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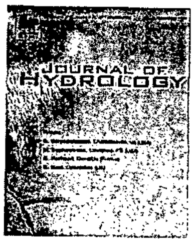

# Evaluation of the impact of groundwater irrigation on streamflow in Nebraska

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Mann–Kendall test;
LOESS techniques

**Summary** Nonparametric techniques were applied to the analysis of streamflow depletion and trends in precipitation and temperature in Nebraska and northwestern Kansas. Fifty years of streamflow data from 110 gauging stations in eight major river basins were examined. Temporal trends of streamflow in Nebraska showed a spatial tendency of decreasing streamflow mostly in the west but was insignificant in the east. This spatial pattern in streamflow depletion is unlikely to be due to a long-term change in precipitation over the entire state because precipitation, based on the records of 28 weather stations from 1948 to 2003, did not indicate a spatial trend. For the Republican River basin, 20 of the 28 gauging stations showed decreasing streamflow. To evaluate the trend of baseflow, the Local Weighted Regression method was used to generate precipitation-adjusted stream discharge. Additional analyses suggested that the local precipitation-adjusted discharge from 17 of the 22 stations decreased since the 1950s in the Republican River basin. This decrease plausibly matches a pattern of an increasing number of irrigation wells and the declines of the groundwater level. Because there was no decreasing trend in 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 Besides Nebraska, where a significant amount of groundwater was withdrawn from the High Plains regional aquifer, irrigators in Kansas and Colorado were the other likely contributors to streamflow depletion in the Republican River.

## 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 1200 in 1936 to about 100,000 serving about 85% of the state's irrigation land (Flowerday et al., 1998; Hovey, 2005). The average growth of the number of registered wells was over 1000 per year; even recently, the number of registered wells grew in 2002, 2003, and 2004. 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

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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 baseflow 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 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 few 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) used a multiple regression to annual time series data. With it, they quantified the influence of precipitation and irrigation on streamflow as gauged from one station in the Republican River basin of 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 and depletion 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 to their adjacent 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 or ladder power, say $x^{-1/3}$, may be applied, the problems cannot be fully eliminated. For example, the monthly streamflow data (years 1939–2003) from gauging station 683800 on Red Willow Creek in the Republican River basin, Nebraska, show such problems: the data of 768 records possess serious skewness (4.36), kurtosis (29.31) and several outliers; the *P*-value for the normality test with the Shapiro–Wilk statistic is 0.0001. After a logarithmic transform, the skewness (0.61) and kurtosis (0.055) are improved, but potential outliers remain and the *P*-value still is 0.0001, with significant non-normal distribution. By using a ladder power transform, the skewness (0.028) and kurtosis (−0.093) are also improved, but the *P*-value is 0.0001 for the 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 (Local Weighted Regression, Cleveland, 1979; Cleveland et al., 1988) for fitting a regression line with robustness; that is, it is suitable when there are outliers in the data.

A depletion of streamflow at some specific locations has often been the starting point of water-rights disputes between states or between surface water and groundwater users in Nebraska and 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 very few stream gauges.

The first part of the study explored the spatial distribution of streamflow trends and climatic impacts for eight major river basins in Nebraska. The second part concentrated on the analysis of streamflow residuals for gauging stations in the Republican River basin, including Kansas, to determine the baseflow decrease due to groundwater withdrawals. The local precipitation-adjusted discharge (or streamflow residual) was generated by the LOESS method. The adjusted-runoff streamflow reflects the levels of groundwater discharge to streams; its trends have not been analyzed for any rivers in Nebraska.

## Data sources

Streamflow data come from two datum assemblies. One is the National Water Information System (NWIS) Database of US Geological Survey (USGS, 2004, http://www.water.usgs.gov), and the other is the Data Bank of the Nebraska Department of Natural Resources (NDNR, 2004, 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. Fig. 1 illustrates the spatial distribution of the locations of these gauging stations in Nebraska. All depletion analyses from the 110 gauging stations were based on the records of streamflow after 1948, since most stations have records from the late 1940s. Groundwater-level data of the three observation wells from three counties in Nebraska, Colorado, and Kansas were also selected from the USGS database.

In addition, the daily climatic records (precipitation and high/low temperature) of 30 weather stations, including two weather stations in Kansas, were obtained from the High Plains Regional Climate Center (HPRCC, 2004, 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 Fig. 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, historical measurements of groundwater pumping data relative to the Republican River basin in Nebraska do not exist. Therefore, the study has to rely on the record of the data of groundwater-well registration managed by the NDNR for an indication of the amount of pumping that occurred through a certain period. As expected, the number of registered wells provides only an indirect estimate of pumping because the actual operation differs from one farmer to another and well capacity may vary considerably. Pumping capacity often ranges from 300 to 12,000 gallons of water per minute.

## 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), Burn (1994), Lins and Slack (1999), Zhang et al. (2001), Kahya and Kalayci (2004). Douglas et al. (2000), Zhang et al. (2001), and others used a "pre-whitened" method for the Mann–Kendall test to account for the serial correlation of streamflow. Kahya and Kalayci (2004) used five different test methods to confirm the results in order to have more confidence in the presence of streamflow trends in time series data. 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 baseflow change, i.e., the baseflow depletion in terms of the local precipitation-adjusted discharge, in the Republican River basin of Nebraska–Kansas using a combination of the Mann–Kendall and LOESS approaches.

## 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 and Richard, 1987) and has been widely used to test for randomness against trends in hydrology and climatology (Hirsh 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

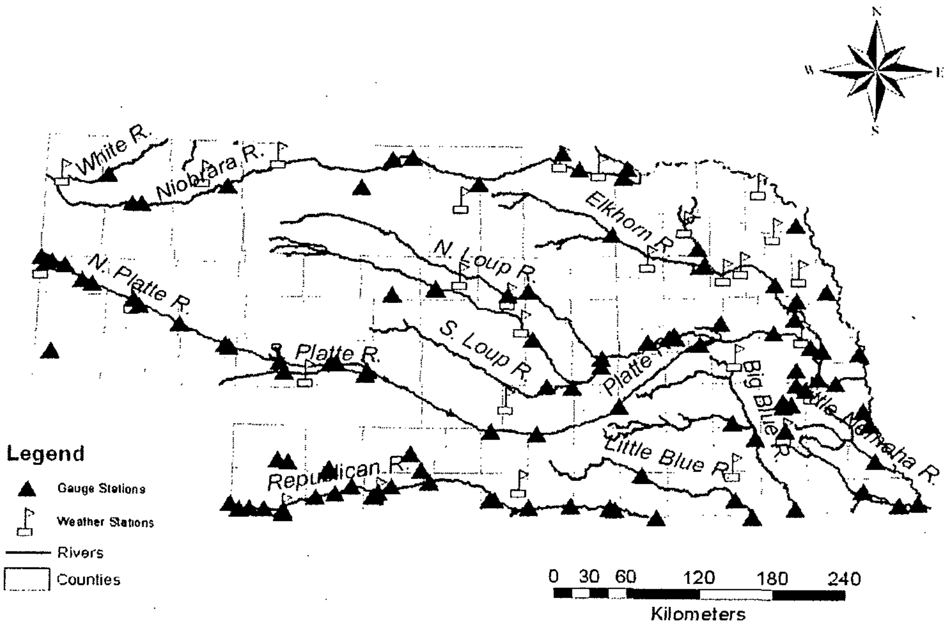


Figure 1 Main river basins in Nebraska: gauging stations and weather station distribution. The Missouri River is on the east border of Nebraska.

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 $K$

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

where

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1, & \text{if } x_j - x_i > 0, \\ 0, & \text{if } x_j - x_i = 0, \\ -1, & \text{if } x_j - x_i < 0, \end{cases}$$

and $n$ is the number of observations.

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 40 or fewer observations, the probability values associated with the Mann–Kendall $K$ can be found in numerous textbooks, for example, Table A30 (Hollander and Wolfe, 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

$$E[K] = 0, \tag{2}$$

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

where $n$ is the number of observations, $q$ is the number of tied groups and $t_p$ is the number of data in the $p$th group (Gilbert and Richard, 1987). If the sample size is more than 40 observations, a $Z$-score is calculated based on the $K$ statistic and the variance $\operatorname{Var}(K)$. 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:

$$\begin{aligned} Z &= \frac{K-1}{\sqrt{\operatorname{Var}(K)}} && \text{for } K > 0, \\ Z &= 0 && \text{for } K = 0, \\ Z &= \frac{K+1}{\sqrt{\operatorname{Var}(K)}} && \text{for } K < 0. \end{aligned} \tag{4}$$

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:

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

where $x_i$, $x_j$ are the data value at times $i$ and $j$, respectively, and where $j > i$. The median of these N values of $\left(\frac{x_j - x_i}{j - i}\right)$ is Sen's estimator of the slope.

The concern for the Mann–Kendall approach is that the existence of positive serial correlation in time series data increases the probability that a trend is detected when it does not exist (Kulkarni and von Stroch, 1995; Von Stroch and Navarra, 1995; Yue et al., 2002). In order to eliminate the overestimation, Von Stroch and Navarra (1995) and Kulkarni and von Stroch (1995) proposed applying the Mann–Kendall trend test to the pre-whitened series $x^*$, when there is a time series with autocorrelation coefficients larger than 0.1:

$$x_t^* = x_t - r_1 x_{t-1}, \tag{6}$$

where $r_1$ is the lag-1 serial correlation coefficient. $x_t$, $x_{t-1}$ are the data values at times t and lag-1. In this study, the suggestion was applied to all the Mann–Kendall trend tests.

## Local Weighted Regression (LOESS)

The local weighted least squares regression developed by Cleveland (1979) and Cleveland et al. (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 in dealing with water resource data with several specific characteristics, like positive skewness, presence of outliers, autocorrelation, and so on, as described by Helsel and Hirsch (1992). In the LOESS, for $i = 1-n$, the $i$th measurement $y_i$ of the response $y$, such as streamflow, and the corresponding measurement $x_i$, say precipitation, are related by

$$y_i = f(x_i) + \varepsilon_i, \tag{7}$$

where $f$ is the regression function and $\varepsilon_i$ 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 $d_1, d_2, \ldots, d_m$ denote the distances in increasing order of the $m$ points closest to $x$. The point at distance $d_l$ from x is given a weight $w_l$ in the local regression that decreases as the distance from $x$ increases. The LOESS procedure (SAS OnlineDoc, Version 9.1.2, SAS Institute Inc., 2002–2004) uses a tri-cube weight function defined as

$$w_l = \frac{32}{5}\left[1 - \left(\frac{d_l}{d_m}\right)^3\right]^3. \tag{8}$$

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 (i.e., Bias-corrected Akaike Information Criterion), which combines both the tightness of the fit and model complexity.

## Results and discussions

### Trend for streamflow, precipitation and temperature

The trend detection for streamflow was first conducted on the annual mean streamflow of 110 gauging stations using the Mann–Kendall method. The trend test results are summarized in Table 1 and shown in Fig. 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*-scores of the *K* statistic (see Table 1). Herein, the statistically significant level was set as 0.05 for the two-sided test.

As shown in Table 1, no trends were found for the Big/Little Blue River, the Elkhorn River, the Big/Little Nemaha River and the Missouri River basins. However, four out of 27 gauging stations in the Platte River basin showed decreasing trends; the rest had no trends. Among the four stations, three were located in western Nebraska, and one (6796500) was located in eastern Nebraska. Note that station 6796500 had only a 10-year record of streamflow (1994–2003), and this set of data are largely weighted with streamflow records from the time of a severe drought in Nebraska, which began in 2000. Other nearby stations with much longer records of streamflow did not show a decreasing trend.

The Niobrara River and the Loup River basins had not only decreasing but increasing trends. Four upward and one downward trend from the 14 gauges were detected in the South/North/Middle Loup river basin. The stations with upward trends are located on the Dismal, Middle Loup, and North Loup rivers. Chen et al. (2003) discussed the slow response of the streamflow to a drought in these rivers due to a unique geologic condition. The station (6784000) of a downward trend is on the South Loup River at St. Michael; the irrigation wells in this area are densely distributed. There were three downtrends and two uptrends detected from the 12 gauges in the Niobrara River basin. Two of the stations with a decreasing trend are located north of Box Butte County in northwestern Nebraska. Over-draft of groundwater has caused a large decline of the water table in that county. The third station with a decreasing streamflow trend is located just downstream. The decline in streamflow for these three stations is probably associated with the use of groundwater in Box Butte County.

More stations with a decreasing trend were observed in the Republican River basin; 20 out of 28 stations have downward trends and the other eight show no trend. Groundwater irrigation has caused a significant decline of the water table in several counties of the Upper Republican River valley in Nebraska, as well as in the adjacent areas of Colorado and Kansas in the Republican River basin.

All the trend test results were illustrated in Fig. 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 downward trends in western Nebraska and insignificant or increasing trends appearing in the east. In an analysis of trends of 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 they used fewer stream stations and out-of-date data (1948–1988). In comparison, the streamflow trends in our study demonstrated both negative and positive trends, which should generally agree with theirs, even though this study focused only on Nebraska and with a greater detail.

The Mann–Kendall test was also applied to the annual cumulative precipitation and average high/low temperatures. This is because precipitation is an important component in streamflow, and temperature change is another major influential factor (Viessman et al., 1977). The 28 weather stations used for this analysis were randomly scattered across the state as illustrated in Fig. 1. Fig. 2b shows the precipitation trend test results. As seen, neither increasing nor decreasing trends could be detected based on the annual 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. However, 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 the southern part of the United States. Note that the time intervals between our analysis (1948–2003) and Lettenmaier et al. (1994) (1948–1988) differ. In Nebraska, drought conditions persisting since the late 1990s may have affected the trend. Even though the annual cumulative precipitation over the past 50 years, from the 28 stations in Nebraska, did not show any increasing or decreasing trend, after shortening the analytic period, a few decreasing trends were detected for some stations: in the period 1971–2003, two downward trends were detected, in the period 1981–2003, 13 decreasing trends, and in the period 1991–2003, 17 such trends.

The trend tests for the high/low temperatures were also carried out and shown in Fig. 2c and d, based on 17 of the 28 stations randomly chosen with temperature records (others were without temperature records). There was one negative trend detected for the annual high average temperature, while there were two positive and two negative trends for the annual low average temperature. Our analysis did not suggest that the temperature range between the high and low records had any significant change.

### Analysis of streamflow from 1950 to 2003

In Nebraska, the groundwater systems before 1950 were considered under pre-development conditions because the use of groundwater for irrigation was not extensive and its impact on streamflow was minimal. We analyzed the

**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 | 0.01 | 0.992 | Insignificant |
| | 6881000 | 2710 | 1953–2003 | 0.87 | 0.384 | Insignificant |
| | 6882000 | 4447 | 1932–2003 | 1.449 | 0.147 | Insignificant |
| | 6883000[a] | 984 | 1953–2003 | −0.405 | 0.685 | Insignificant |
| | 6884000[b] | 2350 | 1910–2003 | 1.367 | 0.172 | Insignificant |
| | 6884025 | 2752 | 1971–2003 | – | – | Insignificant |
| Elkhorn Rivers | 6797500 | 1400 | 1947–2003 | 0.417 | 0.677 | Insignificant |
| | 6799000 | 2790 | 1945–2003 | 0.094 | 0.925 | Insignificant |
| | 6799100 | 701 | 1960–2003 | 0.942 | 0.346 | Insignificant |
| | 6799350 | 5100 | 1972–2003 | – | – | Insignificant |
| | 6799500 | 1015 | 1941–2003 | 1.786 | 0.074 | Insignificant |
| | 6800000 | 369 | 1951–2003 | 1.839 | 0.066 | Insignificant |
| | 6800500 | 6900 | 1928–2003 | 1.921 | 0.055 | Insignificant |
| S/N/Middle Loup Rivers | 6775500 | 1830 | 1945–2003 | 2.804 | 0.005 | Increasing |
| | 6775900 | 966 | 1966–2003 | – | – | Increasing |
| | 6776500 | 2040 | 1945–1995 | 0.029 | 0.977 | Insignificant |
| | 6779000 | 5019 | 1937–1995 | −1.122 | 0.262 | Insignificant |
| | 6783500 | 707 | 1946–2003 | −1.81 | 0.07 | Insignificant |
| | 6784000 | 2320 | 1943–2003 | −1.996 | 0.046 | Decreasing |
| | 6785000 | 8075 | 1928–2003 | 0.393 | 0.694 | Insignificant |
| | 6786000 | 2350 | 1936–2003 | 2.154 | 0.031 | Increasing |
| | 6787500 | 994 | 1940–2003 | −0.285 | 0.776 | Insignificant |
| | 6790500 | 4302 | 1928–2003 | 2.351 | 0.019 | Increasing |
| | 6792000 | 1220 | 1940–1995 | 1.452 | 0.147 | Insignificant |
| | 6792500 | N/A | 1937–2003 | 1.428 | 0.153 | Insignificant |
| | 6793000 | 14,320 | 1943–2003 | 1.167 | 0.243 | Insignificant |
| | 6794000 | 677 | 1940–2003 | −0.273 | 0.785 | Insignificant |
| Missouri River | 6601000 | 174 | 1945–2003 | 1.248 | 0.212 | Insignificant |
| | 6608000 | 23 | 1950–1980 | – | – | Insignificant |
| | 6610000 | 326,759 | 1928–2003 | 1.29 | 0.197 | Insignificant |
| | 6806500 | 241 | 1950–2003 | 1.25 | 0.211 | Insignificant |
| | 6807000 | 413,959 | 1929–2003 | 1.101 | 0.271 | Insignificant |
| | 6813500 | 418,859 | 1949–2003 | 0.791 | 0.429 | Insignificant |
| Big/Little Nemaha Rivers | 6803000 | 167 | 1970–2001 | – | – | Insignificant |
| | 6803500 | 685 | 1950–2001 | 1.3 | 0.194 | 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 | 0.91 | 0.363 | Insignificant |
| | 6811500 | 792 | 1949–2003 | 0.627 | 0.531 | Insignificant |
| | 6814500 | 548 | 1952–1996 | 0.475 | 0.635 | Insignificant |
| | 6815000 | 1339 | 1944–2003 | −0.157 | 0.875 | Insignificant |
| Niobrara River | 6444000 | 313 | 1947–2003 | 2.361 | 0.018 | Increasing |
| | 6453500 | 505 | 1949–1994 | −1.086 | 0.278 | Insignificant |
| | 6453600 | 812 | 1957–2003 | 1.212 | 0.226 | Insignificant |
| | 6454500 | 1400 | 1946–2003 | −2.912 | 0.004 | Decreasing |
| | 6455500 | 1460 | 1946–2003 | −3.428 | 0.001 | Decreasing |
| | 6457500 | 4290 | 1945–1991 | −2.708 | 0.007 | Decreasing |
| | 6459500 | 660 | 1947–2003 | −1.675 | 0.094 | Insignificant |
| | 6461000 | 390 | 1948–1994 | −0.757 | 0.449 | Insignificant |
| | 6461500 | 7150 | 1945–2003 | −1.529 | 0.126 | Insignificant |
| | 6463500 | 458 | 1948–2003 | 2.367 | 0.018 | Increasing |
| | 6465000 | 11,070 | 1940–2001 | 1.699 | 0.089 | Insignificant |
| | 6465500 | 11,580 | 1938–2003 | 1.804 | 0.071 | Insignificant |

Table 1 (*continued*)

| Basin | Station ID | Drainage (mile$^2$) | Period | Z-score | *P*-value | Trend |
|---|---|---|---|---|---|---|
| S/N Platte Rivers | 6674500 | 22218 | 1932–2001 | −1.582 | 0.114 | Insignificant |
| | 6677500 | 1707 | 1931–2003 | 1.735 | 0.083 | Insignificant |
| | 6678000 | 356 | 1931–2003 | −0.141 | 0.888 | Insignificant |
| | 6679500 | 24,300 | 1931–2003 | −0.129 | 0.898 | Insignificant |
| | 6681500 | 79.8 | 1931–2003 | 1.22 | 0.223 | Insignificant |
| | 6682000 | 24,700 | 1930–2003 | −0.813 | 0.416 | Insignificant |
| | 6684500 | 25,300 | 1948–2003 | 0.053 | 0.957 | Insignificant |
| | 6685000 | 1011.7 | 1944–2003 | −2.958 | 0.003 | Decreasing |
| | 6686000 | 26,700 | 1930–2002 | −0.773 | 0.44 | Insignificant |
| | 6687000 | 897.9 | 1931–2002 | −0.681 | 0.496 | Insignificant |
| | 6687500 | 28,600 | 1940–2003 | −1.435 | 0.151 | Insignificant |
| | 6690500 | 29,300 | 1942–2003 | 0.205 | 0.837 | Insignificant |
| | 6691000 | 29,800 | 1936–1991 | 0.363 | 0.717 | Insignificant |
| | 6692000 | 940 | 1931–1991 | −1.767 | 0.077 | Insignificant |
| | 6693000 | 30,900 | 1931–2003 | −0.405 | 0.686 | Insignificant |
| | 6762500 | 1227.15 | 1934–2003 | −3.435 | 0.001 | Decreasing |
| | 6764880 | 23,900 | 1982–2003 | – | – | Decreasing |
| | 6765500 | 24,300 | 1931–2003 | 0.958 | 0.338 | Insignificant |
| | 6768000 | 56,300 | 1930–2003 | 0.757 | 0.449 | Insignificant |
| | 6770200 | 57,260 | 1982–2003 | – | – | Insignificant |
| | 6770500 | 57,650 | 1934–2003 | 1.072 | 0.284 | Insignificant |
| | 6774000 | 59,300 | 1928–2003 | 0.961 | 0.337 | Insignificant |
| | 6795500 | 294 | 1947–2003 | 1.408 | 0.159 | Insignificant |
| | 6796000 | 70,400 | 1949–2003 | 0.895 | 0.371 | Insignificant |
| | 6796500 | N/A | 1994–2003 | – | – | Decreasing |
| | 6801000[c] | 84,200 | 1928–2003 | 1.129 | 0.259 | Insignificant |
| | 6805500 | 85,370 | 1953–2003 | 1.205 | 0.228 | Insignificant |
| Republican River | 6821500 | 1700 | 1932–2003 | −5.212 | 0 | Decreasing |
| | 6823000 | 2370 | 1935–2003 | −3.488 | 0 | Decreasing |
| | 6823500 | 172 | 1940–2003 | −2.574 | 0.01 | Decreasing |
| | 6824000 | 23.6 | 1940–2003 | −3.701 | 0 | Decreasing |
| | 6824500 | 4880 | 1947–1994 | −2.164 | 0.03 | Decreasing |
| | 6827500 | 2740 | 1950–2003 | −3.398 | 0.001 | Decreasing |
| | 6828500 | 8200 | 1950–2003 | −2.738 | 0.006 | Decreasing |
| | 6829500 | 8340 | 1946–1993 | −1.541 | 0.123 | Insignificant |
| | 6831500 | 1050 | 1941–2003 | −3.001 | 0.003 | Decreasing |
| | 6832500 | 1140 | 1946–1993 | −3.375 | 0.001 | Decreasing |
| | 6834000 | 1300 | 1950–2003 | −2.294 | 0.022 | Decreasing |
| | 6835000 | 1500 | 1949–2003 | −2.701 | 0.007 | Decreasing |
| | 6835500 | 2990 | 1935–2003 | −3.203 | 0.001 | Decreasing |
| | 6836000 | 361 | 1951–1980 | – | – | Insignificant |
| | 6836500 | 361 | 1946–2003 | −1.315 | 0.189 | Insignificant |
| | 6837000 | 12,240 | 1954–2003 | −3.439 | 0.001 | Decreasing |
| | 6838000 | 820 | 1939–2003 | −2.706 | 0.007 | Decreasing |
| | 6841000 | 770 | 1945–2002 | −3.622 | 0 | Decreasing |
| | 6842500 | 880 | 1950–2003 | −3.812 | 0 | Decreasing |
| | 6843500 | 14,460 | 1945–2003 | −3.381 | 0.001 | Decreasing |
| | 6844500 | 15,580 | 1947–2003 | −2.99 | 0.003 | Decreasing |
| | 6847000 | 2081 | 1937–2003 | −2.69 | 0.007 | Decreasing |
| | 6847500 | 3840 | 1946-2003 | −0.943 | 0.346 | Insignificant |
| | 6849500 | 20,820 | 1952–2003 | −1.446 | 0.148 | Insignificant |
| | 6852500 | 290 | 1954–2003 | 1.164 | 0.245 | Insignificant |
| | 6853000 | 22,040 | 1950–1984 | – | – | Insignificant |
| | 6853020 | 22,100 | 1984–2003 | – | – | Insignificant |
| | 6853500 | 22,401 | 1932–2001 | −2.253 | 0.024 | Decreasing |

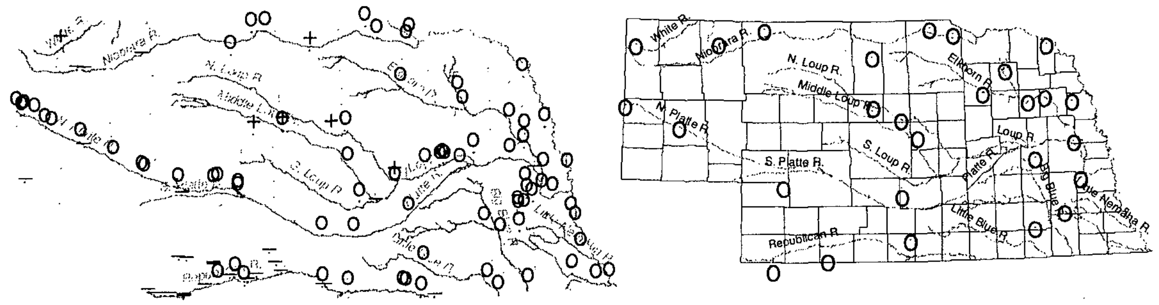
[a] *Gauge6883000* lacks the records in 1973 and 1974.

[b] *Gauge6884000* lacks the records in the period of 1916–1929.

[c] *Gauge6801000* lacks the records in the period of 1960–1988.

(a) Annual Streamflow

(b) Annual Precipitation



(c) High Temperature

(c) Low Temperature

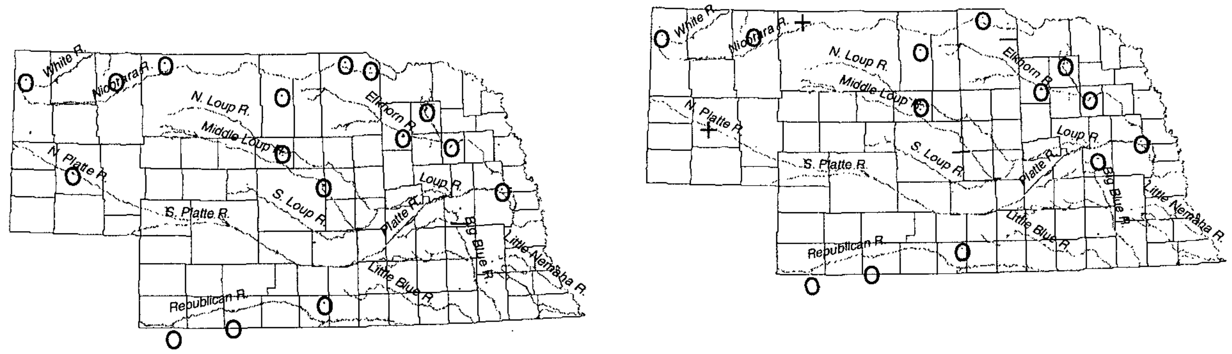


**Figure 2** Spatial distribution of trend analysis based on annual mean streamflow, annual precipitation, and high/low temperature.

streamflow trends for the period between 1950 and 2003, as well as for other multiple-decade periods (1960–2003, 1970–2003, and 1980–2003) and for 10-year periods (1950–59, 1960–69, 1970–79, 1980–89, and 1990–2003). Table 2 summarizes the statistical test results of the trends. For the period 1950–2003, five stations showed an upward trend, but 24 showed a downward trend among the 110 gauges, as shown in Fig. 3. In the periods of 1970–2003, and 1980–2003, the upward trends increased to 10 stations, and the downward trends decreased to 20. Among the 10 upward trends, six occurred in the Loup River basin; and among the 20 downward trends, 16 occurred in the Republican River basin (Table 2). Results from the 10-year analyses indicate that the number of the stations with a downward trend tended to increase from two in the 1950s to 18 in the 1990s, while fewer stations showed an upward trend of streamflow.

The streamflow trend differs in individual basins. For example, the Big/Little Nemaha River basin possessed a stable streamflow without any upward or downward trend. This basin is located in the southeastern Nebraska, where annual precipitation was higher than other river basins in Nebraska and groundwater use for irrigation was not as extensive as in most other basins. For the Big/Little Blue River, the Elkhorn River, and the Missouri River basins, the streamflow kept relatively stable. Only one upward trend showed up in the periods of 1970–2003 and 1980–2003 for the Elkhorn River and the Missouri River basins. One increasing trend was observed in the 1970s and one decreasing trend was found from another station in the 1990s among the six stations analyzed for the Big/Little Blue River.

For the Niobrara River basin, three downward and two upward trends were found among 12 gauges in the period of 1950–2003. 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. As shown in Table 2, the streamflow was decreasing in three or four stations across the multiple-decade periods. One station with an increasing trend was detected in the period of 1950–2003.

In the period of 1950–2003, 17 of the 28 stations in the Republican River basin showed a decreasing trend. Sixteen stations show a decreasing trend for 1960–2003, 1970–2003, and 1980–2003, respectively. For the 10-year period analyses, the number of stations with downward trends increased from zero in the 1950s and 1960s to 13 out of 24 stations in the 1990s. Among the eight main river basins in Nebraska, the severest depletion of the streamflow occurred in the Republican River basin in the last five decades. In order to determine whether groundwater withdrawal had an impact on the streamflow depletion, the authors further examined the information on the number of irrigation wells.

The number of irrigation wells, obtained from the NDNR, is considered an indicator of groundwater use for irrigation and water supplies in Nebraska, even though it was not representative of complete groundwater withdrawal, which includes other land use and conservation practices. In the Republican River basin, a number of registered irrigation wells in eight counties (Dundy, Hitchcock, Red Willow, Furnas, Harlan, Franklin, Webster and Nuckolls) are illustrated in Fig. 4. There were only 84 wells by 1940, and 304 wells by 1950. However, by 1991, the total number of registered wells had rapidly increased to 4646. During the earlier per-

**Table 2** Mann—Kendall trend test results for timing of decades on streamflow

| Years of record | 1950–2003 | 1960–2003 | 1970–2003 | 1980–2003 | 1950–59 | 1960–69 | 1970–79 | 1980–89 | 1990–03 |
|---|---|---|---|---|---|---|---|---|---|
| *Entire State* | | | | | | | | | |
| Stations tested | 110 | 110 | 110 | 110 | 88 | 97 | 105 | 107 | 101 |
| Number with increasing | 5 | 5 | 10 | 10 | 0 | 2 | 1 | 0 | 1 |
| Number with insignificant | 81 | 85 | 80 | 80 | 86 | 88 | 92 | 96 | 82 |
| Number with decreasing trends | 24 | 20 | 20 | 20 | 2 | 7 | 12 | 11 | 18 |
| *Big/Little Blue River Basin* | | | | | | | | | |
| Number with increasing | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Number with insignificant | 6 | 6 | 6 | 6 | 4 | 5 | 5 | 6 | 5 |
| Number with decreasing trends | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| *Elkhorn River Basin* | | | | | | | | | |
| Number with increasing trends | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Number with insignificant | 7 | 7 | 6 | 6 | 5 | 6 | 7 | 7 | 7 |
| Number with decreasing trends | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Loup River Basin* | | | | | | | | | |
| Number with increasing trends | 2 | 2 | 6 | 6 | 0 | 0 | 0 | 0 | 1 |
| Number with insignificant | 12 | 12 | 8 | 8 | 13 | 8 | 14 | 14 | 12 |
| Number with decreasing trends | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 1 |
| *Big/Little Nemaha River Basin* | | | | | | | | | |
| Number with increasing trends | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Number with insignificant | 10 | 10 | 10 | 10 | 5 | 5 | 10 | 10 | 10 |
| Number with decreasing trends | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Niobrara River Basin* | | | | | | | | | |
| Number with increasing trends | 2 | 3 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Number with insignificant | 7 | 8 | 10 | 10 | 9 | 10 | 11 | 11 | 10 |
| Number with decreasing trends | 3 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 |
| *Platte River Basin* | | | | | | | | | |
| Number with increasing trends | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Number with insignificant | 22 | 24 | 24 | 24 | 23 | 23 | 19 | 22 | 22 |
| Number with decreasing trends | 4 | 3 | 3 | 3 | 1 | 0 | 4 | 3 | 2 |
| *Republican River Basin* | | | | | | | | | |
| Number with increasing trends | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Number with insignificant | 11 | 12 | 11 | 11 | 27 | 27 | 20 | 21 | 11 |
| Number with decreasing trends | 17 | 16 | 16 | 16 | 0 | 0 | 7 | 7 | 13 |
| *Missouri River Basin* | | | | | | | | | |
| Number with increasing trends | 0 | 0 | 1 | 1 | 0 | 2 | 0 | 0 | 0 |
| Number with insignificant | 6 | 6 | 5 | 5 | 6 | 4 | 6 | 5 | 5 |
| Number with decreasing trends | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

iod, from 1930 to 1950, the development of irrigation wells grew slowly. In the 1950s, 1960s and 1970s, the registered irrigation wells showed a rapid increase, and by the end of the 1970s, the number of irrigation wells was up to 4513. Accordingly, streamflow in the upstream part of the Republican River has declined since 1970s as shown in Table 2.

## Trend of baseflow in the Republican River basin

By the late 1980s, Kansas began to assert that Nebraska was consuming more water in the Republican River than legally allowed. The two states had disputed their rights to streamflow relative to those set forth under a federal interstate river compact. Kansas filed a lawsuit against Nebraska in federal court arguing that "decreases in annual estimate of virgin streamflows are not due to natural phenomena but due to increases in groundwater withdrawals" (Bennet and Howe, 1998).

The streamflow mainly consists of groundwater discharge (baseflow) and surface runoff (due to precipitation). The latter includes direct surface runoff, interflow and channel precipitation (Viessman et al., 1977). To estimate the depletion of baseflow by groundwater use in the Republican River basin, the local precipitation-adjusted discharge was generated to approximate the baseflow and further examined for the baseflow trend detection.

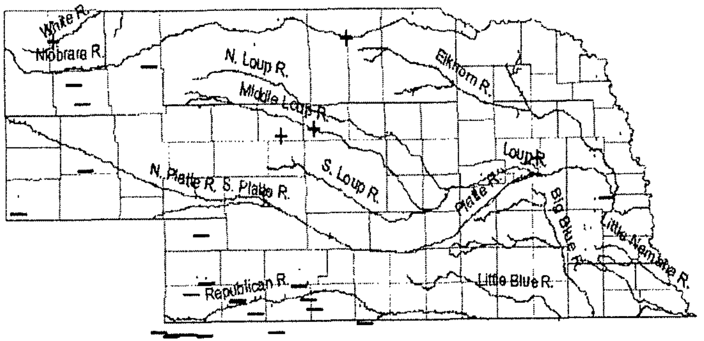


**Figure 3** Spatial distribution of trend analysis based on annual mean streamflow in the period of 1950–2003.

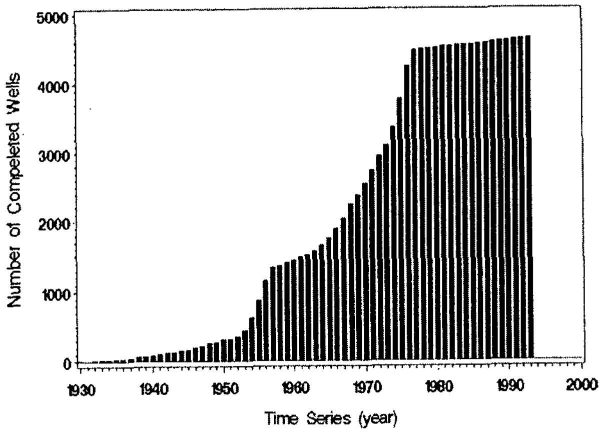


**Figure 4** Cumulative number of registered irrigation wells in the Republican River basin, Nebraska.

In the analysis, first, the LOESS was used to conduct a regression of the average annual streamflow on the yearly cumulative precipitation that was averaged from several nearby weather stations. By this process the yearly surface runoff fluctuation, i.e., the LOESS smooth curve, which represents annually cumulatively fluctuating precipitation variation, was removed from the streamflow even though the linear trend of precipitation was not significant. The residuals or the local precipitation-adjusted discharge better reflect the characteristics of baseflow in streams. Then, the Mann–Kendall test was used to calculate the trend of streamflow residuals. We used this method to analyze 24 gauge stations, including two (6846500, 6848500) in Kansas, which contained about 50-year records under the local precipitation-adjusted discharge, and 18 of them had decreasing trends shown on the column of "adjusted trend" in Table 3. For comparison, the streamflow depletion trends without the precipitation adjustment were listed on the column of "unadjusted trend" in Table 3. As can be seen, the majority of the results are consistent with the tests without the precipitation adjustment. The gauges 6836500 had a decreasing trend instead of no-significance after removing the fluctuating variation of precipitation. Conversely, the gauge 6823500 had a non-significant trend instead of a decreasing one. Furthermore, to some extent, the amounts of the corresponding *Z*-scores, *P*-values and slopes were changed when compared without the precipitation adjustment. Clearly, the local precipitation adjustment offered additional insight in the streamflow trend. We selected 12 gauging stations, listed in bold in Table 3, for discussing the magnitude of the trend of residual streamflow; their locations are shown in Fig. 5.

Fig. 6a–d, respectively, shows the local precipitation-adjusted discharge for gauge 6821500 on the Arikaree River at Haigler, 6823000 on the North Fork Republican River at Colorado–Nebraska, 6824000 on the Rock Creek at Parks, and 6827500 on the South Fork Republican River near Benkelman in Dundy County, Nebraska, where two weather stations recorded precipitation from 1948 to 2003. The average of annual cumulative precipitation from the two stations was used in generating the local precipitation-adjusted streamflow. For quantification of the decrease rate of the baseflow, LOESS was used a second time to plot regression lines through the streamflow residuals. All of the four gauging stations showed continuous decreasing trends in the 55-year period. Fig. 6d exhibits a larger rate of decrease in streamflow residuals, with a magnitude of 0.284 $ft^3 s^{-1}$/yr, whereas Fig. 6c shows a gentler downward nslope, with a depletion rate of 0.026 $ft^3 s^{-1}$/yr. Gauge 6821500 in Fig. 6a actually measured the streamflow for the Arikaree River coming from Colorado. The residuals in Fig. 6c show a relatively small fluctuation compared to the other three stations, possibly due to the small drainage area shown in Table 1. Note that the streamflow residuals did not show a trend in 1950s and early 1960s for the four stations. Decline of baseflow was shown in late 1960s and early 1970s; the time agrees with the rapid growth of irrigation wells (Fig. 4). It thus suggests that the decreasing streamflow from the four gauging stations in the Republican River basin in Dundy County is likely due to groundwater withdrawal.

Fig. 7 shows the streamflow residuals for two gauges located in Hitchcock County, Nebraska, where the precipitation data from three weather stations were available for adjusting the streamflow residuals. Gauge 6828500 is located on the Republican River at Stratton, and 6835500 on the Frenchman Creek at Culbertson. The two gauges showed downward trends for the 52-year period. Fig. 7a exhibits a monotonic depletion with a negative slope of 0.732 $ft^3 s^{-1}$/yr. Fig. 7b displays a decreasing tendency, but in the early 1960s, the streamflow bounced back to the highest discharge, then went down again. Overall, it

Table 3 Streamflow depletion estimates for the local precipitation-adjusted discharge for the Republican River basin

| | Gauge ID | Period | Adjusted trend | Unadjusted trend | Z-score | P-value | Slope ($ft^3 s^{-1}$/yr) |
|---|---|---|---|---|---|---|---|
| 1 | **rep6821500** | **1948–2003** | **Decreasing** | **Decreasing** | **−3.543** | **0.000** | **−0.153** |
| 2 | **rep6823000** | **1948–2003** | **Decreasing** | **Decreasing** | **−2.904** | **0.004** | **−0.113** |
| 3 | **rep6824000** | **1948–2003** | **Decreasing** | **Decreasing** | **−3.296** | **0.001** | **−0.026** |
| 4 | **rep6827500** | **1948–2003** | **Decreasing** | **Decreasing** | **−2.221** | **0.026** | **−0.284** |
| 5 | **rep6828500** | **1951–2003** | **Decreasing** | **Decreasing** | **−2.501** | **0.012** | **−0.732** |
| 6 | **rep6835500** | **1951–2003** | **Decreasing** | **Decreasing** | **−2.407** | **0.016** | **−0.307** |
| 7 | **rep6836500** | **1955–2003** | **Decreasing** | **Insignificant** | **−3.351** | **0.001** | **−0.133** |
| 8 | **rep6837000** | **1955–2003** | **Decreasing** | **Decreasing** | **−3.351** | **0.001** | **−1.244** |
| 9 | **rep6843500** | **1950–2003** | **Decreasing** | **Decreasing** | **−2.907** | **0.004** | **−2.077** |
| 10 | **rep6844500** | **1948–2003** | **Decreasing** | **Decreasing** | **−2.483** | **0.013** | **−1.708** |
| 11 | **ks6846500** | **1947–2003** | **Decreasing** | **Decreasing** | **−2.094** | **0.042** | **−0.051** |
| 12 | **ks6848500** | **1947–2003** | **Decreasing** | **Decreasing** | **−2.309** | **0.041** | **−0.238** |
| 13 | rep6823500 | 1948–2003 | Insignificant | Decreasing | −1.858 | 0.063 | N/A |
| 14 | rep6831500 | 1951–2003 | Decreasing | Decreasing | −1.981 | 0.048 | −0.105 |
| 15 | rep6834000 | 1951–2003 | Decreasing | Decreasing | −2.170 | 0.030 | −0.263 |
| 16 | rep6835000 | 1951–2003 | Decreasing | Decreasing | −2.249 | 0.024 | −0.114 |
| 17 | rep6838000 | 1955–2003 | Insignificant | Insignificant | −1.111 | 0.267 | N/A |
| 18 | rep6841000 | 1950–2002 | Decreasing | Decreasing | −3.306 | 0.001 | −0.322 |
| 19 | rep6842500 | 1950–2003 | Decreasing | Decreasing | −3.674 | 0.000 | −0.584 |
| 20 | rep6847000 | 1950–2003 | Decreasing | Decreasing | −2.232 | 0.026 | −0.172 |
| 21 | rep6847500 | 1948–2003 | Insignificant | Insignificant | −1.162 | 0.245 | N/A |
| 22 | rep6849500 | 1953–2003 | Insignificant | Insignificant | −1.489 | 0.137 | N/A |
| 23 | rep6852500 | 1955–2003 | Insignificant | Insignificant | 0.530 | 0.596 | N/A |
| 24 | rep6853500 | 1955–2001 | Insignificant | Insignificant | −1.138 | 0.167 | N/A |

Adjusted trend: trends based on the local precipitation-adjusted discharge; unadjusted trend: trends without the precipitation adjustment; N/A: not applicable.

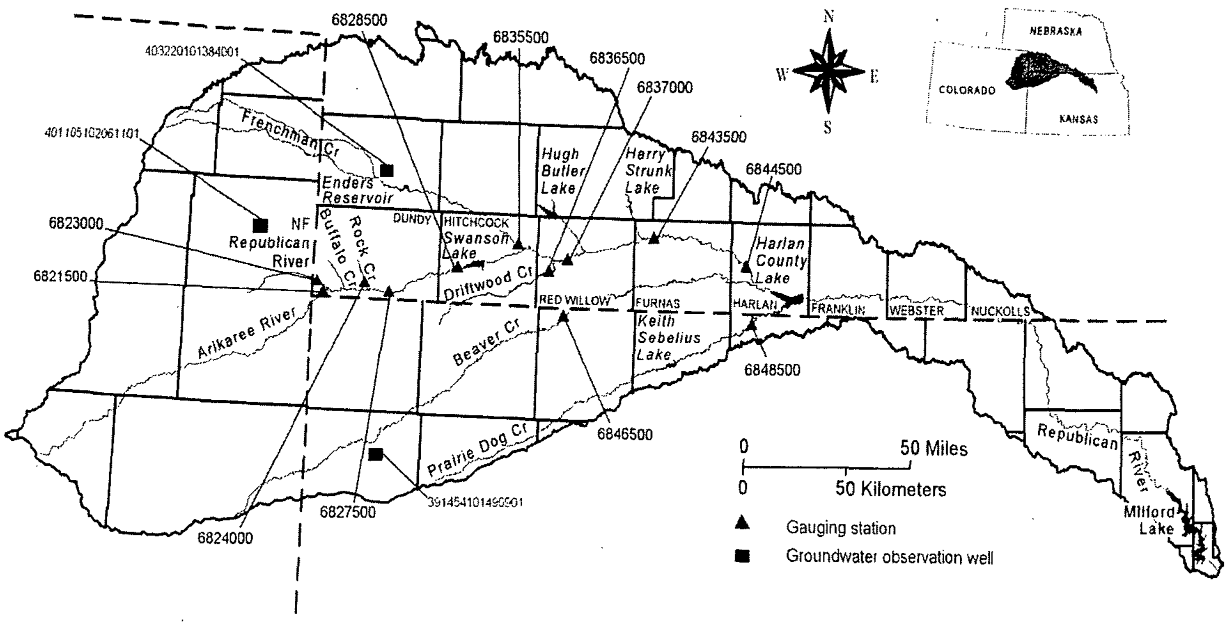
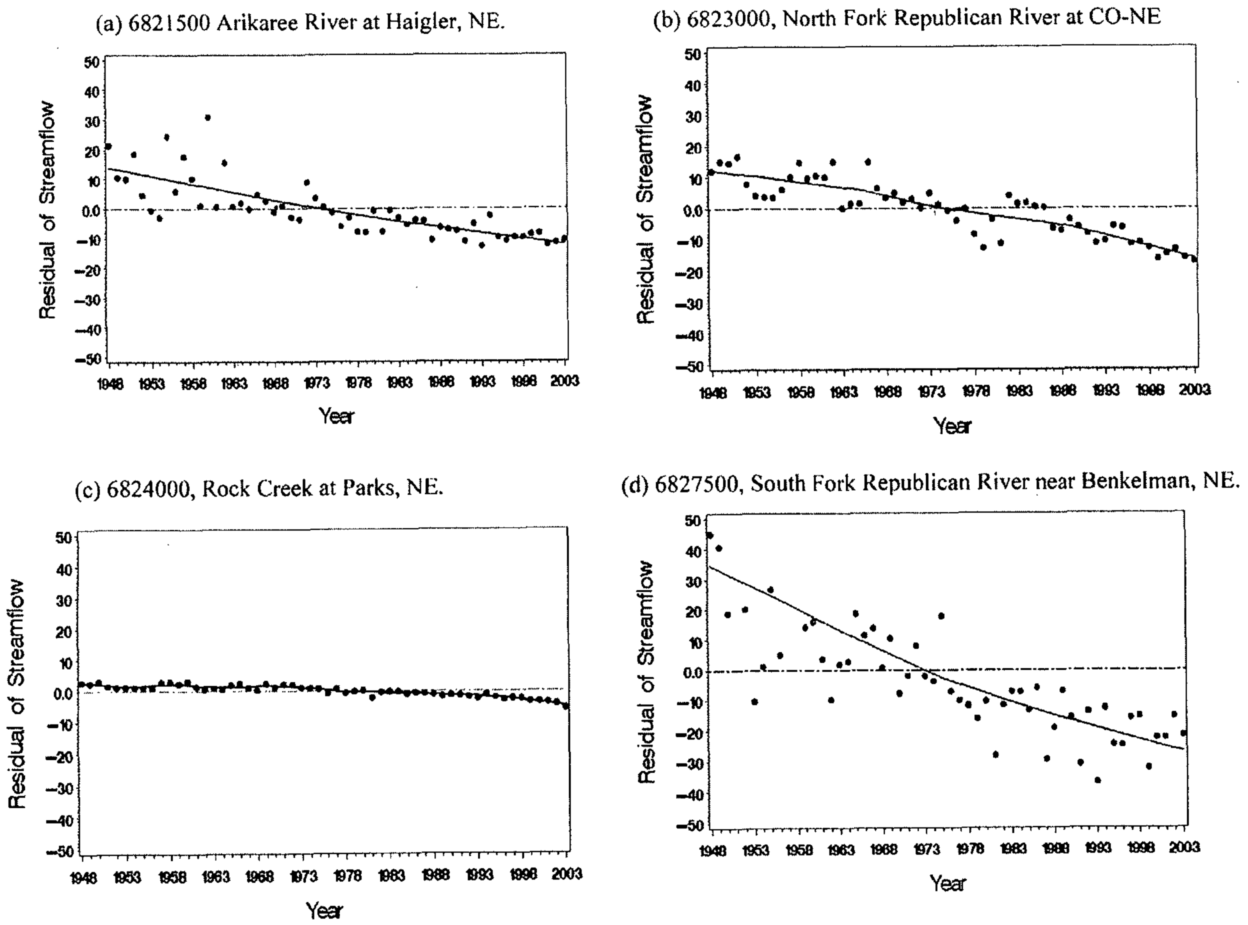


Figure 5 Gauging stations and groundwater observation wells in the Republican River basin.

600 had a negative slope of 0.307 $ft^3 s^{-1}$/yr. Again, the stream-
601 flow residuals do not show an apparent trend in the 1950s
602 and early 1960s. Negative streamflow residuals occurred
603 around 1970.

Fig. 8 shows the streamflow residuals of two gauges lo- 604
cated in Red Willow County, Nebraska, where one weather 605
station was available for adjustment of streamflow. Gauge 606
6836500 is on Driftwood Creek near McCook and gauge 607

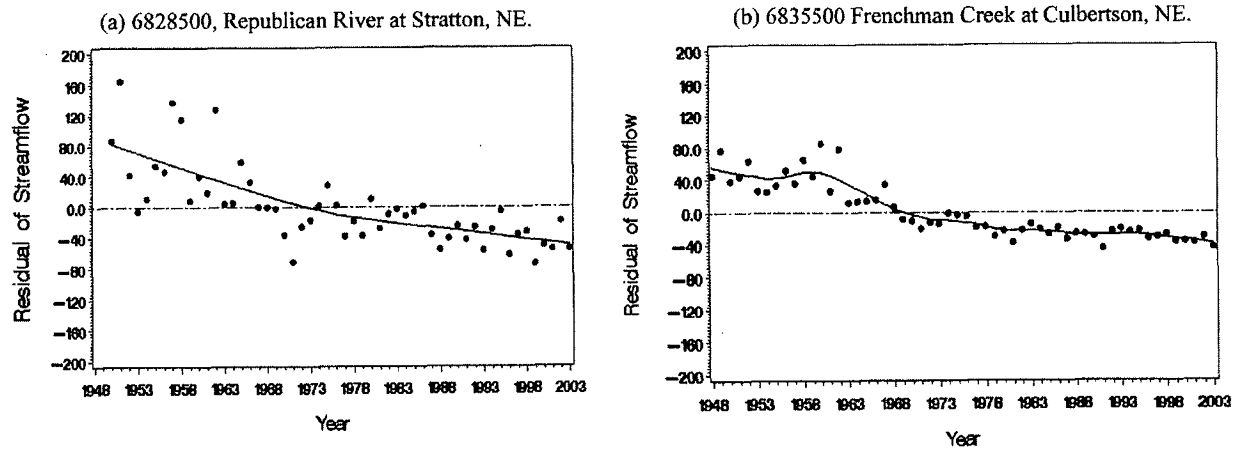

(a) 6821500 Arikaree River at Haigler, NE.

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

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

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

**Figure 6** Trend of streamflow residuals for the gauging stations in Dundy County in the Republican River basin.

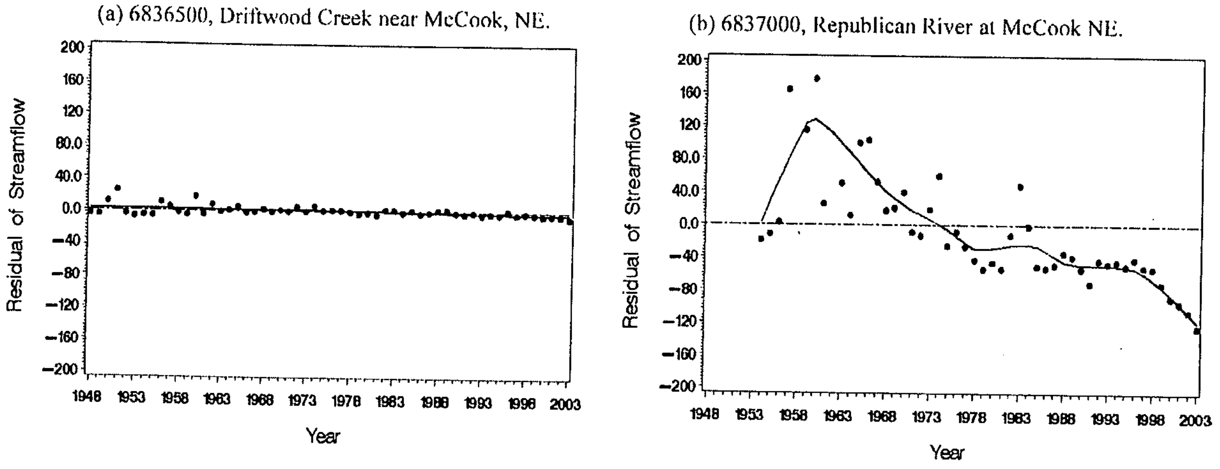

(a) 6828500, Republican River at Stratton, NE.

(b) 6835500 Frenchman Creek at Culbertson, NE.

**Figure 7** Trend of streamflow residuals for the gauging stations in Hitchcock County in the Republican River basin.

6837000 is on the Republican River at McCook. The two stations showed a significant decline trend of streamflow residuals, even though the trend for gauge 6836500 was not significant without the local precipitation adjustment to the earlier analysis; for the local precipitation-adjusted discharge, the decreasing rate of streamflow residual was 0.133 $ft^3 s^{-1}$/yr. Fig. 8b behaves as a varied curve that had the highest discharge in the later 1950s, then steeply decreases with an average annual depletion of 1.244 $ft^3 s^{-1}$/yr. This pattern was similar to that shown in Fig. 7b.

Fig. 9 is the streamflow residuals of gauge 6843500 for the Republican River at Cambridge, located in Furnas County, Nebraska, where precipitation records from three


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

(b) 6837000, Republican River at McCook NE.

**Figure 8** Trend of streamflow residuals for the gauging stations in Red Willow County in the Republican River basin.

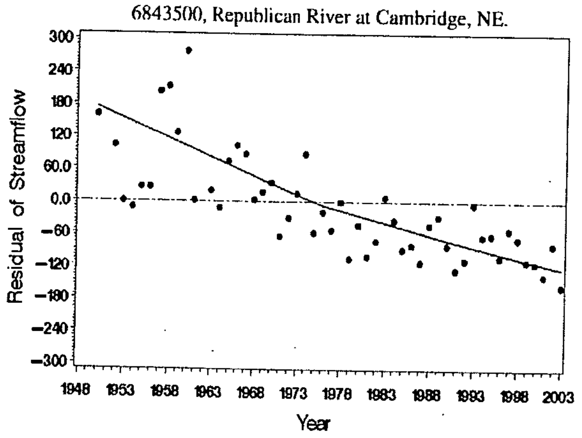

6843500, Republican River at Cambridge, NE.

**Figure 9** Trend of streamflow residuals for the gauging stations in Furnas County in the Republican River basin.

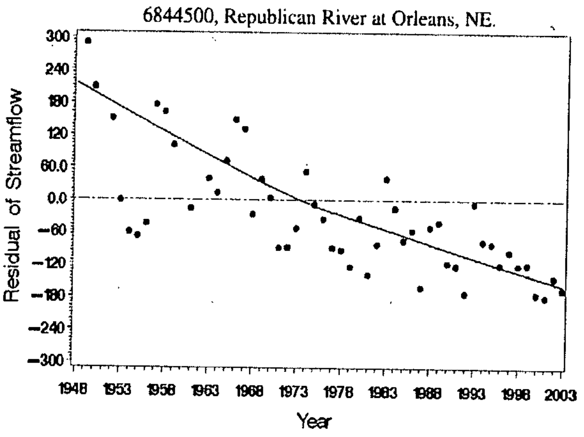
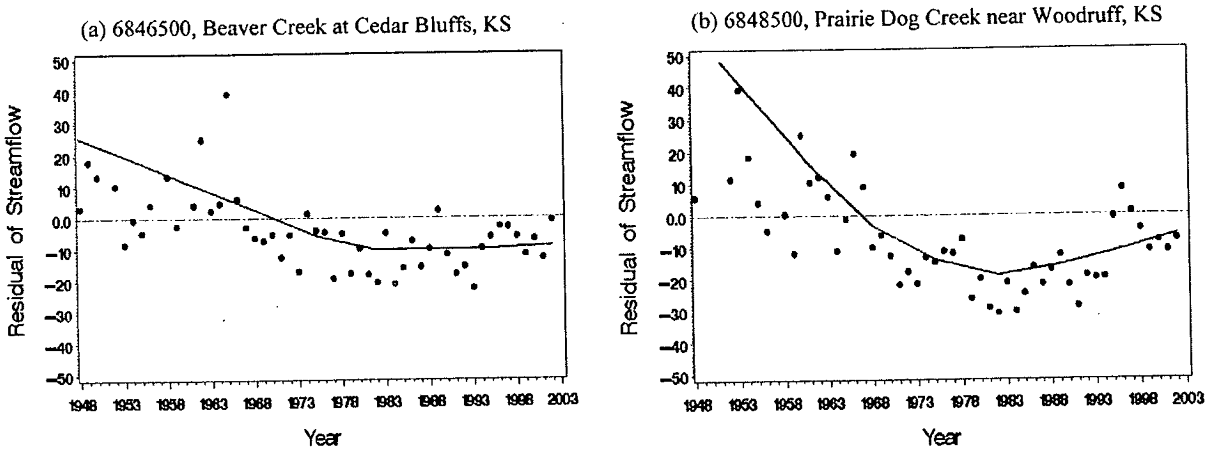

6844500, Republican River at Orleans, NE.

**Figure 10** Trend of streamflow residuals for the gauging stations in Harlan County in the Republican River basin.

weather stations were used in the analysis. The LOESS regression curve displays a continuous decrease of streamflow residuals with the biggest negative slope being 2.077 ft$^3$ s$^{-1}$/yr. Fig. 10 shows the graph representing the gauge (6844500 for the Republican River near Orleans) located in Harlan County, Nebraska, where three weather stations were available. This graph exhibits a continuous downward trend. Gauge 6844500 had the second biggest decrease rate of streamflow residuals, 1.708 ft$^3$ s$^{-1}$/yr.

Fig. 11 shows the graphs representing streamflow residuals of two gauging stations located in two counties in Kansas, where two weather stations were chosen for computing the average annual precipitation. They represent gauge 6846500 for Beaver Creek at Cedar Bluff, and 6848500 for Prairie Dog Creek near Woodruff, respectively. These two showed downward trends, with the different streamflow depletion displayed in Table 3. One cannot say that the streamflow depletion in Kansas did not contribute to the depletion in the Republican River basin.

Fig. 12 shows historical groundwater levels for three observation wells, which are located in Chase County, Nebraska, Sherman County, Kansas, and Yuma County, Colorado, respectively. These wells are constructed in the Ogallala Formation. The observation well (USGS403220101384001) in Chase County, Nebraska, is located within the watershed of Frenchman Creek. It is 43.6 m deep and is about 5 km from this creek. As shown in Fig. 12, the decline of the water table began in the mid-1960s and has continued since then. A major decline of the water table at the well in Yuma County, Colorado (USGS401105102061101) (Fig. 12) began around 1968. This well is about 28 m deep and approximately 30 km from North Fork of the Republican River. The water table at this well was about 15 m deeper in 2003 compared to that in 1968. The well in Sherman County, Kansas (USGS391454101490901) is 73.8 m deep and around 10 km from the Beaver Creek. The curve for this well shows that the water table declined about 12 m between 1964 and 1980 and the water table continued declining after 1980 but at a smaller rate. Based on the Spearmen coefficient, the depth to the water table at USGS403220101384001 and the baseflow (approximated by the local precipitation-adjusted discharge) at gauge 6835500 for Frenchman Creek at Culbertson (Fig. 7b) had a significant negative correlation



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

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

**Figure 11** Trend of streamflow residuals for the gauging stations located in Kansas in the Republican River basin.

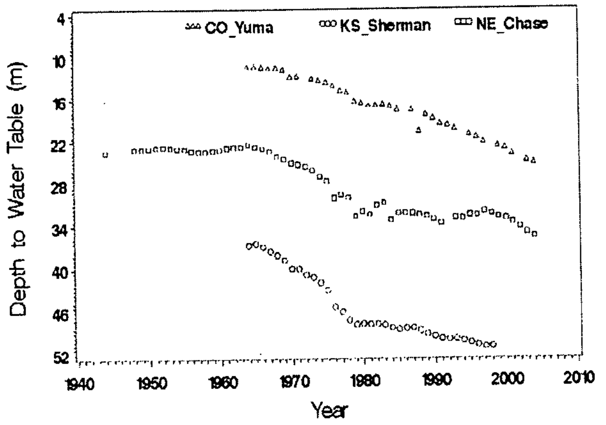


**Figure 12** Historical records of groundwater levels from three observation wells in Yuma County, Colorado, Sherman County, Kansas, and Chase County, Nebraska, respectively, in the Republican River Basin.

(−0.906). Burt et al. (2002) conducted a regression analysis that showed a strong correlation between the streamflow from gauge 6835500 and a number of irrigation wells in the Frenchman Creek basin area, mainly, in Chase County.

## Conclusions

Of 110 gauging stations in Nebraska, 28 were detected with decreasing streamflow. The temporal streamflow trends showed a spatial tendency: the greatest streamflow decrease occurred in western Nebraska. For the eight main basins, the Loup River and Niobrara River basins had not only decreasing but increasing trends scattered upstream or downstream; the Big/Little Blue rivers, the Elkhorn River, the Big/Little Nemaha rivers and the Missouri River basins had neither decreasing nor increasing streamflow; the Platte River and the Republican River basins had only decreasing trends. For the Platte River basin, four gauging stations were detected with decreasing streamflow; for the Republican River basin, there were 20 gauges detected with decreasing streamflow.

As indicated, neither an increasing nor decreasing trend was detected in the annual average precipitation measured from 28 weather stations randomly selected across the state. The average high or low temperature was detected without a significant change. Therefore, precipitation and temperature were not primary factors affecting streamflow depletion in Nebraska over the past 50 years. However, groundwater withdrawal, such as pumping of irrigation wells or other land uses, was a factor leading to the changes in the spatial pattern of temporal streamflow trend.

The trend analyses for all the gauging stations were also conducted using the data of a 10-year period, as well as multiple-decade periods: 1960–2003, 1970–2003, 1980–2003. The Republican River basin had the biggest tendency in streamflow decreases; it started at seven stations in the 1970s, and occurred at more stations in later decades. The Platte River basin is the biggest drainage area in Nebraska, and it showed the second largest number of decreasing streamflow trends starting in the 1950s to 1990s. For the Loup River basin, six out of 14 stations were observed with increasing trends in the period of 1970–2003, even though a decreasing streamflow trend was detected from five gauges in the 1960s.

The local precipitation-adjusted discharge was generated to approximate the baseflow and further analysis was conducted to quantify a decreasing rate of streamflow residuals in the Republican River basin. The rate of decrease in the precipitation-adjusted discharge was calculated for 12 gauging stations. The largest reduction of baseflow occurred at gauge 6843500 on the Republican River at Cambridge, Furnas County, Nebraska; the estimated rate, based on the LOESS technique, was 2.077 $ft^3\,s^{-1}$/yr. The impact of groundwater on streamflow seemed to begin in the late 1960s and early 1970s in the Republican River basin; during this time, the number of irrigation wells grew rapidly. Besides Nebraska, where groundwater withdrawal resulted in the reduction of streamflow in the Republican River basin, Kansas and Colorado also contributed to groundwater use in the region, which helped cause the depletion.

## Uncited reference

Hirsch et al. (1993).

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