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Streamflow Trends and Depletion Study in Nebraska
--- With a Focus on the Republican River Basin

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Nonparametric techniques were applied to the analysis of trends in streamflow, precipitation and temperature in Nebraska and northwestern Kansas. Fifty years of streamflow data from 114 gauging stations in eight major river basins were examined. Temporal trends of streamflow in Nebraska showed a spatial tendency of increasing streamflow (upward trends) mostly in the east but decreasing streamflow (downward trends) mainly in the west. This difference in streamflow from west to east is unlikely to be due to a long-term change in precipitation over the entire state because precipitation data from 1948 to 2003 did not indicate a spatial trend. For the Republican River basin, streamflow data from 25 out of 28 gauging stations showed a downward trend. Based on the local precipitation-adjusted streamflow, additional analyses suggest that the baseflow from most of the 28 stations had decreased since 1970s. This decreasing trend matches well with an increasing number of irrigation wells. Because of no trend in the precipitation, it is most likely that groundwater withdrawal in this basin was a primary factor in streamflow depletion. Besides Nebraska, where a significant amount of groundwater was withdrawn from the High Plains aquifer, Kansas and Colorado were the other contributors to the streamflow depletion of the Republican River.

KEYWORDS: Streamflow, depletion, precipitation, irrigation wells, trend analysis, Mann-Kendall and LOESS techniques

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1. Introduction

Since the mid-1930s, especially after the mid-1950s, the use of groundwater has increased rapidly in Nebraska. The number of registered wells has grown from 1,200 in 1936 to 98,000 currently serving about 85 percent of the state's irrigation land [Flowerday *et al.,* 1998]. Intensive groundwater development for irrigation or other land use typically causes the depletion of nearby streamflow; the analysis of the hydrologic data for the Frenchman Creek in the Republican River basin by Burt *et al.* [2002] suggested that streamflow depletion was closely related to the increase in the number of irrigation wells over the last 50 years. The impact of pumping on the water table and streamflow was described by Sophocleous *et al.* [1995] such that: "When pumping of a well located near a stream or surface water body starts, the well initially obtains its supply of water from aquifer storage. The resulting decline of groundwater levels around the well creates gradients which capture some of the ambient groundwater flow that otherwise would have discharged as base flow to the stream. Eventually the cone of depression of the well intercepts the stream, thus inducing flow out of the stream into the aquifer, and the aquifer drawdown comes to an equilibrium, with the streamflow reduced by the rate at which the well is pumping. The sum of these two effects leads to streamflow depletion."

In the analysis of the long-term hydrologic impact of groundwater withdrawals on streamflow, it is necessary to include climatic data (precipitation and temperature), which are likely to be other factors affecting streamflow. Some previous studies of trends in streamflow have focused on larger regions. Lins [1985] used five principal component models to represent the change in annual steamflow of the period of 1931-78 across the United States. The five regions were associated with those five principal components which were consistent with the regional pattern of precipitation. In the study, data from 106 gauges, two from Nebraska, were used. Lettenmaier *et al.* [1994] used 1009 gauges, through 1948-1988, to conduct a trend analysis across the United States, in which a fewer significant trends were detected in the Northwest. Hirsh *et al.* [1982], Aguado *et al.* [1992], Lins and Michaels [1994], Lins and Slack [1998], and Zhang *et al.* [2001] have carried out trend analyses of surface water and related hydrologic conditions, using daily, monthly, annual streamflow or seasonal discharge. Burt *et al.* [2002] have used a multiple regression to annual time series data to quantify the influence of precipitation and irrigation on streamflow gauged from one station in the Republican River basin of the southwestern Nebraska. Their study concluded that there was a strong statistical relationship between the logarithm of annual streamflow and the number of wells and precipitation. In a further complicated application, Refsgaard [1987] proposed to use a lumped, conceptual model or a distributed, physically based model to distinguish the effects of climatic variation and human management on streamflow through the contrast of simulated and observed models.

Determination of temporal trends of streamflow and their spatial pattern in a river basin is a necessary step for better management of surface and ground water resources in Nebraska and several other states in the High Plains region, where most streams are hydrologically connected with their surrounding aquifers. As summarized by Helsel and Hirsch [1992], water resource data often have a few of the specific characteristics: positive skewness, presence of "outliers," autocorrelation, seasonal pattern and so forth. Most of the time the ordinary methods, like linear regression, are not appropriate for trend analyses of those data. Even though transformation of data such as a logarithm may be applied, the problems can't be fully eliminated. For example, the monthly streamflow data (year 1932 - 2003) from gauging station 6821500 on the Arikaree River at Haigler in the Republican River basin, Nebraska, show such problems: the data of 858 records possess the serious skewness (10.26), the kurtosis (139.55) and several outliers; the p-value for normality test with the Shapiro-Wilk is 0.0001. After a logarithm transform, the skewness (-0.85) and kurtosis (2.10) are improved, but potential outliers remain and the p-value still is 0.0001 with the significant non-normal distribution. The nonparametric approaches could be a better alternative compared with parametric forms. The Mann-Kendall test is a specific nonparametric approach often used to detect trends and estimate magnitude of streamflow; so is the LOESS regression for fitting a regression line with robustness.

A declining trend of streamflow at some specific locations has often been the starting point of water right disputes between states or between surface water and groundwater groups (or users) in Nebraska and its surrounding states. For example, rights to the streamflow in the Republican River basin have been in dispute between Nebraska and Kansas, as well as Colorado. The issues include how to account for the use of hydrologically connected groundwater and surface water resources in the Republican River basin [Nebraska Department of natural Resources, http://www.dnr.state.ne.us]. Systematic analysis of streamflow trends, including climatic variables in Nebraska, however, has received little special treatment. Several earlier studies, Lins [1985], Lettenmaier *et al.* [1994] and Burt *et al.* [2002], on streamflow trends in Nebraska used only a few stream gauges. The first part of the study explored the spatial tendency of the streamflow trends and climatic impacts for eight major river basins in Nebraska using the Man-Kendall test. The second part concentrated on the Republican River basin, including Kansas, to determine the streamflow depletion due to groundwater withdrawals using the local precipitation-adjusted runoffs through the Mann-Kendall and LOESS methods. The adjusted-runoff streamflow reflects the levels of groundwater discharge to streams; its trends have not been analyzed for any rivers in Nebraska.

2. Data Sources

Streamflow data come from two datum assemblies. One is the National Water Information System (NWIS) Database of U.S. Geological Services [USGS, http://www.water.usgs.gov], and the other is the Data Bank of the Nebraska Department of Natural Resources [NDNR, http://www.dnr.state.ne.us]. Presently, both USGS and NDNR are operating streamflow gauges in Nebraska. All 110 gauging stations used in this study, with monthly or annual records, are distributed in eight main river basins in Nebraska and Kansas: the Niobrara River basin, the Platte River basin, the Loup River basin, the Elkhorn River basin, the Big/Little Nemaha River basins, the Republican River basin, the Big/Little Blue River basins and the Missouri River basin. Figure 1 illustrates the spatial distribution of the locations of these gauging stations in Nebraska. All trend analyses with the 110 gauging stations were based on the records of streamflow after 1948.

In addition, the daily climatic records (precipitation and high/low temperature) of 33 weather stations, including five weather stations in Kansas, were obtained from the High Plains Regional Climate Center [HPRCC, http://www.hprcc.unl.edu]. The sampling process was determined by considering the length of records and the availability of measurement. The locations of these weather stations in Nebraska are also illustrated together in Figure 1. All precipitation and temperatures measured after 1948 were used.

Besides the streamflow and climatic information, in order to investigate the streamflow depletion related to groundwater use, it is important to know the pumping of irrigation wells and other land use. Unfortunately, the historical measurement of groundwater pumping in Nebraska doesn't exist, and groundwater uses relative to the Republican River basin in Kansas and Colorado were not available either. Therefore the study has to rely on the record of the data of groundwater well registration managed by the NDNR for an indicating of the amount of pumping that occurred through a certain period. As can be expected, the number of registered wells provides only an indirect estimate of groundwater pumping because the actual operation differs from one farmer to another and well capacity may vary considerably from one well to another. The well capacity often ranges from 300 to 12,000 gallons per minute.

3. Methodology

The trend test has been interesting to researchers in environmental science for several decades. Helsel and Hirsch [1992] reviewed a number of approaches for trend analyses of water resources over time series. The regression and Mann-Kendall, without adjusting for the effects of confounding variables, are the techniques commonly used for such analysis. By adjusting for the effects, however, the Mann-Kendall test can be applied on residuals from the LOESS (Local Weighted Regression or Locally Weighted Smoothing Scatter-Plot Regression) or other regressions that account for the confounding variables. Detection of both sudden and gradual trends of streamflow and climatic factors over time, without any adjustment, has been implemented by Lettenmaier *et al.* [1994], Burt [1994], Lins and Slack [1999], Zhang *et al.*[2001]. Burt *et al.* [2002] have used a multiple regression to fit a streamflow model accounting for irrigation wells and precipitation variation. Our study attempts to compute the depletion of streamflow in the Republican River basin of Nebraska-Kansas in terms of the adjusted-runoff streamflow using a combination of the Mann-Kendall and LOESS approaches.

3.1. Mann-Kendall Trend Test

The Mann-Kendall is a nonparametric trend test [Mann, 1945; Kendall, 1975], which does not require any particular distributed data [Gilbert, 1987] and has been widely used to test for randomness against trends in hydrology and climatology [Hirsch *et al.,* 1982]. The null hypothesis is no trend, while the alternative is that there is a trend. The test first ranks all observations by time series. Then the difference between each successive value is calculated, and the sum of the signs of those differences is evaluated as the Mann-Kendall statistic, or K.

$$K = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_i - x_j) \qquad (1)$$

where $$\operatorname{sgn}(x_i - y_j) = \begin{cases} 1 & if \quad x_i - y_j > 0 \\ 0 & if \quad x_i - y_j = 0 \\ -1 & if \quad x_i - y_j < 0 \end{cases}$$

and n is the number of observations.

This process is repeated iteratively until all successive differences have been evaluated. The Mann-Kendall statistic K is then compared to a critical value. If it exceeds that value, there is a significant upward trend when K>0, or a significant downward trend when K<0. The sample size is important in determining the critical value for K. For a dataset with fewer than four observations, no critical values are available for the statistic K. For a dataset with forty or fewer observations, the probability values associated with the Mann-Kendall K can be found in numerous textbooks, for example, Table A30 [Hollander and Wolf, 1999].

Mann [1945] shows that, under H_0, K is symmetrical and is normally distributed as $n \to \infty$. Kendall [1975] gives the mean and variance of K under H_0 given the possibility that there may be ties in the x values.

$$E[K] = 0 \qquad (2)$$

$$Var(K) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5) \right] \qquad (3)$$

where n is the number of observations, q is the number of tied groups and t_p is the number of data in the pth group [Gilbert, 1987]. If the sample size is more than 40 observations, a Z-score is calculated based on the K statistic and the variance (K). The variances of K are used to calculate a Z-score, which represents a standard normal distribution, as a test statistic according to the following:

$$Z = \frac{K-1}{\sqrt{Variance(K)}} \qquad \text{for K > 0}$$

$$Z = 0 \qquad \text{for K = 0} \qquad (4)$$

$$Z = \frac{K+1}{\sqrt{Variance(K)}} \qquad \text{for K < 0}$$

The positive (or negative) value of Z indicates an upward (or downward) trend. If no trend exists, the Z-score represents a standard normal distribution. Alternatively, Z has a positive or negative value.

The magnitude of trend slopes can be also calculated [Sen, 1968]. Sen's estimate for slope is associated with the Mann-Kendall test as follows:

$$Slope = Median\left(\frac{x_i - x_j}{i - j}\right) \qquad (5)$$

where the median of these N values of $\left(\frac{x_i - x_j}{i - j}\right)$ is Sen's estimator of the slope.

3.2. Local Weighted Regression (LOESS)

The local weighted least squares regression developed by Cleveland *et al.* [1979, 1988], also called the locally weighted smoothing scatter-plots (LOESS), is a nonparametric approach for fitting a regression line. Like the Mann-Kendall, the LOESS does not require an assumption about the parametric form of the regression line. It allows situations where no relationship between the independent variables and response variables are specified, such as linear or nonlinear. Moreover, it is suitable when there are possible outliers in the data and a robust fitting method is necessary. So, the LOESS has great flexibility, making it better at dealing with the water resource data with several specific characteristics, like positive skewness, presence of outliers, autocorrelation, and so on, described by Helsel and Hirsch [1992]. In the LOESS, assume that for i=1 to n, the i*th* measurement y_i of the response y, such as streamflow, and the corresponding measurement x_i, say precipitation, are related by

$$y_i = f(x_i) + \varepsilon_i \tag{6}$$

where f is the regression function and ε_i is a random error. The idea of the LOESS is that at a predictor x, the regression function *f(x)* can be locally approximated by the value of a function in some specified parametric class. Such a local approximation is obtained by fitting a regression surface to the data points within a chosen neighborhood of the point x.

Suppose *m* denotes the number of points in the local neighborhoods and d_1, d_2,..., d_m denote the distances in increasing order of the *m* points closest to *x*. The point at distance d_i from *x* is given a weight w_i in the local regression that decreases as the distance from *x* increases. The LOESS procedure [SAS OnlineDoc, Version8, SAS Institute Inc, 1999-2001] uses a tri-cube weight function to define as:

$$W_i = \frac{32}{5}\left[1-\left(\frac{d_i}{d_m}\right)^3\right]^3 \tag{7}$$

In the LOESS method, the weighted least squares are used to fit linear function *f(x)'s* of the predictors at the center of neighborhoods. The radius of each neighborhood is chosen so that the neighborhood contains a specified percentage of the data points. The fraction of the data in each local neighborhood, called the smoothing parameter, controls the smoothness of the estimated line. There are several approaches to select the smoothing parameter for a neighborhood. One used here is to minimize the criterion AICC, which combines both the tightness of the fit and model complexity, called the bias-corrected AIC (i.e., Akaike Information Criterion).

The LOESS can be used to aid data analysis, especially for the trend analysis recommended by Helsel and Hirsch [1992]. One of the applications is that it emphasizes the shape of the relationship between two variables on a scatter plot by adding a line through the middle to aid understanding of how the two variables are related. Secondly, the LOESS is able to remove the effect of an explanatory variable without first assuming the form of the relation (linear or nonlinear). In the situation where several variables may affect the magnitude of a response variable Y, like streamflow, removal of the effect of variable X effect, like precipitation, may be accomplished by the LOESS procedure.

4. Results and Discussions

4.1. Trend Detection for Streamflow, Precipitation and Temperature

Trend analysis was first conducted on the annual mean streamflow of 110 gauging stations using the Mann-Kendall method. The trend test results are summarized on Table 1 and shown in Figure 2a. For the Mann-Kendall test, the gauging stations with less than 4 years of records were excluded, and the stations with 40 or fewer years were directly applied to the K statistic test, but without the z-scores and p-values. The gauging stations with more than 40 years of records were applied to the standard normal distribution test with the z-score of the K statistic (see Table 1). Herein, the statistically significant level was set as 0.05 for the two-sided test.

As shown on Table 1, no decreasing trends were found for the Big/Little Blue River basins, the Big/Little Nemaha River basin and the Missouri River basin, except for the increasing and insignificant trends (meaning neither downward nor upward). Of the three river basins, the

Missouri River basin possesses the larger number of stations with an increasing trend (5 upward trends out of 6 stations). The Big/Little Blue River basin had one increasing trend out of 6 stations. The Big/Little Nemaha River basin with 10 gauging stations had neither increasing nor decreasing trends detected. In comparison, the Elkhorn River, the Niobrara River, the Loup River, the Platte River and the Republican River basins not only had increasing trends but also decreasing trends. For the Elkhorn River basin, one downtrend was found out of six gauges; two downtrends from 14 gauges were detected in the South/North/Middle Loup rivers. There were 5 downward trends and 4 upward trends detected in the 12 gauges for the Niobrara River basin, whereas there were 5 downward trends and 6 upward trends detected in the 27 gauging stations for the Platte River basin.

However, in the Republican River basin with a total of 28 gauging stations there were 25 sites that were detected with downward trends, except for 3 with insignificance. It draws specific attention to the situation, where 89.3% of the gauging stations were found to have decreasing trends over the 50-year period of record. All the trend test results were illustrated on Figure 2a with the signs "+" for an increasing trend, "--" for a decreasing trend and "o" for an insignificant trend. It can be clearly seen from this figure that the streamflow trends show a contrast in the east and west of Nebraska with the most increasing trends appearing in eastern Nebraska and the downward trends in the west, except for the Platte River and Loup River basins, both of which had increasing trends scattered evenly upstream or downstream. In an analysis of trends in annual streamflow for the entire United States during 1948-1988, Lettenmaier *et al.* [1994] showed declining streamflow trends in the Northwest and positive trends in the Midwest of the United States. The results of Lettenmaier *et al.* [1994] may not fully represent the spatial variation of streamflow trends in Nebraska because of fewer steream stations used and out-of-date data (1948-1988). In comparison, the streamflow trends in our study demonstrated both positive and negative, that should fairly agree with theirs, even though this study focused only on Nebraska with a greater detail.

The Mann-Kendall trend test was also applied to the annual accumulative precipitation and average high/low temperatures. The 28 weather stations used for this analysis were randomly scattered across the state as illustrated in Figure 1. Figure 2b shows the precipitation trend test results. As seen, neither increasing nor decreasing trends could be detected based on the annually cumulative precipitation from 28 stations across the state. It can be concluded that, based on the annual time scale, no precipitation trends were exhibited over the past 50 years in Nebraska. This result seems in conflict with the conclusions of Lettenmaier *et al.* [1994], in which they showed that annual precipitation possessed upward trends across the whole Midwest to southern part of the United States. Note that the time intervals between our analysis (1948-2003) and Lettenmaier *et al* [1994] differ. In Nebraska, drought conditions persisting since 2000 may have affected the trend.

The trend tests for the high/low temperatures were also carried out and shown in Figures 2c and 2d based on the 17 stations randomly chosen with temperature records. There are four negative trends detected for the annual high average temperature, while six positive trends for the annual low average temperature, except for two negative trends. It meant that the temperature range between the high and low records narrowed because the decreasing trends occurred for the high temperatures and the increasing trends appeared for the low temperatures. It can be said, to some extent, that the temperature range tended to reduce, which agrees with the analysis of Lettenmaier *et al.* [1994], when they demonstrated downtrends in a temperature range from 1948-88, even though they based their analysis of the daily temperature on a short time series.

4.2. Trend Analysis of Monthly Streamflow across Seasons and Decades

Because streamflow typically fluctuates seasonally, further analysis based on monthly average streamflow was conducted to determine the streamflow trend for each of 12 months for a period of more than 50 years. A total of 76 gauging stations were used for monthly streamflow trend detection.

The results of trend tests for monthly mean streamflow were displayed in Table 2. The streamflow trends for monthly mean streamflow exhibited temporal patterns in upward trends. The number of stations with increasing trends from September to February is greater than other months; between March and August, there were the lowest numbers of upward trends, which possibly was related to climatic patterns and groundwater uses. For the period between March and August, more than half of the gauging stations showed no trends (insignificant). The decreasing trend stayed fairly constant through 12 months, except that May through August had relatively lower numbers, which may be correlated with the season of greatest rainfall. These patterns in monthly trends seem to be fairly consistent with the results found by Lettenmaier *et al.* [1994], in which they showed that the pattern of uptrends in streamflow evolved through October to April, with a greater number of upward trends. As described by Lins [1985], Lettenmaier *et al.* [1994], and Burt [1994], the temporal coherence in streamflow trends with seasons is expected since the soil moisture storage, which depends on the precipitation, has a strong influence on the discharge, and there is an annual minimum in average streamflow in the fall due to depletion of soil moisture and aquifer storage by irrigation, land use or summer evaporation. In Nebraska, groundwater irrigation typically occurs between June and September with a peak in July and August. For basins with a larger quantity of groundwater withdrawal, the impact on streamflow is expected to be more significant in August and September. However, the trend patterns of streamflow in the Republican River basin showed up differently, where the largest number of downward trends occurred of every month of the year. It obviously indicated that depletion of the streamflow occurred continuously in the river basin. For the Platte River basin, the seasonal trend pattern was interrupted and possessed sharp changes, so it was evident that human management and influence affected the behavior of the streamflow.

Streamflow trends were also calculated using the data of a 10-year period for the time since 1950. Table 3 summarizes the statistical test results of the trends. Among the 110 gauges analyzed, 25 stations showed an upward trend, but 37 showed a downward trend. After careful examination of the results, the number of the stations with an upward trend tended to get fewer, while more stations showed a downward trend of streamflow, even though the number of the gauging station records was different for each time interval (10 years). Moreover, an individual basin in each decade shows a different tendency. The Elkhorn River, the Big/Little Nemaha River, the Missouri River, and the Niobrara River basins possessed relatively stable streamflow; therefore no significant trend pattern of the streamflow was examined during the five decades. For the Loup River basin, the streamflow tended to be increasing in the last three decades. Especially in 1970's, it had the highest increase of the five upward trends observed. For the Big/Little Blue River basins, the streamflow slightly decreased, mainly after 1970's when an increasing trend was observed in 1970's and a decreasing trend was found in 1990's. In 1950's and 1960's, the streamflow showed no significant change. The Platte River basin is the biggest drainage area in the whole state. There are a total of 27 gauging stations available for the trend analysis in the different periods. Because the trend pattern of streamflow changed irregularly decade by decade, neither increasing nor decreasing continuous tendencies were clearly identified, As observed, in 1960's there were seven increasing trends, but in 1970's there were 15 decreasing trends. It is most likely that much human management of the surface water, such as reservoirs and canals, was carried out and had an effect on natural streamflows. Indeed, the largest reservoir, Lake McConanghy, is on the Platte River; water from the Platte River is constantly diverted to irrigation cannel network in every irrigation season. In Figure 3, the 10-year trends of streamflows were illustrated for the eight main river basins from the 1950's to the 1990's. Gauges with decreasing trends began in 1970's were concentrated in southwestern Nebraska. This pattern continued in the 1980's and 1990's.

From the earlier trend analysis of the annual mean streamflow for the Republican River basin, 25 of 28 gauging stations showed a downtrend. It is also necessary to examine the trend change decade by decade. From the 1950's to the 1970's, a stronger decreasing tendency of streamflow was identified, as illustrated on Table 3. Among the 27 gauges, the number of stations with the downward trends increased from zero in the 1950's, to two in the 1960's and up to 14 in the 1970's, while the number of the upward trends declined from three in the 1950's to zero in the 1970's. Also a strong downward trend occurred through the 1980's and 1990's.

The irrigation well information, obtained from the NDNR, is considered an indicator of the groundwater use for irrigation and water supplies in Nebraska, even though it was not representative of complete groundwater withdrawal that includes other land use and conservation practice. In the Republican River basin, the number of registered irrigation wells in eight counties (Dundy, Hitchcock, Red willow, Furnas, Harlan, Franklin, Webster and Nuckolls) are illustrated in Figure 4. There were only 84 wells in 1940, and 304 wells by 1950. However, by 1991, the total number of the registered wells had rapidly increased to 4,646. During the earlier period, from 1930 to 1950, the development of the irrigation wells grew slowly. In the 1950's, 1960's and 1970's, the registered irrigation wells showed a rapid increase, and by the end of the 1970's, the number of irrigation wells was up to 4,513. Accordingly, streamflow in the upstream part of the Republican River has declined since 1970s (Figure 3c, 3d, and 3e).

4.3. Streamflow Trend in the Republican River Basin

By the late 1980's, Kansas began to assert that Nebraska was consuming more water in the Republican River than legally allowed. Water rights to the streamflow had been in dispute between the two states under a federal interstate river compact. Kansas filed a lawsuit against Nebraska in federal court with the disputation that "decreases in annual estimate of virgin streamflows are not due to natural phenomena but due to increases in groundwater withdrawals" [Bennet *et al.*,1998]. The streamflow is mainly constituted of groundwater discgarge (baseflow) and surface runoff (due to precipitation). The latter includes direct surface runoff, interflow and channel precipitation [Viessman *et al.*, 1977]. In order to estimate the depletion of baseflow of streamflow by groundwater uses in the Republican River basin, the local precipitation-adjusted discharge, in which the impact of precipitation was somewhat removed, was used for further examination of the trends and estimating the magnitude of depletion.

The LOESS technique was used to remove the variation of precipitation within the streamflow, and the Mann-Kendall test was applied to the local precipitation-adjusted discharge to estimate the depletion [Helsel *et al.*, 1992]. In the process, first, the LOESS was used to conduct a regression of the average annual streamflow for the yearly cumulative precipitation, which was based on the average of several nearby weather stations. Then, the Mann-Kendall test was implemented to estimate the magnitudes of trends on the basis of the residuals from the LOESS procedure. Figure 5 illustrates the spatial distribution of the 19 gauging stations in the Republican River basin, including in Kansas. Table 4 exhibits the trend test results and slope estimates for the 19 gauges from the USGS with the length of records being more than 50 years (except for gauges ks6844900 and ks6847900 in Kansas, with records of 44, 48 years, respectively) under the local precipitation-adjusted discharge. As can be seen, 18 stations had downward trends, and only one gauges were insignificant. The results are consistent with the earlier test without the precipitation adjustment.

Figure 6a, 6b, 6c, 6d and 6e, respectively, represent gauge 6821500 for the Arikaree River at Haigler, 6823000 for the North Fork Republican River at Colorado-Nebraska, 6823500 for the Buffalo Creek near Haigler, 6824000 for the Rock Creek at Parks, 6827500 for the South Fork Republican River near Benkelman in Dundy County, Nebraska, where two weather stations recorded precipitation from 1948 to 2003. The average of annually cumulative precipitation from the two stations was used for locally adjusted streamflow. For presentation of trends, LOESS was used a second time to plot trend lines. All of the five gauging stations showed continuous downward trends in time series. Figure 6e exhibits a larger depletion, with a magnitude of 0.945 $ft^3.s^{-1}/yr$, whereas Figure 6c shows a gentler downward slope, with a depletion rate of 0.100 $ft^3.s^{-1}/yr$. The gauge 6821500 in Figure 6a actually measured the streamflow for the Arikaree River coming from Colorado. For a comparison, gauge 6775500, located in the upstream reach of the Middle Loup River at Dunning, in the Sand Hills of Nebraska, where very fewer nearby irrigation wells were drilled for groundwater withdrawal, was subjected to the same analysis, and the graph was plotted on Figure 6f. As can be seen, it is a smoothly increasing trend line and behaved according to a natural pattern of streamflow. Obviously, the fact that the streamflow from the five gauging stations in the Republican River in Dundy County showed a downward trend was due to groundwater withdrawal. The residual in Figures 6c shows a relatively small fluctuation compared to the other three stations, possibly due to a small drainage area.

Figure 7 shows the graphs representing the trends of three gauges located in Hitchcock County, Nebraska, where the precipitation data from three weather stations were available for adjusting the discharge. Figures 7a, 7b and 7c represent the gauge 6828500 for the Republican

River at Stratton; 6834000 for the Frenchman Creek at Palisade; 6835500 for the Frenchman Creek at Culbertson. All three showed downward trends. Figure 7a exhibits a monotonic trend with a negative slope of 2.281$ft^3.s^{-1}$/yr. Figure 7b and 7c display a decreasing tendency, but in the early 1960's, the streamflow bounced back to the highest discharge, then went down. They had negative slopes of 1.476 and 1.766 $ft^3.s^{-1}$/yr overall. These patterns were likely associated with the development of irrigation wells shown in Figure 4.

Figure 8 shows the three gauges located in Red Willow County, Nebraska, where one weather station was available for precipitation. They represent gauges 6836500 for the Driftwood Creek near McCook; 6837000 for the Republican River at McCook; and 6838000 for Red Willow Creek near Red Willow, respectively. All of three show downtrends. Figure 8a and 8c exhibit a continuous decline with a depletion of 0.09 and 0.516 $ft^3.s^{-1}$/yr. Figure 8b behaves as a varied curve that had the highest discharge in later 1950's, then steep decreases with an average annual depletion of 3.473 $ft^3.s^{-1}$/yr. This pattern was similar with Figure 7b and 7c, and it might also be caused by groundwater withdrawal. Note that the fluctuations of the residuals for the two creeks are much smaller, probably due to smaller drainage areas.

Figure 9 is a representative of gauge 6843500 for the Republican River at Cambridge, located at Furnas County, Nebraska, where three weather stations were available. The regression plot displays a continuous downtrend with a bigger negative slope of 4.954$ft^3.s^{-1}$/yr. Figure 10a and 10b show the graphs representing two gauges (6844500 for the Republican River near Orleans; 6847500 for Sappa Creek near Stamford) located in Harlan County, Nebraska, where three weather stations were available. These graphs exhibit continuous downward trends, in which the gauge 6844500 had the biggest depletion, 6.059 $ft^3.s^{-1}$/yr among the 18 downward trends. Gauge 6847500 measured the streamflow of the Sappa Creek, mostly coming from Kansas, which had an intermediate depletion of 1.333 $ft^3.s^{-1}$/yr. Figure 11 represents the gauge

6849500 for the Republican River below Harlan County Dam, located in Franklin County, Nebraska, where one weather station was available. The graph displays a downward trend overall, but this was a more complicated curve. In the 1950's, the runoff kept increasing, then from the 1960's it was rapidly down till the later 1970's. After that the smoothed curve exhibited fluctuation in the time series. No doubt, it was a result of human management effects on streamflow due to a reservoir upstream.

Figure 12 shows the graphs representing four gauging stations located in three counties, in Kansas, where five weather stations were chosen for computing the average annual precipitation. They represent gauge 6844900 for Sappa Creek near Achilles; 6846500 for Beaver Creek at Cedar Bluffs; 6847900 for Prairie Dog Creek at Keith Sebelius Lake; and 6848500 for Prairie Dog Creek near Woodruff, respectively. Among the four gauging stations, three showed downward trends, with the different streamflow depletion displayed in Table 4, except for an insignificant trend for gauge 6847900 at Prairie Dog Creek because there is a lake upstream. One cannot say that the several streamflows in Kansas did not contribute to the depletion in the Republican River basin.

5. Conclusions

Of 110 gauging stations in Nebraska, 25 were detected with increasing trends and 37 with decreasing trends for the period 1948-2003. The temporal streamflow trends showed a spatial tendency. It was clear that the trends of most streamflows showed a different pattern between eastern and western Nebraska, with the most upward trends in the east and the most downward trends in the west. Exceptions include the Platte River and Loup River basins, both of which had increasing or decreasing trends scattered evenly upstream or downstream. For the Platte River basin, the seasonal trend pattern was interrupted, and trends changed irregularly decade by decade; therefore, it was evident that human management of surface water, such as reservoirs and canals, was carried out and had an effect on natural streamflow over the past 50 years. For the Loup River basin, most of the streamflow trends showed increasing or insignificant results across upstream to downstream reaches. For the Republican River basin, there were 25 gauges detected with downtrends, accounting for 89.3% of the 28 gauging stations.

As indicated, neither an increasing nor decreasing trend was detected in the annual average precipitation measured by the 28 weather stations across the state, but the temperature range between the high and low records was smaller because the high temperature emerged with a decreasing tendency and the low temperature appeared with an increasing tendency. It can be seen, to some extent, that the temperature range tended to be narrow. Generally, precipitation and temperature were not the significant factors affecting the trends of streamflow in Nebraska over the past 50 years. However, groundwater withdrawal, such as pumping of irrigation wells or other land uses, was the main effect on the streamflow pattern change.

The trend analysis of individual months demonstrated another seasonal pattern. The uptrends increased from August to January. This was because more surface water was available in this season. With respect to trends in decades, the biggest tendency of the streamflow trends for the Republican River basin was that the decreasing trends increased by decade; so did the Big/Little Blue River basin to a weaker extent, where more irrigation wells were constructed for groundwater withdrawal in these regions. So, the pattern of the streamflow decreasing trends was strongly correlated with the development of registered irrigation wells.

The local precipitation-adjusted discharge was employed to further quantify the depletion of streamflow in the Republican River basin, where 19 gauging stations were used for the depletion analysis, including the four in Kansas. The impact of groundwater withdrawals on the streamflow in the Republican River basin was significant, based on 18 stations scattered over

Nebraska, Kansas, and along the Nebraska-Colorado border. The largest occurred at gauge 6844500 on the Republican River near Orleans, located above Harlan County Dam and Reservoir, with a magnitude of $6.0596\text{ft}^3.\text{s}^{-1}/\text{yr}$, accounting for 14.6% of the average discharge in 2003. Besides Nebraska, where groundwater withdrawal resulted in the depletion of the Republican River basin, Kansas and Colorado also contributed to groundwater use in the region that caused the depletion.

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References

Aguado, E., D. Cayan, L. Riddle, and M. Roose (1992), Climatic fluctuations and the timing of West Coast streamflow, *J. Clim.*, 5, 1468-1483.

Bennett, L. L., and C. W. Howe (1998), The interstate river compact: Incentives and compliance, *Water Resour. Res.*, 34(3), 485-495.

Burt, H. D. (1994), Hydrologic effect of climatic change in west-central Canada, *J. of Hydrology*, 160, 53-70.

Burt, R. O., M. Baker, and G. A. Helmers (2002), Statistical estimation of streamflow depletion from irrigation wells, *Water Resour. Res.*, 38(12), 1296.

Cleveland, W. S. (1979), Robust locally weighted regression and smoothing scatter-plots, *J. Am. Stat. Ass.*, 74, 829-836.

Cleveland, W.S., S. J. Devlin, and E. Grosse (1988), Regression by local fitting, *J. of Econometrics*, 37, 87-114.

Flowerday, C. A., D. R. Kuzelka, and T. D. Pederson, Compilers 1998 (seconded), University of Nebraska-Lincoln Conservation and Survey Division Research Atlas 4a, 44p.

Gilbert, O. Richard (1987), Statistical Methods for Environmental Pollution Monitoring, New York: Van Nostrand Reinhold.

Haan, T. C. (1977), Statistical Method in Hydrology, the Iowa State University Press/Ames, pp. 275-286.

Haan, T. C. (2002), Statistical Method in Hydrology, the Iowa State University Press/Ames, pp 128-158.

High Plains Regional Climate Center, University of Nebraska-Lincoln, Available at http://www.hprcc.unl.edu., accessed in May 2004.

Hirsh M. R., J. R. Slack, and R. A. Smith (1982), Techniques of trend analysis for monthly water quality data, *Water Resour. Res.*, 18, 107-121.

Helsel, R. D., and R. M. Hirsch (1992), Statistical Methods in Water Resources, New York: Elsevier Science Publishing Inc.

Hollandder, M., and D. A. Wolfe (1999), Nonparametric Statistical Methods, New York: John Wily and Sons.

Hirsch, M. R., R. H. Dennis, A. C. Timothy, and J. G. Edward (1993), Statistical Analysis of Hydrologic Data, Handbook of Hydrology. New York: McGraw-Hill, Inc.

Kendall, M. G. (1975), Rank Correlation Methods, Charles Griffin, London.

Lettenmaier, D. P., E. F. Wood, and J. R. Wallis (1994), Hydro-climatologic trends in the continental United States, 1948-88, *J. Clim.*, 7, 586-607.

Lins,H. F., and P. J. Micheals (1994), Increasing U.S. streamflow linked to greenhouse forcing, *Eos Trans. AGU,* 75(25), 281, 284-285.

Lins, H. F., and J. R. Slack (1999), Streamflow trends in the United States, *Geophys. Res. Lett.*, 26, 227-230.

Lins, F. H. (1985), Streamflow variability in the United States: 1931-78, *J. of Climate and Applied Meteorology,* 24, 463-471.

Mann, H. B. (1945), Non-parametric tests against trend, *Econometrica,* 245-259.

Nebraska Department of Natural Resources, Republican River basin report of preliminary findings, 2003, http://www.dnr.state.ne.us, accessed in July 2004

Refsgaard, J. C. (1987), A methodology for distinguishing between the effects of human influence and climatic variability on the hydrology cycle, *IAHS Publ.,*168, 557-570.

SAS, OnlineDoc, SAS/STAT, Version 8, 1999-2001, SAS Institute Inc., Cary, NC, USA.

Sen, P. K. (1968), Estimates of the regression coefficient based on Kendall' Tau, *J. Am. Stat. Ass.*, 63, 215-216.

Sophocleous, M., A. Koussis, J. L. Martin, and S. P. Perkins (1995), Evaluation of simplified stream-aquifer depletion models for water rights administration, *Ground Water*, 33(4), 579-588.

U. S. Geological Survey, Surface water monthly streamflow, available at http://water.usgs.gov/waterwatch, accessed in April 2004.

Viessman W., J. W. Knapp, G. L. Lewis, and T. E. Harbaugh (1977), Introduction to Hydrology, New York: IEP-Dun-Donnelly.

Zhang, X., K. D. Harvey, W. D. Hogg, and T. R. Yuzyk (2001), Trends in Canadian streamflow, *Water Resour. Res.*, 37, 987-998.

Table 1. Annual mean streamflow trend test results using Mann-Kendall

Basin	Station ID	Drainage (mile^2)	Period	Z-score	P-value	Trend
Big/Little Blue Rivers	6880800	1192	1958-2003	0.080	0.940	insignificant
	6881000	2710	1953-2003	1.240	0.220	insignificant
	6882000	4447	1932-2003	2.150	0.030	increasing
	6883000	984	1953-2003	-0.080	0.930	insignificant
	6884000	2350	1910-2003	1.370	0.170	insignificant
	6884025	2752	1971-2003	.	.	insignificant
Elkhorn Rivers	6797500	1400	1947-2003	1.400	0.160	insignificant
	6799000	2790	1945-2003	0.800	0.430	insignificant
	6799100	701	1960-2003	1.350	0.180	insignificant
	6799350	5100	1972-2003	.	.	increasing
	6799500	1015	1941-2003	3.440	0.000	increasing
	6800000	369	1951-2003	3.150	0.000	increasing
	6800500	6900	1928-2003	4.600	0.000	increasing
S/N/Middle Loup Rivers	6775500	1830	1945-2003	7.620	0.000	increasing
	6775900	966	1966-2003	.	.	increasing
	6784000	2320	1943-2003	-1.620	0.100	insignificant
	6785000	8075	1928-2003	0.980	0.330	insignificant
	6786000	2350	1936-2003	4.890	0.000	increasing
	6790500	4302	1928-2003	4.100	0.000	increasing
	6792500	N/A	1937-2003	2.680	0.010	increasing
	6793000	14320	1943-2003	3.090	0.000	increasing
	6794000	677	1940-2003	0.540	0.590	insignificant
	6776500	2040	1945-1995	-2.586	0.010	decreasing
	6779000	5019	1937-1995	-1.247	0.212	insignificant
	6783500	707	1946-2003	-1.717	0.086	insignificant
	6787500	994	1940-2003	-3.626	0.000	decreasing
	6792000	1220	1940-1995	1.822	0.068	insignificant
Missouri River	6601000	174	1945-2003	2.911	0.004	increasing
	6608000	23	1950-1980	.	.	insignificant
	6610000	326759	1928-2003	4.160	0.000	increasing
	6806500	241	1950-2003	2.265	0.024	increasing
	6807000	413959	1929-2003	3.921	0.000	increasing
	6813500	418859	1949-2003	3.306	0.001	increasing
Big/Little Nemaha Rivers	6811500	792	1949-2003	0.900	0.370	insignificant
	6814500	548	1952-1996	0.730	0.460	insignificant
	6815000	1339	1944-2003	-0.390	0.700	insignificant
	6803000	167	1970-2001	.	.	insignificant
	6803500	685	1950-2001	1.665	0.096	insignificant
	6803510	43.6	1970-2001	.	.	insignificant
	6803520	47.8	1970-2001	.	.	insignificant
	6803530	120	1970-2001	.	.	insignificant
	6803555	1050	1970-2001	.	.	insignificant
	6804000	273	1950-2001	1.444	0.149	insignificant
Niobrara River	6461500	7150	1945-2003	-2.510	0.010	decreasing
	6463500	458	1948-2003	7.060	0.000	increasing

	6465500	11580	1938-2003	3.030	0.000	increasing
	6444000	313	1947-2003	2.361	0.018	increasing
	6453500	505	1949-1994	-0.625	0.532	insignificant
	6453600	812	1957-2003	1.724	0.085	insignificant
	6454500	1400	1946-2003	-4.431	0.000	decreasing
	6455500	1460	1946-2003	-5.764	0.000	decreasing
	6457500	4290	1945-1991	-3.368	0.001	decreasing
	6459500	660	1947-2003	-3.435	0.001	decreasing
	6461000	390	1948-1994	-0.532	0.595	insignificant
	6465000	11070	1940-2001	2.089	0.037	increasing
S/N Platte Rivers	6762500	1227.15	1934-2003	-6.080	0.000	decreasing
	6764880	23900	1982-2003	.	.	decreasing
	6768000	56300	1930-2003	0.880	0.380	insignificant
	6770200	57260	1982-2003	.	.	insignificant
	6770500	57650	1934-2003	2.980	0.000	increasing
	6774000	59300	1928-2003	2.300	0.020	increasing
	6795500	294	1947-2003	1.760	0.080	insignificant
	6796000	70400	1949-2003	1.870	0.060	insignificant
	6796500	N/A	1994-2003	.	.	insignificant
	6801000	84200	1928-2003	2.200	0.030	increasing
	6805500	85370	1953-2003	3.230	0.000	increasing
	6674500	22218	1932-2001	-0.338	0.736	insignificant
	6677500	1707	1931-2003	2.509	0.012	increasing
	6678000	356	1931-2003	-3.018	0.003	decreasing
	6679500	24300	1931-2003	0.502	0.616	insignificant
	6681500	79.8	1931-2003	3.908	0.000	increasing
	6682000	24700	1930-2003	0.728	0.467	insignificant
	6684500	25300	1948-2003	0.457	0.647	insignificant
	6685000	1011.7	1944-2003	-7.652	0.000	decreasing
	6686000	26700	1930-2002	-0.544	0.586	insignificant
	6687000	897.9	1931-2002	0.177	0.860	insignificant
	6687500	28600	1940-2003	-0.445	0.656	insignificant
	6690500	29300	1942-2003	0.968	0.333	insignificant
	6691000	29800	1936-1991	1.588	0.112	insignificant
	6692000	940	1931-1991	-3.045	0.002	decreasing
	6693000	30900	1931-2003	-0.155	0.876	insignificant
	6765500	24300	1931-2003	1.887	0.059	insignificant
Republican River	6821500	1700	1932-2003	-7.100	0.000	decreasing
	6823000	2370	1935-2003	-6.120	0.000	decreasing
	6823500	172	1940-2003	-8.810	0.000	decreasing
	6824000	23.6	1940-2003	-8.560	0.000	decreasing
	6827500	2740	1950-2003	-6.460	0.000	decreasing
	6828500	8200	1950-2003	-5.770	0.000	decreasing
	6834000	1300	1950-2003	-7.510	0.000	decreasing
	6835500	2990	1935-2003	8.720	0.000	decreasing
	6836500	361	1946-2003	2.170	0.030	decreasing
	6837000	12240	1954-2003	-6.240	0.000	decreasing
	6838000	820	1939-2003	7.410	0.000	decreasing
	6843500	14460	1945-2003	7.310	0.000	decreasing
	6844500	15580	1947-2003	5.600	0.000	decreasing

	6847500	3840	1946-2003	4.790	0.000	decreasing
	6849500	20820	1952-2003	2.420	0.020	decreasing
	6851500	290	1948-2003	0.172	0.863	insignificant
	6853020	22100	1984-2003	.	.	insignificant
	6824500	4880	1947-1994	-4.787	0.000	decreasing
	6829500	8340	1946-1993	-5.207	0.000	decreasing
	6831500	1050	1941-2003	-9.223	0.000	decreasing
	6832500	1140	1946-1993	-6.438	0.000	decreasing
	6835000	1500	1949-2003	-6.984	0.000	decreasing
	6836000	361	1951-1980	.	.	insignificant
	6841000	770	1945-2002	-4.764	0.000	decreasing
	6842500	880	1950-2003	-3.312	0.001	decreasing
	6847000	2081	1937-2003	-4.983	0.000	decreasing
	6853000	22040	1950-1984	.	.	decreasing
	6853500	22401	1932-2001	-4.950	0.000	decreasing

Table 2. Mann-Kendall trend test results on monthly mean streamflow basis

	Increasing Trends	**Insignificant**	**Decreasing Trends**
January	32	18	26
February	22	23	31
March	5	41	30
April	11	38	27
May	11	42	23
June	6	47	23
July	12	41	23
August	13	42	21
September	23	29	24
October	24	29	23
November	29	18	29
December	30	20	26

Table 3. Mann-Kendall trend test results for timing of a decade on streamflow

Years of Record	1950-2003	50-59	60-69	70-79	80-89	90-03
Entire State						
Stations tested	110	92	97	105	105	97
No. with increasing	25	4	8	9	2	3
No. with insignificant	48	76	80	66	94	83
No. with decreasing trends	37	14	8	30	10	16
Big/Little Blue River Basin						
No. with increasing	1	0	0	1	0	0
No. with insignificant	5	4	5	5	6	5
No. with decreasing trends	0	0	0	0	0	1
Elkhorn River Basin						
No. with increasing trends	3	0	0	0	0	0
No. with insignificant	3	1	6	7	7	7
No. with decreasing trends	1	4	0	0	0	0
Loup River Basin						
No. with increasing trends	6	1	0	5	1	2
No. with insignificant	6	9	11	9	13	12
No. with decreasing trends	2	3	3	0	0	0
Big/Little Nemaha River Basin						
No. with increasing trends	0	0	0	2	0	0
No. with insignificant	10	5	5	8	10	10
No. with decreasing trends	0	0	0	0	0	0
Niobrara River Basin						
No. with increasing trends	4	0	0	1	0	1
No. with insignificant	3	8	10	10	11	11
No. with decreasing trends	5	2	2	1	1	0
Platte River Basin						
No. with increasing trends	6	0	7	0	0	0
No. with insignificant	17	22	16	8	24	22
No. with decreasing trends	4	2	0	15	0	1
Republican River Basin						
No. with increasing trends	0	3	0	0	1	0
No. with insignificant	3	24	25	13	17	7
No. with decreasing trends	25	0	2	14	9	14
Missouri River Basin						
No. with increasing trends	5	0	1	0	0	0
No. with insignificant	1	3	5	6	5	5
No. with decreasing trends	0	3	0	0	0	0

Table 4. Trend tests and slope estimates for the precipitation-adjusted streamflow for the Republican River basin.

	Gauge ID	Test Period	Trend Test	Z score	P-value	Slope ($ft^3.s^{-1}$/year)
1	rep6821500	1948-2003	decreasing	-7.499	0.000	-0.416
2	rep6823000	1948-2003	decreasing	-7.739	0.000	-0.523
3	rep6823500	1948-2003	decreasing	-8.488	0.000	-0.100
4	rep6824000	1948-2003	decreasing	-8.22	0.000	-0.116
5	rep6827500	1950-2003	decreasing	-7.174	0.000	-0.945
6	rep6828500	1950-2003	decreasing	-6.998	0.000	-2.281
7	rep6834000	1950-2003	decreasing	-7.565	0.000	-1.473
8	rep6835500	1948-2003	decreasing	-8.389	0.000	-1.766
9	rep6836500	1948-2003	decreasing	-2.127	0.033	-0.090
10	rep6837000	1954-2003	decreasing	-6.608	0.000	-3.473
11	rep6838000	1948-2003	decreasing	-6.75	0.000	-0.516
12	rep6843500	1948-2003	decreasing	-6.905	0.000	-4.954
13	rep6844500	1948-2003	decreasing	-6.523	0.000	-6.059
14	rep6847500	1948-2003	decreasing	-4.742	0.000	-1.333
15	rep6849500	1952-2003	decreasing	-2.154	0.031	-2.953
16	ks6844900	1959-2003	decreasing	-2.025	0.043	-0.039
17	ks6846500	1948-2003	decreasing	-5.082	0.000	-0.451
18	ks6847900	1962-2003	insignificant	-1.777	0.076	-0.129
19	ks6848500	1948-2003	decreasing	-4.898	0.000	-0.767

Figure Captions

Figure 1. Main river basins in Nebraska: gauging stations and weather station distribution

Figure 2. Spatial distribution of trend analysis based on annual mean streamflow, annual precipitation, and high/low temperature.

Figure 3. Spatial distribution of timing trend analysis based on annual mean streamflow within the periods of 1950's, 1960's, 1970's, 1980's, 1990's.

Figure 4. Accumulative number of the registered irrigation wells in the Republican River basin, Nebraska.

Figure 5. Gauging stations in the Republican River basin

Figure 6. Trends analysis for the gauging stations in the Republican River Basin in Dundy County and the Middle Loup River based on the residuals of LOESS process.

Figure 7. Trends analysis for the gauging stations in the Republican River Basin in Hitchcock County based on the residuals of LOESS process.

Figure 8. Trends analysis for the gauging stations in the Republican River Basin in Red Willow based on the residuals of LOESS process.

Figure 9. Trends analysis for the gauging stations in the Republican River Basin in Furnas County based on the residuals of LOESS process.

Figure 10. Trends analysis for the gauging stations in the Republican River Basin in Harlan County based on the residuals of LOESS process.

Figure 11. Trends analysis for the gauging stations in the Republican River Basin in Franklin County based on the residuals of LOESS process.

Figure 12. Trends analysis for the gauging stations in the Republican River Basin in the 4 counties, Kansas, based on the residuals of LOESS process.

Figure 1.

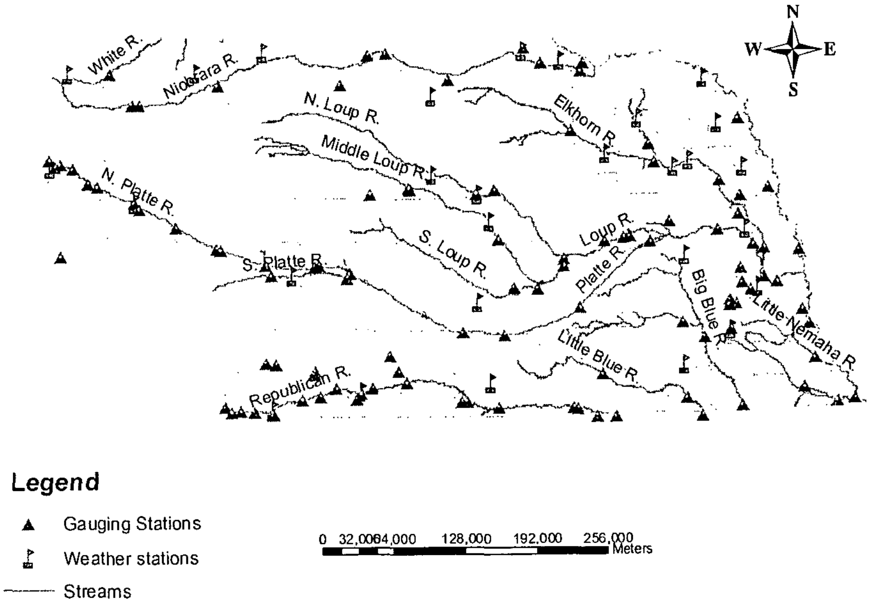
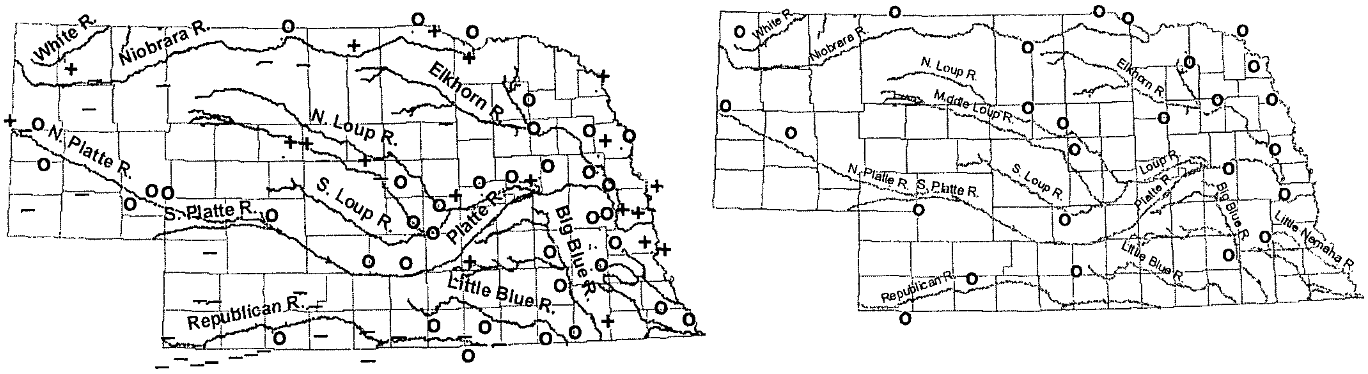
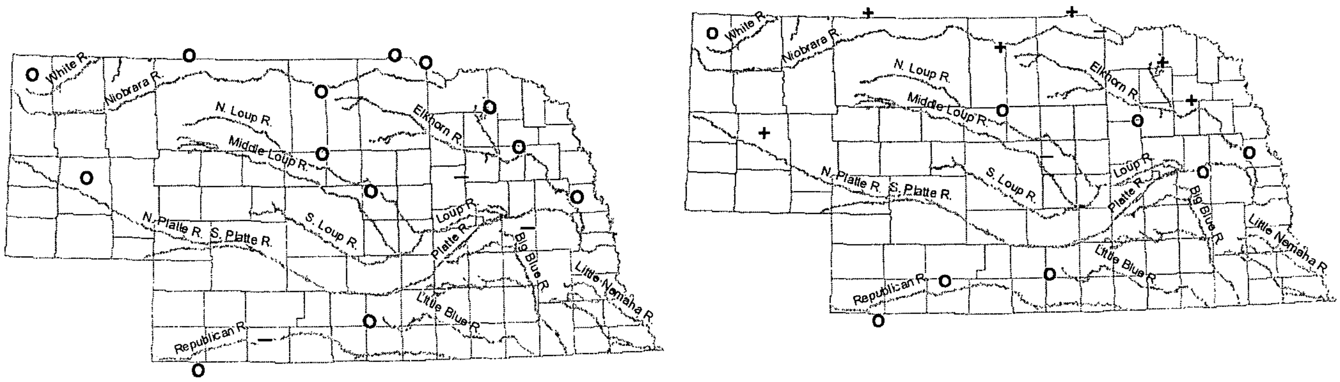

N
W
E
S
White R.
Niobrara R.
N. Loup R.
Elkhorn R.
Middle Loup R.
N. Platte R.
S. Loup R.
Loup R.
S. Platte R.
Platte R.
Big Blue R.
Little Nemaha R.
Little Blue R.
Republican R.
Legend
▲ Gauging Stations
Weather stations
Streams
0 32,000 64,000 128,000 192,000 256,000
Meters

Figure2.



(a) Annual Streamflow

(b) Annual Precipitation

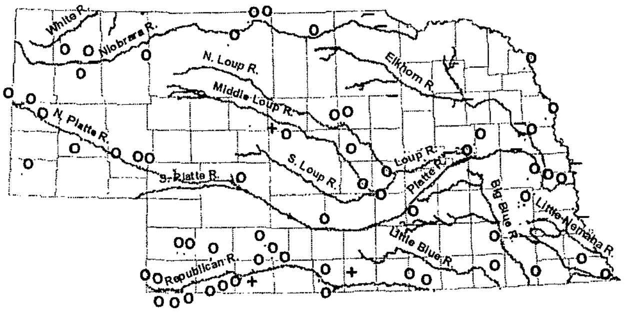


(c) High Temperature

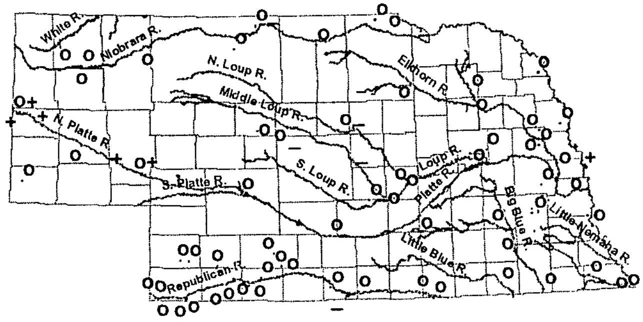
(d) Low Temperature

Figure3.

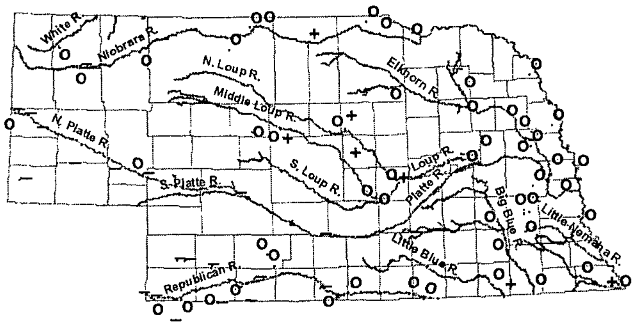
(a) 1950's



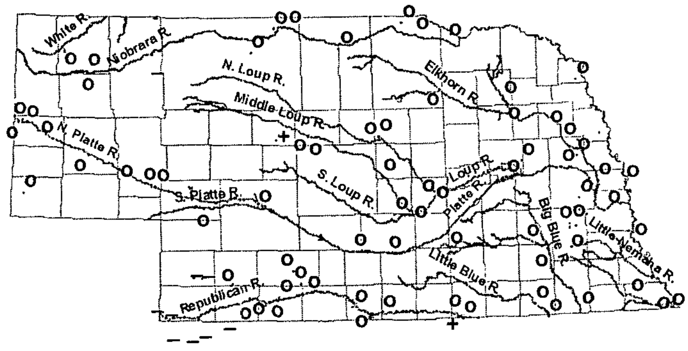
(b) 1960's



(c) 1970's



(d) 1980's



(e) 1990's

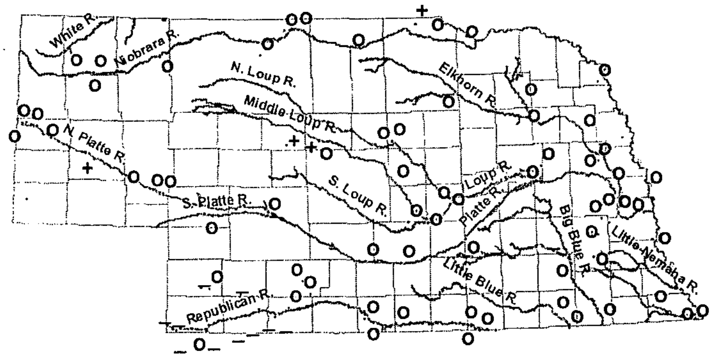
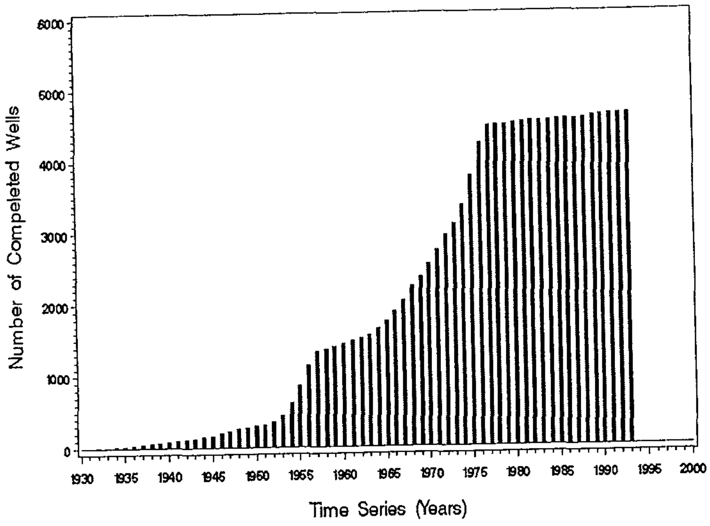
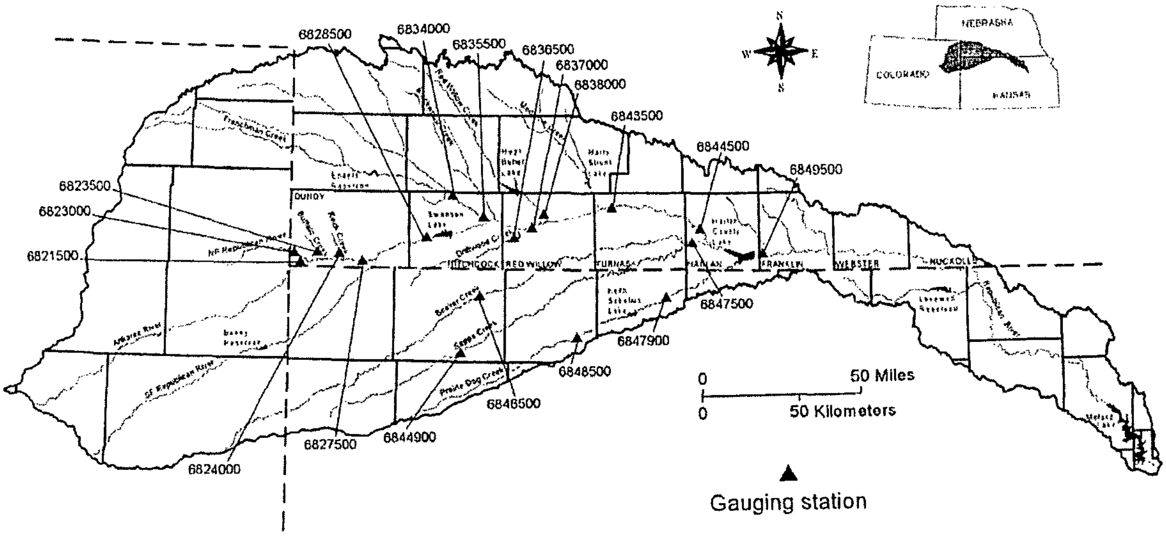


Figure 4.



Number of Compeleted Wells
6000
5000
4000
3000
2000
1000
0
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Time Series (Years)

Figure 5.

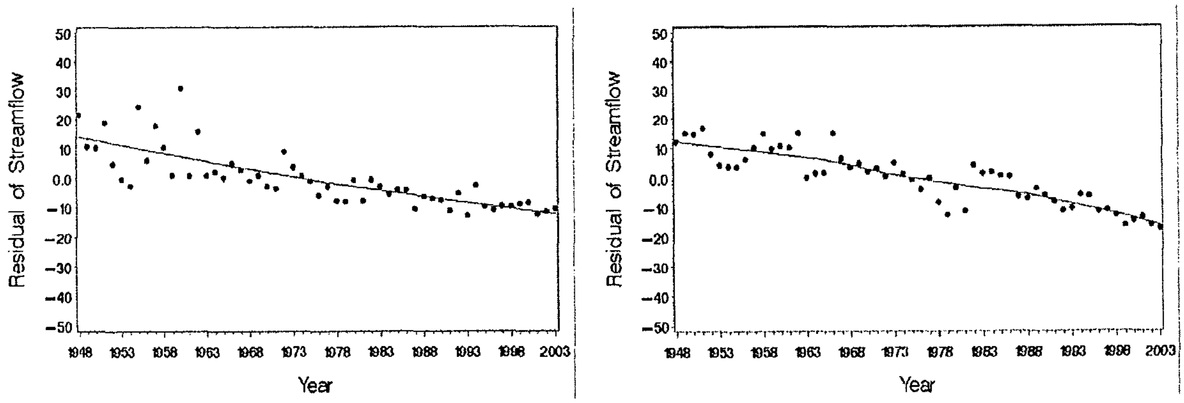


6828500
6834000
6835500
6836500
6837000
6838000
6843500
6844500
6849500
6823500
6823000
6821500
6824000
6827500
6844900
6846500
6848500
6847900
6847500
Frenchman Creek
Enders Reservoir
NF Republican River
Buffalo Creek
Rock Creek
Swanson Lake
Red Willow Creek
Medicine Creek
Hugh Butler Lake
Harry Strunk Lake
Driftwood Creek
Harlan County Lake
DUNDY
HITCHCOCK
RED WILLOW
FURNAS
HARLAN
FRANKLIN
WEBSTER
NUCKOLLS
Arikaree River
Bonny Reservoir
SF Republican River
Beaver Creek
Sappa Creek
Prairie Dog Creek
Keith Sebelius Lake
Lovewell Reservoir
Republican River
Milford Lake
N
S
E
W
NEBRASKA
COLORADO
KANSAS
0
50 Miles
0
50 Kilometers
Gauging station

Figure 6.

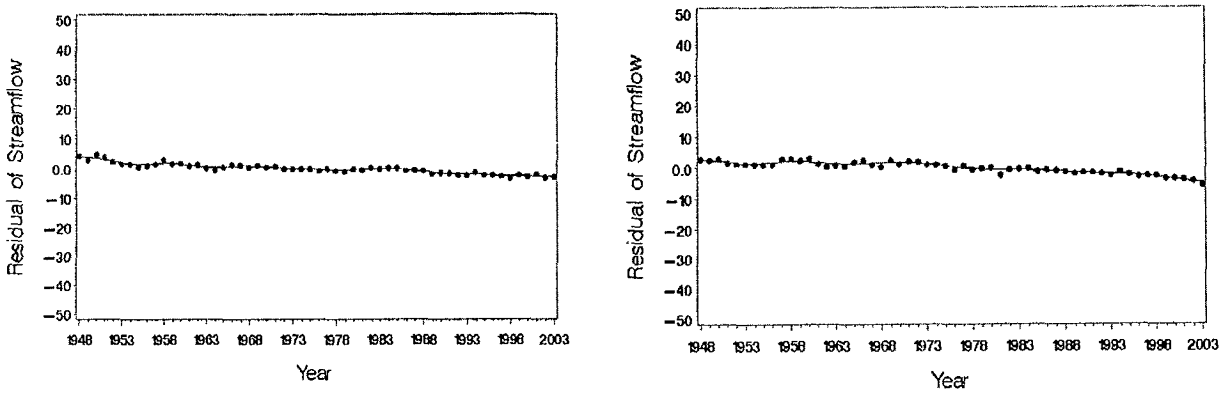
(a) 6821500 Arikaree River at Haigler, NE.

(b) 6823000, North Fork Republican River at CO-NE



(c) 6823500, Buffalo Creek near Haigler, NE.

(d) 6824000, Rock Creek at Parks, NE.



(e) 6827500, South Fork Republican River near Benkelman, NE.

(f) 6775500, Middle Loup River at Dunning, NE.

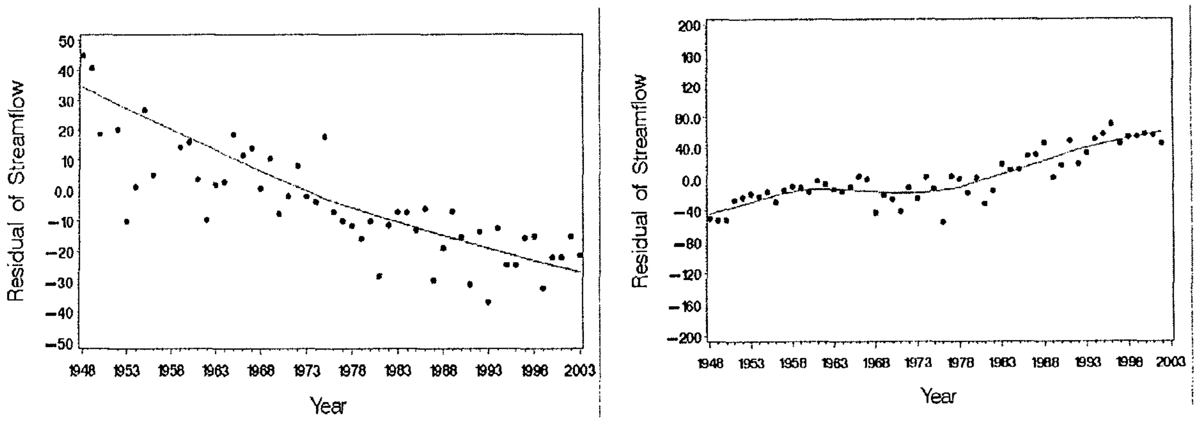
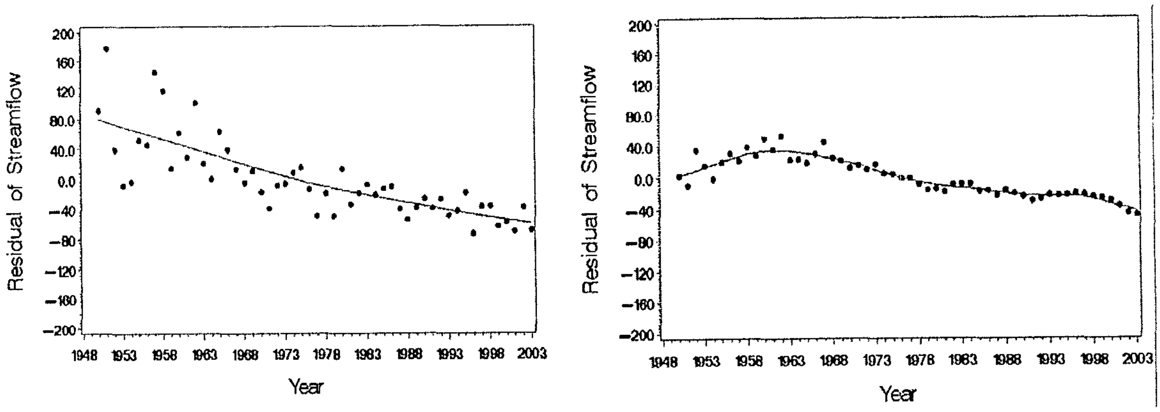


Figure 7.



(a) 6828500, Republican River at Stratton, NE.

(b) 6834000, Frenchman Creek at Palisade, NE.

(c) 6835500, Frenchman Creek at Culbertson, NE.

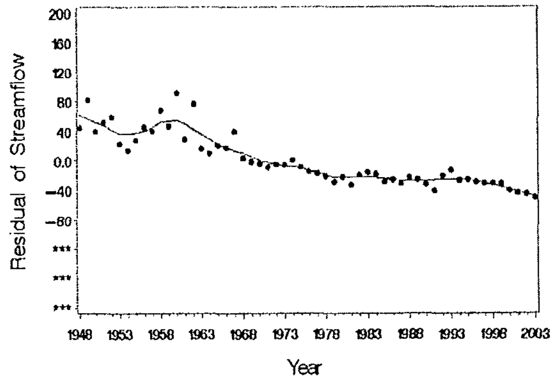
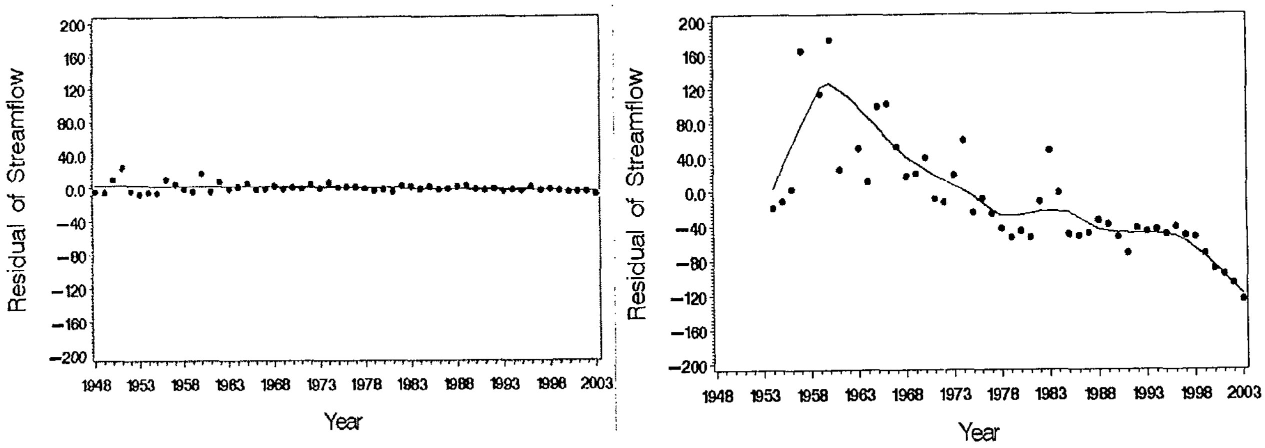


Figure 8.


(a) 6836500, Driftwood Creek near Mccook, NE.

(b) 6837000, Republican River at Mccook NE.

(c) 6838000, Red Willow Creek near Red Willow, NE.

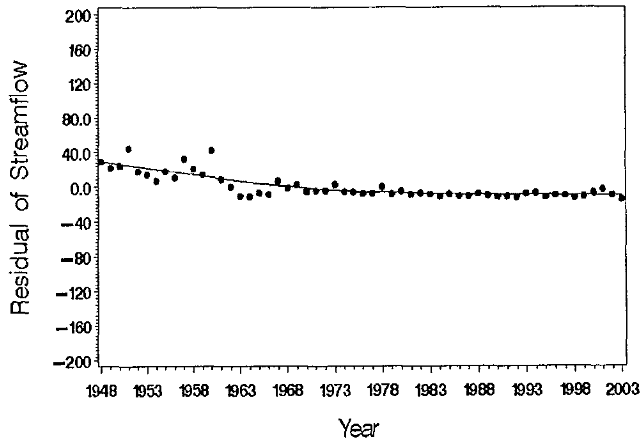


Figure 9.

(a) 6843500, Republican River at Cambridge, NE.

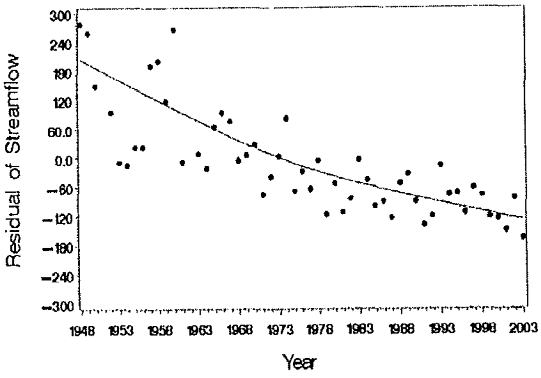
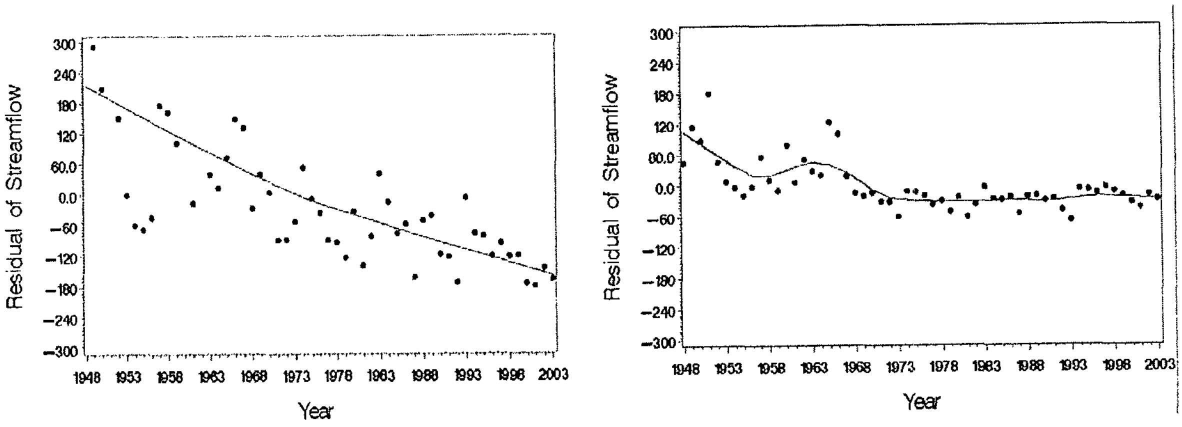


Figure 10.



(a) 6844500, Republican River near Orleans, NE.

(b) 6847500, Sappa Creek near Stamford, NE.

Figure 11.

(a) 6849500, Republican River at Harlan county dam, NE.

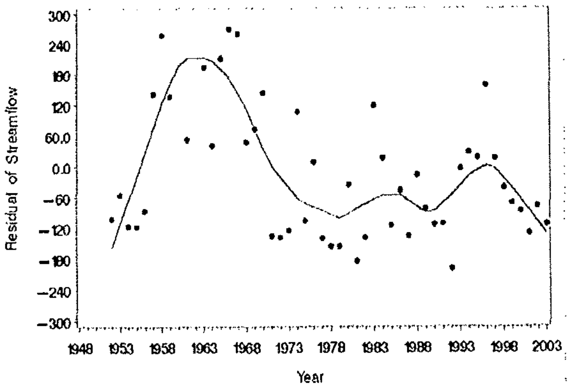
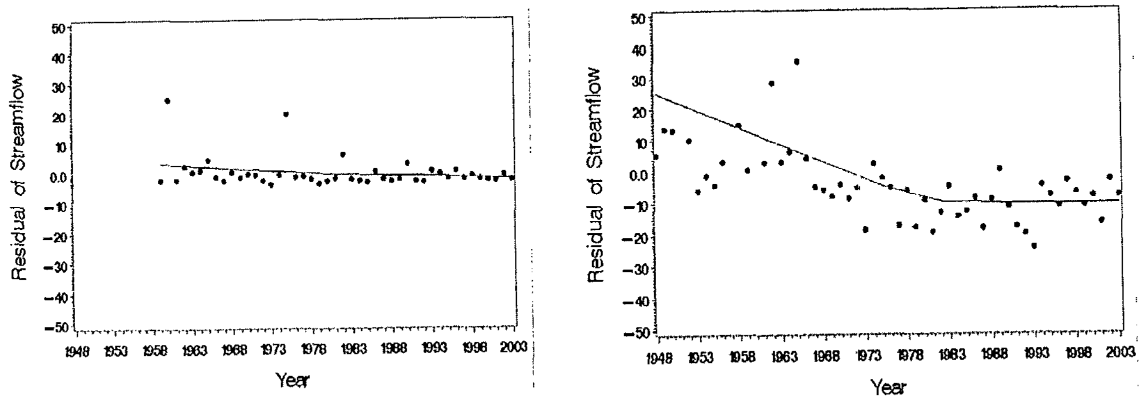
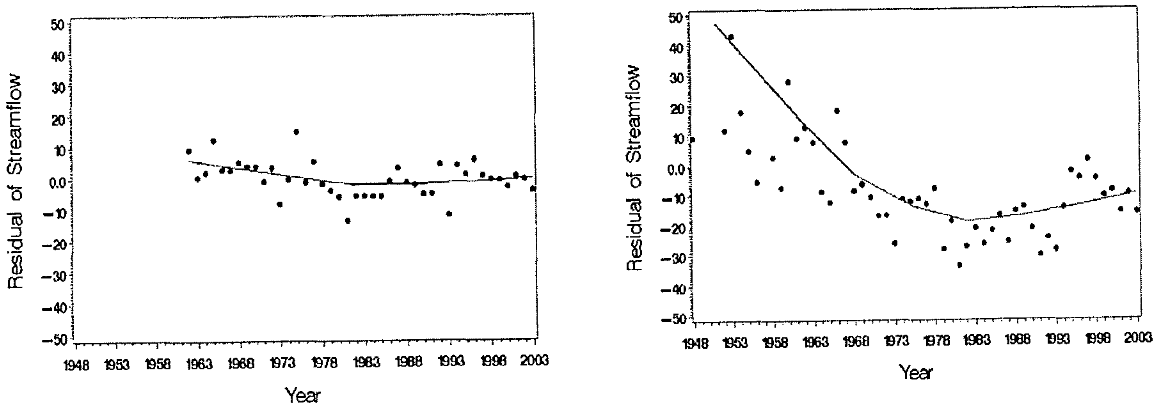


Figure 12.



(a) 6844900, SF Sappa Creek near Achilles, KS

(b) 6846500, Beaver Creek at Cedar Bluffs, KS



(c) 6847900, Prairie Dog Creek at Keith Sebelius Lake, KS

(d) 6848500, Prairie Dog Creek near Woodruff, KS