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Evaluation of the impact of groundwater irrigation on streamflow in Nebraska

Fujiang Wen, Xunhong Chen *

School of Natural Resources, 102 Nebraska Hall, University of Nebraska-Lincoln, Lincoln, NE 68588-0152, United States

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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 Besides Nebraska, where a significant amount of groundwater was withdrawn from the High Plains regional aquifer, irrigators in Kansas and Colorado were the other likely contributors to streamflow depletion in the Republican River.
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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

* Corresponding author. Tel.: +1 402 472 0772; fax: +1 402 472 4608.
E-mail address: xchen2@unl.edu (X. Chen).

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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

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