due to the climate change versus the long-term average of the total rainfall in Jordan (dashed line).

Although water resources in Jordan are already exhausted, any reduction in the annual precipitation (the main feed water to existed resources), due to current climate changes, represents another threat the limited water resources. Considering the result of recent study (e.g. Rahman et al., 2015) that predicted an overall reduction in the total rainfall of 0.41mm/year observed after 1995 due to climate change, the cumulative total rainfall reduction over years after 1995 was computed. Figure 5 shows the potential reduction in the total annual rainfall amounts over the Jordanian lands after 1995, i.e. over the period 1995 – 2013.

It is clear that the resources feed water has decreased from the long-term average value of 7300Mm^3 in 1995 to nearly 6550Mm^3 in 2013, approximately 10% reduction, due to possible change in the climate. In addition to the decrease in the potential water supply to consumers, such reduction negatively affects the quality of ground and surface water, i.e. possible increase in the water salinity.

Conclusions

The generic theoretical models presented in this study to compute the return period and the expected number of any dry or wet events, that may emerge during a fixed period, have succeeded to model the historical dry and wet events occurred in Madaba region in Jordan. Furthermore, the proposed generic models are able to accommodate any planning period, therefore, they can be used to improve water resources planning and management studies in any region.

In relation to dry and wet events analysis in the study region, while the analysis of the 71 years of historical precipitation in Madaba region indicated the occurrence of short dry and wet events (1 – 4 years at most), the analysis of the 239 years of tree-ring reconstructed precipitation showed the occurrence of several long dry and wet periods (6 and 7 years events). Focusing on the wet period analysis, the greatest magnitude of the wet event in Madaba detected from the analysis of the tree-ring reconstructed precipitation was 551mm of precipitation surplus compared to the historical 454mm wet period, i.e. 120% greater. One promising finding of this study, is the ability of the tree-ring reconstructed precipitation to capture wet events of magnitude that could be much greater than the magnitude of any historical wet event ever recorded. Therefore, it can be concluded that future studies related to surface water storage sizes may need to incorporate the existence of past wet periods of magnitude and duration greater than what the analysis of the historical data tells.

Regarding the existed surface water storage in arid regions, this study concluded that it is recommended to construct few micro-dams downstream any existed major dams to maximize the storage capacity of the precious water in such regions. This practice may provide an additional storage, besides the existed water storage, to compensate for the reduction in the rainfall due to the climate change.

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