A Study Of Hydrological Trends And Variability Of Upper Mazowe Catchment-Zimbabwe

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Abstract

This paper describes the development and application of a procedure that identifies trends in hydrologic variables. The non-parametric Mann-Kendall (MK) statistic test to detect trends was applied to assess the significance of the trends in the time series. Different pats of the hydrologic cycle were studied through 15 hydrologic variables, which were analysed for a network of Upper Mazowe catchment. A bootstrap test was used since it preserves the cross correlation structure of the network in assessing the field significance of upward and downward trends over the network. At the significance level of 0.05,the site significance of trends with more than 30 years and less than 30 years of trends was assessed by the MK test with the Trend Free Pre Whitening (TFPW) procedure. The distribution of the significant trends indicate that for the two periods monthly flow significantly decreased with the exception of the month of September for the less than 30 years series. The field significance of trends over the two time series was evaluated by the bootstrap test at the significance level of 0.05 and none of the two flow regimes expressed field significant changes.

Keywords: Hydrological Trends, Hydrologic variable, cross correlation

Introduction

One of the most significant impacts of global climate change will be on the hydrological system and hence the river flows and water resources Alemaw and Chaoka (2002). Recent explorations of potential climate change in the Southern Africa region reveal evidence that a warming of almost 1^{o}C, with high rainfall variability ($\pm$ 30%) accompanied by the recent droughts of 1992 and 1995,has highlighted the sensitivity of the region's water resources to variations of climate Hulme, Arntzen, Downing, Leemans, Malcolm, Reynard, Ringrose and Rodgers (1996). These studies impresses upon us then to acknowledge that the sensitivity of water resources to climate factors, or to changes in land use and catchment characteristics on national and regional scales must be addressed.

Several researchers have given a great deal of attention to the potential impacts of climatic change and variability in several fields at international level. As an example Alemaw and Chaoka (2002), and Gleick (1989) have hypothesized on the hydrologic regime for various geographic areas including Southern Africa as a particular case.

Alemaw and Chaoka (2002) investigated possible trend in the annul river flow of 502 rivers in the region of Southern Africa and observed that the trends have been linear and declining in general. The record that they used range from 1950s to late 1990s and several areas were found with evidence of declining runoff.

The Intergovernmental Panel on Climate Change in Canada (IPCC, 1998) provides a comprehensive review of the potential impacts on climate. Climatic change is considered likely to increase runoff in the higher latitude regions because of increased precipitation on the other hand flood frequencies are expected to change also in some locations and the severity of drought events could increase as a result of those changes in both precipitation and evaporation. In all these considerations ‘the issue’ then becomes the effects of global warming and its impacts on the environment, and water resources in particular.

Douglas, Vogel, Kroll, (2000) examined trends in flood and low flow and found evidence for upward trends in low flows. They also demonstrated the importance of properly considering the effects of cross-correlation in the data. Whitefield (2001) found significant precipitation decreases during the fall and significant increases during winter and spring and also that hydrologic responses to climate variations followed distinctive patterns

One way to address these concerns at local level is to determine whether any hydrologic changes or trends are evident in historical records of runoff and whether they are related to global warming, and what might be the implications for water supply. This paper represents an initial stage in research designed to identify some of the hydrologic impacts of climatic change for the Mazowe catchment in Zimbabwe. The main objective of the study was therefore to explore trends in monthly flow records at local scale in a hydro-climatically homogenous region. The second objective was to assess the significance of the detected local trends by means of a bootstrap simulation technique.

The emphasis in the research reported herein is on the quantification of trends in hydrologic variables and the investigation of the relationship between trends in hydrologic variables and trends in meteorological variables. Further work will examine the issue of trend attribution and thus attempt to establish a linkage between climate change and observed hydrologic trends. Section two of this paper will describe the hydrologic variables that are examined in this work. This will be followed by a presentation of the trend detection techniques that are used. The methodology outlined in this work is then applied to a collection of sub catchments that make up Mazowe Catchment. The paper ends with a summary of the results and conclusions.

Methodology

There are several trend detection tests that can be carried out, though in earth sciences applications, where the assumption of normality of the data can rarely be accepted, nonparametric tests are usually preferred. Nonparametric tests are robust with respect to missing values, censored data, and tied values, seasonality, non-normality, non-linearity and serial dependency. The most frequently used non-parametric test for identifying trends in hydrologic variables is the Mann-Kendall (MK) test (Mann, 1945,Kendall, 1975) of the randomness of the data against trend.

Local Trend Detection

A serious problem in detecting and evaluating trends in hydrologic data is the effect of serial dependence, Cundelick and Bun (2002). A positive serial correlation can overestimate the probability of a trend and negative correlation may cause its underestimation. Von Storch and Navarra (1995) proposed a ‘pre-whitening’ approach that removes the serial correlation from the data. A modified MK test for auto-correlated data based on a correction of the variance test for the effective number of observations was proposed by Hamed and Rao (1998).

Burn (1994b) recognizes the fact that when attempting to detect trends in a natural series it is imperative that one be cognizant of the inherent variability of hydrologic time series. There is a difficulty though associated with differentiality between natural variability and trends (Askew 1987). In view of this, it then becomes more prudent that, the development of a rigorous approach be adopted to determine the significance of the detected trends using outlined steps below.

1. The initial step was to choose the variables to be studied. Stream flow variables were used, as they tend to reflect an integrated response of the catchment area as a whole.
2. Secondly, the stations were chosen that were to be investigated. The primary factor on which the choice was based was the record length. Further criteria were applied as part of the process of defining the Mazowe Catchment hydrometric network from which all stations were drawn.
3. Checking for presence of trends in the data was the next step and this was done using the Mann-Kendall non-parametric test.

4. The significance of the detected trends was determined as the fourth step and this was accomplished using a permutation procedure. A global or field, significance level, reflecting the correlation structure in the data set was determined.

These steps are described in the sections that follow below. A linear trend test was also used to identify if the time series has a declining or an increasing trend or no trend at all in the time domain of record of annual flow. Any observed phenomenon was considered not to be a chance phenomenon if it was observed simultaneously at a number of stations within the upper Mazowe Catchment.

Selection Of Hydrologic Variables

Climatic change can be indicated by hydrologic variables. The relationship between hydrology and climate can be understood with the help of what these variables can reflect in terms of climatic change. Numerous studies have suggested different variables for detecting climatic change. Pilon, Winkler, Harvey, and Kimmett (1991) suggested stream flow variables, while Anderson, Shiau, and Harvey (1992) considered mean, low and high flow regimes for climate change investigation. Another suggestion to study a large number of hydrologic variables since climatic change was likely to affect various variables in different ways was made by Burn and Soulis (1992).

Stream flow variables are advocated herein because of the spatially integrated hydrologic response that they provide. The procedure adopted is to select a collection of variables encompassing the important components of the hydrologic regime. In addition to hydrologic variables reflecting low flow, average flow, and high flow regimes, the timing and duration of hydrologic events were also included.

Selection Of Stations

In climatic change research, the selection of stations is one of the important steps that are observed. This work takes advantage of the work done by ZINWA, which represents an appropriate collection of hydrometric gauging stations. Mazvimavi (2003) contends that the main consideration in selecting catchments for inclusion in studies relating to flow is the availability of flow data on each catchment to enable accurate estimation of flow statistics like means of daily and monthly flows, flow duration curves and separation of base flows from total flow. Previous studies in Zimbabwe showed that a minimum of 10 years of flow data gives a reasonable estimation of most flow statistics (Bullock, 1988) In this study stations were selected from the ZINWA network with a minimum record length of 25 years to ensure statistical validity of the trend results.

Trend Detection Tests

The Mann-Kendall non-parametric test for trend was used to analyse all the time series of all the hydrologic variables. Mann (1945) originally used this test and Kendall (1975) subsequently derived the test statistic distribution. Trend detection by other researchers in similar applications using this tool has been found to produce reliable results. The Mann-Kendall test statistic is given below:

$$S = {}^{n-1}\sum_{l-1} {}^{n}\sum_{j-l-1} \text{Sgn } (X_j - X_i) \qquad (1)$$

Where X_i and X_j are the sequential data values, *n* is the data set record length, and

$$\text{Sgn } \theta = \begin{cases} +1 & \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \theta < 0 \end{cases} \qquad (2)$$

(2)

The Mann-Kendall test has two parameters that are of significance to trend detection. The significance level that indicates the trend's strength and the slope magnitude estimate that indicates the direction as well as the magnitude of the trend constitute the parameters.

A permutation approach is used to generate the distribution of the test statistic. The Mann-Kendall statistic *S,* is calculated for each of the large number of different random orderings (permutations) of the data set. Comparison of the test statistic for the original data set to the distribution of the test statistic obtained from the permutated data sets and a significance level is done. The rationale behind this approach is that under the null hypothesis of no trend in the data, each ordering of the data set is likely to be equal. Therefore, the null distribution of the test statistic can be estimated from the permutation approach. This approach can be applied with any statistical test for trend.

The non-parametric robust estimate of the magnitude of the slope, β, is given by:

$$\beta = \text{Mean } [(X{-}X) / (j\text{-}i))] \quad \text{for all } i<j \qquad (3)$$

Significance Of Trend Results

The results of the trends can be used to determine whether or not the observed collection of time series for a hydrologic variable exhibits a number of trends that is greater than the number that is expected to occur by chance. The correlation structure of the data becomes necessary for this to be realised. Focus should be placed on both the serial correlation of the data series and the cross-correlation between the hydrologic variables at different locations

Serial Correlation

Von Storch and Navarra (1995) observed that the presence of serial correlation could complicate the identification of trends since a positive serial correlation can increase the expected number of false positive outcomes for the Mann-Kendall test. Suggestions have been made to remove the serial correlation from the data set prior to applying a trend test. Approaches common have been to pre-whiten the series or to 'prune' the data set to form a new subset of observations that are sufficiently separated temporally to reduce the serial correlation.

The approach is adopted herein and involves the calculation of the serial correlation and removing the correlation if the calculated serial correlation is significant at the 0.05 level. The following procedure is used:

$$yp_t = y_{t+1} - ry_t \qquad (4)$$

where yp_t is the pre-whitening series value for time interval *t, yt,* the original time series value for time interval *t*, and *r*, is the estimated serial correlation coefficient. From the total of 108 (12*9) analysed monthly series, only 11 (92.6%) had a lag-1 autocorrelation coefficient significant at the 0,05 level for the 30 years plus series and for the less than 30 years series with a total of 120 (10*12) analysed monthly series, only seven (87.5%) had a lag-1 autocorrelation coefficient significant at the 0.05 level.

Cross Correlation

The effect of cross-correlation in the data is to increase the expected number of trends under the hypothesis of no trend in data. There is then the need to consider the field significance in ascertaining the overall significance of the outcomes from a set of statistical tests. Field significance allows the determination of the percentage of tests that are expected to show trend, at a given local (nominal) significance level, purely by chance. An approach for determining the field significance that involves calculating a regional value for the Mann-Kendall statistic was developed by Douglas, Vogel, Kroll,(2000).

A bootstrap, or resampling, approach was used herein to determine the critical value for the percentage of stations expected to show a trend by chance. The approach involves the following:

1. From a specified range of years select a year randomly. The specified range is either the entire period of record for which data are available or a defined period of record for which analysis is to be conducted (e.g. 1970 – 1980).
2. The data value for each station that has a data value for the selected year is entered in the data set being assembled (i.e. is added to the resampled data set).

3. Steps 1 and 2 should be repeated until the resampled data set has the required number or target of station-years of data. This target number of station-years of data is equal to the number of station-years in the initial data set.
4. The Mann-Kendall test is applied to the data from each station in the resampled data set and the percentage of results that are significant at the $\alpha_1\%$ level is determined. $\alpha_1\%$ is referred to as the local significance level.
5. Steps 1-4 are repeated a total of Number of Stations (NS) times resulting in a distribution for the percentage of results that are significant at the $\alpha_1\%$ level. From this distribution, the value that exceeded $\alpha_f\%$ of the time is selected as the critical value, p_{crit}* α_f is referred to as field, or global, significance level. Results obtained with a percentage of stations showing a significant trend larger than p_{crit} will be considered significant at the $\alpha_f\%$ level. In this work, NS was set to 19.

Any temporal structure that exists in the original data set will not be reproduced in the resampled data sets because of the nature of the resampling process, which selects the years to be included at random. However, the cross-correlations in the original data sets are preserved through including all data values for a given year in the resampled data set. This allows the impact of cross-correlation to be determined in establishing the critical value for the percentage of stations exhibiting a trend.

Applications of the Methodology

The 1990 stream flow summaries

The study to detect trends in hydrologic variables was performed on stations from the ZINWA 1990 summaries, a data collection network from rivers in Zimbabwe. The criteria according to which stations were selected are:

- Record length. A station must have a minimum record length of 20 years to be included in the study. This was chosen to make sure that under –represented geographic areas, which are characterised by minimal data availability, were included in the network.
- Longevity. This criterion was based on the judgement of the ZINWA staff.
- Data accuracy. Data accuracy was assessed qualitatively by ZINWA staff based on the knowledge of the hydraulic condition of the stations to ensure that only stations with good quality data were included in the study.

The Mazowe Catchment is made up of 70 hydrometric stations of which only19 of them are used in this study since not all stations have continuous stream flow. Only upstream gauging stations of the Mazowe catchment, which make up the local regional classification of upper Mazowe basin, were considered. The selected stations have at least 20 years of record, with an average record length of

31 years. The longest record length is 48 years, while 47% of the stations have 30 or more years of record. Sub-catchment sizes range from 8.6Km^2 to 3300.0Km^2 with a mean size of 884Km^2, 33% of the sub-catchments have a drainage area greater than 1000Km^2,and 11% have a drainage area less than 100Km^2.The identification of flow measuring stations with accurate flow data was based on the 1990 Stream Flow Summaries prepared by ZINWA who have compiled files documenting maintenance of gauging stations and accuracy of rating curve of the flow measuring structure. These files were review to identify stations with acceptable flow data that meets the criteria above.

Selection of hydrologic variables

A total of 15 hydrologic variables were selected for this research. The variables include the annual mean flow, and the mean monthly flow for each month. This collection of variables was analysed in order to gain a broader understanding and appreciation of the hydrologic response to climate change.

Study Period

The trend detection procedure was performed on two study periods. These periods started in 1940s and were divided into those with more than 30 years record and those with less than 30 years series. In addition, a final study period corresponding to all of the available records at each station, subsequently referred to as the 'All Records' case, was considered. The different fixed study periods selected represent a trade-off between the temporal coverage afforded by the selected data set. It should be noted that for a station to be included in a given study period, there could be no more than three years/ data entries during the study period for which the station did not have data. Selecting a common period of record in this way facilitates investigation of variable climatic conditions during the common prescribed period. The investigation of all available data through the 'All Records' study period allows for an optimal spatial coverage, although the periods of record reflected at each station will potentially differ, making interpretation of the results more difficult.

Results obtained from the trend tests were analysed using a local significance level of 0.05 and a field significance level of 0.05.

Results

In this section we present summary tables of the Mann-Kendal test results at the 0.05 local and global significance levels. Finally, the relationships between hydrologic variables and precipitation variables are explored for a selection of locations.

Mann-Kendall Test Results

The results for trend for the 1948 to 1998 study period for the 15 variables is presented in Table 1.The trend results for the 1950s to 1998 for Pote river catchment are presented in Table 2.Apparent from Tables 1 and 2 is the indication that there are differences in the results for the individual hydrologic variables and that there are differences in the results for the different study periods selected.

The ‘All Records Case’ results has the greatest number of significant trends with all variables except for July flow, resulting in a number of trends that is field significant. Several hydrologic variables were noted to have strong trend results. The Figures 1 and 2 below summarises the relative sites with increasing/ decreasing trends at 0.1 and 0.05 local significance levels.

Summary Trends

The noteworthy trends based on the 1948–1998 study period are summarised in this section. The results are summarised for the whole catchment. There is an apparent increase in the annual flow and a decreasing monthly flow trend for the ‘All Record’ case. The ‘All Record’ case for the less than 30 years series shows an increasing trend with a linear trend model Y_t = -3.21737 + 0.682082*t although the more than 30 years ‘All Record’ case series shows a decreasing trend with a linear trend model of Y_t = 108.638 – 0.210408*t. The flow series exhibits an increasing trend likely because of the onset of the rain season, Figure 1 and Figure 2.Generally there is an indication of probable increase in the trend for the period under study showing that the flow could be indicative of the nature of precipitation in the catchment. The annual trend analysis for the “All Record Cases” shows an increasing trend explained by the linear trend model Y_t = 55.5699 + 0.305105 * t.

Increasing flow trend is noted for the months of September for those stations with less than 30 years series otherwise the month on month cross correlation depicts a temporal structure, that is, a trend or pattern that exists in the original data.

The results of trend detection according to the MK test are summarized below. The most striking results are observed in the October, November, August and September months for the –30 years series, while the +30 years series does not have any striking result, where a high number of months exhibit a significant positive trend. The MK test identified 37.5% of all sites significant at 0,1 local level for the +30 years series and none in the –30 years series. Significant decreasing flows were observed in the –30 years series especially for the months of March, April, May and September. An almost similar pattern is described for the eight sites of the +30 year’s series for January, February and March.

However the occurrence of the same trends signs in all months for the +30 year's series is a highly local significant result.

Eleven of the 12 serial correlation coefficients are statistically significant at the 95% confidence level. The serial and cross correlation structure of the more than 30 years series and less than 30 years series for trend detection was applied. From the total of 108 (12 x 9) analysed monthly series of the +30 year's series record only 11 (92.6%) had a lag^{-1} autocorrelation coefficient significant at the 0.01 level. On the other hand a total of 12 cases in the –30 year series the month of March had a relatively weak autocorrelation and for the +30 year series March and April showed weak values.

The +30 and –30 years series of the monthly flows are in most cases significantly cross-correlated. Table below shows the autocorrelations coefficients, which are statistically significant at 95% confidence level.

The average values of cross correlation coefficients for Upper Mazowe flow calculated from coefficients between given gauging stations are shown in Table 2 above. The figures clearly show the dependence of the average cross correlation coefficient values on the period of analysis. The months of October, December, January, February, April, May July and August have more significant cross correlation time series than November, March, June and September for the +30 years series while the –30 years series exhibits a slightly different scenario. The months of October, February, March, April and June have significantly higher values of autocorrelation coefficients while November, December. January, May, July, August and September have lower values.

This feature is likely caused by the variation in the onset of the rain season and the droughts that have occurred.

Relationships between hydrologic variables and meteorological variable

Graphs depicting selected hydrologic variables and one meteorological variable for the catchments are presented. The correlation between the hydrologic variable and the meteorological variable were evaluated and pairs that demonstrated a relationship were examined further. The available meteorological variable consisted of annual precipitation for the Catchments. Figures 3 and 4 present the results for Pote river catchment and that of a few selected stations.

Figure 5 shows the data values for precipitation plotted against flow data .The rainfall start date exhibits a decreasing trend that is significant at the 95% level. Stream flow series exhibits a similar pattern over the period of record to that of precipitation. This similarity in pattern implies that changes in stream flow during the historic record might be expected to be associated with corresponding changes in the precipitation conditions. Apparent from Figure 5 is the non-uniformity of the pattern in both precipitation and stream flow values.

Conclusions and recommendations

The application of a trend detection framework to the Upper Mazowe catchments has resulted in the identification of more significant trends than are expected to occur by chance. Temporal differences were noted in the occurrence and the direction of trends implying that a systematic framework is essential for detecting trends that might arise as a result of climatic variability. Spatial differences in the trend results can be expected to occur as a result of spatial differences in the changes in precipitation and temperature and spatial differences in the catchment characteristics that translate meteorological inputs into a hydrologic response. Temporal differences in the trends likely reflect non-uniform changes in the meteorological variable.

Several hydrologic variables were noted to have particularly strong trend results. There is a decreasing trend in the annual maximum flow in the catchment. From the monthly flow variables several months were observed to have strong trend results displaying an increasing trend.

The similarities in trends and patterns in the hydrologic variables and in meteorological variable in the catchment imply that the trends in hydrological variables are related to the meteorological variable. The results indicate that the temporal patterns in the variables have not been uniform and that the hydrologic variables may accentuate trends and patterns that exist in the meteorological variable that act as inputs to the hydrological cycle. The similarities of trend patterns in the hydrologic variables and meteorological variable at selected stations imply that the trends in the hydrologic variables are related to trends in meteorological variable.

Future work will address the issue of trend attribution and will attempt to establish a linkage between climatic change and the observed hydrologic trends. At this stage it is not appropriate to state that the observed trends have occurred as a result of climatic change.

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FIGURES AND GRAPHS

Table 1. All Records Case Serial correlation Coefficients

Lag[1]	Serial correlation coefficient
1	0.45
2	0.31
3	0.28
4	0.21
5	0.14
6	0.08
7	0.23
8	0.37
9	0.27
10	0.20
11	0.22
12	0.19

Table 2. Cross correlation coefficients for the +30 and –30 years series

Lag[-1]	+30 years series	-30 years series
1	0.46	0.68
2	0.35	0.53
3	0.35	0.41
4	**0.20**	0.35
5	**0.17**	0.33
6	**0.06**	0.23
7	**0.23**	**0.19**
8	0.40	0.68
9	0.30	0.67
10	0.28	0.27
11	0.33	**0.17**
12	0.28	**0.17**

FIG.1 TRENDS IN MONTHLY FLOW RECORDS +30 YEARS SERIES FOR 8 STATIONS

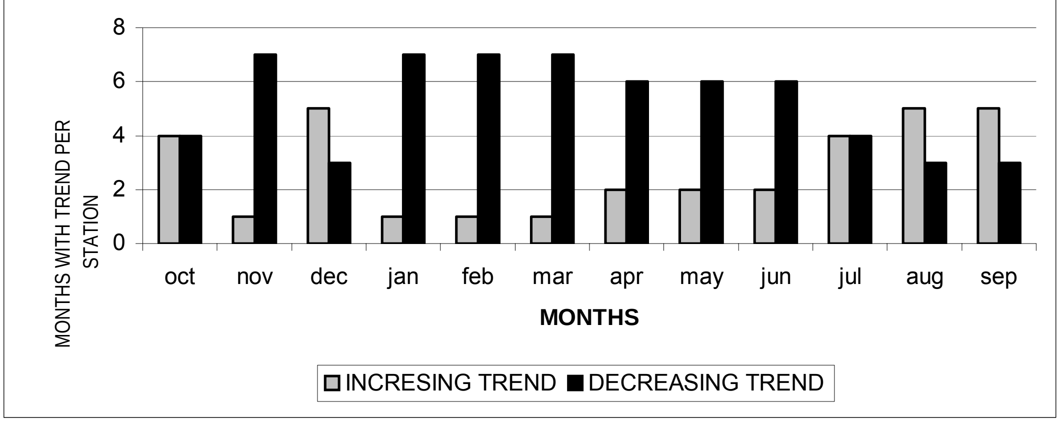

FIG. 2 TREND IN MONTHLY FLOW RECORD -30 YEARS SERIES FOR 11 STATIONS

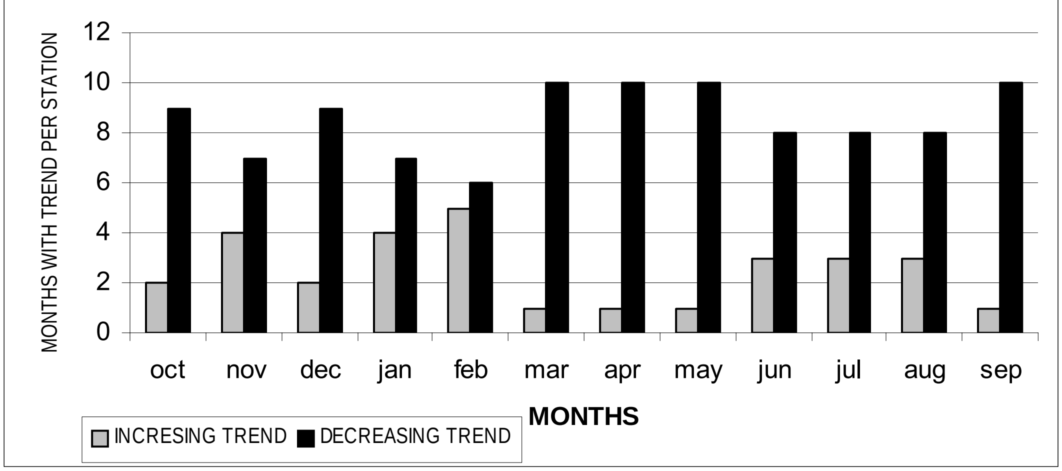

FIGURE 4 CORRELATION PRECIPITATION AND STREAMFLOW
SELECTED STATIONS

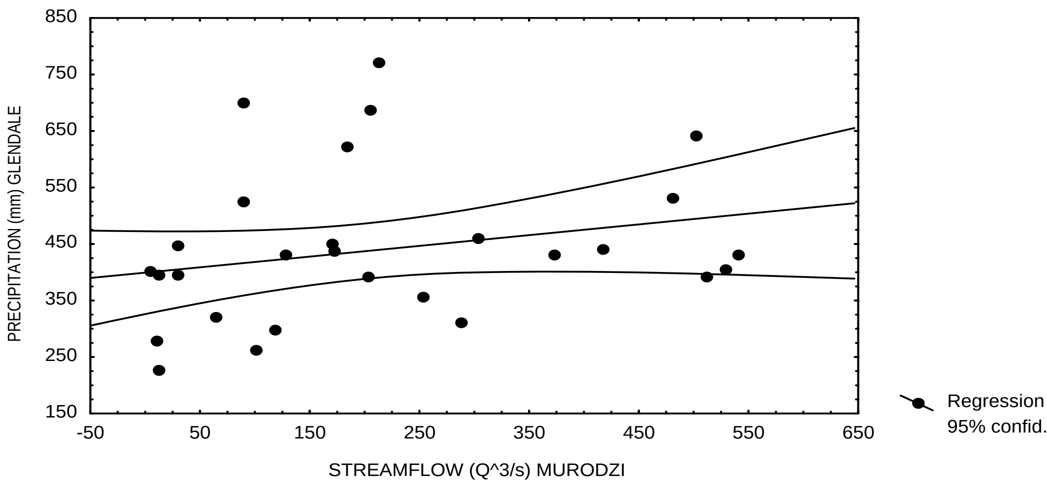

FIGURE 5 TIME SERIES PLOT FOR PRECIPITATION AND FLOW FOR POTE RIVER

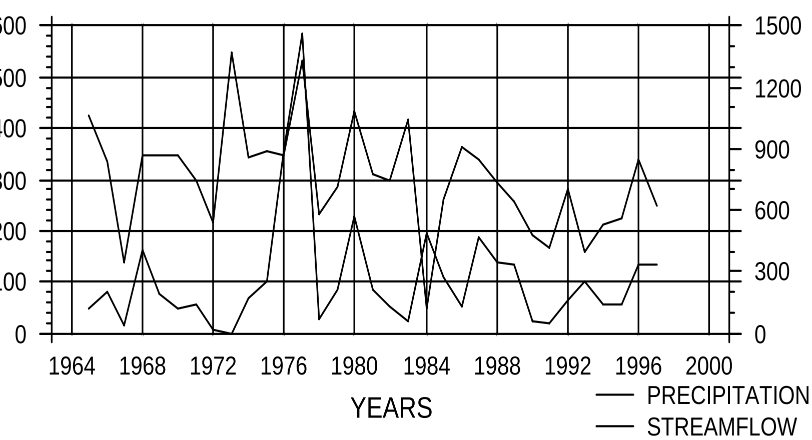

FIGURE 3 CORRELATION BETWEEN STREAMFLOW AND PRECIPITATION

P = -1.871 + .14336 * Q

Correlation: r = .33276