AUGMENTING SHORT HYDROLOGICAL RECORDS TO IMPROVE WATER RESOURCES STUDIES

Zeyad S. Tarawneh

Civil Engineering Department
The Hashemite University
13115 Zarqa – Jordan
E-mail: zeyadt@hu.edu.jo

ABSTRACT

Characterizing extreme hydrological events depending on short hydrological records may result in unreliable estimates of the extreme event characteristics. The linear regression model has been widely used to extend short hydrological records, however extensions produced using the linear regression model usually fail to preserve the serial correlation of the short historical record. This paper presents a new record extension model that can be used to augment short hydrological records while preserving the serial correlation of the short record. Using generated data of a normally distributed bivariate (y_t and x_t), the performance of the new model has been tested. Compared to the simple linear regression model, the new model performed quite well in terms of maintaining the characteristics of the short record. The new model was used to extend a short precipitation record at Rabba gauging site in Jordan back to the year 1924 for the purpose of analyzing drought events. The analysis shows the occurrence of 19 drought events of duration ranging between 1 – 6 years, the 1 year drought event is the most common. In Rabba region, if a drought condition has just ended, the analysis shows that the average waiting time for the next drought event to occur is nearly 2 years.

Keywords: Record augmentation, Precipitation, Droughts in Jordan.

1. INTRODUCTION

Water resources studies related to the planning, design, and management of surface water systems depend on the properties of extreme hydrological events like the magnitude of the flood and its return period, the magnitude of the drought and its duration. Such and other properties can be estimated benefiting of existed historical hydrological records (precipitation or streamflow), however the reliability of these properties increases as the number of the observed extreme events increases, which could not be the case when short hydrological records are used (Salas et al., 2005). In general, using short records to estimate the population parameters of certain hydrological statistics may result in poor estimates of these parameters (Fiering, 1963).

Tree ring indices have been widely used in literature as predictor variables to augment short hydrological records of precipitation or streamflow. Extending the length of short hydrological records using tree ring indices was made for several purposes like detecting the climate change (e.g. Gou et al., 2007; Lara et al., 2008; Davi et al., 2009), and predicting the occurrence of extreme droughts (e.g. Touchan et al., 1999; Gonzales and Valdes, 2003; Akkemik et al., 2008; Woodhouse et al., 2009; Tarawneh and Hadadin, 2009; Fang et al., 2010). Except in Gonzales and Valdes (2003) where they used an extension model that includes a stochastic term and a term to account for the serial correlation, the majority of the previous studies have employed tree ring indices as predictor variable and used the traditional linear regression model to augment the short precipitation or streamflow records.

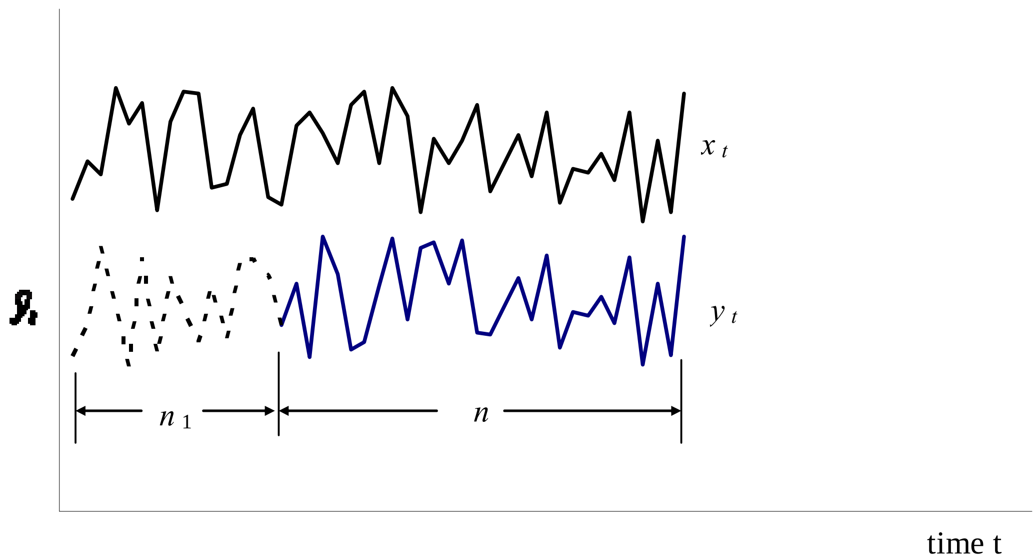

Figure 1 Schematic plot of the short record (y_t), the long record (x_t), the short period n, the extension period n_1, and the extensions $\hat{y}_t$ (dashed series)

In literature, there are several theoretical models that can be used to extend the length of short historical records. Such models were developed initially to extend the short records targeting two main themes. The first theme was to improve the estimates of the population parameters like the mean and the variance of the short record (e.g. Matalas and Jacobs, 1964; Vogel and Stedinger, 1985), while the second theme was to maintain the estimates of the parameters of the short record (e.g. Hirsch, 1982; Grygier and Stedinger, 1989; Gonzales and Valdes, 2003). However few extension models (e.g. Grygier and Stedinger, 1989; Gonzales and Valdes, 2003) include a term that accounts for preserving the serial correlation of the record to be extended. The record extension model in Gonzales and Valdes (2003) contains also a stochastic term (white noise), therefore it can not produce a unique extension. The model proposed by Grygier and Stedinger (1989) produces extensions that preserve the serial correlation, but such extensions usually overestimate the variance of the original short record specially when the cross correlation between the short record and the long record (predictor) is low.

The traditional linear regression model that has been widely used to extend the short records relies on transferring information from the long record (x_t) to the short record (y_t) over the extension period. The usefulness of the information being transferred (the amount of the explained variance) depends on the cross correlation (ρ_{xy}) between the variables x_t and y_t over their common period (n). The common period n is called the calibration period and usually has the length of the short record (Figure1). If n_1 is the length of the extension period (Figure1), then simple linear regression model expresses the extensions ($\hat{y}_t$) over the extension period n_1 as follows:

$$\hat{y}_t = \bar{y} + b\left(x_t - \bar{x}\right) \qquad t = 1, 2, \ldots, n_1 \tag{1}$$

where $\bar{y}$ and $\bar{x}$ are the mean values of the short record y_t and the long record x_t over the calibration period n respectively, and b is the model parameter. Johnson and Wichern (2005) expressed the least square estimator of the model parameter b as:

$$b = \frac{C_{xy}}{C_{xx}} \tag{2}$$

where C_{xy} is the lag-0 covariance between the variables x_t and y_t, and C_{xx} is the lag-0 covariance of x_t, i.e. the variance of x_t.

The linear regression model (Equation 1) produces extensions $\hat{y}_t$ of the short record y_t such that the mean $\bar{y}$ of the short variable y_t and the cross correlation between y_t and x_t are maintained. However when the short record y_t is serially correlated then there is no guarantee that the linear regression model will produce extensions $\hat{y}_t$ that preserve the serial correlation of the short record y_t, consequently the time dependence structure of the extended record $\hat{y}_t$ and the short record y_t may be different.

Beyond to what the traditional linear regression model can produce, the main objective of this paper is to propose a new model that can be used to extend a short hydrological record while preserving most of the characteristics of the short record. Such characteristics to be maintained are the mean, the variance, the serial correlation of the short record, and the cross correlation between the short and the long record. The performance of the new model will be tested and compared with the performance of the linear regression model using synthetic data. Later the new model will be used to extend a short precipitation record at Rabba gauging site in Jordan. The combined record, e.g. the short historical and the extended part, will be used to characterize droughts in Rabba region in Jordan.

2. MODEL FORMULATION AND PERFORMANCE

The development of the new record extension model starts from the general shape of the traditional simple linear regression model (Equation 1). The formulation of the new model will contain a term that will care about the serial correlation of the short historical record.

2.1 Model Formulation

Given the short record y_t and the long record x_t, the new model that can be used to produce extensions of the short record y_t is:

$$\hat{y}_t = \bar{y} + a(\hat{y}_{t-1} - \bar{y}) + b(x_t - \bar{x}) \qquad t = 1, 2, \ldots, n_1 \tag{3}$$

where $\hat{y}_t$ is the extension at the time step t, $\bar{y}$ and $\bar{x}$ are the mean values of y_t and x_t over the calibration period n respectively, a and b are the model parameters. Using the method of moments (Appendix), the moment estimators of a and b are:

$$a = \frac{C_{xy}\, C_{xy^-} - C_{xx}\, C_{yy^-}}{(C_{xy^-})^2 - C_{xx}\, C_{yy}} \tag{4}$$

and

$$b = \frac{C_{xy} - a\, C_{xy^-}}{C_{xx}} \tag{5}$$

where C_{xy} and C_{xx} as defined previously, C_{xy}- is the lag-1 covariance between x_t and y_t with y_t lagged one time step behind x_t, C_{yy} and C_{yy}- are the lag-0 and lag-1 covariance of the variable y_t, respectively.

Comparing the new model (Equation 3) with the simple linear regression (Equation 1), it is expected that the addition of the term $a(\hat{y}_{t-1} - \bar{y})$ will contribute in producing extensions $\hat{y}_t$ that will preserve the serial correlation of the short record y_t.

2.2 Testing the Model Performance

To test the performance of the new model versus the widely used simple linear regression model a huge amount of synthetic data were used. 1000 samples of a normally distributed bivariate (y_t and x_t) were generated at each of the cross correlation (ρ_{xy}) values of 0.5, 0.65, 0.8, and 0.9. Such correlation range is common between natural data. Each sample of the bivariate (y_t and x_t) was generated to a length of 150 data points. A mean of 100 and standard deviation of 30 were selected arbitrarily for each of the generated y_t and x_t. The serial correlation coefficient of the short variable y_t was kept at a value of 0.3 (significant time dependence), while the serial correlation coefficient of the predictor variable x_t was kept at a value of 0.02 (time independent) like most of the tree ring indices that are used as predictors to extend short precipitation or streamflow records. The reason behind selecting time independent variable x_t while y_t is time dependent is to show the capability of the new record extension model to produce extensions $\hat{y}_t$ that will preserve the serial correlation of the short y_t throughout the addition of the term $a(\hat{y}_{t-1} - \bar{y})$ although the predictor variable x_t is time independent. Since the linear regression model lacks of a term that accounts for the time dependence then it produces extensions $\hat{y}_t$ that will highly likely fail to preserve the serial correlation of the original variable y_t specially when the predictor variable x_t is time independent.

Out of the 150 data points generated for y_t, the last 50 data points (t = 101, 102, …, 150) were kept a side for validation purposes, therefore the variable y_t is considered a short record of a length of 100 data points (n = 100). The new model and the simple linear regression model were used to estimate $\hat{y}_t$ for t = 101, 102, …, 150 to replace the 50 data points that were kept a side. If the extended part $\hat{y}_t$ for t = 101, 102, …, 150 is combined with the short part y_t (t = 1, 2, …,100), then the combined record $\tilde{y}_t$ is obtained:

$$\tilde{y}_t = \begin{cases} y_t & t = 1, 2, ..., 100 \\ \hat{y}_t & t = 101, ..., 150 \end{cases} \tag{6}$$

For each of the 1000 generated samples, the mean $\bar{y}$, the variance σ_y^2, the lag-1 serial correlation coefficient ϕ_y of the short record y_t for t = 1, 2, …, 100, and the cross correlation ρ_{xy} between y_t and x_t for t = 1, 2, …100 were calculated. Also the mean $\bar{\tilde{y}}$, the variance $\sigma_{\tilde{y}}^2$, the lag-1 serial correlation coefficient $\phi_{\tilde{y}}$ of the combined record $\tilde{y}_t$, and the cross correlation $\rho_{x\tilde{y}}$ between $\tilde{y}_t$ and x_t for t = 1, 2, …, 150 were calculated. Moreover the sum of the squared errors ($\sum e^2$) between the extensions $\hat{y}_t$ and the replaced 50 data points of y_t were also calculated noting that $e^2 = (y_t - \hat{y}_t)^2$.

Defining the performance statistics $\bar{\tilde{y}}/\bar{y}$, $\sigma_{\tilde{y}}^2/\sigma_y^2$, $\phi_{\tilde{y}}/\phi_y$ and $\rho_{x\tilde{y}}/\rho_{xy}$ the performance of both extension models, i.e. the new model and the simple linear regression, can be tested. At each ρ_{xy} value of 0.5, 0.65, 0.8, and 0.9, there were 1000 generated samples of the bivariate y_t and x_t, hence there were 1000 value for each of performance statistics by which the expectations E[$\bar{\tilde{y}}/\bar{y}$], E[$\sigma_{\tilde{y}}^2/\sigma_y^2$], E[$\phi_{\tilde{y}}/\phi_y$], E[$\rho_{x\tilde{y}}/\rho_{xy}$], and E[$\sum e^2$] were calculated. Tables 1, 2, 3, and 4 show the expectations of the performance statistics at ρ_{xy} values of 0.5, 0.65, 0.8, and 0.9 respectively.

Table 1 The performance statistics at ρ_{xy} value of 0.5

Performance statistics	New model	Simple linear regression
E[$\bar{\tilde{y}} / \bar{y}$]	1.0001	1.0001
E[$\sigma_{\tilde{y}}^2 / \sigma_y^2$]	0.7489	0.7496
E[$\phi_{\tilde{y}} / \phi_y$]	1.0046	0.8999
E[$\rho_{x\tilde{y}} / \rho_{xy}$]	1.1442	1.1583
E[$\sum e^2$]	34682	35004

Table 2 The performance statistics at ρ_{xy} value of 0.65

Performance statistics	New model	Simple linear regression
E[$\bar{\tilde{y}} / \bar{y}$]	1.0000	0.9999
E[$\sigma_{\tilde{y}}^2 / \sigma_y^2$]	0.8145	0.8126
E[$\phi_{\tilde{y}} / \phi_y$]	1.0002	0.8411
E[$\rho_{x\tilde{y}} / \rho_{xy}$]	1.1071	1.1167
E[$\sum e^2$]	26794	26894

Table 3 The performance statistics at ρ_{xy} value of 0.8

Performance statistics	New model	Simple linear regression
E[$\bar{\tilde{y}} / \bar{y}$]	1.0013	1.0011
E[$\sigma_{\tilde{y}}^2 / \sigma_y^2$]	0.8903	0.8866
E[$\phi_{\tilde{y}} / \phi_y$]	0.9838	0.7711
E[$\rho_{x\tilde{y}} / \rho_{xy}$]	1.0598	1.0679
E[$\sum e^2$]	16748	16692

Table 4 The performance statistics at ρ_{xy} value of 0.9

Performance statistics	New model	Simple linear regression
E[$\bar{\tilde{y}} / \bar{y}$]	1.0005	1.0004
E[$\sigma_{\tilde{y}}^2 / \sigma_y^2$]	0.9537	0.9483
E[$\phi_{\tilde{y}} / \phi_y$]	0.9629	0.7139
E[$\rho_{x\tilde{y}} / \rho_{xy}$]	1.0249	1.0313
E[$\sum e^2$]	9429	9449

3. RESULTS AND DISCUSSION

Tables 1 – 4 show the expectation of the statistics $\overline{\tilde{y}}/\bar{y}$, $\sigma^2_{\tilde{y}}/\sigma^2_y$, $\phi_{\tilde{y}}/\phi_y$, and $\rho_{x\tilde{y}}/\rho_{xy}$ suggested here to judge the performance of both models as the cross correlation varies (as the relation between y_t and x_t varies). If the expectation of a selected statistic as calculated from the extensions $\hat{y}_t$ produced by a record extension model is 1, then that model produces extensions $\hat{y}_t$ that are able to preserve the selected statistics. In relation to preserving the mean value $\bar{y}$ of the short record y_t, Tables 1 – 4 show that both models performed quite well, i.e. E[$\overline{\tilde{y}}/\bar{y}$] = 1, which means that both models produced extensions that well preserved the mean value of the short record regardless of the cross correlation value.

In terms of the amount of the explained variance, both models produced extensions $\hat{y}_t$ that always underestimated the variability of the short record y_t, i.e. the value of E[$\sigma^2_{\tilde{y}}/\sigma^2_y$] is always is less than 1 regardless of the model that was used to produce the extensions $\hat{y}_t$, therefore less amount of the variance was explained by the extensions $\hat{y}_t$ produced by both models. However as the cross correlation ρ_{xy} increases, the extensions $\hat{y}_t$ produced by both models showed an increased amount of the explained variance, i.e. E[$\sigma^2_{\tilde{y}}/\sigma^2_y$] has increased, which is expected due to the increased relation between y_t and x_t.

Tables 1 – 4 show the results in relation to the power of both models to produce extensions $\hat{y}_t$ that preserve the lag-1 serial correlation coefficient ϕ_y of the short record y_t. Regardless of the cross correlation between y_t and x_t, the expectation E[$\phi_{\tilde{y}}/\phi_y$] of the statistic $\phi_{\tilde{y}}/\phi_y$ as estimated from the extensions $\hat{y}_t$ produced by the new model is nearly 1, which means that such extensions have a serial correlation that is so close to the short record serial correlation, i.e. the extended part well reproduced the serial correlation of the short record. On the other hand, the expectation E[$\phi_{\tilde{y}}/\phi_y$] as estimated from the extensions $\hat{y}_t$ produced by the linear regression model is always much less than 1, i.e. such extensions always underestimating the serial correlation of the short record. Such result is expected since the formulation of the simple linear regression model (Equation 1) ensures the production of extensions that only will preserve the mean value of the short record and the cross correlation between the short and the predictor variable, but not the serial correlation.

Extensions produced by both models behaved similarly in terms of preserving the cross correlation between y_t and x_t. At low cross correlation values (Table 1), the extensions produced by both models slightly overestimated the original cross correlation (ρ_{xy}) between y_t and x_t, however as the cross correlation increases the expectation E[$\rho_{x\tilde{y}}/\rho_{xy}$] gets closer to 1, which means that both models evenly gave extensions that closely reproduced the cross correlation between the short y_t and the predictor variable x_t.

The sum of the squared errors is a criterion that is used to validate extensions produced by a record extension model. It measures how much the produced extensions deviate from there exact values. Over the 1000 generated samples at different cross correlation values, the expectation of the sum of the squared errors E[$\sum e^2$] is shown in Tables 1 – 4 as calculated from the extensions produced by both models. Generally the extensions produced by both models departed similarly from there exact values, however as the cross correlation increases the sum of the squared errors decreases indicating that the extensions $\hat{y}_t$ produced by both models become more close to there exact values.

The new model shown by Equation (3) was used to extend the precipitation record at Rabba gauging site in Jordan (Figure 2) for the purpose of drought analysis. In Rabba region, crops like wheat are usually cultivated depending on the rainy season that starts by October of the current year and ends by April of the next calendar year. The monthly precipitation record used in this study for Rabba gauging site starts the year 1952 and ends the year 1998. The annual rainy season precipitation is the sum of precipitation for the months October to April. The mean, the variance, and the serial correlation of the rainy season precipitation (1953 – 1998) at Rabba station are: 339.5mm, 12821.9, -0.076 respectively. Truncating the annual rainy season series (1953 – 1998) at the level of the long term mean for drought analysis shows the occurrence of 11 drought events of duration ranging between 1 – 6 years.

The nearby precipitation gauging site of a relatively long record is Amman airport gauging station. The annual rainy season precipitation as the sum of October to April monthly precipitation spans over the period 1924 – 1998. The mean, the variance, and the serial correlation of the rainy season precipitation at Amman airport gauging station are: 271.7mm, 8443.2, -0.185 respectively. The cross correlation between the precipitation at the two gauging sites over the calibration period (1953 – 1998) is 0.77. This longer precipitation series was used as a predictor in the new model to extend the precipitation record at Rabba gauging site over the period 1924 – 1952. The model parameters a and b were estimated using Equations (4) and (5) having values of 0.0571 and 0.9289 respectively. The combined precipitation record at Rabba gauging site (the extended over 1924 – 1952 + the historical over 1953 – 1998) was used to analyze droughts.

The combined precipitation record at Rabba gauging site has a mean, variance, and serial correlation of 344.4mm, 10285.3, and -0.83 respectively. Comparing such statistics with these obtained from the short historical record it can be seen that the extensions obtained from the new record extension model well reproduced the mean and the serial correlation while the variance was underestimated. Such result very well match with the results obtained from the analysis of the 1000 synthetic samples shown by Tables 1 – 4. Figure 3 shows the historical precipitation at both gauging sites and the extended precipitation at Rabba site.

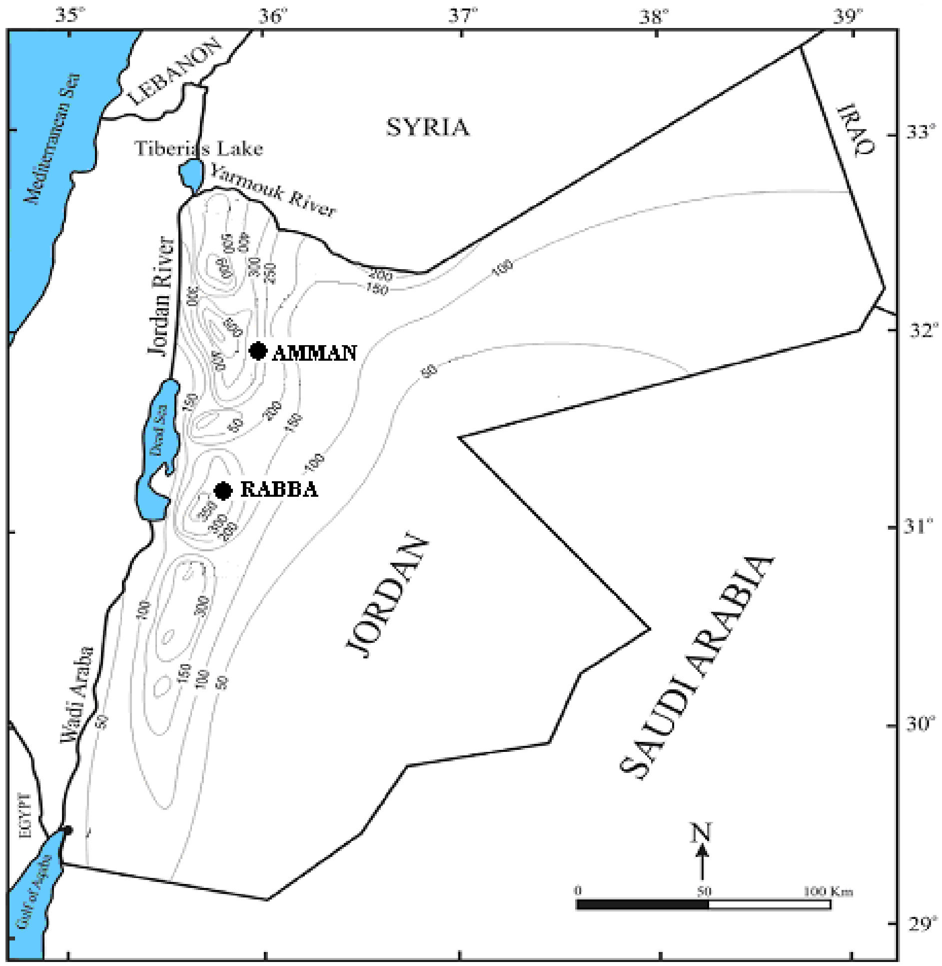

Figure 2 Rabba and Amman airport precipitation gauging sites. The contours show the spatial distribution of the annual precipitation.

Figure 4 shows the combined precipitation record at Rabba gauging site truncated at the level of the long term mean of 344.4 mm for the purpose of drought analysis. Compared to just 11 drought events obtained by analyzing the short historical precipitation record (1953 – 1998), the analysis of the longer combined precipitation record (1924 – 1998) shows the occurrence of 19 drought events of duration ranging between 1 – 6 years. Such drought events are distributed as: 63.2% for the 1-year event, 15.8% for the 2-years event, 5.2% for the 3-years event, 0% for the 4-years event, 10.5% for the 5-years event, and 5.2% for the 6-years event. In Rabba region, the average waiting time between the end and the start of subsequent drought events is 1.75 years, i.e. given that a drought situation has just ended then on average the time needed for the next drought event to show up is nearly 2 years.

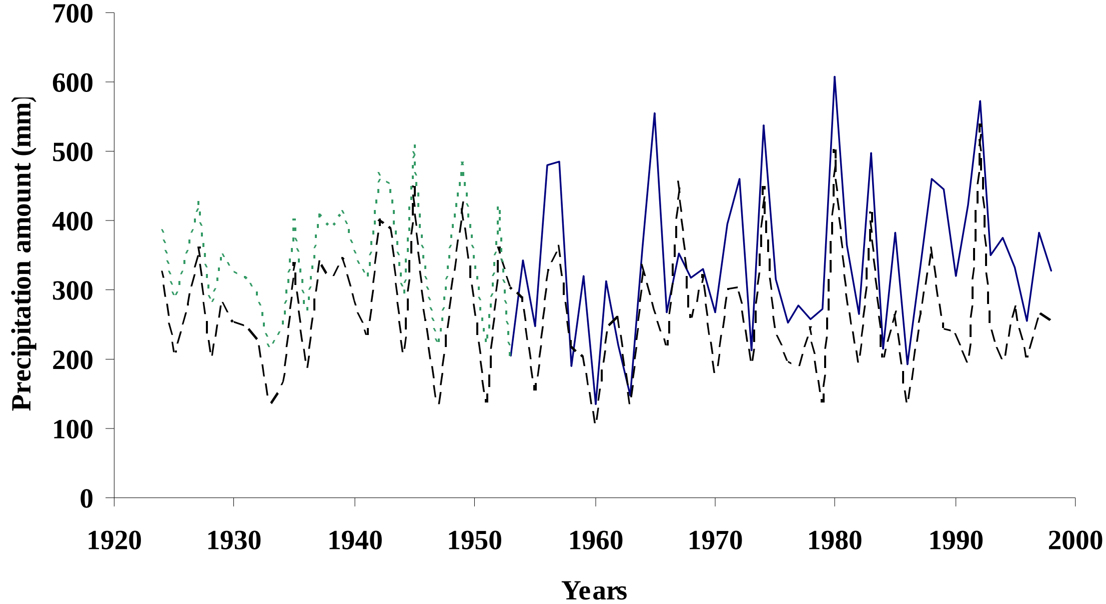

Figure 3 The historical precipitation (solid line) and the extended precipitation (small dashed line) at Rabba gauging site versus the historical precipitation at Amman airport gauging site (large dashed line)

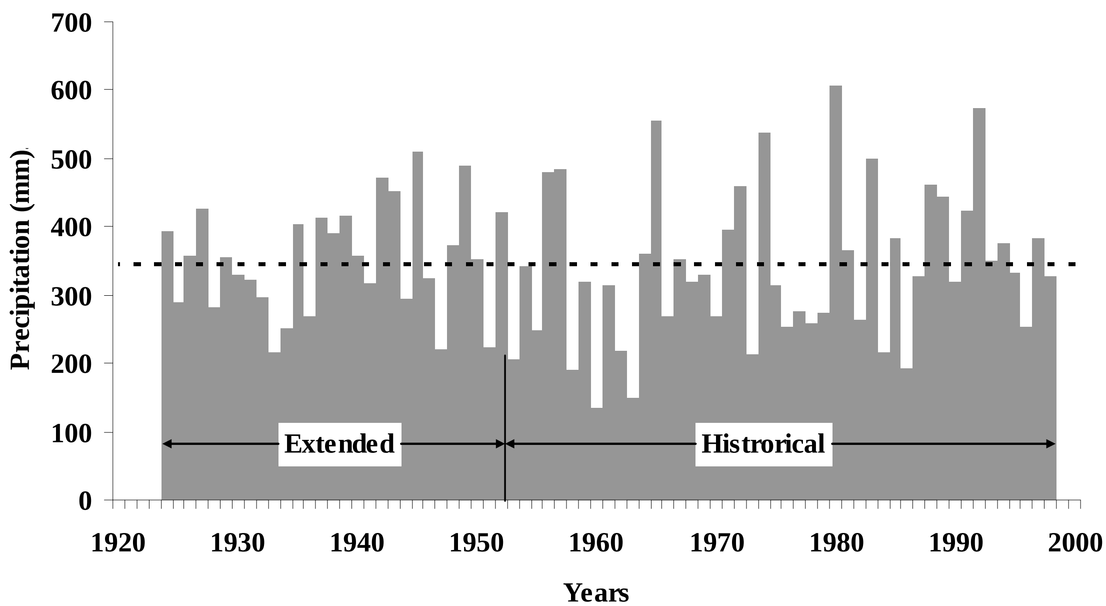

Figure 4 The combined (historical + extended) precipitation at Rabba gauging site truncated at the level of 344.4 mm (dashed line)

4. CONCLUSIONS

Current record extension models like the widely used linear regression model generate extensions that may not reproduce all the statistics of the short historical records specially the serial correlation. This paper presents theoretical aspects for a new model that can be used to extend short hydrological records such that most of the short record statistics are well preserved focusing on the reproduction of the short record serial correlation. The model was tested versus the simple linear regression model using simulated normally distributed bivariate samples at different cross correlations. In conclusion the new model preformed quite well compared to the simple linear regression in terms of preserving the serial correlation. The new model was then used to extend the historical precipitation record at Rabba gauging site in Jordan back to the year 1924. The combined series of the historical and the extended precipitation was used to analyze drought events in Rabba region in Jordan. The analysis showed the occurrence of 19 drought events of duration ranging between 1 – 6 years. Drought of 1 year duration was found to be the most common event. Assuming that drought condition has just ended in Rabba region, then the average waiting time for the next drought event to occur is nearly 2 years.

APPENDIX

The new record extension model is:

$$y_t = \bar{y} + a\left(y_{t-1} - \bar{y}\right) + b\left(x_t - \bar{x}\right) \tag{1a}$$

Re-writing Equation (1a) as:

$$y_t - \bar{y} = a\left(y_{t-1} - \bar{y}\right) + b\left(x_t - \bar{x}\right) \tag{2a}$$

Multiplying both sides of Equation (2a) by $\left(y_{t-1} - \bar{y}\right)$ and taking the expectation on both sides:

$$E\left[\left(y_t - \bar{y}\right)\left(y_{t-1} - \bar{y}\right)\right] = a\,E\left[\left(y_{t-1} - \bar{y}\right)\left(y_{t-1} - \bar{y}\right)\right] + b\,E\left[\left(x_t - \bar{x}\right)\left(y_{t-1} - \bar{y}\right)\right] \tag{3a}$$

The expectation $E\left[\left(y_t - \bar{y}\right)\left(y_{t-1} - \bar{y}\right)\right]$ is estimated by the lag-1 covariance of the variable y_t, i.e. C_{yy^-}, likewise the expectation $E\left[\left(y_{t-1} - \bar{y}\right)\left(y_{t-1} - \bar{y}\right)\right]$ is estimated by C_{yy}, and the expectation $E\left[\left(x_t - \bar{x}\right)\left(y_{t-1} - \bar{y}\right)\right]$ is estimated by C_{xy}, therefore Equation (3a) becomes:

$$C_{yy^-} = a\,C_{yy} + b\,C_{xy} \tag{4a}$$

Multiplying both sides of Equation (2a) by $\left(x_t - \bar{x}\right)$ and taking the expectation on both sides and replacing the expectations by there estimates (covariances) then:

$$C_{xy} = a\,C_{xy^-} + b\,C_{xx} \tag{5a}$$

Solving Equations (4a) and (5a) for *a* and *b*, then:

$$a = \frac{C_{xy}\,C_{xy^-} - C_{xx}\,C_{yy^-}}{(C_{xy^-})^2 - C_{xx}\,C_{yy}} \quad \text{and} \quad b = \frac{C_{xy} - a\,C_{xy^-}}{C_{xx}}$$

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