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GEOLOGICAL AND CLIMATIC CONTROLS ON STREAMFLOWS IN THE NEBRASKA SAND HILLS[1]

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ABSTRACT: This paper presents hydrological characteristics of the streamflow of the Dismal, Middle Loup, North Loup, and Cedar Rivers in the Nebraska Sand Hills and their relation to climate and ground water variation. Time series of streamflow, precipitation, temperature, and ground water levels from 1976 to 1998 were used to analyze trends and fluctuations of streamflow and to determine relationships among streamflow, climate, and the ground water system. An increase of precipitation and a decrease of maximum temperature over the period resulted in higher ground water levels and increased streamflow in the region. The high permeability of the soil and the thick unsaturated zone enhance precipitation recharge, limit surface runoff, and prevent ground water losses through evapotranspiration. Thus, an abundance of ground water is stored, supplying more than 86 percent of streamflow in the four rivers. Streamflow is generally more constant in the Sand Hills than elsewhere in the region. The four rivers present different hydrologic characteristics because of the spatial heterogeneity in hydrogeologic conditions. Streamflow of the Dismal and Middle Rivers, which are less sensitive to climatic variation, is much steadier than that of the North Loup and Cedar Rivers.
(KEY TERMS: Sand Hills; streamflow fluctuation; climate variation; ground water accumulation; statistical analysis; hydrogeology.)

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INTRODUCTION

The Nebraska Sand Hills, approximately 49,965 km^2 of sand dunes stretching 426 km across Nebraska and into South Dakota, is the largest sand dune area in the Western Hemisphere and one of the largest grass stabilized dune areas in the world (Figure 1). Given the limited precipitation associated with subhumid to semiarid climates and the high potential evapotranspiration rates found in the Sand Hills, one would think that the availability of water in the region would be low. Yet, there is sufficient water to maintain a grass cover on the dunes, supply numerous lakes and wetlands, and recharge a ground water system. The highly permeable soils of the sand dunes limit runoff, enhance infiltration, and allow the accumulation of a substantial ground water reservoir that holds about half of all the ground water found in Nebraska (Bleed, 1989).

This ground water contributes significantly to the rivers in the Sand Hills. As a result, these rivers differ in several respects from most other rivers in Nebraska, and for that matter, in the world. Not only do they appear to have had a unique origin, but they have few tributaries and flow at a remarkably steady rate (Bentall, 1989). Bentall (1989) compared Mud Creek, which is wholly outside the region but near its border, with the Dismal River, whose full length is within the Sand Hills. The ratio of maximum to minimum mean monthly discharge is 2.71 for Mud Creek but only 1.19 for the Dismal River. Nevertheless, for the rivers within the Sand Hills, each has its own hydrologic characteristics resulting from the spatial heterogeneity of topography, climate, and geology. In the west central Sand Hills, where there is a high proportion of ground water input to streams, rivers are often narrow with steep gradients; their flow normally is steady, typically lasting a few weeks during

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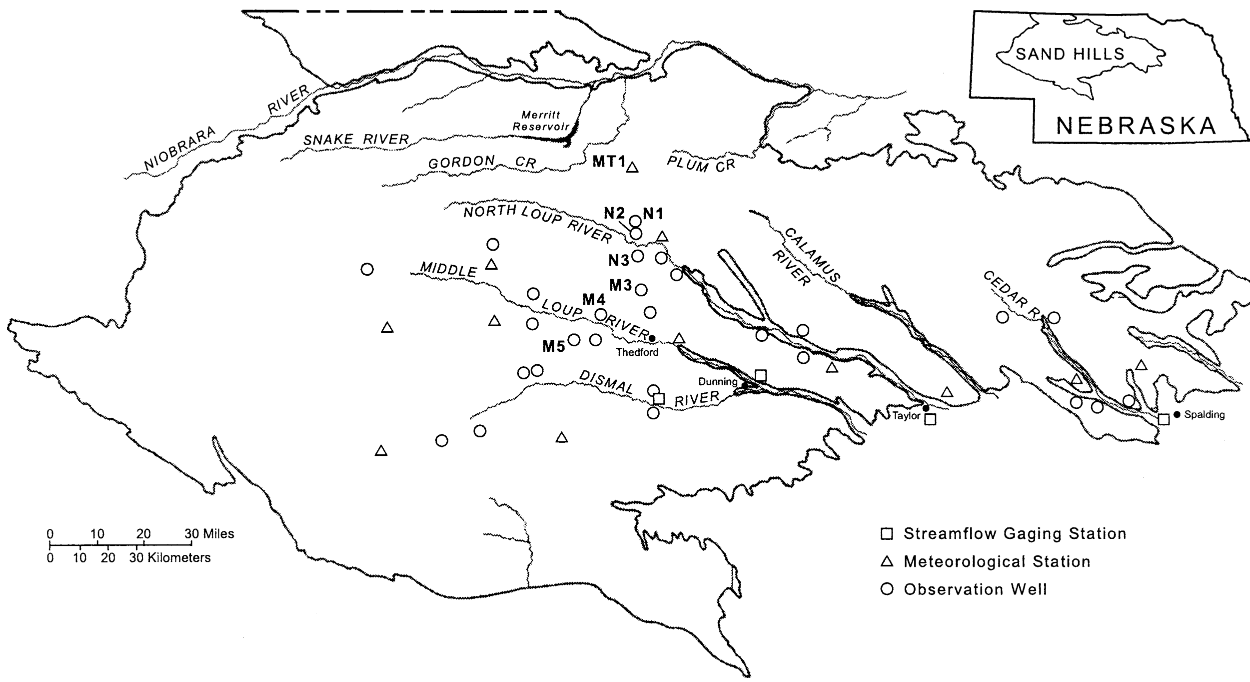

Figure 1. Location Map Showing the Rivers, Gauging Stations, Meteorological Stations, and Ground Water Observation Wells in the Nebraska Sand Hills.

rainless periods but slowly decreasing in the case of an extended dry period. In contrast, rivers are wide and shallow in the eastern Sand Hills, where ground water contributes a lower percentage of total streamflow. Streamflow in these rivers usually shows more seasonal fluctuation.

Comprehensive information about the hydrologic condition of the Sand Hills is provided in *An Atlas of the Sand Hills* (Bleed and Flowerday, 1989), a compilation of work on the regional climate, geology, soils, ground water, streams, lakes and wetlands, and mineral resources. One contribution (Bentall, 1989) summarizes the general characteristics of the stream systems in the Sand Hills using data collected before 1985. Other hydrologic studies of the Sand Hills include Winter (1986), LaBaugh (1986), Church (1996), and Gosselin *et al.* (1994), which focus on the interactions between ground water and lakes in the Sand Hills. Drda (1998) used a conceptual hydrological model to identify the factors responsible for the hydrological regime in two neighboring interdunal valleys in the Sand Hills. One is a wet meadow drained by a human made ditch, and the other is topographically lower but dry at the surface. Bentall and Hamer (1980) described the stream aquifer relationships in Nebraska and the importance of stream reaches in maintaining ground water supplies for irrigation, municipal well fields, and industrial use.

A rise in the ground water table and a consequent streamflow increase in the Sand Hills have taken place since the mid-1970s. These changes have significantly affected the water supply and environment in the region, including such features as lake area, wetland extent, and vegetation growth. The purpose of this study is to evaluate the role of the ground water system in maintaining the relatively steady streamflow and to analyze the influence of climate variation on the surface water and ground water systems in the Sand Hills. Four rivers, the Dismal, Middle Loup, North Loup, and Cedar, were selected for statistical analysis of the temporal and regional characteristics of streamflow between 1976 and 1998. The sensitivities of streamflow in these rivers to variations in climate and ground water systems were evaluated. The percentage of ground water contribution to the streamflow in each of the four rivers and the increased availability of water resources between 1976 and 1998 also were estimated.

REGIONAL HYDROLOGY

Streams

Six major rivers originate in the Sand Hills: the Dismal, Middle Loup, North Loup, Calamus, Cedar, and Snake (Figure 1). They are located mostly in the central and eastern parts of the region. Much of the western third of the Sand Hills lacks streams and is referred to as the "closed basins area," where a great number of small, shallow lakes and wetlands occur. Of the six rivers, four were selected for this study – the Dismal, Middle Loup, North Loup, and Cedar. The Snake and Calamus Rivers were not included in this study because their streamflows were affected by reservoir regulation. Figure 1 shows the locations of the streamflow gauging stations. Table 1 summarizes the drainage areas and streamflow characteristics of the four unregulated rivers. The total drainage area of the four rivers represents about one-third of the Sand Hills area. Daily streamflow data have been collected by the U.S. Geological Survey from 1976 to 1994 at the gauging station of the Cedar River and from 1976 to 1998 at the gauging stations for the other three rivers.

Aquifer Systems

The sand dunes constitute the major part of the vadose zone in the Sand Hills. The thickness of the vadose zone in the study area shows significant spatial variation. The mean depth to ground water in October 1986 in the drainage areas of the Dismal, Middle Loup, North Loup, and Cedar Rivers was calculated to be 15.5 m, 15.0 m, 7.2 m, and 9.1 m, respectively. The dominant vegetation on the sand dunes is prairie grass, which helps reduce surface runoff and soil erosion. The Dismal and Middle Loup Rivers are located in the center of the Sand Hills; the thickness of the unsaturated zone is up to 122 m, and shallow ground water exists only in the interdunal valleys. A large portion of the North Loup River and the entire Cedar River are located in the eastern part of the Sand Hills, where the thickness of the unsaturated zones is significantly less. Furthermore, in these two basins, surface runoff often occurs during rainfall periods, as the soil in this part of the Sand Hills is quickly saturated.

The Ogallala Group is a principal aquifer in the Sand Hills; it consists of sand, gravel, silt/clay, and sandstone. The major water bearing zones also include overlying unconsolidated alluvial sand and silt ranging from 15 m to 60 m in thickness. This unit is beneath the highly permeable unsaturated sand dunes. The aquifer thickness exhibits strong spatial variation in the region, with a maximum thickness of more than 305 m in the west central Sand Hills and decreasing toward the Sand Hills boundary. The average thickness of the aquifer is about 168 m, yielding a large volume of porous material for ground water storage.

There are about 700 observation wells in the Sand Hills at which ground water levels have been collected once or twice per year. Some of these well records extend back to the 1930s and most wells have been monitored since the mid-1970s. Ground water levels in the Sand Hills are high in the west and low in the east. Accordingly, ground water flows from the west to the east, discharging into rivers in the central and eastern regions.

Climate Conditions

The broad climate pattern, from subhumid in the east to semiarid in the west, is characteristic of the region. Precipitation in the Sand Hills ranges from an average annual total of 680 mm in the east to 550 mm

TABLE 1. Basic Statistical Results of Monthly Streamflow of the Four Rivers.

	Dismal River (1976 to 1998)	**Middle Loup River (1976 to 1998)**	**North Loup River (1976 to 1998)**	**Cedar River (1976 to 1994)**
Drainage Area (km^2)	2501	4737	6081	1684
Means (10^6 m^3)	15.35	33.32	39.04	13.80
Standard Deviation (10^6 m^3)	1.17	3.34	10.38	4.63
Minimum (10^6 m^3)	12.72	25.00	11.84	7.14
Maximum (10^6 m^3)	18.67	44.74	85.54	45.53
Ranges (10^6 m^3)	5.95	19.74	73.70	38.39
LM (10^6 m^3)	15.22	32.92	37.83	13.21
UM (10^6 m^3)	15.49	33.72	40.25	14.40
UM/LM	1.018	1.024	1.064	1.090
CV	0.076	0.1	0.266	0.336

Note: The drainage areas for the Dismal, Middle Loup, and North Loup Rivers is from USGS (2001), and the drainage area for the Cedar River is estimated according to a digital elevation model (DEM) with 30 m resolution.

in the west. Approximately 70 percent of the average annual precipitation occurs during the spring and summer. The mean annual maximum and minimum temperatures are 15.6°C and 2.5°C, respectively. The mean temperature in summer ranges from 15°C to 25°C. Average winter temperature in the region from October to March is about 0°C. Potential evaporation, similar to the seasonal pattern of rainfall, increases during the growing season, usually exceeding precipitation, and reaches a maximum in July. In winter, evapotranspiration is very small, and precipitation is usually in the form of snow. Snowmelt becomes a main source of ground water and streamflow. The thickness of the unsaturated zone coupled with high permeability in the Sand Hills, particularly in the Dismal and Middle Loup regions, not only is beneficial for precipitation infiltration but also prevents much ground water loss by evapotranspiration, and therefore is beneficial for net recharge of ground water systems.

Twelve meteorological observation stations and one special station with evapotranspiration data (MT1) within the Sand Hills were selected for this study (Figure 1). The data from meteorological stations near each river were used to calculate area averaged precipitation, and maximum and minimum temperature in the drainage area of the river.

STREAMFLOW

Steadiness

A previous study (Bentall, 1989) indicates that rivers in the Sand Hills are noted for their nearly constant discharge. However, monthly discharge for each of the four rivers has had an increasing tendency since 1976 (Figure 2). Although the streamflow of the Dismal River is close to that of the Cedar River, and the streamflow of the Middle Loup River is close to that of the North Loup River, the streamflow of the Dismal and Middle Loup Rivers is much steadier than that of the North Loup and Cedar Rivers.

Table 1 lists the basic statistical features of mean monthly streamflow of the four rivers. The upper mean (UM) and the lower mean (LM) are the upper and the lower 95 percent confidence limits on the mean monthly streamflow (assuming normality), respectively. The ratio UM/LM indicates the relative magnitude of streamflow fluctuations; and the coefficient of variation (CV) indicates the relative variation of streamflow departures from the mean discharge. These two indices are much smaller for the Dismal and Middle Loup Rivers than those for the North Loup and Cedar Rivers, which confirms that the streamflow of the Dismal and Middle Loup Rivers is much steadier than that of the other rivers.

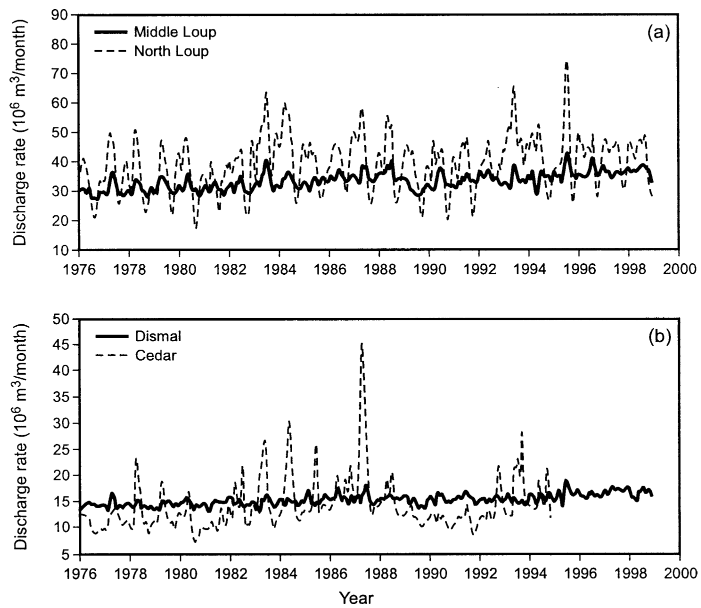

Figure 2. Monthly Streamflow of (a) the Middle and North Loup Rivers, and (b) the Dismal and Cedar Rivers.

Temporal Trend

Annual streamflow data from 1976 to 1998 were used to analyze for trends in annual streamflow for the four rivers. The annual discharge of the Cedar River from 1995 to 1998, due to a lack of data, is extrapolated through the established linear relationship of annual discharge between the Cedar River and the North Loup River using data from 1976 to 1994 (R^2 = 0.73). The trend of the annual discharge from 1976 to 1998 was tested using a first-order autoregressive error model to eliminate autocorrelation of model residuals. The maximum likelihood (ML) method was applied to estimate the model parameters using the SAS® AUTOREG procedure.

The trends for the Dismal, Middle Loup and North Loup have slopes different from zero at the significance level α = 0.05 (Figures 3a, 3b, and 3c). The mean increase in annual streamflow (MIS or slope in Figure 3) of the four rivers is listed in Table 2. Values of relative increase in discharge (RIQ) and relative increase in discharge in percent (RIP) for the four rivers are also shown in this table. RIQ is the MIS divided by mean annual discharge, $\overline{Q}_{1976\text{-}1998}$, providing a measure of the relative increase in streamflow per year. RIP is the relative increase between 1976

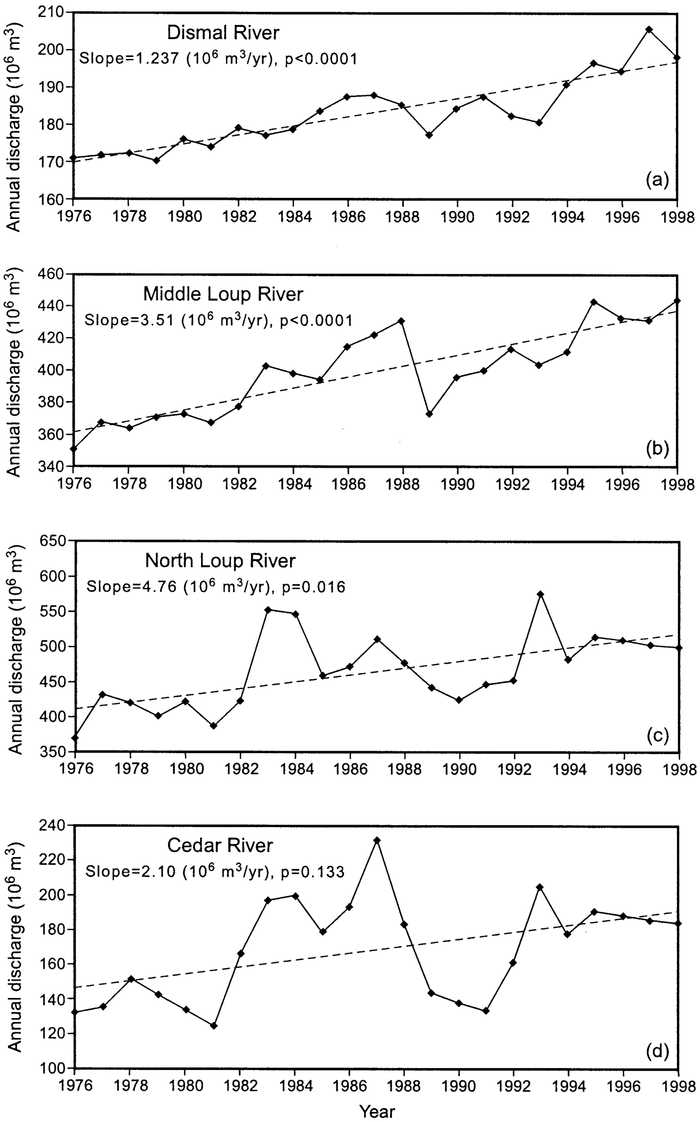

Figure 3. Annual Streamflow and Linear Regression Line of (a) Dismal River, (b) Middle Loup River, (c) North Loup River, and (d) Cedar River.

TABLE 2. Mean Annual Streamflow and Its Increase for the Four Rivers.

	Dismal	Middle Loup	North Loup	Cedar
$\bar{Q}_{1976-1998}$ (10^6 m^3/yr)	183.5	399.4	466.1	168.5
MIS (10^6 m^3/yr)	1.24	3.51	4.76	2.10
RIQ (percent)	0.67	0.88	1.02	1.25
$\bar{Q}_{1976-1980}$ (10^6 m^3/yr)	172.6	365.3	408.8	138.9
$\bar{Q}_{1994-1998}$ (10^6 m^3/yr)	197.4	432.8	501.2	185.2
RIP (percent)	14.4	18.5	22.6	33.3

and 1980 and 1994 and 1998 as a percentage of mean annual discharge and is calculated from ($\bar{Q}_{1994-1998}$ - $\bar{Q}_{1976-1980}$) / $\bar{Q}_{1976-1980}$. These results indicate greater streamflow increases for the river basins located in the eastern part of the Sand Hills.

Fluctuation and Seasonal Cycle

The variation in streamflow around the trend lines in Figure 3 shows the fluctuation of the annual streamflow of all four rivers. Residual series, the differences between the observed values and the trend component in a corresponding year, were calculated to analyze the deviation from the expected value in the streamflow series. A comparison of the relative deviation among the four rivers was made using the relative discharge residual (REQ) given as

$$REQ = \frac{Q - Q_{tr}}{\bar{Q}} \tag{1}$$

where Q is observed annual discharge, Q_{tr} is its trend component in a corresponding year and $\bar{Q}$ is its mean value over the period analyzed.

If the trend component is considered to be the expected streamflow in a given year, a negative REQ indicates that the river received relatively less inflow in that year and its streamflow was lower than the expected value; a positive REQ indicates the opposite. Table 3 lists calculated results of mean and minimum REQ of the four rivers in dry periods: 1980 to 1981 and 1989 to 1991, and mean and maximum in wet periods: 1982 to 1988 and 1992 to 1995. The results show that the absolute value of mean and maximum or minimum REQ for the Dismal and Middle Loup Rivers is much smaller than that for the North Loup and Cedar Rivers in the four periods, indicating less fluctuation and easier recovery to their expected streamflow after extremely wet years or extremely dry years. For the first three periods, the sign of the deviation is the same for all four rivers, but during 1992 to 1995, the mean value of REQ is negative for the Dismal and Middle Loup Rivers and positive for the North Loup and Cedar Rivers. In addition, after the extremely dry year of 1989, the streamflow of the Dismal River and the Middle Loup River recovered until 1991 and 1992, respectively, and then decreased through 1993, while the streamflow of the North Loup River and the Cedar River continued to decrease until 1990 and 1991, respectively, and then increased through 1993 before falling to near the expected levels (Figure 3).

The seasonal cycle of streamflow for the four rivers was analyzed based on mean monthly streamflow

TABLE 3. Relative Change Between Observed Annual Discharge and Its Trend Component.

Period	REQ	Dismal	Middle Loup	North Loup	Cedar
1980 to 1981	Mean (percent)	-0.05	-1.7	-6.6	-15.7
	Minimum (percent)	-0.9	-2.7	-10.8	-19.0
	Year of Minimum	1981	1981	1981	1981
1989 to 1991	Mean (percent)	-2.0	-5.0	-9.0	-21.6
	Minimum (percent)	-4.5	-8.3	-11.7	-25.7
	Year of Minimum	1989	1989	1990	1991
1982 to 1988	Mean (percent)	1.1	3.4	7.5	16.8
	Maximum (percent)	3.1	7.1	22.6	37.6
	Year of Maximum	1986	1988	1983	1987
1992 to 1995	Mean (percent)	-2.0	-0.9	2.0	1.2
	Maximum (percent)	1.9	4.0	17.4	14.4
	Year of Maximum	1995	1995	1993	1993

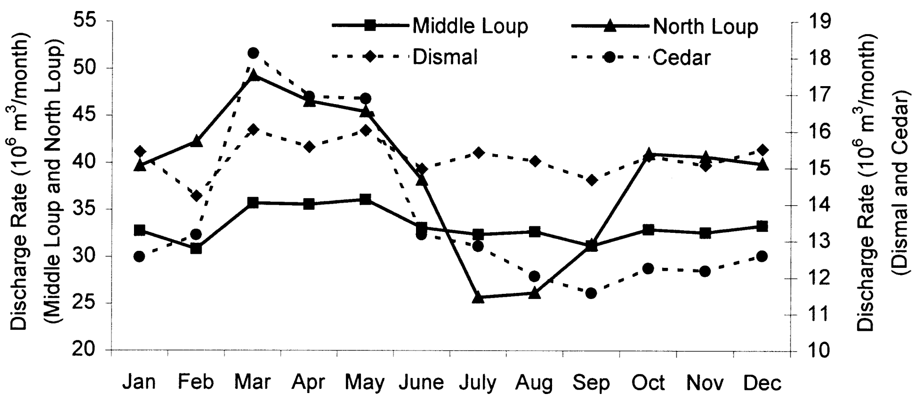

Figure 4. Seasonal Variation of Streamflow of the Middle Loup, North Loup, Dismal, and Cedar Rivers.

(Figure 4). The average seasonal cycle of streamflow of the four rivers is similar, with streamflow being higher from March through May and lower from July through September. Figures 2 and 4, and the values of CV in Table 1 suggest that the seasonal cycle of the North Loup and Cedar Rivers is greater than that of the other two rivers.

EFFECT OF CLIMATE ON STREAMFLOW

Figure 5 shows the annual precipitation in the Sand Hills and a five-year moving average for the period 1976 to 1998. The mean annual precipitation is 664 mm, with the highest annual total (848 mm) in 1998 and the lowest (376 mm) in 1989. Generally, successive wet years occur in three periods: during 1977 to 1979 with a mean annual precipitation of 755 mm, during 1982 to 1988 with a mean of 699 mm and during 1992 to 1995 with a mean of 810 mm; and successive dry years in two periods: during 1980 to 1981 with a mean annual precipitation of 458 mm and during 1989 to 1991 with a mean of 501 mm. The fluctuations of streamflow in Figure 3 and the values of REQ in Table 3 generally correspond to these wet and dry periods.

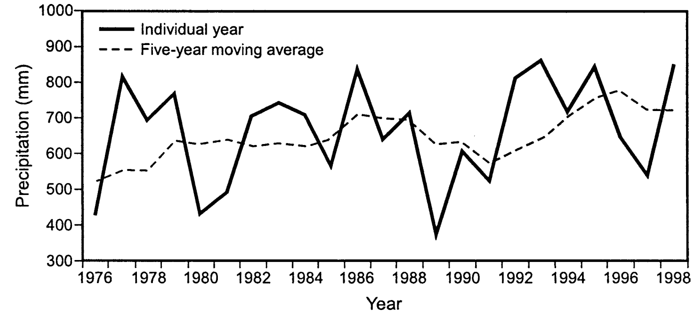

Figure 5. Annual Precipitation and Five-Year Moving Average in the Sand Hills.

The moving average of annual precipitation demonstrates a trend of increasing precipitation during 1976 to 1998. The precipitation from 1994 to 1998 was about 15 percent more than that from 1976 to 1980.

The variations of annual mean maximum and minimum temperature and their five-year moving averages are shown in Figure 6. For the period 1976 to 1998, the mean maximum temperature is 15.6°C, with lower temperature in wet periods: 14.9°C during 1977 to 1979, 15.0°C during 1982 to 1985, and 14.5°C during 1992 to 1996. The highest temperature was in a dry period: 17.2°C during 1980 to 1981. However, there are exceptions, such as an extremely wet year (1986) with a higher mean maximum temperature and an extremely dry year (1989) with a slightly lower mean maximum temperature. The five-year moving averages of the two temperature series indicate that annual mean maximum temperature decreases during 1978 to 1998, and that this decreasing trend has become more evident since 1990 but that there is no trend for annual mean minimum temperature. The increase in annual precipitation and the decrease in annual mean maximum temperature suggest that more water is available for recharging the ground water and stream systems in the study area. The trends of increasing streamflow are in agreement with these climatic trends.

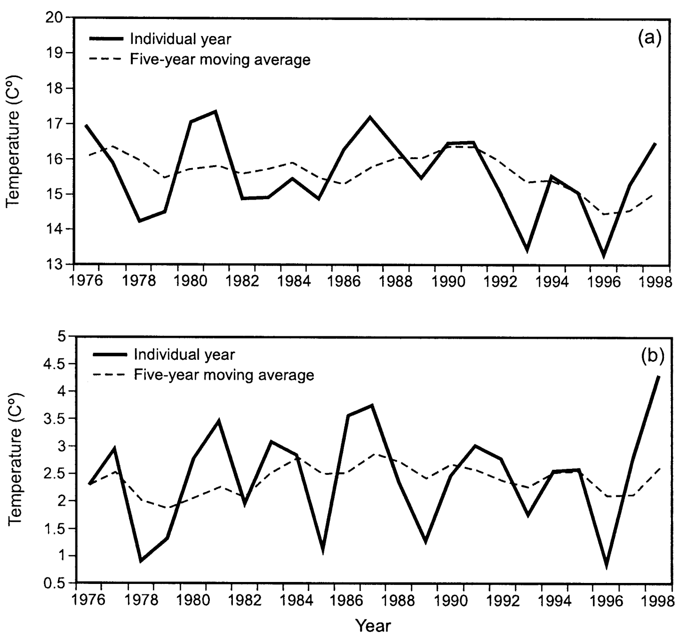

Figure 6. (a) Annual Mean Maximum Temperature and Five-Year Moving Average, and (b) Annual Mean Minimum Temperature and Five-Year Moving Average in the Sand Hills.

Seasonality in climate and its influence on streamflow during 1976 to 1998 was analyzed using mean monthly precipitation and mean monthly potential evapotranspiration. During the growing season (April to October), potential evapotranspiration is very large and reaches a maximum in July (Figure 7). Rainfall does not meet the demand for soil evaporation and plant transpiration during the growing season, even though most of the annual precipitation falls in this period. Therefore, the Sand Hills have a water deficiency period. In contrast, evapotranspiration in winter months and early spring is negligible or less than precipitation. Precipitation in this period is the main source of ground water recharge. The largest amount of aquifer recharge occurs in the early spring when snow melts as the temperature increases. This recharge results in higher river discharge during this period (see Figure 4).

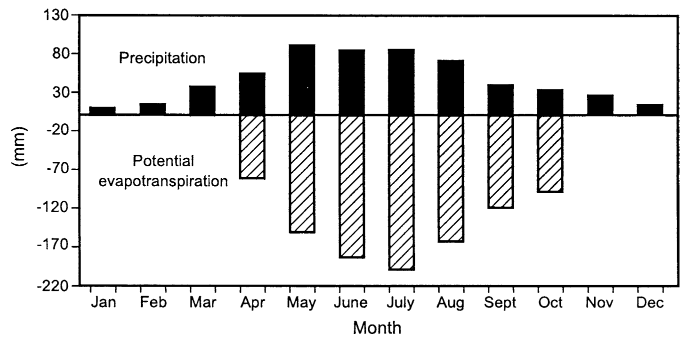

Figure 7. Average Monthly Precipitation and Potential Evapotranspiration in the Sand Hills.

Although the streamflow variations generally correspond to the climate variations when both are averaged over several years or longer, the correlation between the changes in streamflow and in climate is not well established at shorter time scales, such as a year or less. Table 4 shows that the correlation between annual precipitation or annual mean temperature and annual streamflow is low and that climate's influence on streamflow variation is not significant at $\alpha = 0.05$. Tables 2 and 5 also demonstrate that the differences in the magnitude of streamflow fluctuations for the four rivers are not caused by climatic variations. Precipitation in the Cedar and North Loup catchments is greater than that in the Middle Loup and Dismal catchments. Annual mean maximum and minimum temperature are slightly lower in the Middle Loup and North Loup catchments. However, the ratio of the upper mean to the lower mean (UM/LM) and CV of monthly precipitation indicate that the relative magnitude of precipitation fluctuations in the

TABLE 4. Correlation Coefficients Between Annual Precipitation P, Annual Mean Temperature T, and Annual Streamflow Q.

	Dismal River		Middle Loup River		North Loup River		Cedar River	
Correlation	P ~ Q	T ~ Q	P ~ Q	T ~ Q	P ~ Q	T ~ Q	P ~ Q	T ~ Q
r	0.09	0.02	0.13	0.07	0.21	0.40	0.21	0.32
p-Value	0.67	0.94	0.56	0.74	0.34	0.06	0.34	0.14

TABLE 5. Climatic Conditions in the Four Areas.

	Precipitation					Temperature	
	Monthly				Annual	Annual Mean Maximum Temperature	Annual Mean Minimum Temperature
	LM (mm)	UM (mm)	UM/LM	CV	Mean (mm)	(˚C)	(˚C)
Dismal River	39.1	47.8	1.224	0.866	561	16.36	1.25
Middle Loup River	38.7	47.1	1.215	0.838	570	16.25	1.15
North Loup River	44.1	53.5	1.215	0.836	646	16.14	0.21
Cedar River	50.2	60.9	1.214	0.834	735	16.46	1.87

four basins is nearly the same. Thus, the different streamflow characteristics of the four rivers are likely caused primarily by the spatial variation of the unsaturated and saturated zones of the aquifer system, which discharges ground water to the rivers.

RELATION BETWEEN GROUND WATER AND STREAMFLOW

In the Sand Hills, the high permeability of the topsoil and sand dunes permits rapid infiltration of precipitation, some of which recharges the ground water. Surface water occurs only in those limited areas where the ground water level intercepts the ground surface. Therefore streamflow variation in the Sand Hills is considered to be closely related to variations of the ground water system.

Contribution of Ground Water to Streamflow

Bentall (1989) estimated the volume of ground water discharge to rivers according to streamflow in November since November discharges are the least likely to be affected by freezing weather, evaporation, precipitation, or transpiration. The average of normal November discharges (excluding any that were excessively small or large) is considered a conservative measure of the percentage of ground water in average annual discharge. But, using this method, the calculated percentages of ground water in the streamflow of the four rivers were greater than 100 percent for most years if monthly streamflow data from 1976 to 1998 were used. Therefore, the average of the normal November discharges could not truly represent the mean monthly contribution of ground water to streamflow from 1976 to 1998. Considering that surface runoff still exists in the November discharges, we used a hydrograph component separation approach (Kresic, 1997) to estimate the base flow from the daily streamflow in November 1987, a normal precipitation year. Then a percentage of base flow contribution to streamflow (PB) in November was calculated. Lastly, the multiyear mean percentage contribution of ground water to a river (PG) could be determined as

$$PG = \frac{1}{N} PB \sum_{i=1}^{N} \frac{Q_{11i} * 12}{Q_i} \tag{2}$$

where Q_{11i} is the discharge in November and Q_i is the annual discharge in the ith year, and N is the total years of the calculation.

The calculated percentage contributions of ground water (PG) in the Dismal, Middle Loup, North Loup and Cedar Rivers were 98, 95, 87, and 86 percent, respectively, according to the monthly discharges of the Cedar River from 1976 to 1994 and the other three rivers from 1976 to 1998. Therefore, the main source of streamflow in this area is ground water, but its contribution to the streamflow of the Dismal and

Middle Loup Rivers is about 10 percent more than that of the North Loup and Cedar Rivers.

Ground Water Level Versus Streamflow

Ground water level data for 1976 to 1998 from several observation wells in the vicinity of each river were used to calculate the correlation between the depth to ground water in October and the streamflow in a water year (from October of one year through the following September). The results of regression analysis (Table 6) demonstrate that (1) for each of the four rivers, there exists a close relationship between streamflow and ground water levels, which means the magnitude of the streamflow primarily depends on the rise and decline of the ground water levels; and (2) among these four rivers, streamflow of the Dismal River is most closely related to changes in ground water levels. For the other three rivers, the correlation coefficient decreases gradually from west to east, which indicates that the influence of the ground water system on streamflow becomes less significant in the eastern Sand Hills.

TABLE 6. Correlation Coefficients Between the Depth to Ground Water in October and the Streamflow in a Hydrologic Year in the Four Regions.

	Dismal River	Middle Loup River	North Loup River	Cedar River
Mean r	0.89	0.75	0.64	0.60
Maximum r	0.90	0.89	0.79	0.82
Minimum r	0.86	0.36	0.26	0.39
No. of Observation Wells	3	5	13	6

Two cross-sections were made to show the hydraulic relationship between the Middle Loup and North Loup Rivers and the adjacent ground water systems (Figure 8). Several of the ground water observation wells are located near the rivers (N1, N2, N3, M3, M4, and M5). Depth to the water table is larger near the Middle Loup River, and the hydraulic gradient of the ground water is steeper toward the river.

Ground water level at all these observation wells rose since 1976 (Figure 9). Moreover, during the period, ground water rise (DH) was proportional to mean depth to ground water (MD). For example, compared with a 0.27 m rise in observation well N3 where MD is only 0.67 m, the ground water table rises 1.88 m in observation well M4 where MD is as large as 23.6 m.

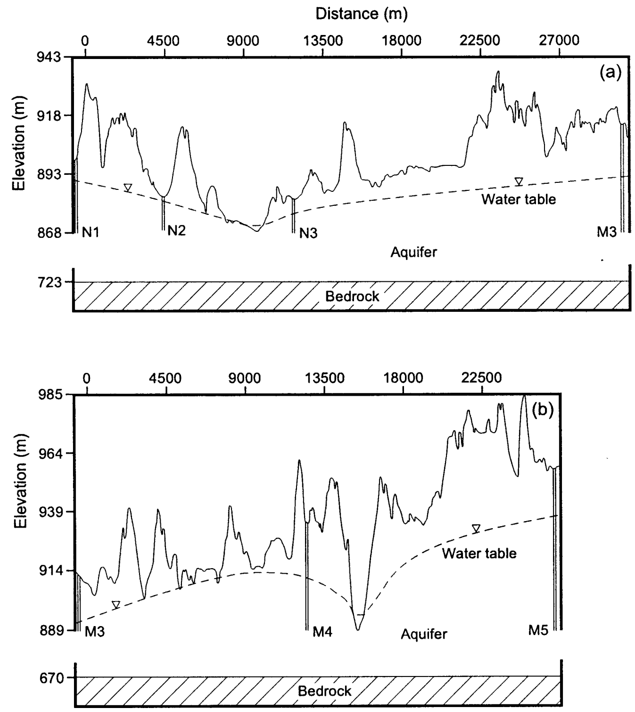

Figure 8. Ground Water Profile (a) Intersecting the North Loup River (wells N1 ,N2, N3, and M3); and (b) intersecting the Middle Loup River (wells M3, M4, and M5).

Furthermore, in the period from the extremely dry year 1989 to the wet year 1993, temporal variations of ground water tables under the thinner vadose zone (N1, N2, and N3) also differ from those under the thicker vadose zone (M3, M4, and M5). Ground water tables at wells N1, N2, and N3 vary accordingly with climatic changes, declining in the dry years 1989 and 1990 and then rising in wet years till 1993. On the contrary, ground water tables at wells M3, M4, and M5 rose during 1989 to 1991, and declined around 1993, a relationship that seems to have little to do with the climatic changes. This difference in water table fluctuations is consistent with the streamflow characteristics of the four rivers after 1989. Because vadose zones in the North Loup and Cedar catchments are thinner, streamflow variations, as well as the ground water table, are relatively sensitive to climate variations. In contrast, the climatic effects on the streamflow and ground water system are damped by the thicker vadose zone for the areas of the Dismal and Middle Loup Rivers.

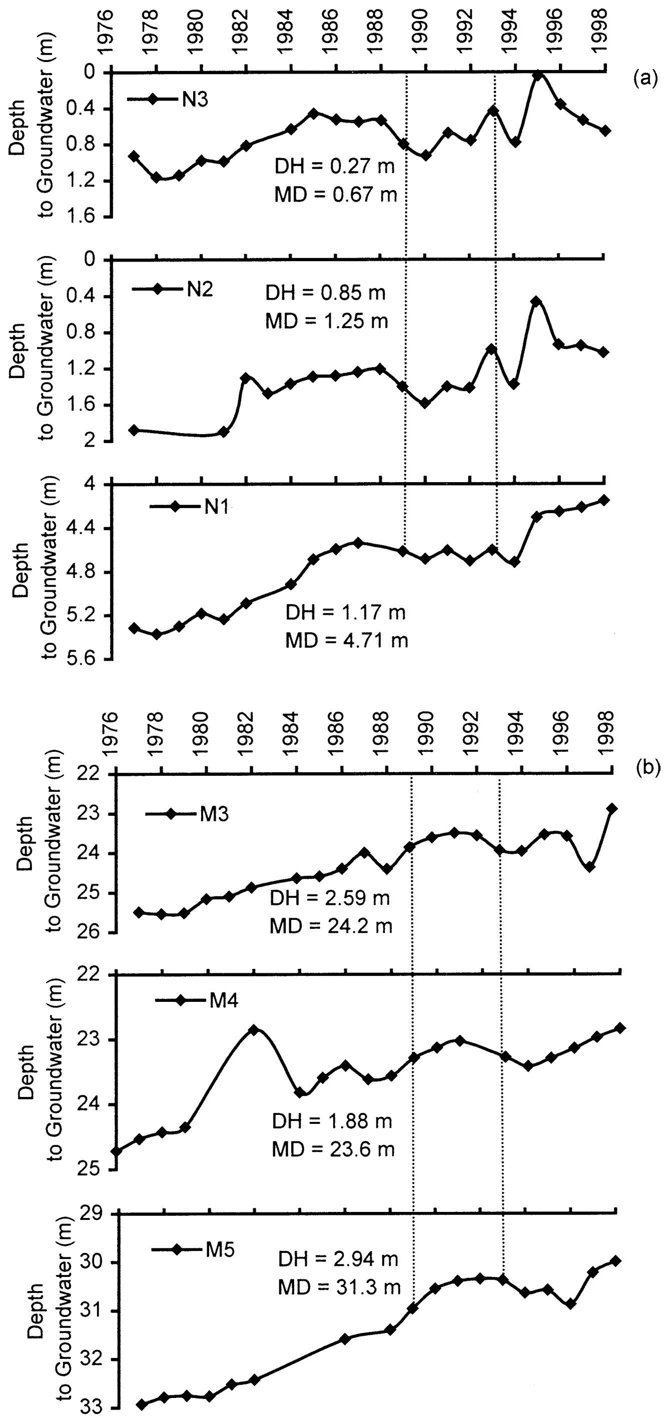

Figure 9. Variation of Depth to Ground Water During 1976 to 1998 at (a) Observation Wells N1, N2, and N3 (North Loup basin); and (b) Observation Wells M3, M4, and M5 (Middle Loup basin). DH is the ground water rise between 1976 and 1998 and MD is the mean depth to ground water in the basin.

CHANGES OF AVAILABLE WATER RESOURCES

Increasing precipitation and a rising ground water table from 1976 to 1998 (Figure 10) resulted in greater available water resources in the Sand Hills. The mean increase of the ground water levels in the whole region is 1.5 m, with the largest increase (greater than 3.0 m) in the vicinity of the Dismal and Middle Loup Rivers and the smallest increase (less than 1.0 m) in the eastern and the western parts of the Sand Hills. Compared with those in October 1976, the average ground water levels of the Dismal, Middle Loup, North Loup, and Cedar Rivers in October 1998 rose 2.1 m, 2.2 m, 1.5 m, and 1.2 m, respectively. Assuming an average specific yield for the aquifer system in the study area of 0.1, the increase in ground water storage from 1976 to 1998 in the Sand Hills was estimated to be about 7,500 million m^3 (Table 7). For each river catchment, the increase in ground water storage per year for this period is presented in Table 7. The results in Table 7 demonstrate that (1) compared with those of the North Loup and Cedar catchments, the larger rise of ground water levels and smaller RIP (shown in Table 2) in the Dismal and Middle Loup catchments indicate that, as precipitation increased during 1976 to 1998, more water was stored in the aquifer and less was released to the rivers; and (2) for total available water resources (ground water and streamflow), the increase per unit area in the North Loup and Cedar catchments was smaller than that in the Dismal and Middle Loup catchments. The larger aquifer storage capacity provides sufficient room for storage of precipitation recharge, and a thicker vadose zone prevents ground water losses by evapotranspiration. The increased ground water storage and streamflow are beneficial to both surface water and ground water users in the Sand Hills.

CONCLUSIONS

In the Nebraska Sand Hills, because of the high permeability of sand dunes and large aquifer storage, the ground water system plays a key role in the hydrological cycle. Baseflow estimates for the study period indicated that more than 86 percent of streamflow is from ground water. Thus, all four rivers studied have a relatively constant streamflow.

Streamflow variations generally correspond to climate variations when both are averaged over several years or longer, but the correlation between streamflow and climate is not well established at short time

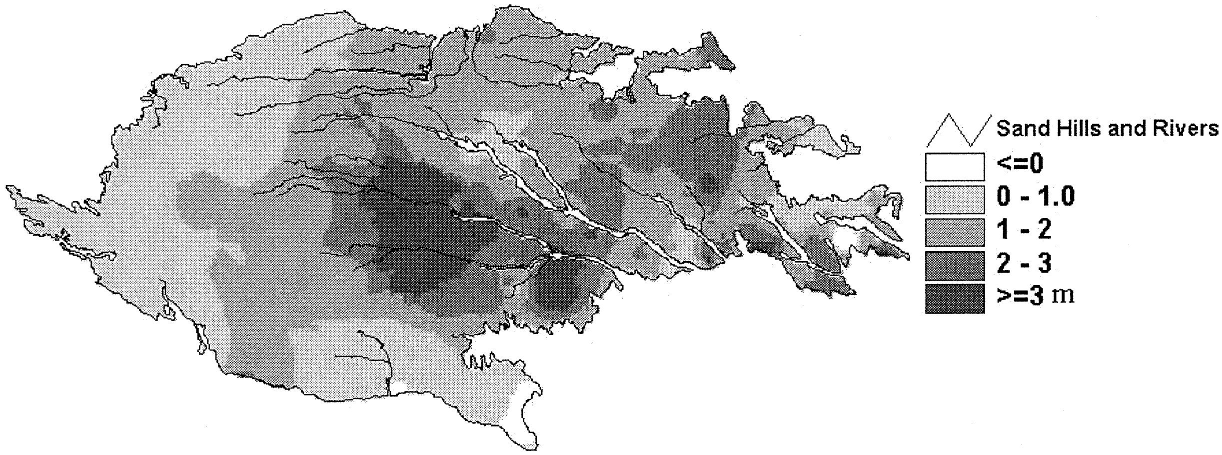

Figure 10. Change in Depth of Ground Water Tables in the Sand Hills Between October 1976 and October 1998.

TABLE 7. Increase in Ground Water Storage, Streamflow, and Available Water Resources Between the Period 1976 and 1998.

	Dismal River	Middle Loup River	North Loup River	Cedar River
Rise of Ground Water Levels Between 1976 and 1998 (m)	2.1	2.2	1.5	1.2
Increase in Ground Water Storage (10^6 m^3/yr)	22.8	45.3	39.9	8.78
Increase in Streamflow ($\bar{Q}_{1994\text{-}1998}$ - $\bar{Q}_{1976\text{-}1980}$) (10^6 m^3/yr)	24.9	67.4	92.4	46.3
Increase of Total Available (10^6 m^3/yr)	47.7	112.8	132.1	55.1
Water Resources (mm/yr)	9.13	9.57	6.52	5.22

scales, such as a year or less. The long term increase of streamflow between 1976 and 1998 is the result of an increase of precipitation and a decrease of maximum temperature. The increased ground water storage and streamflow in recent years has provided more available water resources to surface water and ground water users in this region.

The spatial heterogeneity of the region's hydrogeology also leads to differences in streamflow characteristics. The thicker vadose zone and steeper hydraulic gradient near the Dismal and Middle Loup Rivers result in more than 95 percent of the streamflow coming from ground water. Thus, the streamflow of the Dismal and Middle Loup Rivers is more constant and responds more slowly to climate variations than do the North Loup and Cedar Rivers, where only 86 to 87 percent of streamflow comes from ground water. Near the Dismal and Middle Loup Rivers, the thicker vadose zone also prevents ground water losses from evapotranspiration and the thicker aquifer provides a larger storage capacity, resulting in very efficient transfer of precipitation into ground water, which is beneficial to ground water accumulation.

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