# Hydrological Data Analysis of the Niobrara River

**Final Project Report**

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## 1. Introduction

The Niobrara River that runs from northwest to northeast of Nebraska is primarily a groundwater-fed stream with a basin area of approximately 12,000 $mi^2$. The headwaters of the Niobrara River begin near Lusk, Wyoming, but the portion of the river in Wyoming is incrementally small. The main stem of the river runs east across north central Nebraska with four major tributaries: Snake River, Minnechaduza Creek, Keya Paha River, and Long Pine Creek. The Nebraska Sandhills has a dominant role in the hydrology of the main stem of the basin and the Snake River.

River structures developed for water diversion and power generation may impact hydrologic runoff production and streamflow variability. This is especially critical in groundwater driven streams. While groundwater could buffer streamflow against severe hydrological effects of droughts, lowering of ground water may lead to abrupt drops in baseflow. There are four major man made structures along the Niobrara river that could affect flow: the Mirage Flats Project, Merritt Dam and Reservoir, Cornell Dam, and Spencer Dam. There is growing evidence that infrastructure built in river systems to divert water for agricultural purposes can significantly impact basin hydrology. Changes in crop pattern and irrigation may increase or decrease annual runoff in the river and alter flood frequency and magnitude (Zhang and Schilling, 2006).

While the Niobrara River has experienced significant infrastructure and groundwater developments in the second half of the 20$^{th}$ century, little is known about the influence of these developments on surface hydrology of the basin. Detecting changes in hydrology and understanding their causes and consequences requires a detailed study of the past and present of the climate and hydrology of the Niobrara River system. The objectives of this project include (1) develop a data base for weather variables, drought indices, streamflow, and surface water diversions in the Niobrara River; (2) develop a historical view of basin hydrology and flood frequencies; (3) modify a readily available Nebraska Department of Natural Resources (DNR) Arc-GIS data base with the statistics calculated using the most recent flow data; and (4) develop a simple annual water balance model of the basin.

In this report first archived regional climate, stream flow, and surface water diversions data is described. Then the data is used to examine the hydrology of the Niobrara river basin, including trends in the annual precipitation, runoff, and flood frequencies before and after major water diversions from the river. A simple water-balance model for calculating the annual water budget of the river is developed and used to simulate annual runoff with and without water diversions from the river.

## 2. Data Descriptions

## 2.1. Climate Data

Regional climatology of north eastern and north central Nebraska is documented based upon both modern and paleo climatological records. Two different data types are archived; point data, such as local measurements of weather variables and precipitation from weather stations; and regional data, based on spatial averaging of point measurements. Point data sources are useful for quantifying the spatial variability of climate forcing within a river basin, while the regional averages are useful for examining the impact of climate on river flow, formed by the accumulation of surface and subsurface flow throughout the basin.

### 2.1.1. Regional Data

Regional data we archived included time series of regional averages of the Palmer Drought Severity Index (PDSI), a dimensionless number used as a proxy to describe drought intensity calculated using regional weather variables (Palmer, 1965); minimum, maximum and mean monthly temperature and precipitation; and gieded monthly precipitation fields that cover the entire Niobrara River. All the data archived are provided in different folders in the CD delivered as described below.

To facilitate time-series analysis of regional climate, the National Oceanic and Atmospheric (NOAA) provides spatially averaged monthly data sets for each climatic division in each state of the United States. Monthly data for a climate division is calculated by NOAA by weighing equally all the stations reporting both temperature and precipitation within that division. Historical data for:

1) monthly PDSI, and regional paleo-PDSI (see below for description);
2) annual minimum, maximum, and mean temperatures;
3) precipitation for the instrumented (modern) period (1895-2007),

were downloaded for the Panhandle, North Central, and Northeast climate divisions of Nebraska from the following NOAA website: http://lwf.ncdc.noaa.gov/oa/climate/onlineprod/drought/xmgr.html. From the monthly data, annual averages of PDSI, temperature, and total annual precipitation were calculated.

In addition to the modern PDSI data, recently NOAA developed a website for downloading regional paleo PDSI data (http://www.ncdc.noaa.gov/paleo/newpdsi.html). This data is based on the work of Cook et al. (2004), who reported drought reconstructs based on a number of different methods including lake-bed sediments and tree-ring histories to extend records of past droughts. The spatial data available in the NOAA website was developed by interpolating combined paleo (more than 600 data points within the conterminous US) and the modern (instrumented time period) data into a regular grid structure. These long-term records are useful for placing the modern droughts into a longer time perspective, and evaluating the frequency of the major droughts of the 20th century, such as the 1930s and 1950s, within a longer temporal context. The NOAA Paleo PDSI data was archived at three locations with the following latitude and longitudes: 102.5W, 42.5N (Sheridan county); 100W, 42.5N (Sand Hills region in Brown County); and 97.5W, 42.5N (north eastern Nebraska, near Niobrara-Missouri confluence).

The above mentioned regional climate data are organized in the "*Regional Climate Data*" folder. Within this folder a sub-folder called "*NOAA_PDSI_Temperature_Precipitation*" contains the regional time series of PDSI, precipitation and temperature for the panhandle, north central, and north east climate regions.

We also archived spatially distributed monthly PRISM precipitation data at 30 arcsec (1/120th degree) resolution (http://www.prism.oregonstate.edu/). Regional PRISM data was prepared for basin areas above the Sparks and Verdel gages by spatial clipping the data using watershed boundaries for the basins that drain into these two gages. Because the intention was to use the PRISM data for hydrological analysis, we prepared PRISM data sets for only the duration of the flow records in Sparks (1946-2006) and Verdel (1959-2006) gages. However, for future studies we included full duration of the PRISM data available from 1895 to 2006. Monthly and annual PRISM products (annual is calculated by adding up the monthly precipitation fields) are included in the *PRISM* sub-folder.

### 2.1.2. Weather Station Data

Point data for weather variables were obtained from the High Plains Regional Climate Center (HPRCC) website (http://www.hprcc.unl.edu/). This website allows access to weather data collected by the National Weather Service Cooperative Station Network (NWS/COOP) stations as well as the Automated Weather Data Network (AWDN), administrated by the HPRCC. The weather stations that fall within/vicinity of the Niobrara River Basin were identified by using the interactive map tool available in the HPRCC website (Figure 1). A list of AWDN and NWS/COOP stations located in the study area are given in the Appendix, Table 1 and Table 2 respectively. AWDN stations report daily minimum and maximum temperatures, relative humidity, net radiation, wind speed, precipitation, soil temperature at 4 inches depth, and calculated alfalfa reference evapotranspiration based on a modified Penman-Monteith equation. Weather information reported by the NWS/COOP stations are usually limited to daily precipitation, temperature, and snow depths. NWS/COOP often have longer records than the AWDN. The weather data from these stations are provided in ADWN and NWS/COOP subfolders in the "*Regional_Climate_Data/Weather Stations*" directory.


**Figure 1.** Weather stations in the Niobrara River Basin.

## 2.2. Streamflow Data

Historical flow records, including the discontinued records from the U.S. Geological Survey (USGS) and Nebraska Department of Natural Resources (NDNR) were used in this study (Appendix Table 3). Most of the discontinued data are on the tributaries of the Niobrara River. The long-term gage records are critical to examine the hydrological response of the basin to a fluctuating climate under the stress of growing water diversions. The locations of the streamflow gages used in this study are given in Figure 2. All of the daily streamflow data are provided in the "*Flow Data and Analyses/All Discharge Data*" directory of the CD. This data include both the discontinued and current NDNR and USGS data, as well as combined data from both sources for stations where there is existing and earlier discontinued data. Various statistical analyses conducted using the streamflow data are discussed later.

## 2.3. Streamflow Diversion: Historical Development and Data

There are four major man-made structures along the Niobrara river that may affect the natural course of streamflow: the Mirage Flats Project, the Merritt Dam and Reservoir, Cornell and Spencer dams.

<u>The Mirage Flats Project</u> is a large-scale water storage, diversion, and irrigation project in northwestern Nebraska. The project includes the Box Butte Dam and Reservoir, Dunlap Diversion Dam, Mirage Flats Canal, and the water distribution and drainage system. The Box Butte dam on the

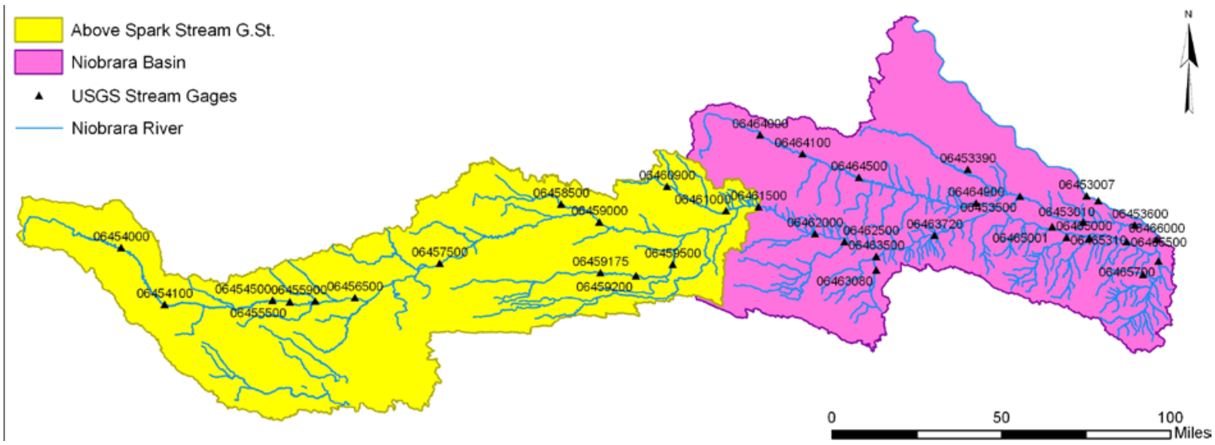



**Figure 2.** The Niobrara River basin with the basin areas above Sparks (yellow region) and Verdel (approximately the entire area) gages.

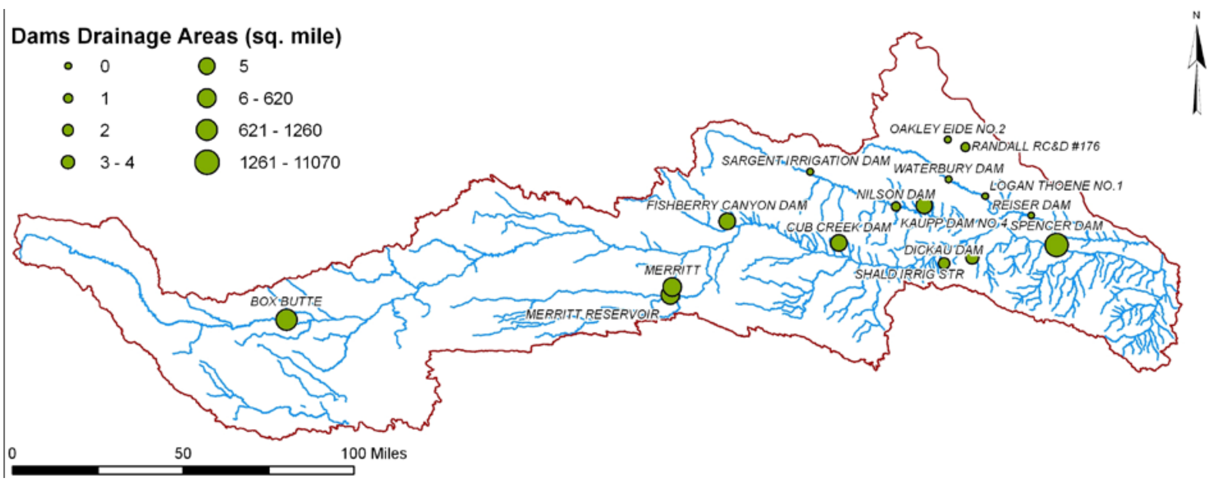



**Figure 3**. Dams along the Niobrara River. Box Butte and Merritt dams are two important irrigation dams in this river.

Niobrara River about 10 miles north of Hemingford, stores water for timely release for irrigation. The Dunlap Diversion Dam is located 8 miles downstream of the Box Butte Dam and diverts water into the Mirage Flats Canal for irrigation. This canal extends about 13 miles from the diversion dam to the beginning of the irrigated lands, with design capacity of 220 cfs in the first 12 miles. The project was developed to irrigate 11,679 acres of land on the north bank of the Niobrara. Box Butte Dam was constructed in 1946. Construction of the distribution system was completed in late 1948. There are also a number of other canal diversions upstream of the Box Butte Dam, majority of which are located in Sioux, Dawes, and Box Butte counties.

The Merritt Dam and Reservoir is located southwest of Valentine on the Snake River, a tributary to the Niobrara River approximately 14 miles upstream from the confluence of the Snake and the Niobrara Rivers in Cherry County. Project facilities include the Ainsworth Canal, a system of lateral, surface and subsurface drains that irrigate 34,540 acres of agricultural land with water released from the Merritt Dam. The canal has initial capacity of 580 cfs. Construction of Merritt Dam began in 1961 and was completed in May 1964. Water storage began in February 1964. Construction of the irrigation system began in 1962 and was completed in June 1966. This project is currently operated by the Ainsworth Irrigation District to supply water to the Ainsworth area.

The Cornell Dam is located near the confluence of the Niobrara and Minnechaduza Rivers. The Dam and its power generation plant were completed around 1915, and operated as a private utility until the early 1940s. After 1940, the Nebraska Public Power District (NPPD) operated the hydroelectric power plant until 1985. In 1986, NPPD deeded the land, dam and power plant to the United States Department of the Interior, and they became part of the Fort Niobrara National Wildlife Refuge. The Dam is no longer functional for hydropower generation. Sediment has filled the small reservoir and water passes over the dam creating run-of-the-river flows.

The Spencer Dam, south of Spencer, Nebraska, on the Holt and Boyd County line is the only operating hydroelectric plant on the Niobrara River. The plant with two generators has been operating since 1927. The Spencer Dam is owned and operated by the NPPD and utilizes natural flow surface water appropriations that currently total 2,035 cfs.

Geographic locations of these structures are shown in Figure 3. Among these four major projects, the first two were developed for providing water for irrigation. Therefore they are expected to modify the basin water budget and peak flows, while the other two could influence the timing and magnitude of peaks.

Water diversion data for the Mirage Flats and the Merritt Dam projects as well as all the other canals located along the Niobrara basin were downloaded from the Nebraska Department of Natural Resources (DNR) website (http://dnrdata.dnr.ne.gov) by clicking the gaging/hydrologic data under the Surface Water menu on the right side of the webpage, which leads to the canal diversion data "http://dnrdata.dnr.ne.gov/Canal/canalindex.asp". Canal diversion data was retrieved for each county within the Niobrara River Basin area and reported in the "Diversion Data" folder.

The data retrieved are reported in Microsoft Excel format "Canal_Diversion_Data.xls". This excel spreadsheet contains four worksheets. The first worksheet is "Canal source" that lists the names of all canals and diversions that uses water from the Niobrara River with dynamic internet links to their source data in the NDNR server. Canal name, location, and period of record are reported in Table 4 as well. The second worksheet contains monthly canal data until 2004, which included the length of record that was initially available. For years 2005 and 2006, diversion data were obtained from DNR and included in a separate Excel workbook in the folder. Canal_Diversion_Data.xls also contains monthly and annual total diversions for 1948-2006 period. Figure 4 plots time series of total annual diversions from the Niobrara River (sum of 39 diversion locations), as well as water diverted to the two major projects described above, Ainsworth and Mirage Flats Canals. According to the data downloaded, the Mirage Flats Project was the only major water user from the river between 1948 and 1955. Water diversion records between 1955 and 1965 include various, mostly small-scale water diversion or pumping from the river, in addition to the Mirage Flats project. With the onset of the Ainsworth irrigation canal operations following the construction of the Merritt dam, the water use from the river began to grow significantly. Mirage Flats and Ainsworth projects together divert more than 90% of the total diversions from the river (Figure 4).

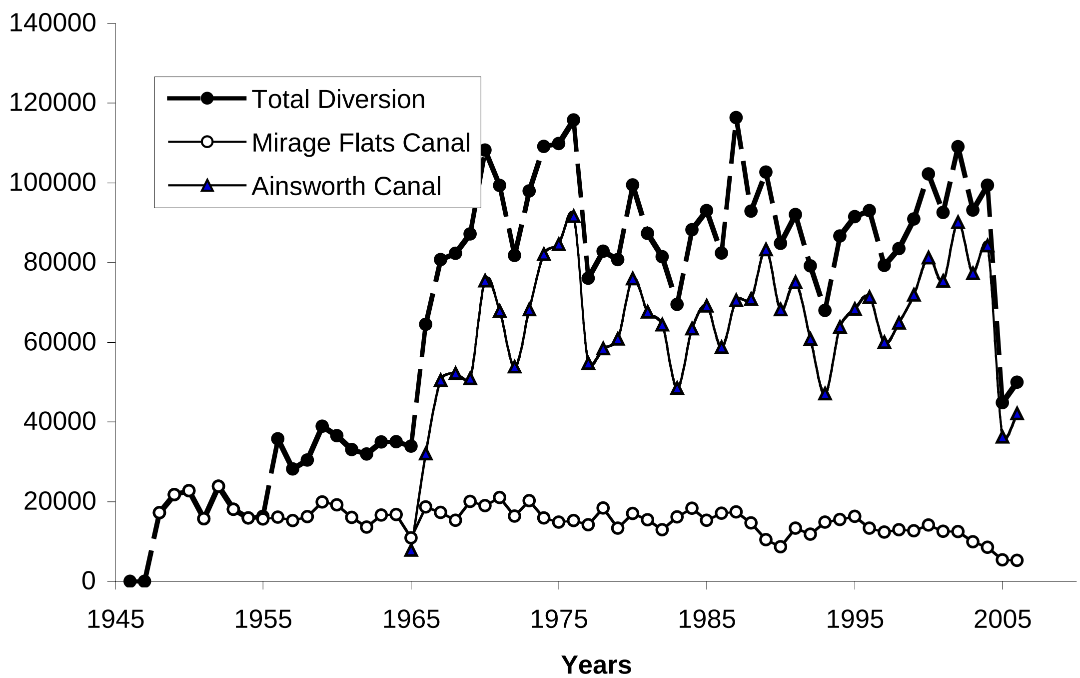



**Figure 4.** Annual diversions from the Niobrara River, including water diverted to the Mirage Flats and Ainsworth projects as well as the total diversion from the Niobrara River.

## 3. Data Analyses

In this section climatologic and hydrologic data analysis are described. We begin this section by reviewing the modern (last ~110) and past (last 2,000 years) climate history of northern Nebraska. Understanding the climate trends in the region is crucial as the climate is an important factor in hydrology. Climate analysis is followed by the presentation of the time series of water diversions from the Niobrara River to develop a historical context of the water demand and its implications on hydrology. Finally we present a hydrological analysis conducted to examine the influence of climate and river development activities on the hydrology of the Niobrara River.

### 3.1. Climatology

#### 3.1.1. Annual Precipitation

We examined spatial and temporal variability in annual precipitation, probability of a year being dry, and periodicity in wet and dry years. Both modern and pre-historic data are used for these analyses.

There is significant precipitation gradient in the Niobrara River Basin from 17.81 inches (452.4 mm) in Harrison, NE located in the western edge of the state, to 22.32 inches (567 mm) in Ainsworth, NE and 23.82 inches (605 mm) in Butte, NE. More than 70% of the annual precipitation falls in the April to September period. The mean annual precipitation map of the basin is presented in Figure 5. This map was clipped from a 30-year average precipitation map prepared for the USA by the PRISM group.

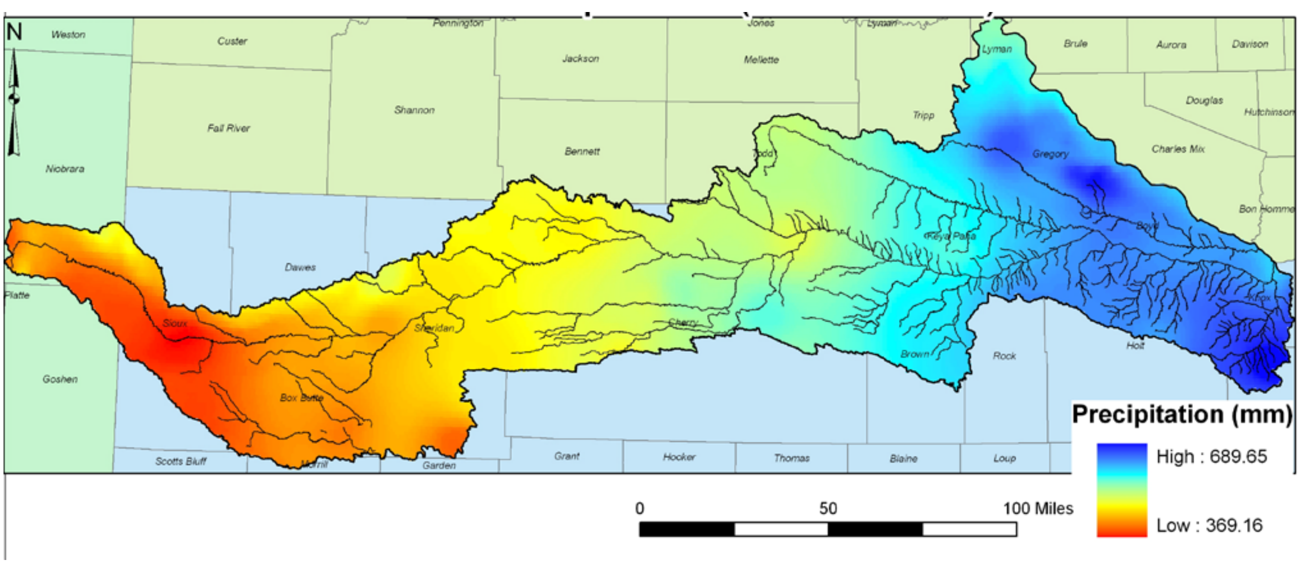



**Figure 5.** Mean annual precipitation of the Niobrara River Basin. PRISM Group, Oregon State University, http://www.prismclimate.org, created 4 March 2008 for this study.

In addition to the observed spatial variability, precipitation in this region shows strong inter-annual variability. Time series of the spatially averaged NOAA precipitation data covering the panhandle and north central climate regions of Nebraska is plotted in Figure 6a. This plot shows the longest record of spatially averaged instrumented data provided by NOAA for this region. We also include the time series of annual precipitation observed at Ainsworth, NE in Figure 6b for comparison.

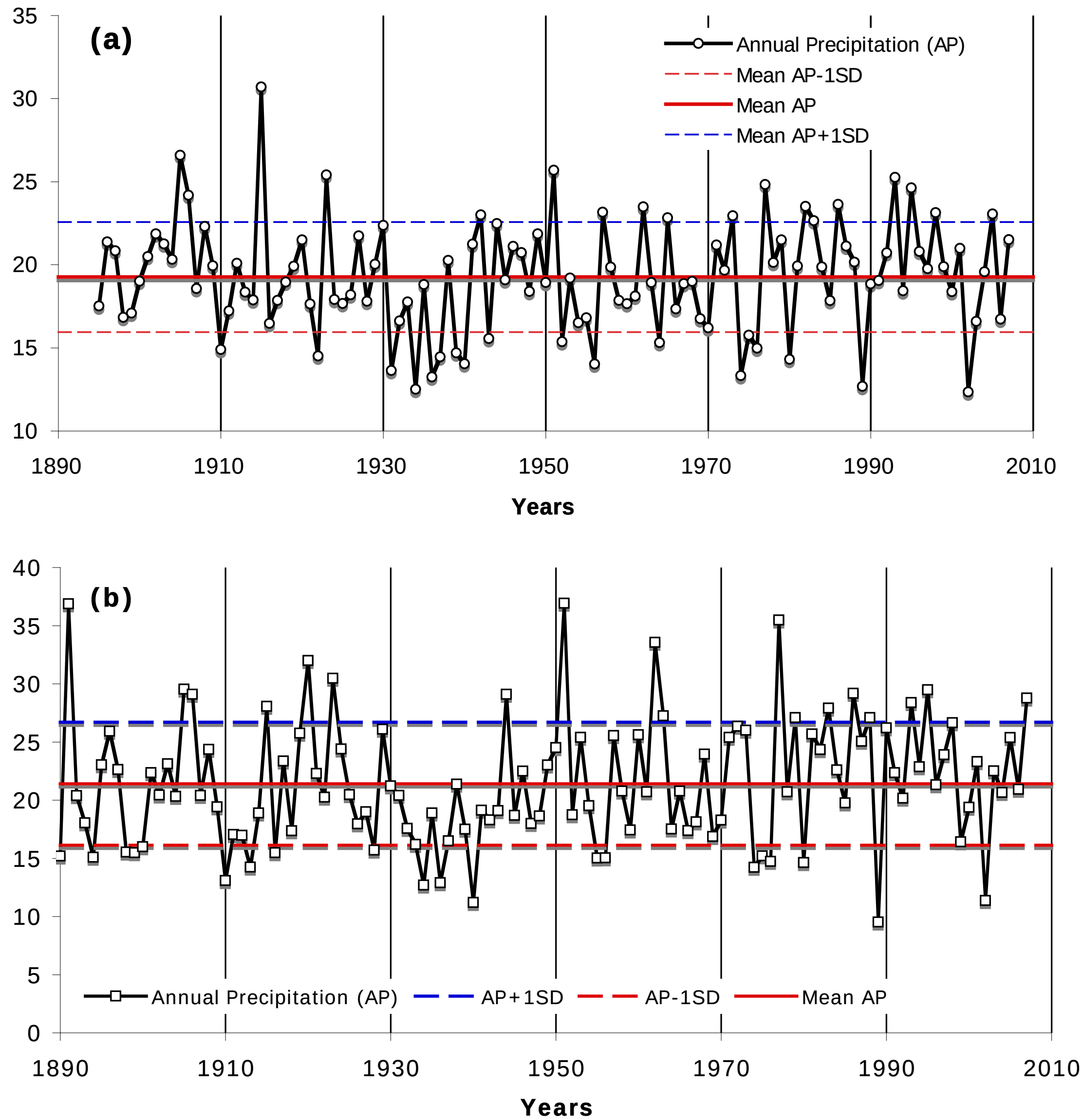



**Figure 6.** Time series of annual precipitation in the Niobrara River valley **(a)** Spatially averaged precipitation data obtained from NOAA (1895-2007); **(b)** weather station in Ainsworth, NE (1890-2007). In the plots, SD represents standard deviation of the annual data. Dashed blue (upper) and red (lower) horizontal lines represent +1 SD and -1 SD from the mean annual precipitation.

In both the regionally averaged (Figure 6a) and local (Figure 6b) annual precipitation series the timing of wet and dry years are in phase with each other. Ainsworth precipitation, however, has both a larger mean and a higher variability. This is expected as Ainsworth is located within the wetter part of the basin.

In both plots, mean annual precipitation and one standard deviation differences from the mean are plotted to illustrate inter-annual precipitation variability. A comparison of the mean and standard deviation of both the regional (NOAA and gridded PRISM) and selected rain gage annual precipitation data are given in Table 1. A close match between the NOAA regional and PRISM spatially averaged basin data for Verdel shows the consistency between the two data sources. PRISM-Sparks data is lower than the other two, as the Sparks gage drains relatively drier portions of the basin. The rain gage data for Harrison, Ainsworth, and Butte illustrate the precipitation gradient in the basin.

**Table 1.** Annual statistics for regional and local precipitation data.

| Station Record Length | NOAA* (1895-2007) | PRISM-Verdel (1959-2006) | PRISM-Sparks (1946-2006) |
|---|---|---|---|
| **Mean** | 19.3 | 19.8 | 17.4 |
| **Std. Dev.** | 3.32 | 3.62 | 2.96 |

| Station Record Length | Harrison, NE (1893-2007) | Ainsworth, NE (1890-2006) | Butte, NE (1948-2007) |
|---|---|---|---|
| **Mean** | 17.81 | 22.32 | 23.82 |
| **Std. Dev.** | 4.21 | 5.58 | 5.84 |

* NOAA data is based on the averages of the panhandle and north central climatic regions.

There is significant inter-annual precipitation variability in the region (Figure 6). The 1930s drought can be clearly seen as a series of years with below-average annual precipitation. The lowest annual precipitation of record was observed in 2002 (12.3 in) followed by precipitation in 1934 (12.5 in) (Figure 6a). Major droughts observed in the instrumented past have annual precipitation values lower than 1 standard deviation of the mean annual precipitation (~ 15 in). Probability of a year with annual precipitation less than 1 SD can be calculated by an empirical cumulative probability distribution. Here we used the Weibull plotting position to calculate this probability in Figure 7 (e.g., Benjamin and Cornell, 1970). In this technique, annual precipitation data is ranked in ascending order. A number n (n=1…N, where N is the total number of years observed), is assigned to each ranked data data. The minimum annual precipitation data has a rank value of 1 and the maximum N. The Weibull plotting position gives the cumulative probability (the probability that annual precipitation will be less than equal to a given precipitation amount, p) as

$$P(P \le p) = \frac{n}{N+1} \qquad (1)$$

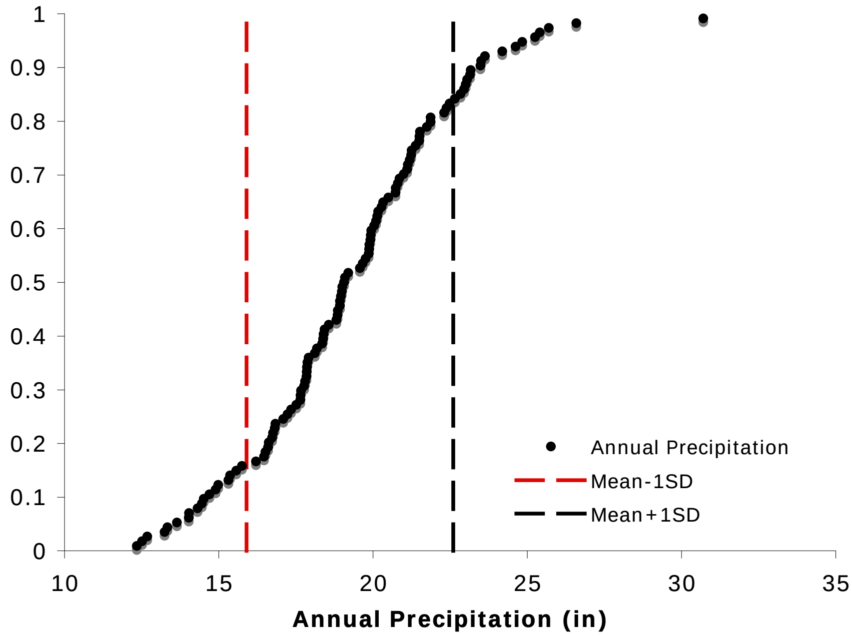



**Figure 7.** Empirical cumulative annual precipitation probabilities ( $P(P \le p)$) for regional precipitation plotted using the Weibull plotting position. Each year is treated as an independent random event.

In Figure 7, the probability of occurrence of a dry year is less than 0.15 in any given year. This means that 3 out of every 20 years, annual precipitation will be below 1 standard deviation of the mean. One caveat in this analysis is that it treats each year as a random event. Probability of drought in a given year will also be based on the conditional probabilities, and whether or not precipitation in one year correlate with the precipitation of the year before. One way to investigate cross-correlations is to develop a correlogram of annual precipitation. A correlogram is a plot of sample cross-correlations as a function of time lags. For annual precipitation this will be a plot of cross-correlations of annual time series of regional precipitation obtained from NOAA withs its lagged replicate (Haan, 2002):

$$r_x(k) = \frac{\sum_i [(x(i) - \bar{x})(x(i-k) - \bar{x})]}{\sqrt{\sum_i (x(i) - \bar{x})^2} \sqrt{\sum_i (x(i-k) - \bar{x})^2}} \qquad (2)$$

where $r_x(k)$ is correlation of series x with lag time k, and i an indice, i=1…N, where N is sample size.

A correlogram of annual precipitation in the region was plotted using MATLAB (software for technical/mathematical computing) and shown in Figure 8. The correlogram for annual precipitation does not show any significant memory in this system, as the calculated correlations between the original and the lagged time series are within the significance limits (Figure 8). That is, a wet year can be followed by a dry year (or vice-versa), and there is no statistically detectable cycles and trends in annual precipitation. Although correlogram analysis is useful to identify apparent cross-correlations, however spectral analysis is a better way of examining periodicity in time series. This is not further discussed in this project.

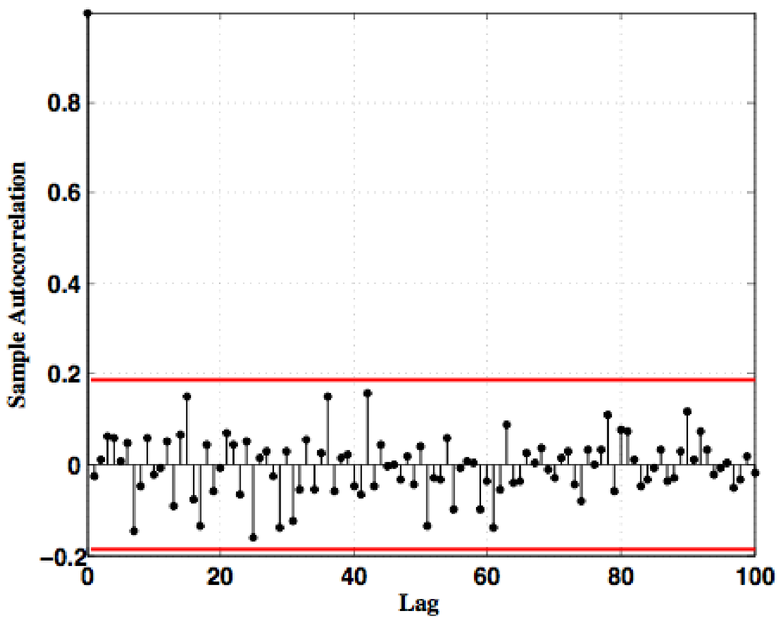



**Figure 8.** Correlogram of Annual Precipitation time series of the Niobrara River. Horizontal lines indicate the 95% confidence limits, within which correlation is not statistically significant. The plot is developed using MATLAB *autocorr* function.

### 3.1.2. Annual Temperatures

In addition to annual precipitation, temperature is also another indicator of climatic fluctuations and trends. To illustrate this, annual mean, minimum monthly mean and maximum monthly mean temperatures in the Niobrara river valley were plotted (Figure 9). Annual mean temperature is the mean of the daily temperature in each year. Minimum (maximum) monthly mean temperatures represent the month in which the mean of daily temperature is minimum (maximum) within a given year. In each plot the horizontal line is the long term mean of the plotted quantity.

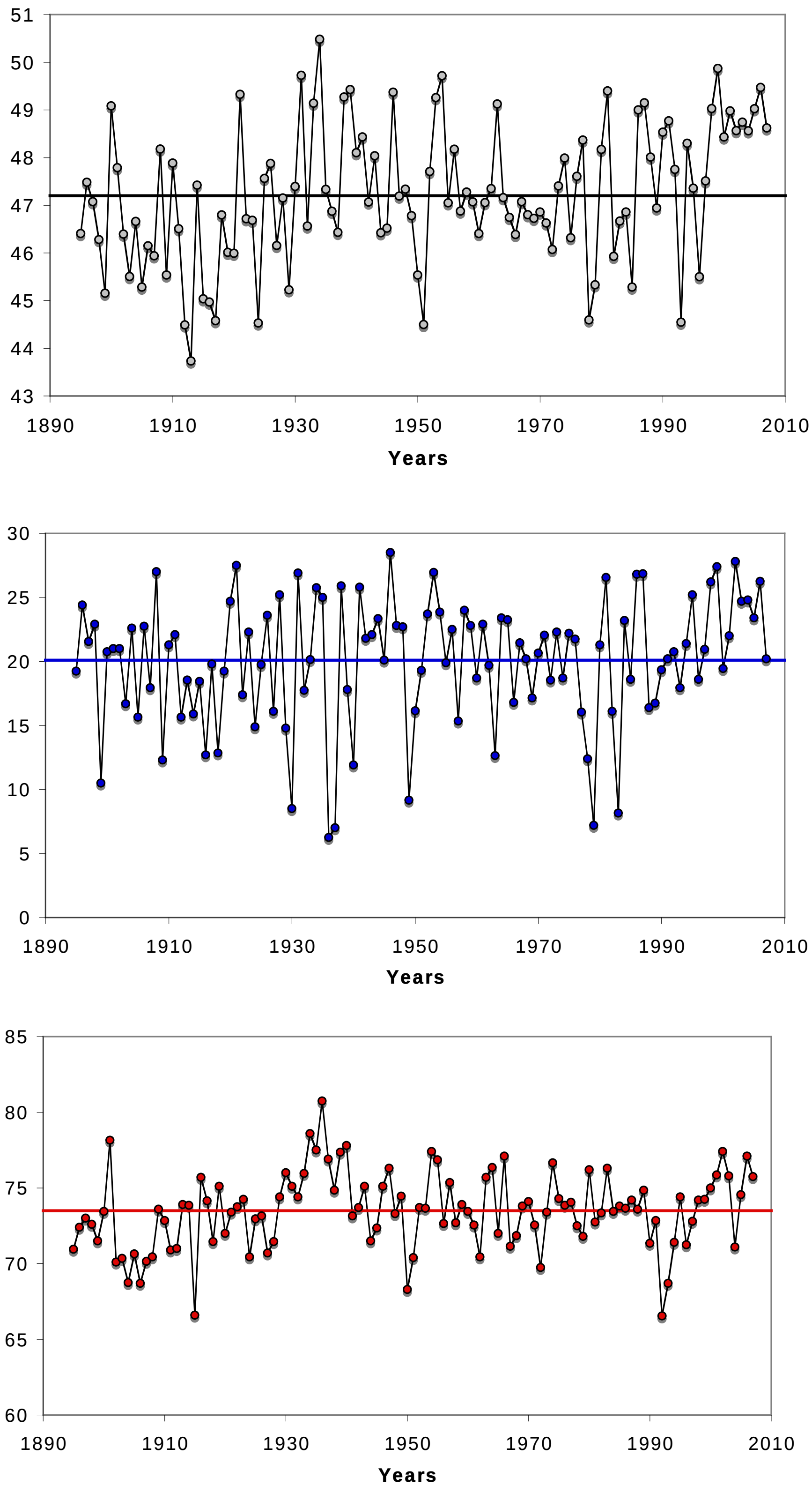



**Figure 9.** Annual, minimum monthly, and maximum monthly mean temperatures in the panhandle and north central climate regions of Nebraska.

In the first plot the mean annual temperatures in the last 10 years are consistently higher than the long term mean. The majority of both the minimum and maximum monthly temperatures also plot higher than their long term means in the last decade or so. This data suggests that within the last decade, mean annual temperatures were in general higher than the long term means. However, these temperatures are within the range of variability observed in the past, but perhaps persisted a little longer especially in the case of mean annual temperatures.

**3.1.3. Palmer Drought Severity Index (PDSI)**

Perhaps a better indication of the variability of meteorological droughts can be obtained by the Palmer Drought Severity Index (PDSI), an index used to assess the severity of dry or wet spells in the weather. This index is based on the principles of a balance between moisture supply and demand (Palmer, 1965). The index generally ranges from -6 to +6, with negative values representing dry, and positive values wet periods. PDSI classifies droughts as normal (PDSI 0 to -.5); incipient (PDSI=-0.5 to -1.0); mild (PDSI-1.0 to -2.0); moderate (PDSI=-2.0 to -3.0); and severe (PDSI=-3.0 to -4.0). When drought is greater than - 4.0, it is rated as extreme. Similar adjectives are attached to positive values of wet period as well.

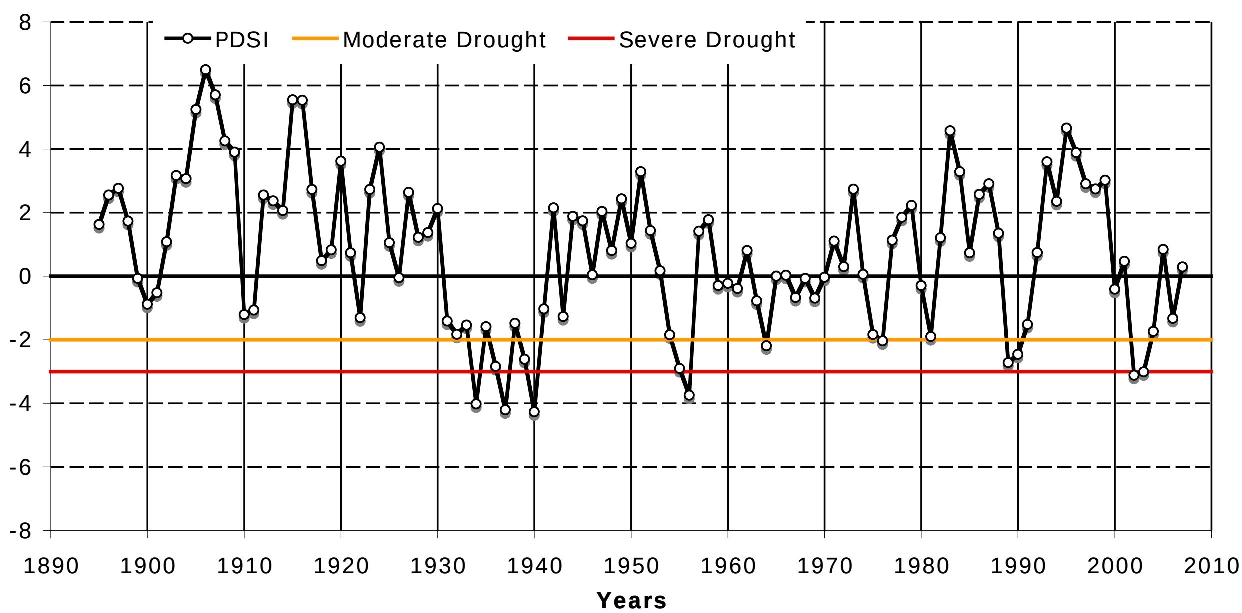



**Figure 10.** NOAA-PDSI calculated for the instrumented past, representing the spatially averaged conditions in the panhandle and north central climatic regions of Nebraska.

Figure 10 illustrates the annual PDSI of the instrumented (modern) period, where the 20th century droughts can be clearly seen. The severe drought of the 1930s shows a 9-year period (1931-1940) in which the PDSI was consistently low. Especially in 1934, 1937 and 1940 the most extreme drought conditions of the instrumented climate history were recorded. The 1930s drought was followed by a wet period for about 10 years, peaking in 1951 with an annual precipitation of 25.7 inches. This peak year also marked the beginning of another downturn towards a dry spell. A continuous decline in PDSI after 1951 resulted in droughts in 1954, 1955 and 1956. Following the 1950s drought, wet and dry periods continued. According to the PDSI data, 1989-1990 and 2002-2003 droughts were both less severe and shorter than the 1930s drought.

Some periodicity can be noticed in the modern PDSI record (Figure 10), as both dry and wet periods persisted for several years. Correlogram analysis was performed to detect the correlation structure in Figure 10. Unlike the annual precipitation time series, PDSI of any given year shows statistically significant positive correlation up to 3 years lag. Although statistically not significant, there are periodic patterns for cross-correlations beyond 3 years in Figure 11 as well. This is expected as upward PDSI trends for several years are often followed, sometimes irregularly, by downward trends in Figure 10. This analysis provides the statistical basis for wet-dry periods that persist for approximately 3-4 years in this region.

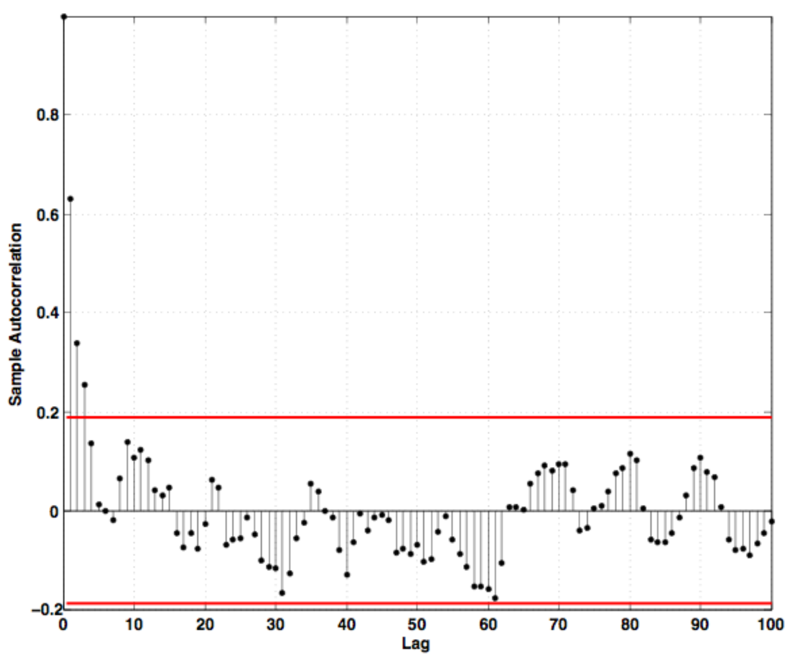



**Figure 11.** Correlogram of calculated PDSI (Palmer, 1965) for the instrumented period from 1895 to 2007 in the panhandle and north central climatic regions of Nebraska.

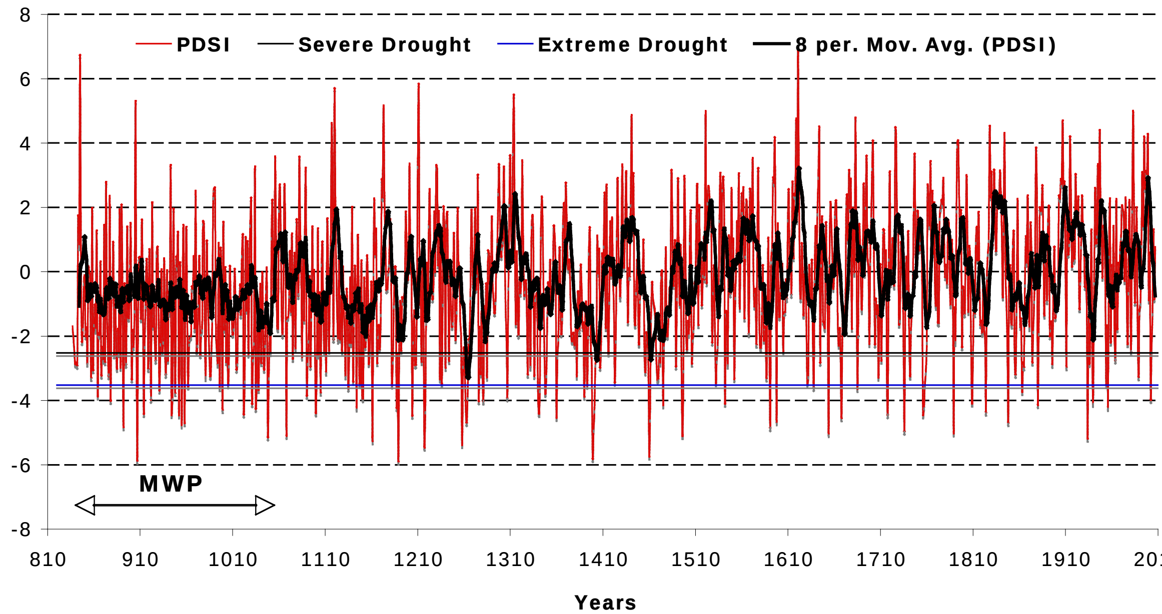



**Figure 12.** Paleo-PDSI, representing the spatially averaged conditions in the panhandle and north central climatic regions of Nebraska (Cooke et al., 2004).

In studying regional hydrology and flood frequency of a region, one also wonders whether the current climate is representative of the pre-historic climates, which might have played important roles in the evolution of the river channel and its aquatic habitats. The paleo-PDSI index data compiled by Cook et al. (2004) allows for the examination of trends in the climate for the last ~1200 years. Figure 12 plots the pale-PDSI time series, obtained as the arithmetic average of the PDSI of panhandle and north central Nebraska climate regions. The data combines both the paleo reconstructs and PDSI calculated using modern records. In Figure 12, an 8-year moving average PDSI is plotted as an average period within which average wet and dry spells occur.

In interpreting this data, caution should be exercised as this data only shows a proxy of climate and is less accurate than the calculated PDSI. Therefore, Figure 12 only provides some qualitative information, and can be used for a relative comparison of the climates of today and the past. In the combined plaeo/modern PDSI time series, two marked trends can be immediately noticed. First, the PDSI trend tends to increase with time, which can be especially seen in the 8-year moving average plot, and becomes more variable. Second, the data reveals a persistent drought between years 850 and 1050 AD. This period of elevated aridity is known as the Medieval Warm Period (MWP), an unusual warm period observed in the North Atlantic region. There are various independent indicators of the MWP reported in the literature especially in the Western US. During this period Nebraska Sand Hills were destabilized as a result of the dessication of the grass layer (Sridhar et al., 2006). As the 8-year moving average data suggests, the MWP perhaps was not much drier than the 1930s drought, however it extended over centuries, long enough to cause dune activity in the Sand Hills. A new hypothesis suggests that MWP was a result of a shift of spring-summer atmospheric circulation over the Plains, where moist southerly air flow was replaced by dry southwesterly air flow (Sridhar et al., 2006).

We examined the correlation structure of the long-term PDSI data by plotting its autocorrelation function (Figure 13). Interestingly the correlation structure of the combined data is very similar to the modern PDSI data, with significant correlations with lags up to 4 years. This may suggest that while the mean climate fluctuates between wet and dry spells, some of which are longer than others, there is at least a few years of memory in the system over the last ~ 1,000 years. This suggests that dry and wet periods continue for approximately 3-4 years.

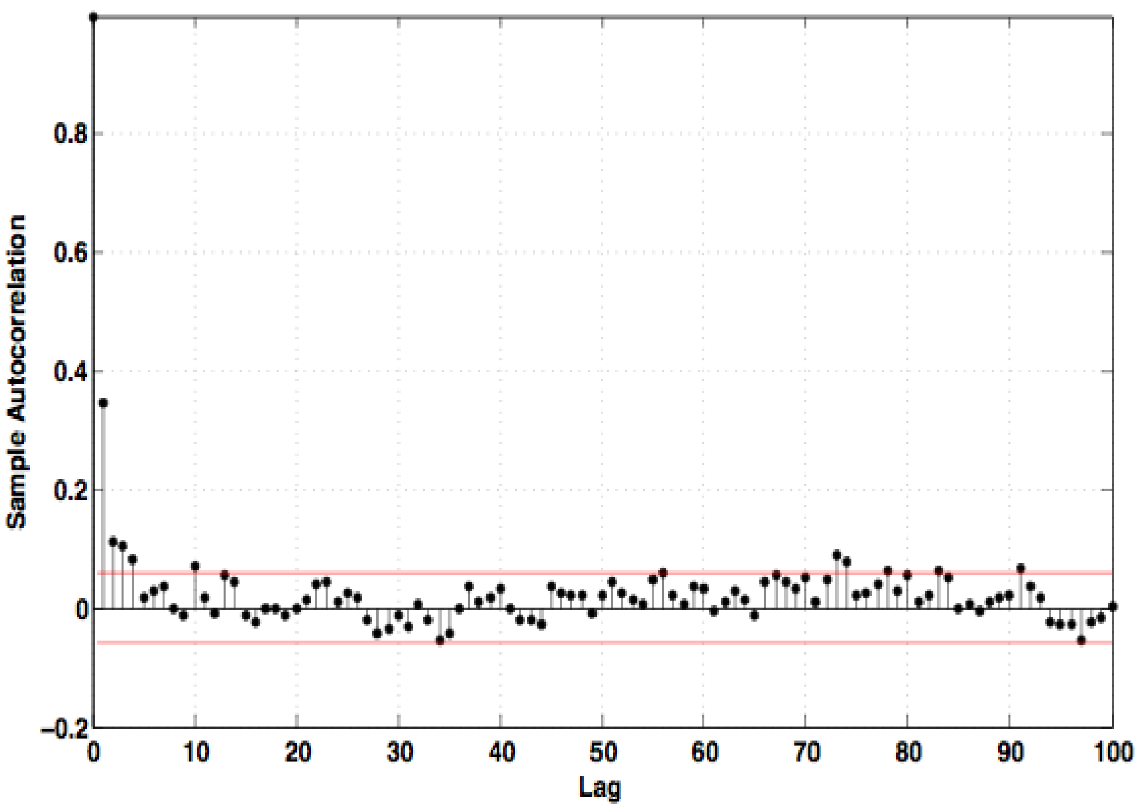



**Figure 13.** Correlogram of the combined paleo and modern PDSI data averaged over the panhandle and north central climatic regions of Nebraska.

**Summary**

In this section the time series of annual precipitation (from various sources), temperatures, and PDSI of the instrumented period from 1895 to 2007, and the paleo reconstructs of the PDSI starting from 830 in the north central and panhandle climate regions of Nebraska where the Niobrara river basin is located were examined. Regional precipitation obtained from NOAA climate regions data show a very close match with the gridded PRISM data. This suggests that for spatial analysis of rainfall and its impact on hydrology, the PRISM data seems to be a good source.

Annual precipitation does not show strong autocorrelation structure, although some periodicity may be detected visually in Figure 6. Annual precipitation shows significant inter-annual fluctuations. Average annual temperatures of the last 10 years seem to be higher than the long-term (~112 years) mean annual temperature. The modern PDSI (Figure 10) shows significant periodicity, with moderate to severe drought occurring every 8 to >10 years. The paleo drought index reconstructs may imply that the region is currently wetter than average over the last ~ 1200 years (Figure 12) and that in the past, like in the present, droughts have recurred in the region with similar periodic behavior. Among these droughts, the MWP stands out as an individual long-term drought during which wetness was reduced persistently over 3 centuries.

### 3.2. Hydrological Analysis

In this report, preliminary analyses are presented to decipher the influence of climatic variability and water diversions on the annual, seasonal, and daily flows in the main stem of the Niobrara River. The analyses presented in this section are for Sparks and Verdel gages. However, as will be discussed in the text, we conducted analyses and provided results for other gages as appropriate. These results are presented on the CD. In what follows, first regression analysis between annual runoff and annual precipitation are presented to examine the dependence of runoff to precipitation at the Sparks (drainage area is 7,150 mi$^2$), and Verdel (11,580 mi$^2$) gages, and to investigate if water diversions had any quantifiable impact on runoff hydrology. Next, monthly and daily flow variability is examined in relation to changes in water demand on the river.

Although water diversions began on the Niobrara River during the mid 1940s, a very significant increase in water diversion occurred around the 1964/1965 period. In the analysis below hydrological implications of this increase is studied by separating the flow data prior and post 1965 periods.

### 3.2.1. Annual Precipitation – Runoff Relations: Sparks and Verdel Gages

Annual mean streamflow at both the Sparks and Verdel gages were divided by their drainage areas to calculate annual runoff (Q) in units of lengths so that it can be correlated to precipitation. Basin averaged precipitation (P) is obtained from PRISM for each year. For each gage, the fraction of precipitation that yields runoff, or runoff ratio in short, Q/P, is calculated. All three variables Q, P, and Q/P for Sparks and Verdel are plotted in Figure 14. Data is provided in the following directory in the CD: *Flow_Data_and_Analysis/Annual Analysis/Annual_data.xls*.

There is no visually apparent trend in precipitation as discussed earlier. Autocorrelation analysis showed no significant periodicity and cross-correlation in precipitation. Interestingly, streamflow data for the two gages display marked differences. Sparks data shows subtle inter-annual fluctuations, and has a slight decreasing trend. The Verdel gage shows significant fluctuations in response to inter-annual variations in rainfall. Both gages have low runoff ratios. The mean runoff ratio for Sparks and Verdel gages are 0.085 and 0.1 respectively.

These runoff ratios are low compared to many other streams in the conterminous US (Sankarasubramanian and Vogel, 2002). Next the dependence of annual flow on precipitation was examined. Figure 15 plots annual runoff as a function of precipitation above Sparks. The regression slope defines a weak dependence between the two variables, leading to a very low coefficient of determination, $R^2$. Annual precipitation only explains approximately 15% of the variability observed in runoff. The majority of the data lie outside the 95% confidence limit of the regression line ($y(x) \pm 1.96\sigma_y$) (Figure 15). A high value of the intercept of the regression equation (28.61 mm) could imply a strong base flow influence. On the other hand, a small value of the slope of the regression suggests a very limited impact of fluctuations in annual precipitation to annual runoff (~0.2% of annual precipitation contributes to runoff in the regression equation).

Large variability in runoff response to given annual precipitation could be an indication of a change in the system behavior such as increased water diversions in the basin. This can be best examined by separating the data to two periods, before and after increased water diversions. According to the diversion data gathered from DNR, water diversion increased in 1965 with the operation of the Ainsworth irrigation project, while water storage in Merritt Dam on the Snake River began in February 1964.

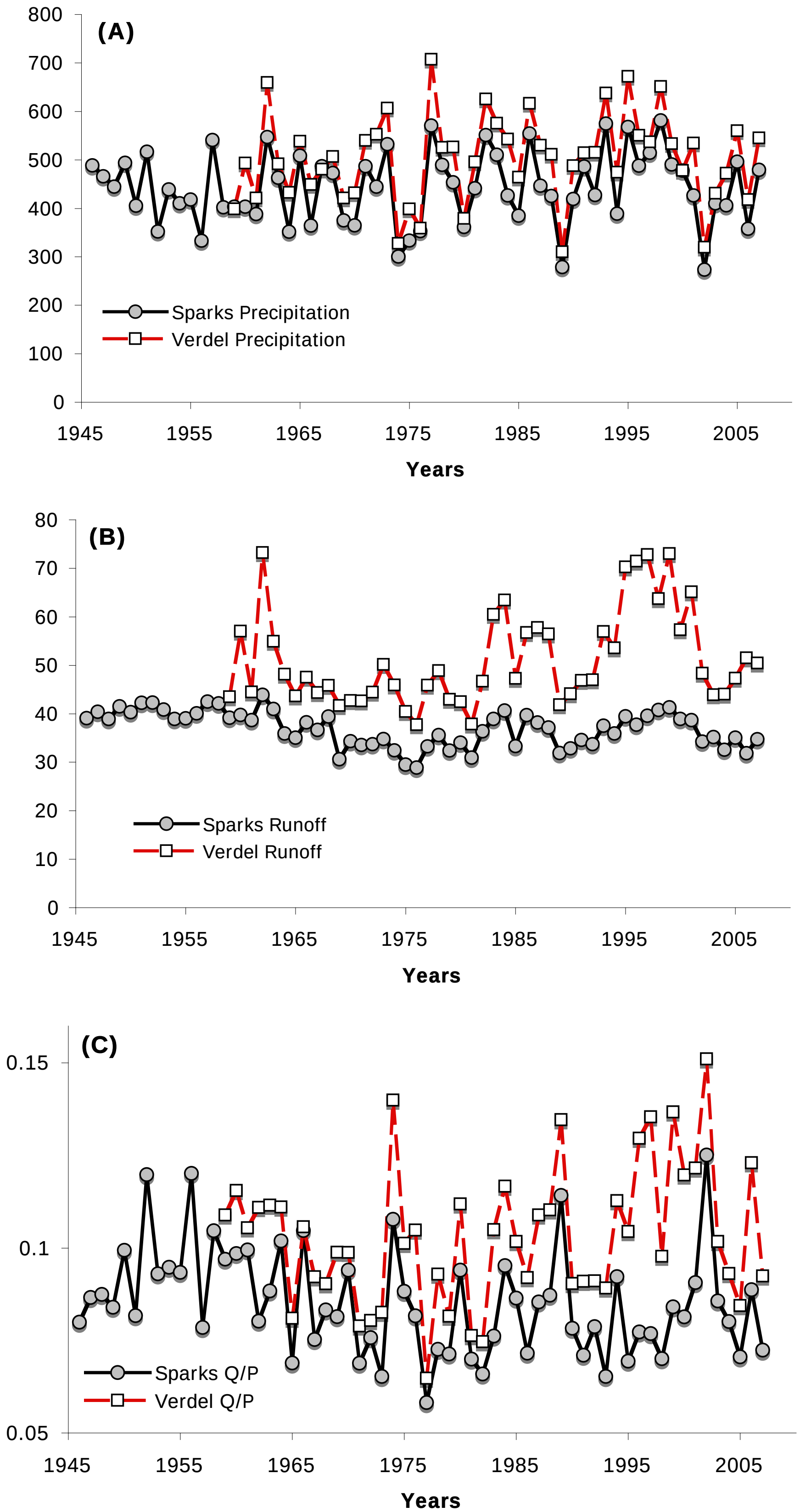



**Figure 14.** Time series of (a) annual precipitation and (b) runoff (c) runoff ratio for USGS Sparks and Verdel gages.

Therefore starting from 1964 and/or 1965, runoff in the main stem of the Niobrara River is likely to have decreased as a result of the developments in the watershed. At the Sparks gage the runoff ratio prior to 1965 was slightly larger (Q/P=0.093) than post 1965 (Q/P=0.081), suggesting a 12.9% reduction in runoff amount per given annual rainfall amount in a given year.

To examine the influence of data separation on the regression between precipitation and runoff at the Sparks gage, data was separately before 1965 (i.e. time period of relatively less water use), and after 1965 (Figure 3), and fit linear regression equations separately to both these data. We expect that this data separation will allow us to identify any changes in runoff production in the basin as a result of water diversions.

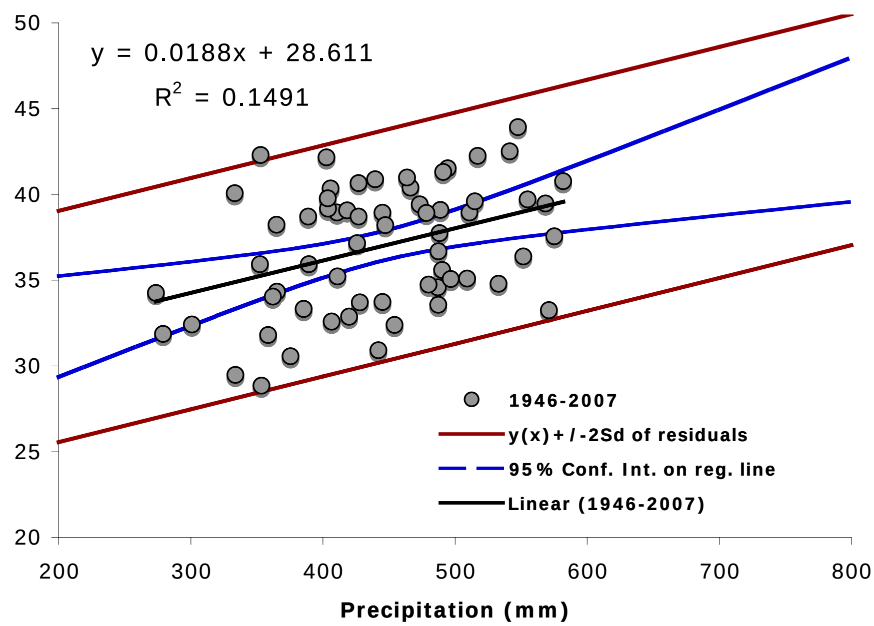



**Figure 15.** Regression analysis of runoff versus precipitation for basin above Sparks. Plus/minus 2 standard deviation (Sd) from the regression equation gives the limit for outliers. Dashed blue line plots the range within which the regression equation can be used with 95% confidence.

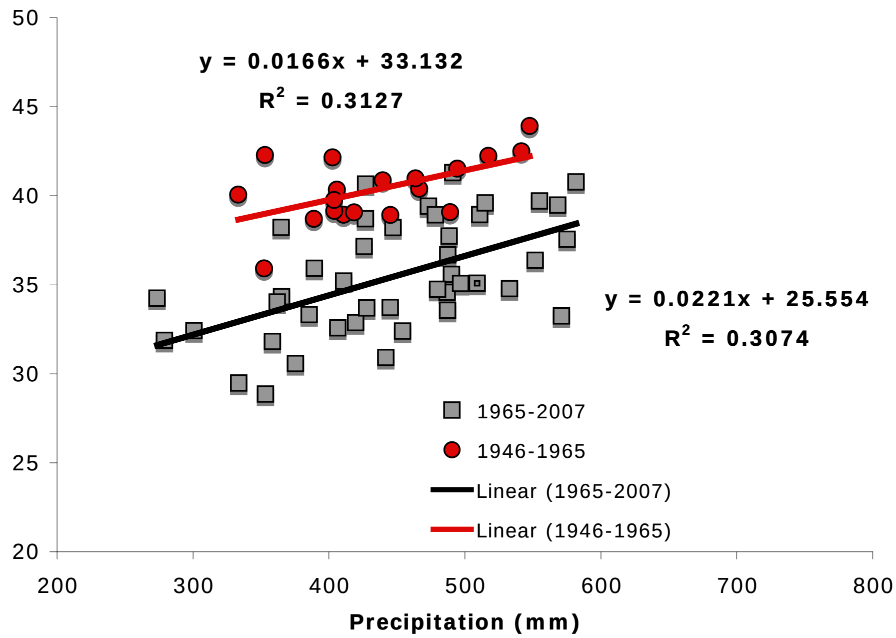



**Figure 16.** Regression analysis of runoff versus precipitation for periods of before and after increased water use in the Niobrara River basin above the Sparks gage.

There is evidence for runoff reduction in the basin as data of the later period plot lower than the earlier. In the diversions data (Figure 4), increased annual diversion from the river began in 1966. Lower runoff in 1965 may be attributed to the beginning of water storage in Merritt Reservoir, suggesting that even though water was not diverted for irrigation, its storage impacted the hydrology of the basin. Slope of the regression line increased from 0.0166 (1946-1965) to 0.022 (1965-2007). Intercept of the regression decreased in the reverse order 33.13 mm (1946-1965) to 25.4 mm (1965-2007). A higher regression slope may indicate growing dependence of annual runoff on precipitation, while a lower intercept of regression may suggest decreasing contribution of groundwater. Further investigations will be needed to make any conclusions.

The question now is whether the observed differences in runoff before and after the 1964-1965 water year are statistically significant. One way to examine this is to test the following hypothesis: "Both precipitation and runoff before and after 1965 have the identical mean values, or mean annual precipitation and runoff did not change before and after 1965". This hypothesis can be written for rainfall as $H_o:(\mu_{P1}-\mu_{P2})=0$ and runoff as $H_o:(\mu_{R1}-\mu_{R2})=0$. The t-test results for precipitation do not reject the hypothesis at up to approximately α=0.60 confidence level, meaning that, there is only 40% chance that the mean of the two precipitation populations could be different. However the second (runoff) hypothesis is rejected at $\alpha$=0.05. This means that there is 95% chance that runoff before and after 1965 have different means. For data and detailed analysis see Flow Data and Analysis/Annual Analysis/Regression_Sparks.xls in the CD.

If the water diverted from the system causes a significant reduction in runoff, then would putting the total amount of diverted water back in the system reconstruct the natural state of the river? Because of the internal dynamics of the system, an exact answer to such a question may not readily available, however, statistically this idea can be examined. Next, total water diversion from the Niobrara River is added to observed runoff and the relationship between annual runoff and precipitation is plotted for pre and post 1965 periods (Figure 17). Although the $R^2$ values decreased significantly compared to Figure 16, there is not any noticeable separation between the two data groups. Both data groups have approximately an identical mean (41.95 mm for 1946-1964; and 41.3 mm for 1965-2007).

A poor correlation was determined between annual runoff and precipitation at Verdel (Figure 18). The majority of the data is beyond the range within which the regression equation can be used with 95% confidence. When data is separated into pre and post 1965 periods, correlation between runoff and precipitation is improved in the earlier period (1959-1965) (Figure 6), however the number

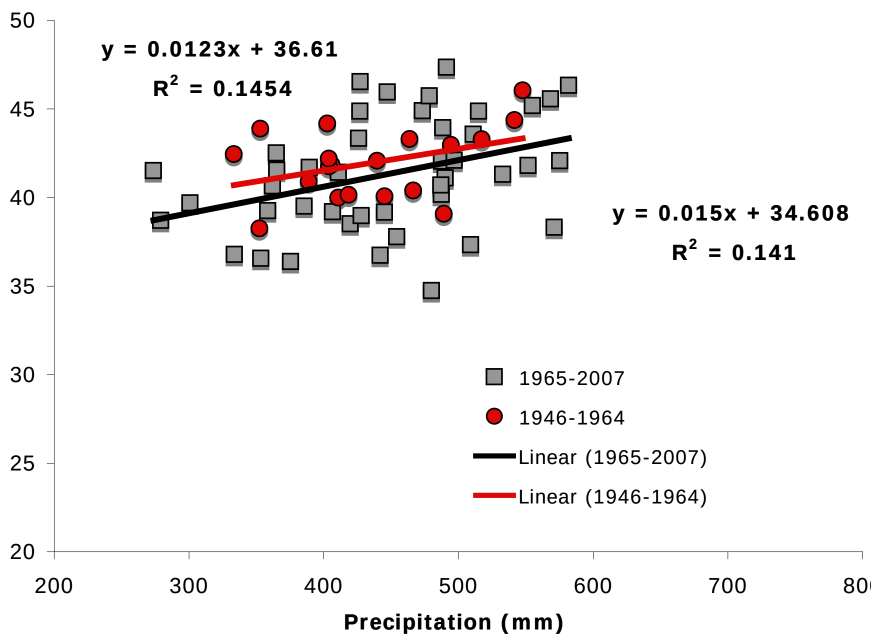



**Figure 17.** Regression analysis of runoff versus precipitation for periods before and after increased water use in the Niobrara River basin above the Sparks gage. The data is plotted after adding the amount of diversions to the observed annual runoff at the Sparks gage.

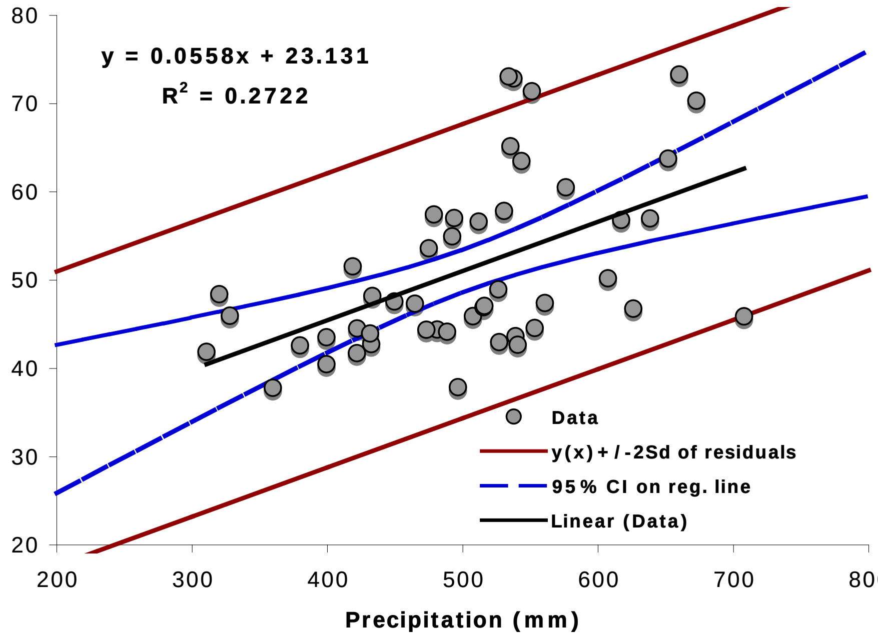



**Figure 18.** Regression analysis of runoff and precipitation for basin above Verdel. Plus/minus 2 standard deviation from the regression equation gives the limit for outliers. Dashed blue line plots range within which the regression equation can be used with 95% confidence.

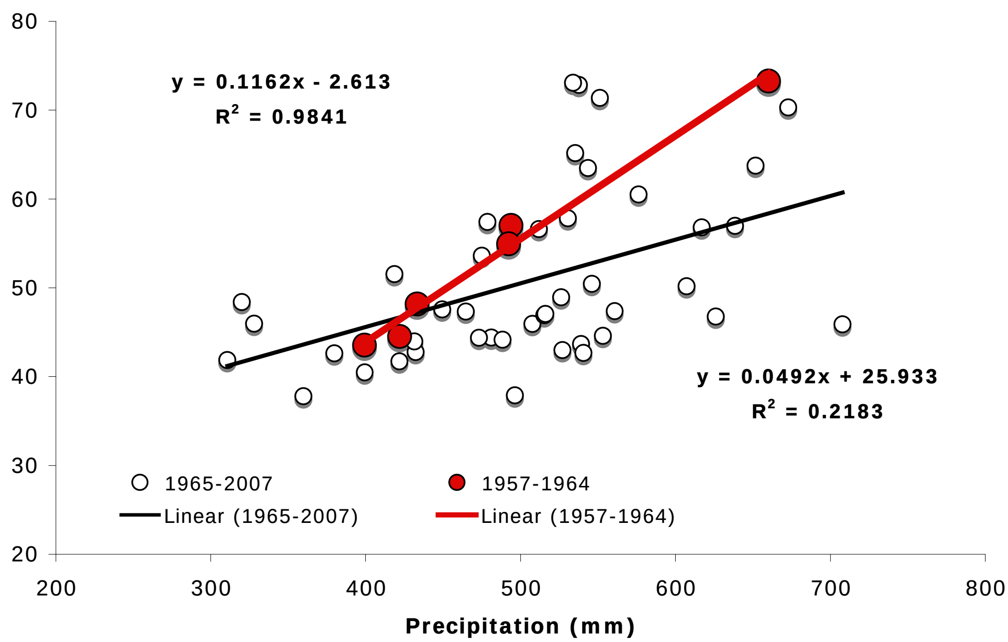



**Figure 19.** Regression analysis of runoff versus precipitation before and after 1964 in Verdel.

of data points to suggest any statistically significant improvement is not sufficient. No statistically significant difference in the mean values of runoff and precipitation are found before and after the 1965 periods. For data and detailed analysis please see the following folder in the CD delivered as part of this report, Flow Data and Analysis/Annual Analysis/Regression Verdel.xls.

The regression analysis above suggests that annual precipitation only explains a limited fraction of the variability in annual runoff in both gages. The predictive capability of the linear regression models were not improved when relatively natural and managed periods were analyzed independently at the Sparks gage. This may imply that annual runoff generation is dominantly controlled by other factors than annual precipitation. Although in the 1957-1964 period at the Verdel gage there is a high correlation between annual runoff and precipitation, the regression is based on a few data points.

In order to further investigate the source of runoff variability we ploted a runoff correlogram for both the Sparks and Verdel gages (Figure 20). In this plot, the longer the decay of lagged correlation, the higher the memory in the system response to previous runoff rates. Typically, in surface water dominated basins where runoff is directly generated from precipitation (or following limited lag as subsurface flow) a correlogram is expected to show a quick decay.  In ground water dominated basins, decay in autocorrelation could be longer as the system responds to a longer-term climatic recharge variability than inter-annual precipitation variability.

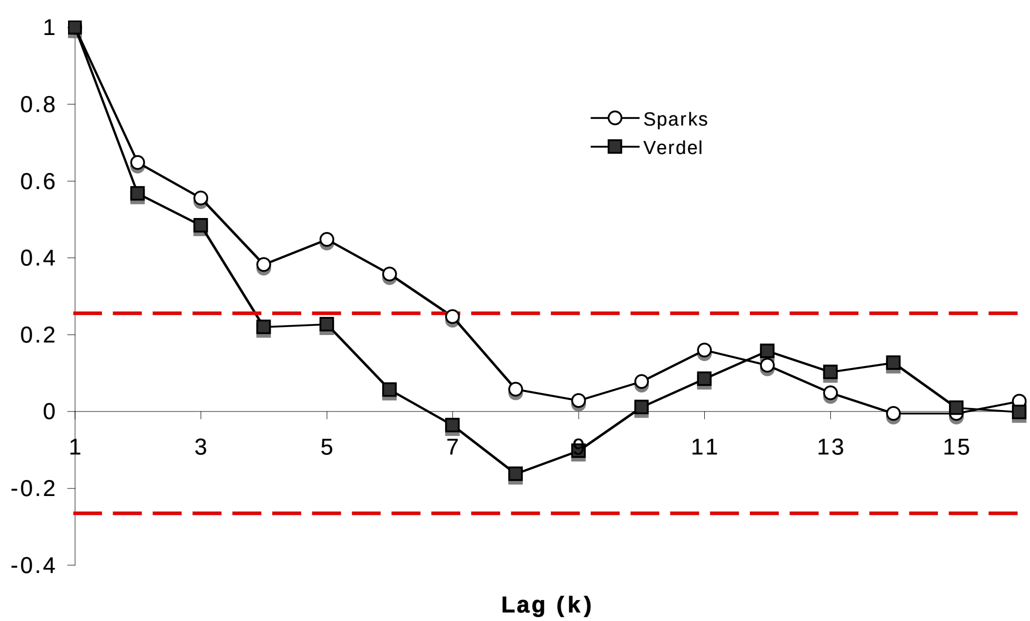



**Figure 20.** Runoff correlogram for Sparks and Verdel gages, k represent years. Correlations above and below the red lines (90% confidence level of no correlation) are statistically significant.

Autocorrelations are high in both stations. In particular, Sparks data shows a longer decay. According to the plot, Sparks runoff in any given year has significant correlation to runoff 5 years ago. Plots indicate that ~42% (~32%) of the variability of runoff at Sparks (Verdel) (obtained by taking the square of r(1) in both gages), in any given year can be attributed to previous year's runoff amount. This suggests that in a climatologically dry year, flow could still be above average, if flow in the past couple years were high. Hence, one could postulate a functional form for annual runoff in the Niobrara River as:

$$Q = f(S; P - E) \qquad (3)$$

where S is a storage term and P-E is effective change in storage in the vertical direction. This formulation is further explored in the hydrological modeling section of this report.

Some important findings of the above work are summarized as follows:

1. Annual runoff of the Niobrara River shows limited correlation to annual precipitation.
2. At the Sparks gage, less than 20% of the variability in historical annual runoff can be explained by annual precipitation. When the data is separated before and after 1964, annual precipitation explained approximately 30% of the variability in annual runoff. At the Verdel gate annual precipitaiton explained approximately 27% of the variability in observed annual runoff.
3. The runoff ratio at the Sparks gage was reduced 12.95% after 1964 likely due to increased water diversions. For a given amount of precipitation, the fraction of that precipitation forming runoff was 12.95% (on average) less than what it was before.
4. Annual runoff analysis confirmed that a reduced runoff ratio is indicative of statistically significant differences in annual runoff before and after 1964 at the Sparks gage, while there is no statistically significant change in annual precipitation in these periods.

### 3.2.2. Changes in Annual Runoff Along the Niobrara River Main Stem

Man made hydraulic structures and water diversions along rivers may impact water accumulation. Changes in the mean annual discharge, and the $20^{th}$ and $80^{th}$ percentile values of mean daily discharges were examined along the main stem of the Niobrara River. For this we used the following streamflow gages from the headwaters to the outlet respectively: WY-NE state border, Agate, Above and Below Box Butte Reservoir, Dunlap, Haysprings, Gordon, Cody, Sparks, Norden, Mariaville, and Verdel (Table 3). The mean annual data is presented in Figure 21.

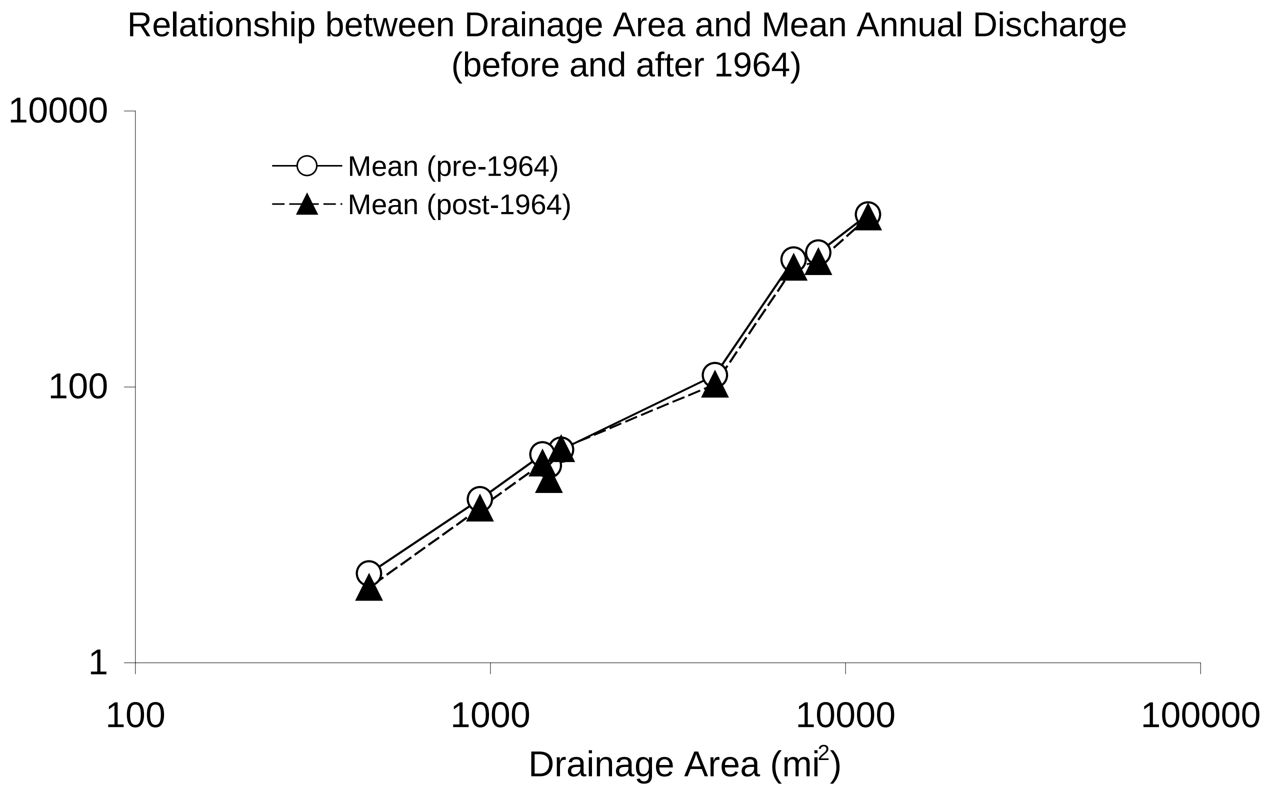



**Figure 21.** Mean annual discharge (MAD) plotted as a function of drainage area for the periods of before and after 1964. In the plot stations with data records only for one of the periods were excluded from the analysis.

In Figure 21, the mean annual discharge grows consistently with drainage area in all stations. For all gaging stations, the mean of the pre-1964 period always plots higher than the post-1964 period. To better examine this difference, percent change of MAD at each station in Figure 21 were calculated as:

{(MAD before 1964 – MAD after 1964) / (MAD before 1964)} x 100

and presented in Figure 22. Note that in this calculation positive values suggest flow reduction. In the plot except for the streamflow gage near Dunlap, NE (ID 06455900), all other stations experienced reductions in the mean annual discharge after 1964. The subtle increase in mean annual discharge at the Dunlap station might be related to either the very short time period of gaging until 1971, or the return flow from irrigations upstream. Change in Verdel was also very subtle. This may be due to the limited data available prior to 1964 at this station. Despite these two gages, others showed decreases between 10 – 20 % of the mean annual discharge.

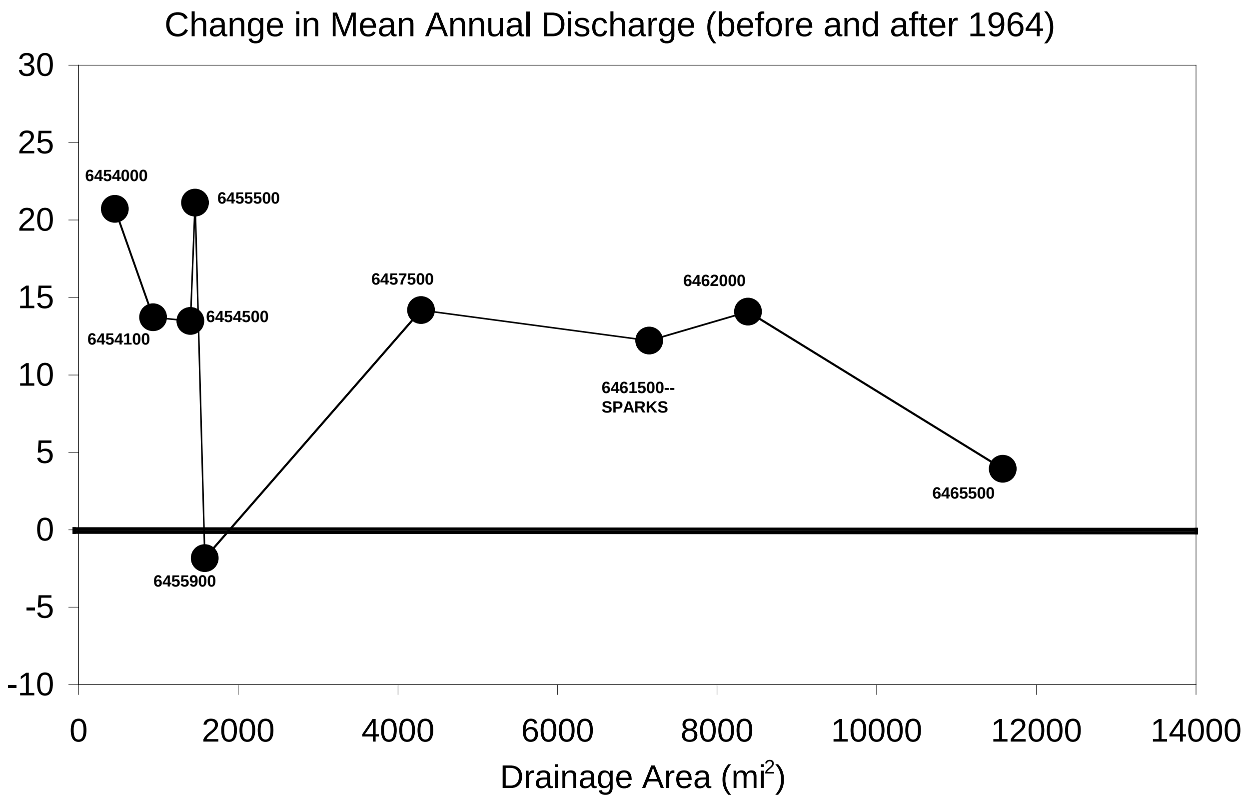



**Figure 22.** Percent change in mean annual discharge (MAD) along the main stem of the Niobrara.

## 4. Monthly Flow Analysis

In addition to the analyses presented for the two major gages on the Niobrara River, basic annual and monthly flow statistics (mean, median, standard deviation, minimum and maximum) are calculated for all streamflow gages using the NHAT software (Henriksen et al., 2006). Different flow time profiles such as before and after 1964 (if data available) were developed and analyzed separately for basic statistics. Streamflow data used in the analysis and NHAT results are presented in the "Flow_Data_and_Analysis" folder . In this directory results from the NHAT software for each stream gage are placed in separate folders, identified by station names. The Flow_Data_and_Analysis folder also includes: Final summary statistics.xls, annual_percentile.xls, and monthly_percentiles_Stationname.xls speadsheets prepared in excel. "Final summary statistics.xls" reports annual, monthly, daily flow statistics prepared using the mean daily streamflow data, and "percentile.xls" reports the 20$^{th}$ and 80$^{th}$ percentiles of the time series of the mean daily flow records. These statistics are also reported in the ArcGIS project file. Percentiles of mean daily flow data for each month are reported in for Sparks and Verdel gages in the folder.

Below are the NHAT output files contained in each stream gage folder:

Daily flow.csv: Mean daily flow for each station.

Stats.csv: Basic statistics of mean daily flows.

Skewness.csv: Hydrological indices for skewness: MA40, MA 45 (Henriksen et al., 2006).

Annual average.csv: Annual average flow (cfs) for each year.

Annual average stats.csv: Summary statistics of annual average flows for each time profile.

Monthly average.csv: Montly average flow (cfs) (mean flow for each month of each year).

Monthly average stats.csv: Summary statistics of monthly average flows.

Annual max.csv, Annual min.csv, monthly max.csv, monthly min.csv are maximum and minimum of mean daily flows in each recorded year and month.

Indices 1.csv: Hydrological variability indices calculated by HIAS. These maybe selected by user. We calculated the following indices and included in the folder for each station: MA5, MA6, MA9, MA37, MA38, MA43, ML1-ML12, ML13, ML15, ML17. The indices are based on Olden and Poff (2003), and their definitions, taken from (Henriksen et al., 2006), are given in the Appendix section. Only for Sparks and Verdel gages are all 171 hydrologic indices calculated.

In addition to the .csv files above, which are created by NHAT, there are two other folders "daily for month" and "daily for month stats" in the Flow_Analysis/Monthly Analysis directory on the CD. Mean daily flow values used in the analysis for each station are included in the "daily for month" folder. Basic statistics calculated for each month separately are given in the "daily for month stats" folder.

Below are the steps to conduct monthly flow analysis using HIAS are given:

Software analysis:

- Click on the File tab and create a new project.
- Click on the Data management tab and import the corresponding USGS discharge flow file.
- Check whether the data set is created or not by clicking on the edit data set tab.
- Click on the time period analysis tab to create time profiles and to compute hydrologic indices.
- Since we are required to analyze the gage stations before 1964 and after 1964, we created a time profile from the starting date to 1964 named "profile 1" and 1964 to ending date named "profile 2" .
- Click on the "graph time period data" in time period analysis tab to create the required graphs.

- By pointing the cursor on the monthly average values, we can create monthly average values for the time profiles. Export the values and statistics using the export key. By pointing the cursor on 'daily for month', we compute the means for each month over the entire flow record.
- Values for each of these indices are written as outputs by the software with their respective file names.
- Once the calculations are done, we created the graphs (Mean, Median and standard deviation) using Excel sheet for the required gage stations.

Interpretation of the majority of the indices calculated by the NHAT software require a detailed understanding of the stream. Therefore in this report annual and monthly statistics of mean daily streamflow are presented and discussed. The above mentioned NHAT indices for flow variability were calculated for each streamflow gage and available for future interpretations. However these did not deemed necessary for the initial understanding of the behavior of the Niobrara River.

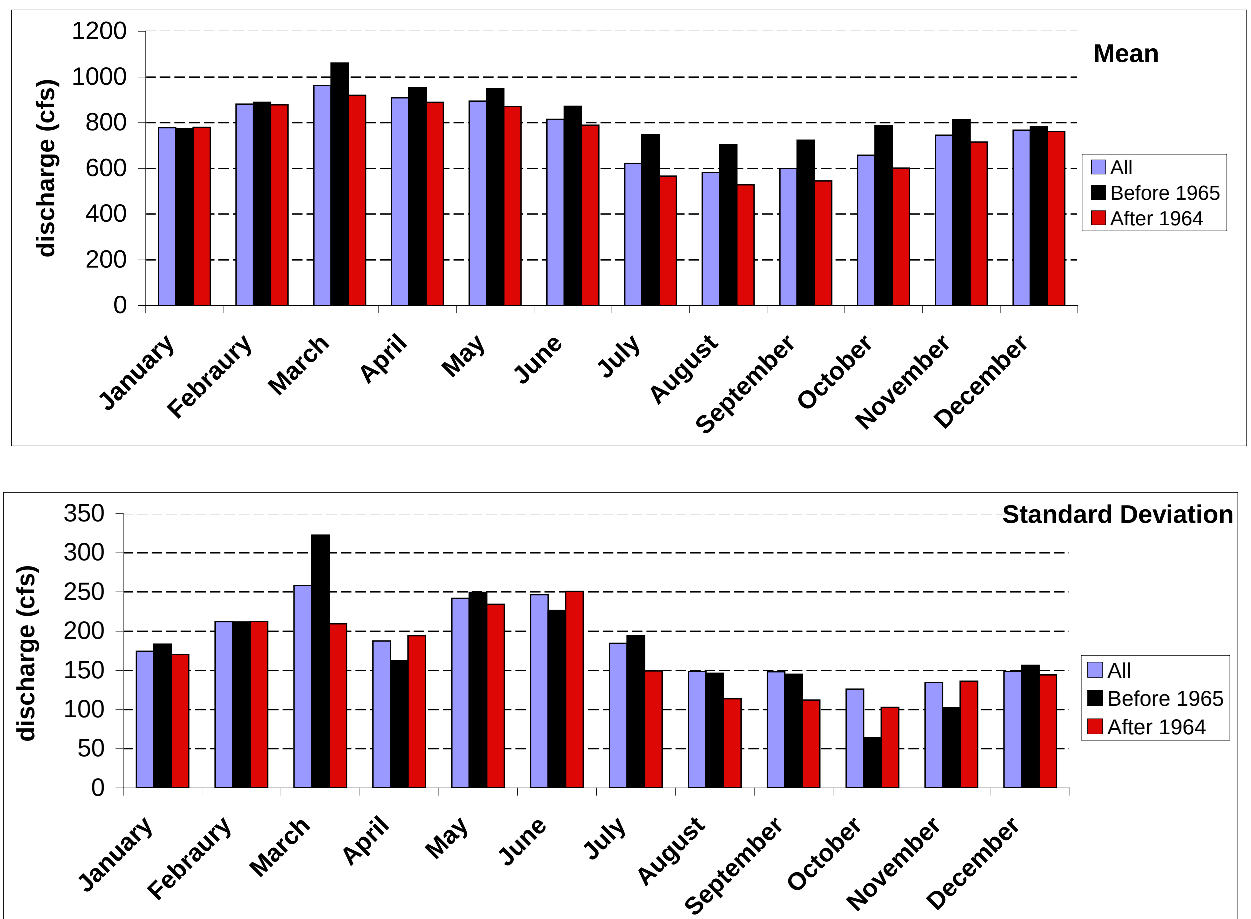



**Figure 23.** The monthly mean and standard deviation of mean daily flows at the Sparks gage.

In regard to the monthly flow results for Sparks and Verdel. Here only the mean and standard deviation of daily flows in each month are plotted to illustrate the flow trends at the Sparks (Figure 23) and Verdel gages (Figure 24) for time profiles before 1964 (includes 1945-1964 for Sparks and 1957-1964 for Verdel) and after 1965 (1965-2007) for both gages.

Mean daily flows at Sparks declined from "before 1964" time period to "after 1965" in all months except January in which only 0.75% increase was observed. The highest decline (up to 25%) occurred in the summer and early fall months as follows: June 9.5%, July 24.4%, August 25%, September 24.7%, October 23.6%. March flows were also reduced significantly up to 13.3%. Standard deviations of the mean daily flows in each month were also altered following developments in the basin. In July, standard deviation of the mean daily flows was reduced by 23%, followed by 22.7% in September and 22.1% in August. In March the standard deviation was also reduced 35%, marking the highest reduction on record.

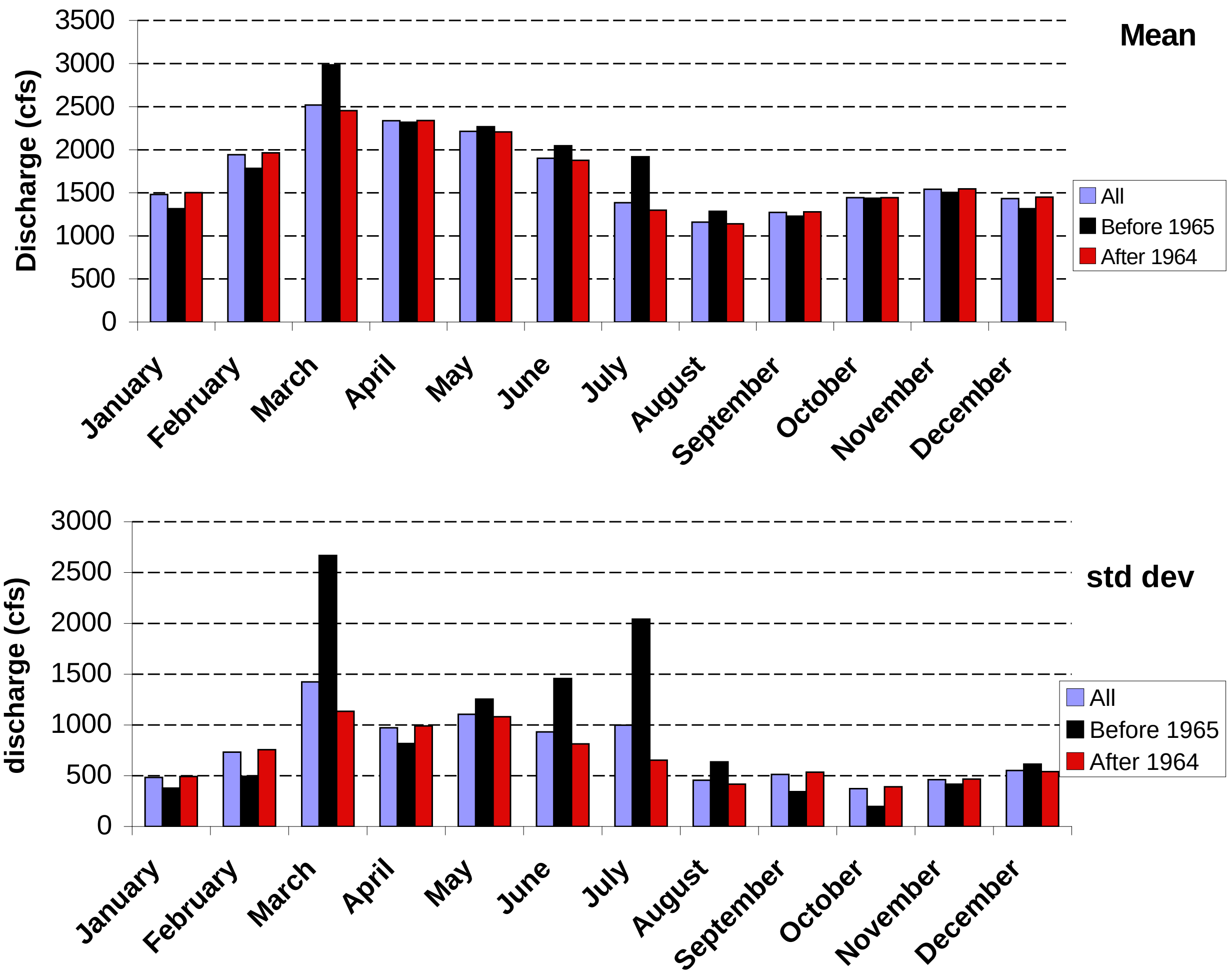



**Figure 24.** The monthly mean and standard deviation of mean daily flows at the Verdel gage for the period of record 1957-2007.

The mean daily flows at Verdel (Figure 24) decreased after 1964 from May to the end of August (maximum decline in July ~ 32%) and in March (17.8%). The impact of water diversion on standard deviation was more pronounced with up to 68% decline in July. The reduction in summer flows were much less at Verdel than at Sparks between the time periods.

In addition to changes in flow discharge in stream gages as a result of water diversion in the basin, comparison of flow records that correspond to the same time period along the stream channel also gives useful information about water diversions between two stations. The figure below shows mean monthly flows for above and below Box Butte gages. Clearly almost all the river flows from July to December, and the majority of the flows from January to March are stored in the Box Butte reservoir (Figure 25).

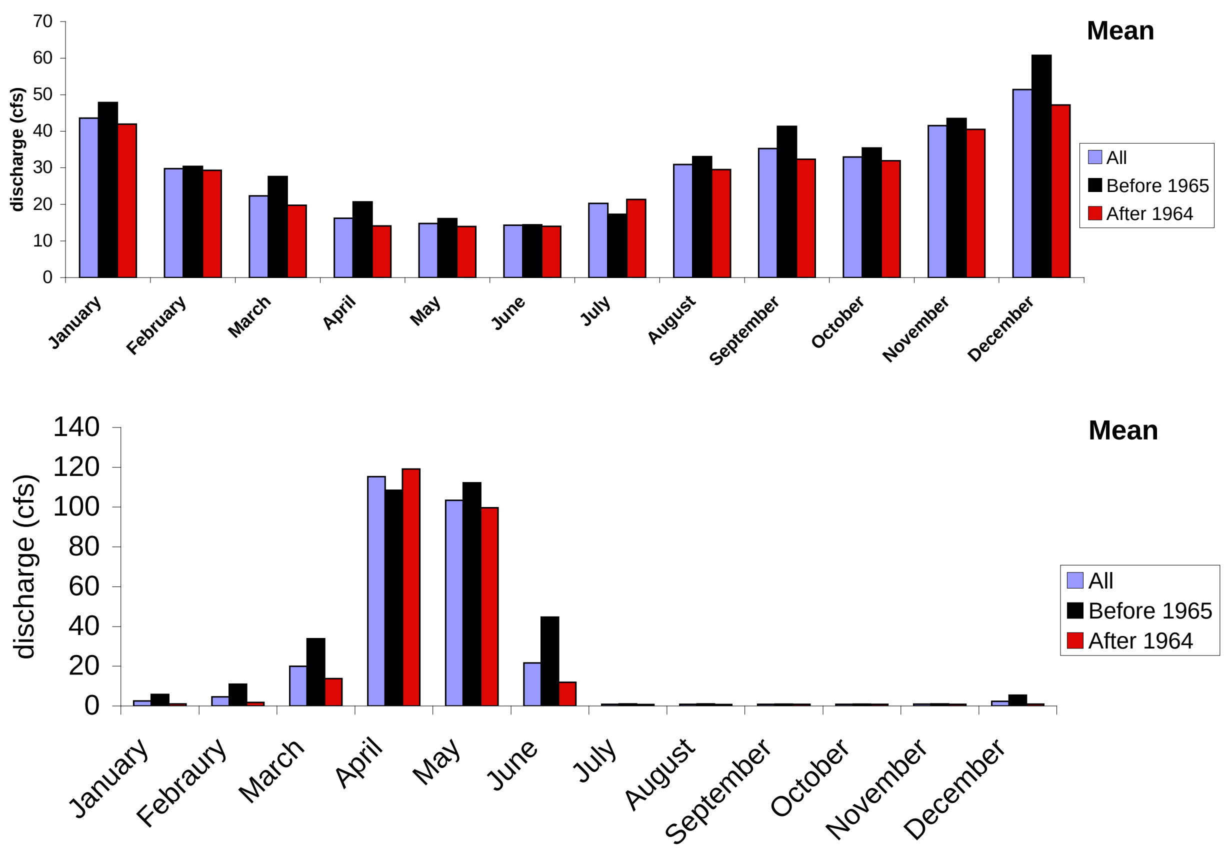



**Figure 25**. Mean monthly flows above (top) and below (bottom figure) the Box Butte gages.

As a more pronounced response was observed in Sparks than Verdel, the mean of daily flows for each day of the year, as well as percent changes in the mean daily flows at the Sparks gage in periods before 1964 and after 1965 were plotted to illustrate the trends (Figure 26). From July to the end of September daily flows were, on average, 30% lower than the pre-development period. There is also a significant reduction in March. Time series of mean monthly rate of diversion (cfs) and streamflow discharge at Sparks (cfs) is given in Figure 27. Figure 28 depicts stream flow at Sparks as a function of mean monthly total upstream diversions.

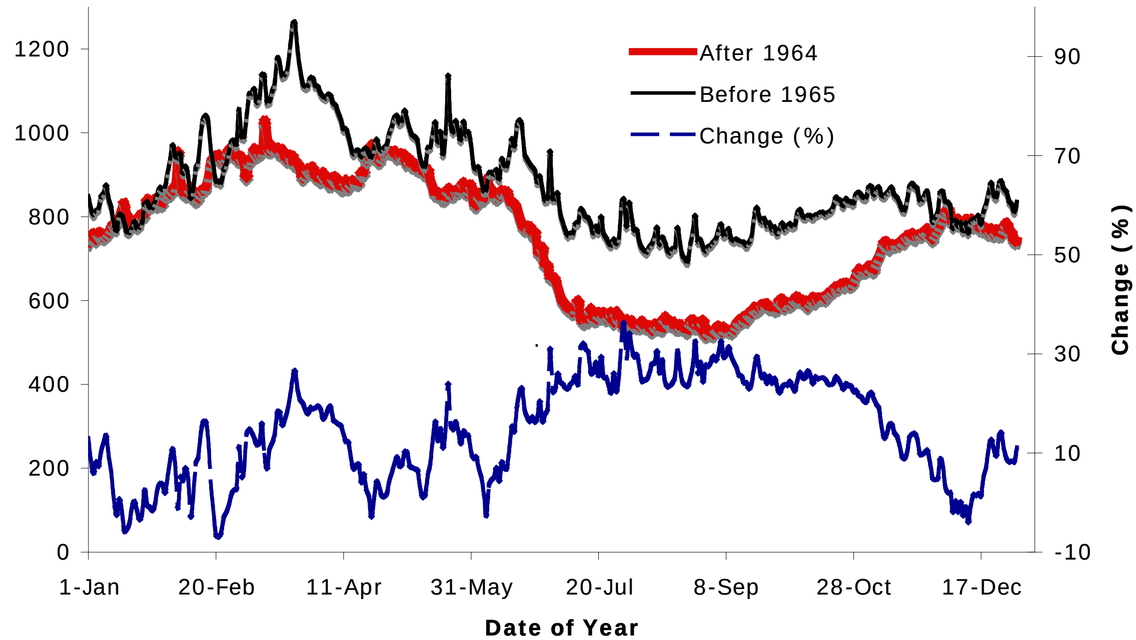



**Figure 26**. Mean daily flows before and after 1964. Data used to plot this figure is included in the Flow Analysis folder, file name "sparks-mean daily data.xls

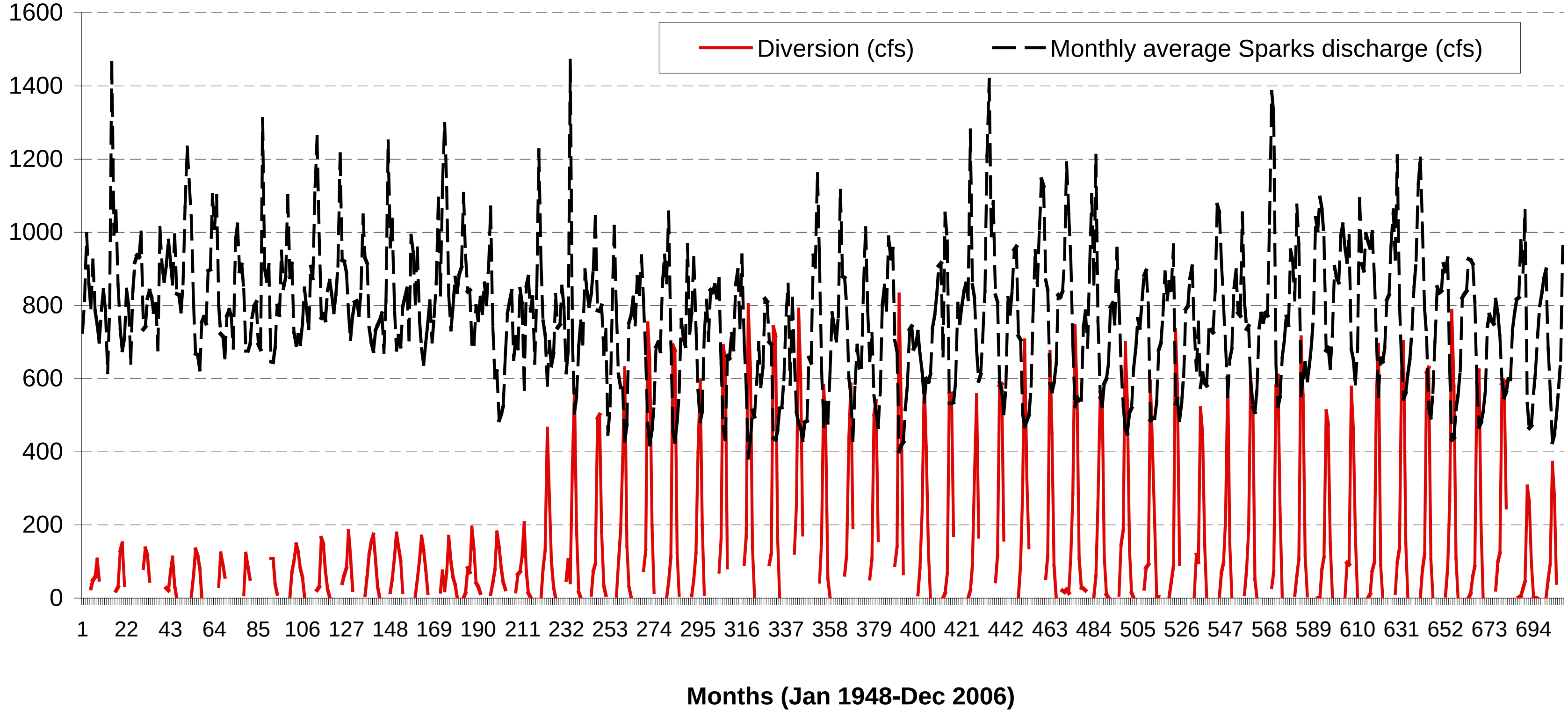



**Figure 27.** Time series of mean monthly stream flow diversion from the Niobrara River above the Sparks gage, and mean monthly discharge at the Sparks gage from January 1948 to December 2006.

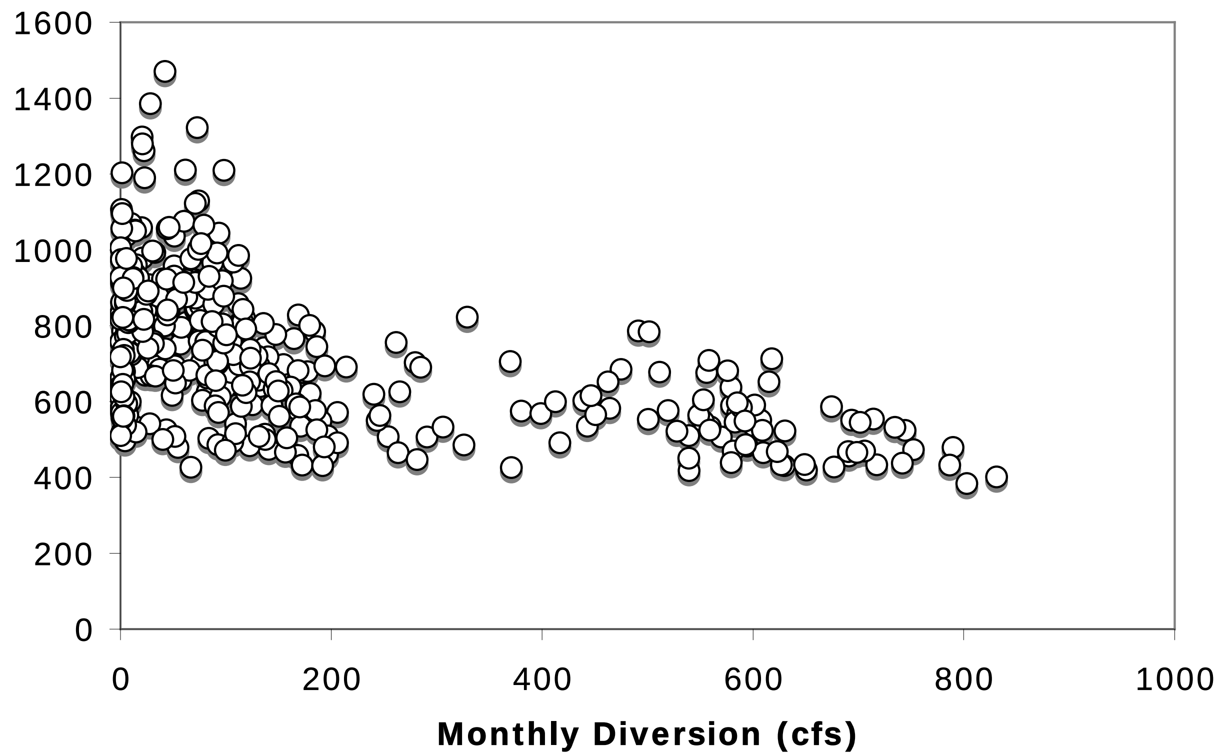



**Figure 28.** Mean monthly streamflow discharge at Sparks plotted against monthly total diversion data at the upstream of the Sparks gage.

In Figure 27, mean monthly streamflow is lowered significantly with the growth of upstream diversion around month 211 which corresponds to year 1965. Figure 28, however, does not support a strong dependence between mean monthly streamflow and total monthly diversion for values of diversion higher than approximately 200 cfs, while streamflow seems to decrease for lower values of diversion. It is important to note that when diversion is larger than 200 cfs, variability of mean monthly streamflow is reduced and most values converge to a constant lower-end flow rate. This point requires both climatological and hydrological considerations before a conclusion can be made.

## 5. Daily Flow Frequency Analysis

Daily flow records were used to calculate the exceedance probabilities (the probability that a given flow will be exceeded in a given day, $P(Q \geq q)$), and the expected number of days that a given flow will be exceeded $N_d(Q \geq q) = T_s \cdot P(Q \geq q)$, where $T_s$ is the length of the season considered. For annual analysis $T_s$ is 365. In this analysis, empirical probabilities of daily flows were calculated using the Weibull plotting position (Benjamin and Cornell, 1970). In this technique, daily flow data is ranked in ascending order. A number from 1 to N, where N is the size of the flow population, is assigned to each ranked flow data. The minimum flow data has a rank value of 1 and the maximum flow data N. The Weibull plotting position gives the cumulative probability as

$$P(Q \leq q) = \frac{n}{N+1} \qquad (4)$$

where n is the rank value of the flow data, N is the sample size. The exceedance probability, that is the probability that a selected flow rate q will be exceeded is

$$P(Q > q) = 1 - P(Q \leq q) = 1 - \frac{n}{N+1} \qquad (5)$$

with this, the expected number of days flow will exceed q is:

$$N_d(Q > q) = T_s \cdot P(Q > q). \qquad (6)$$

The method described above had been used in flow frequency analysis in the literature (e.g., Malamud and Turcotte, 2006; Molnar et al., 2006).

The flow analysis described above was repeated for three periods. First the entire flow record available for each stream gage was used to develop a pre- and post -development scenario. That is, flows before and after 1965 are separated into two groups and the exceedance probabilities (equation 5) and number of days with flows less than a selected q (equation 6) calculated. Second the analysis above was repeated for a 6-month summer and spring (May to October) and a 3-month summer (June-August) period. In these calculations MATLAB was used. The computer code written to perform these analyses is presented in the Appendix. In the code both $P(Q \geq q)$ and $N_d(Q \geq q)$ are calculated for each data point. Then, for presentation purposes, discharge values q were selected for a given $N_d(Q \geq q)$. These values are reported for each station in the CD (Flow Data and Analysis/Frequency Analysis). When the flow record is not sufficient to separate before and after development periods, the entire record is used as one population.

The results of the frequency analyses are provided in the "Flow Analysis/Frequency Analysis" directory available on the CD. In this directory, a folder is developed for each station, which also contains three more folders named as "entire", "after 1965", and "before 1965". In these folders we include MATLAB plots, developed for annual, 6-month, and 3-month time period analysis for the "entire", "after 1965", and "before 1965" time profiles. For each time profile, the mean daily flow data is also included for future use. The Flow Analysis/Frequency Analysis directory also contains MATLAB scripts written for probability calculations; mean daily flow data; the base data used for analysis (from NHAT); and finally, the summary results for all the frequency analyses conducted for that station in Excel spreadsheet format (results.xls) .

Results.xls contains three Excel Worksheets: "entire", "before 1965", and "after 1965", which present the frequency analysis output from MATLAB that includes the number of days a certain mean daily flow is expected to exceed during the entire year, 6-month summer and spring, and 3-month summer periods. This data was used to investigate the influence of water storage and diversions in the basin to flow variability.

While the analysis provided in the CD would allow for comparing flow variability in the streamflow gages throughout the basin, results are only demonstrated for the Sparks (Figure 29) and Verdel (Figure 30) gages. Tables 2 and 3 report the numeric values used in the plots. The data was separated into before and after 1965. Here 1965 is selected as the separation year, as the diversion records show a rapid increase starting with 1965 (Figure 4).

In Figure 29, the before 1965 period data plots above the after 1965 period for all three time periods considered (except one flow in the annual plot). This suggests that the number of days any given flow (on x-axis) is exceeded in the river was higher in the before 1965 period than in the after 1965 period. The separation between the two curves becomes more pronounced in the 6-month (spring to fall) and the 3-month (summer) period. In the summer period, the reduction in flow discharge for a given duration is on average 17.8%, and goes as high as 29% during low flows (Table 2).

At the Verdel gage, the low flows were not altered significantly with increased water diversions. However, the magnitude of the flows that occur less than 10 days a year decreased very significantly up to 50% for the flows that are observed one day a year (Figure 28).

It is important to note that the MATLAB codes can be used to calculate the expected number of days a specified flow is exceeded at a stream gage by providing the number of days (of choice) in the S array.

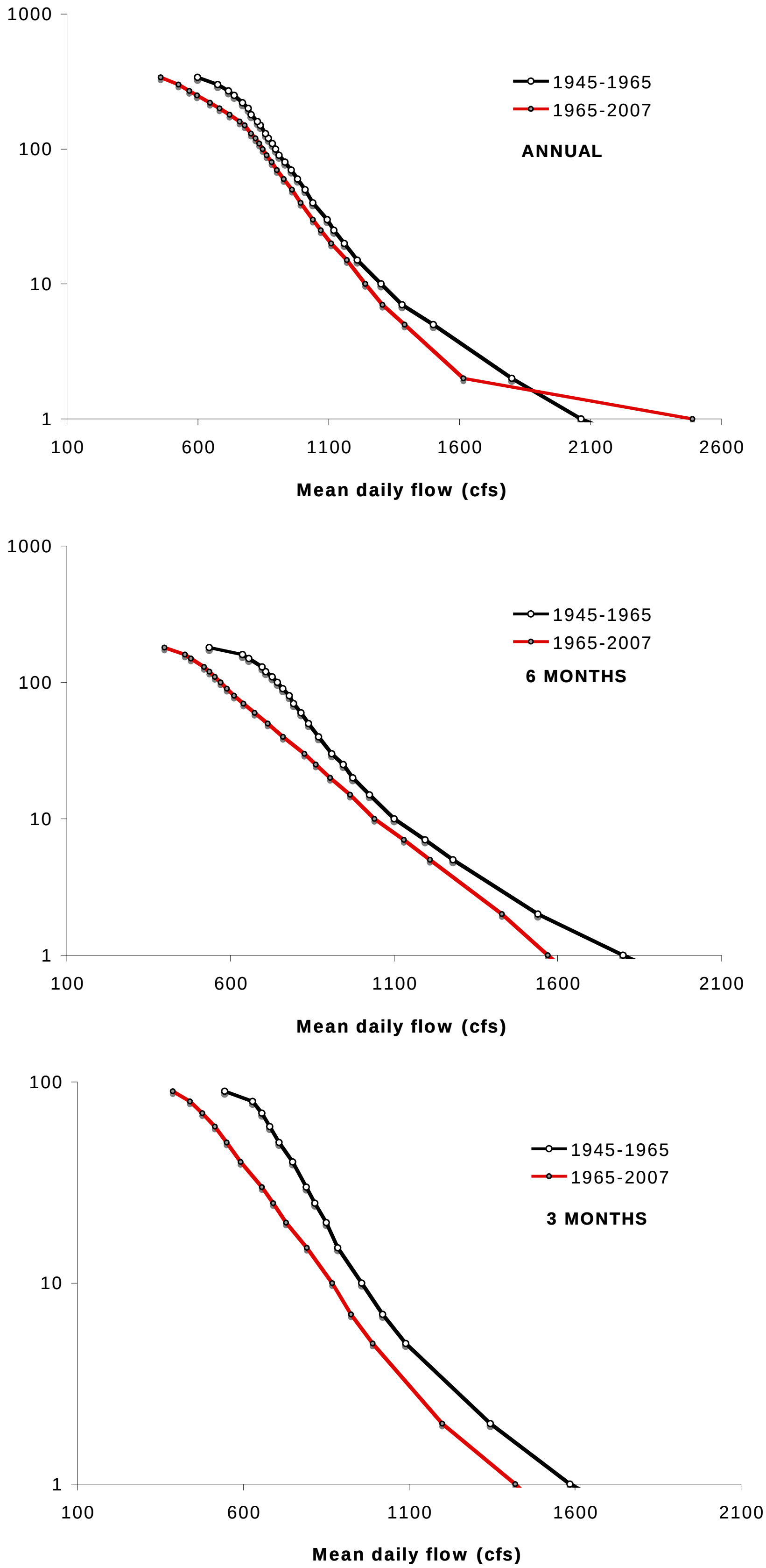



**Figure 29**. Expected number of days of exceedance of a given flow rate at Sparks for the entire year, 6-month (May-October) and 3-month (June-August) periods.

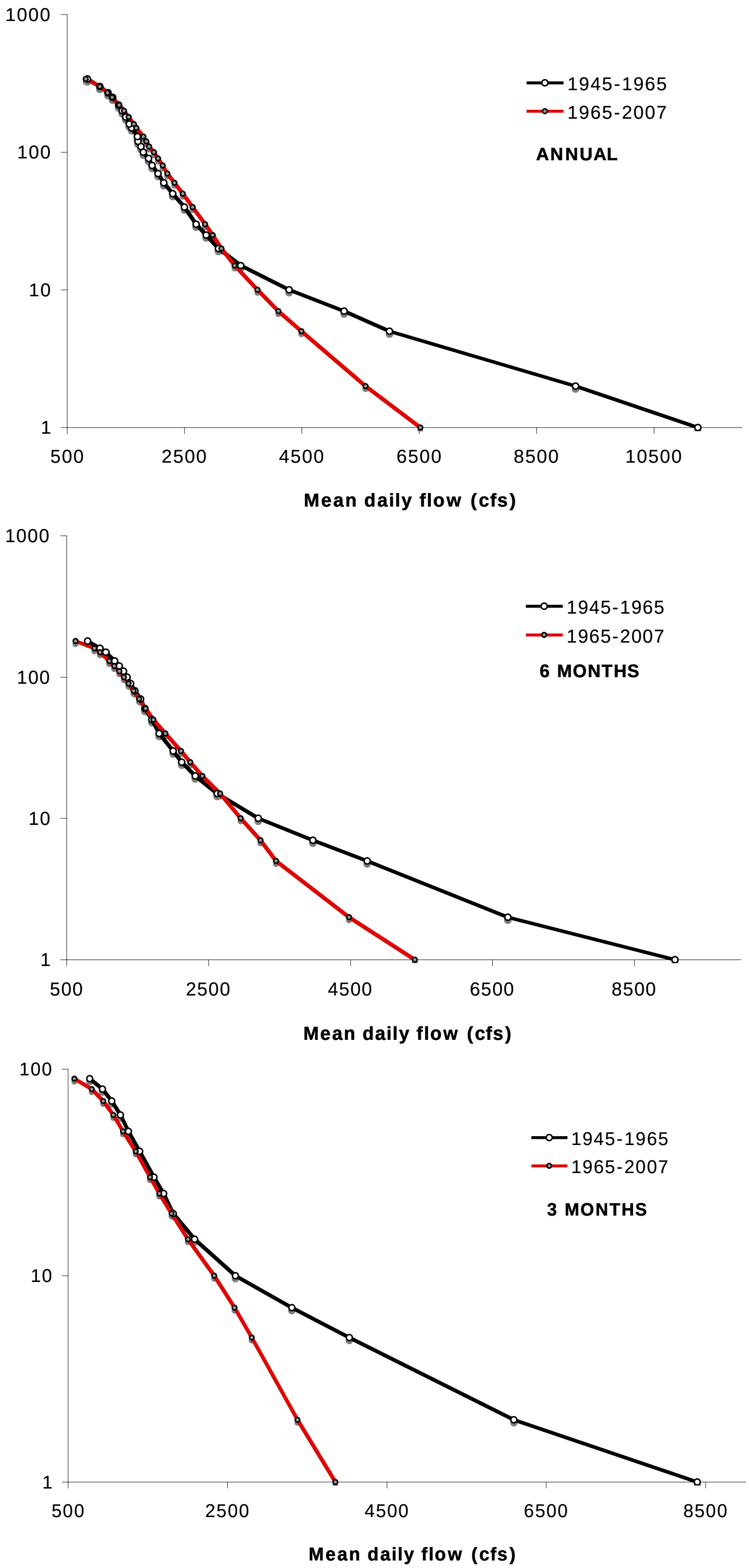


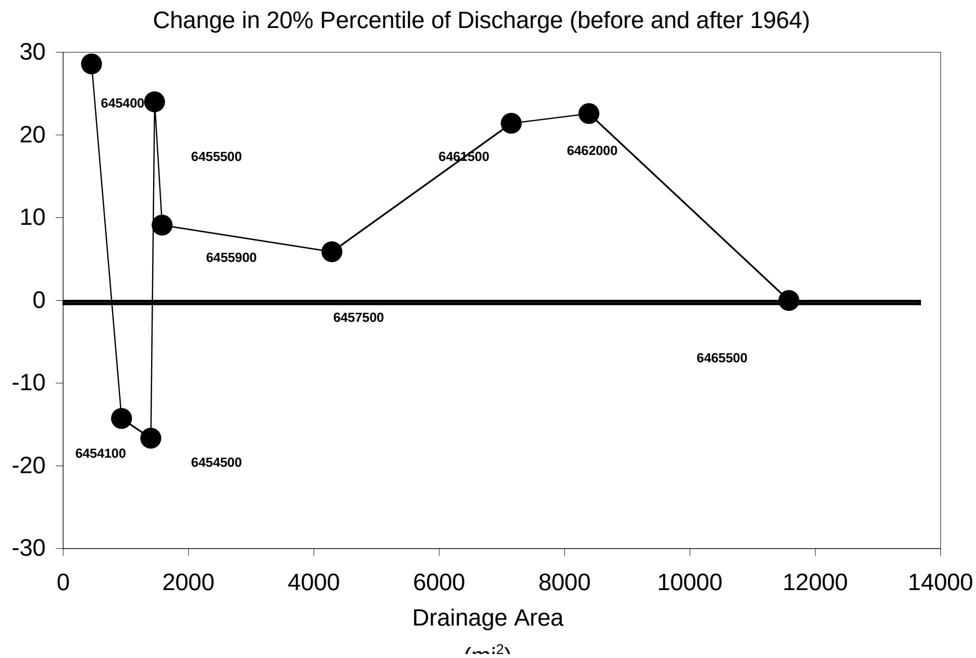

**Figure 30.** Expected number of days of exceedance of a given flow rate at Verdel for the entire year, 6-month (May-October) and 3-month (June-August) periods.

**Table 2.** Expected days of flow exceedance at the Sparks gage before and after 1965. Percent difference is calculated by subtracting flow before 1965 from flow after 1965 and dividing it by the flow before 1965, and multiplying the product by 100.

| Number of Days flow is Expected to Exceed | Annual data | | | 6 months (spring+summer) | | | 3 months (summer) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Before 1965 Q (cfs) | After 1965 Q (cfs) | Difference % | Before 1965 Q (cfs) | After 1965 Q (cfs) | Difference % | Before 1965 Q (cfs) | After 1965 Q (cfs) | Difference % |
| 1 | 2065 | 2490 | -20.58 | 1800 | 1570 | 12.8 | 1585 | 1420 | 10.4 |
| 2 | 1800 | 1615 | 10.3 | 1540 | 1430 | 7.1 | 1345 | 1200 | 10.8 |
| 5 | 1500 | 1390 | 7.3 | 1280 | 1210 | 5.5 | 1090 | 990 | 9.2 |
| 7 | 1380 | 1305 | 5.4 | 1195 | 1130 | 5.4 | 1020 | 924.5 | 9.4 |
| 10 | 1300 | 1240 | 4.6 | 1100 | 1040 | 5.5 | 957 | 868 | 9.3 |
| 15 | 1210 | 1170 | 3.3 | 1025 | 966 | 5.8 | 885 | 791.5 | 10.6 |
| 20 | 1160 | 1110 | 4.3 | 974.5 | 905 | 7.1 | 850 | 729 | 14.2 |
| 25 | 1120 | 1070 | 4.5 | 945 | 861 | 8.9 | 816 | 690 | 15.4 |
| 30 | 1095 | 1040 | 5.0 | 910 | 826 | 9.2 | 790 | 656 | 17.0 |
| 40 | 1040 | 993 | 4.5 | 870 | 761 | 12.5 | 749 | 592 | 21.0 |
| 50 | 1010 | 960 | 5.0 | 839 | 714 | 14.9 | 708 | 550 | 22.3 |
| 60 | 981 | 928.5 | 5.4 | 816 | 674 | 17.4 | 680 | 514 | 24.4 |
| 70 | 957 | 902 | 5.7 | 793 | 640 | 19.3 | 656 | 476.5 | 27.4 |
| 80 | 933 | 882 | 5.5 | 780 | 611 | 21.7 | 628 | 440 | 29.9 |
| 90 | 910.5 | 863 | 5.2 | 760 | 589 | 22.5 | 544 | 388 | 28.7 |
| 100 | 897 | 848 | 5.5 | 744 | 570 | 23.4 | | | |
| 110 | 885 | 835 | 5.6 | 728 | 552 | 24.2 | | | |
| 120 | 870 | 820 | 5.7 | 708 | 536 | 24.3 | | | |
| 130 | 859 | 803 | 6.5 | 697 | 519 | 25.5 | | | |
| 150 | 839 | 779 | 7.2 | 656 | 479 | 27.0 | | | |
| 160 | 828 | 760 | 8.2 | 637 | 461 | 27.6 | | | |
| 180 | 804 | 721 | 10.3 | 535 | 398 | 25.6 | | | |
| 200 | 793 | 683 | 13.9 | | | | | | |
| 220 | 771 | 646 | 16.2 | | | | | | |
| 250 | 739 | 597 | 19.2 | | | | | | |
| 270 | 717 | 567 | 20.9 | | | | | | |
| 300 | 676 | 526 | 22.2 | | | | | | |
| 340 | 599 | 458 | 23.5 | | | | | | |

**Table 3.** Expected days of flow exceedance at the Verdel gage before and after 1965. Percent difference is calculated by subtracting flow before 1965 from flow after 1965 and dividing it by the flow before 1965, and multiplying the product by 100.

| Number of Days flow is Expected to Exceed | Annual data | | | 6 months (spring+summer) | | | 3 months (summer) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Before 1965 Q (cfs) | After 1965 Q (cfs) | Difference % | Before 1965 Q (cfs) | After 1965 Q (cfs) | Difference % | Before 1965 Q (cfs) | After 1965 Q (cfs) | Difference % |
| 1 | 11250 | 6520 | 42.04 | 9070 | 5405 | 40.41 | 8395 | 3855 | 54.08 |
| 2 | 9165 | 5585 | 39.06 | 6715 | 4480 | 33.28 | 6095 | 3380 | 44.54 |
| 5 | 5995 | 4495 | 25.02 | 4735 | 3450 | 27.14 | 4030 | 2805 | 30.40 |
| 7 | 5220 | 4100 | 21.46 | 3970 | 3230 | 18.64 | 3310 | 2590 | 21.75 |
| 10 | 4285 | 3745 | 12.60 | 3200 | 2950 | 7.81 | 2600 | 2335 | 10.19 |
| 15 | 3460 | 3355 | 3.03 | 2620 | 2660 | -1.53 | 2090 | 2005 | 4.07 |
| 20 | 3080 | 3130 | -1.62 | 2310 | 2410 | -4.33 | 1820 | 1800 | 1.10 |
| 25 | 2870 | 2980 | -3.83 | 2120 | 2240 | -5.66 | 1700 | 1645 | 3.24 |
| 30 | 2700 | 2850 | -5.56 | 2000 | 2110 | -5.50 | 1580 | 1530 | 3.16 |
| 40 | 2500 | 2640 | -5.60 | 1800 | 1890 | -5.00 | 1400 | 1350 | 3.57 |
| 50 | 2300 | 2470 | -7.39 | 1700 | 1720 | -1.18 | 1260 | 1190 | 5.56 |
| 60 | 2150 | 2330 | -8.37 | 1600 | 1610 | -0.63 | 1160 | 1070 | 7.76 |
| 70 | 2050 | 2210 | -7.80 | 1540 | 1520 | 1.30 | 1050 | 944 | 10.10 |
| 80 | 1950 | 2130 | -9.23 | 1460 | 1440 | 1.37 | 935 | 800 | 14.44 |
| 90 | 1890 | 2050 | -8.47 | 1400 | 1370 | 2.14 | 772.5 | 579 | 25.05 |
| 100 | 1800 | 1980 | -10.00 | 1350 | 1305 | 3.33 | | | |
| 110 | 1760 | 1900 | -7.95 | 1300 | 1240 | 4.62 | | | |
| 120 | 1710 | 1850 | -8.19 | 1240 | 1170 | 5.65 | | | |
| 130 | 1700 | 1800 | -5.88 | 1175 | 1100 | 6.38 | | | |
| 150 | 1600 | 1680 | -5.00 | 1050 | 970 | 7.62 | | | |
| 160 | 1560 | 1640 | -5.13 | 970 | 892.5 | 7.99 | | | |
| 180 | 1500 | 1550 | -3.33 | 795 | 626.5 | 21.19 | | | |
| 200 | 1440 | 1470 | -2.08 | | | | | | |
| 220 | 1380 | 1390 | -0.72 | | | | | | |
| 250 | 1280 | 1270 | 0.78 | | | | | | |
| 270 | 1200 | 1190 | 0.83 | | | | | | |
| 300 | 1060 | 1060 | 0.00 | | | | | | |
| 340 | 848 | 820 | 3.30 | | | | | | |



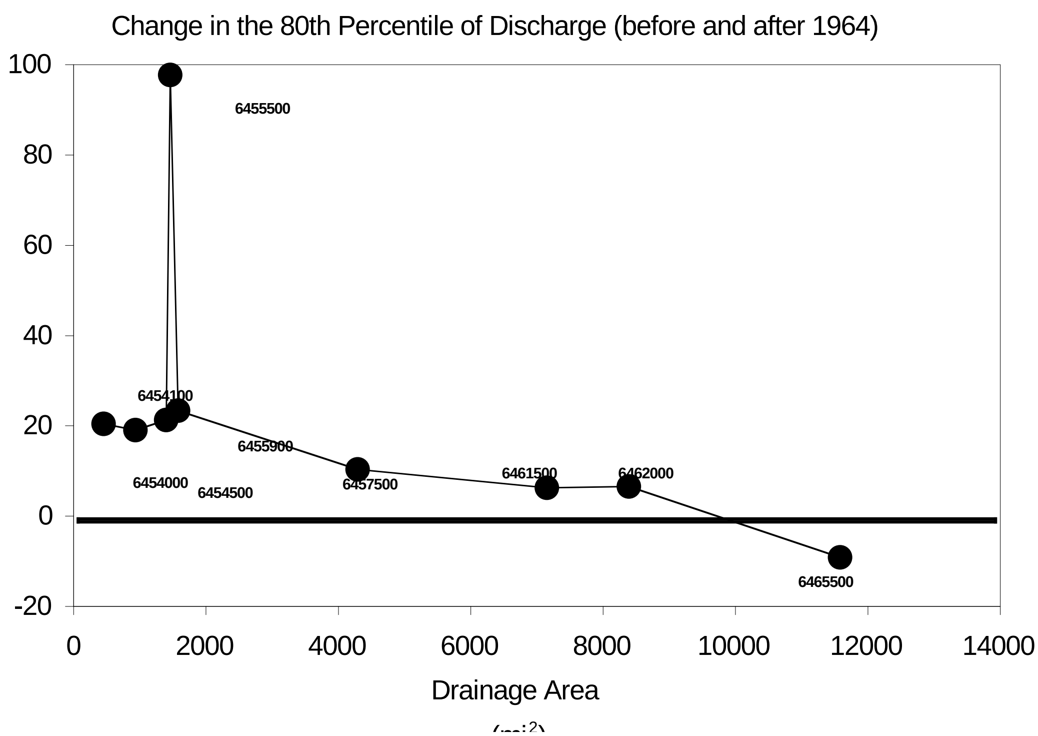




**Figure 31.** Change in the 20th and 80th percentile of mean daily flows along the Niobrara River.

To present a spatial context to changes in daily flows, changes in the 20th and 80th percentiles of mean daily flows were calculated as:

{(Percentile before 1964 – Percentile after 1964) / (Percentile before 1964)} x 100

and presented in Figure 31. In this figure stations used are same as those used in Figure 21 and 22.

Regarding the changes in 20th and 80th percentiles of mean daily discharges, most gaging stations also experienced reductions after 1964 (note that positive change means decrease in quantity in Figure 31). Particularly, for the station below the Box Butte Reservoir (e.g., ID is 06455500), the 80th percentile of discharge dramatically decreased from 56.8 to 1.3 cfs. This reduction might be caused by the Box Butte Reservoir.

## 6. Annual Water Balance Model for the Niobrara River

Annual water balance of a river basin can be written as:

$$P - ET - R = \Delta S \qquad (7)$$

where P, ET, and R are annual precipitation, evapotranspiration, runoff; and $\Delta S$ is change in storage, all in units of L/T (L: mm or inch, and T=year). The equation above does not include surface and groundwater diversions from the system. However these may be incorporated in some relevant forms depending on the description of the storage in the basin and time scales over which the equation is solved.

A general practice in the literature is to assume that over annual or longer time scales $\Delta S = 0$ [Zhang et al., 2001 and the references therein]. This leads:

$$P - ET - R = 0. \qquad (8)$$

With this assumption, basin-wide actual annual evapotranspiration can be calculated as a closure term in (8), $ET = P - R$ [e.g., Hobbins et al., 2001].

We will first examine if calculation of ET as a closure term in the water balance is relevant for the Niobrara River Basin. To proceed with this, first we will need to have independent annual actual evapotranspiration estimates. It has been observed that in climates where potential evapotranspiration ($ET_o$) largely exceeds annual precipitation (P), actual evapotranspiration (ET) approaches annual precipitation (P). This concept has been studied by classifying the climate using the so called aridity index ($\phi$) defined as (e.g., Arora, 2002):

$$\phi = \frac{E_o}{P} \qquad (9)$$

Climate is classified using the aridity index as (Ponce et al., 2000):
Humid: $0.75>\phi>=0.375$
Sub-humid: $2>\phi>=0.75$
Semi-arid: $5>\phi>=2$
Arid: $12>\phi>=5$

Thus, as aridity (humidity) decreases (increases):

$$\phi \rightarrow 0, \quad ET \rightarrow ET_o; \quad \frac{ET}{P} \rightarrow 0; \quad \frac{R}{P} \rightarrow 1 \qquad (10a)$$

while, as aridity (humidity) increases (decreases):

$$\phi \rightarrow \infty, \quad ET \rightarrow P; \quad \frac{ET}{P} \rightarrow 1; \quad \frac{R}{P} \rightarrow 0 \qquad (10b)$$

A number of equations have been proposed to relate $ET_a/P$ to aridity index, some of which are given below (see Arora, 2002 for references of each of the above equations):

$$\frac{ET}{P} = F(\phi), \qquad (11)$$

where F(ϕ):

Schreiber (1904): $F(\phi) = 1 - e^{-\phi}$ (12a)

Ol'dekop (1911): $F(\phi) = \phi \tanh(\frac{1}{\phi})$ (12b)

Budyko (1948): $F(\phi) = \left[\phi \tanh(\frac{1}{\phi})(1 - e^{-\phi})\right]^{1/2}$ (12c)

Zhang et al. (2001): $F(\phi) = \frac{1 + w\phi}{1 + w\phi + \phi^{-1}}.$ (12d)

where, w is plant-available water coefficient, and increases with vegetation density. Zhang et al (2001) found w=2 for forests, 0.5 for short-grass dominated catchments. With the F(ϕ) term obtained from one of the equations above, actual annual evapotranspiration and runoff can be calculated as a function of annual precipitation when ΔS=0:

$$ET = P \cdot F(\phi), \qquad (13a)$$

$$R = P \cdot [1 - F(\phi)]. \qquad (13b)$$

**Calculation of the Annual Aridity Index in the Niobrara River**

The first step in the procedure outlined above is to calculate the aridity index in the Niobrara River. To do that daily potential evapotranspiration is calculated using the the Priestly-Taylor equation with daily High Plains Regional Climate Center (HPRCC) weather data. The Priestly-Taylor equation predicts the wet-environment evapotranspiration rate, and traditionally preferred in aridity index calculations (Zhang et al., 2001).

$$ET_o = 1.26 \frac{\Delta}{\Delta + \gamma} \frac{R_N}{\lambda} \qquad (14)$$

Δ: slope of the saturation vapor pressure – temperature relationship (kPa $^oC^{-1}$);
$R_N$: net radiation at plant surface ($W/m^2$),
G is ground heat flux ($W/m^2$);
λ: latent heat of vaporization (28.34 Wd $m^{-2}$ $mm^{-1}$)

Daily values were added up to calculate annual evapotranspiration. Results for each station are provided in Hydromodel/Annual Potential ET. Combining all the HPRCC calculate $ET_o$ and annual precipitation data in the folder, we developed a relationship between aridity index and annual precipitation (Figure 32):

$$\phi = 3187.5 \cdot P^{-1.112} \qquad (15)$$

This relationship allows us to approximate annual evapotranspiration as a function of basin-average annual precipitation. Basin-averaged annual precipitation was used to calculate ϕ (eq. 15). Substituting eq. 15 into eq. 12d, $ET_a$ can be estimated as a function of annual precipitation.

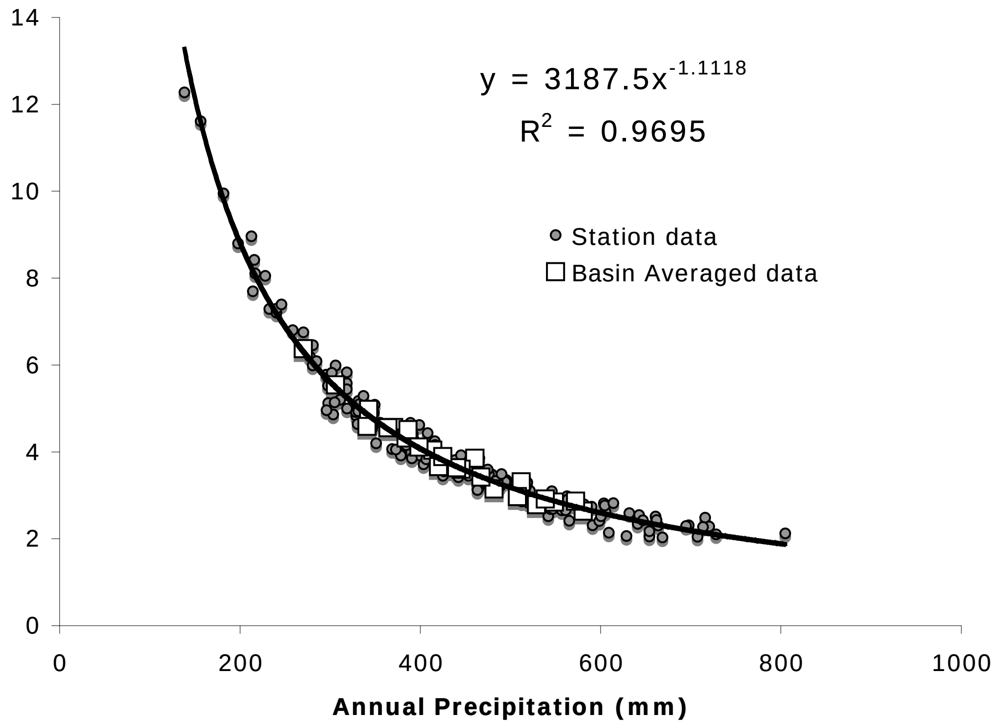



**Figure 32.** Aridity index plotted as a function of annual precipitation.

Differences between the water balance calculated $ET_a/P$ and that calculated by eq. 12 are examined. $ET_a$ is estimated as a closure term to water balance as, $ET_a$=P-R, for each year. The implicit assumption in this calculation is that change in basin water storage is negligible. In closing the water balance, irrigation water diverted from the system is added back to annual runoff. Figure 33 presents estimated $ET_a/P$ from water balance as a function of $\phi$, as well as the $ET_a/P$-$\phi$ curves plotted using the Zhang et al. (2001) equation. Interestingly, annual data of the Niobrara River shows an opposite trend with respect to the theoretical curves that are based on the assumption of no inter-annual change in the water storage in the basin. Figure 33 suggest that in dry years, the actual evapotranspiration to annual precipitation ratio decreases in the basin. This implies that because there is little fluctuation in the river discharge from one year the next, during dry years, $ET_a$ estimated as a closure term drops as reduction in precipitation is much larger than reduction in the annual flow.

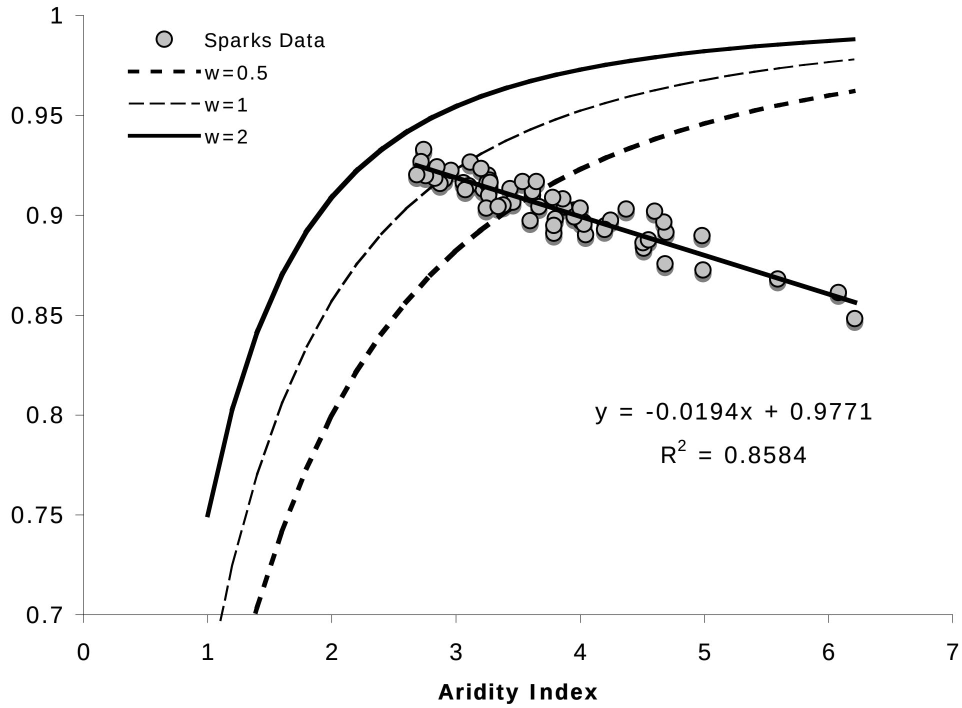



**Figure 33.** $ET_a$ estimated as a closure term to water balance (normalized with annual precipitation) as a function of Aridity index calculated for each year. Lines plot the Zhan et al. 2001 equation that gives the fraction of annual precipitation partitioned to $ET_a$.

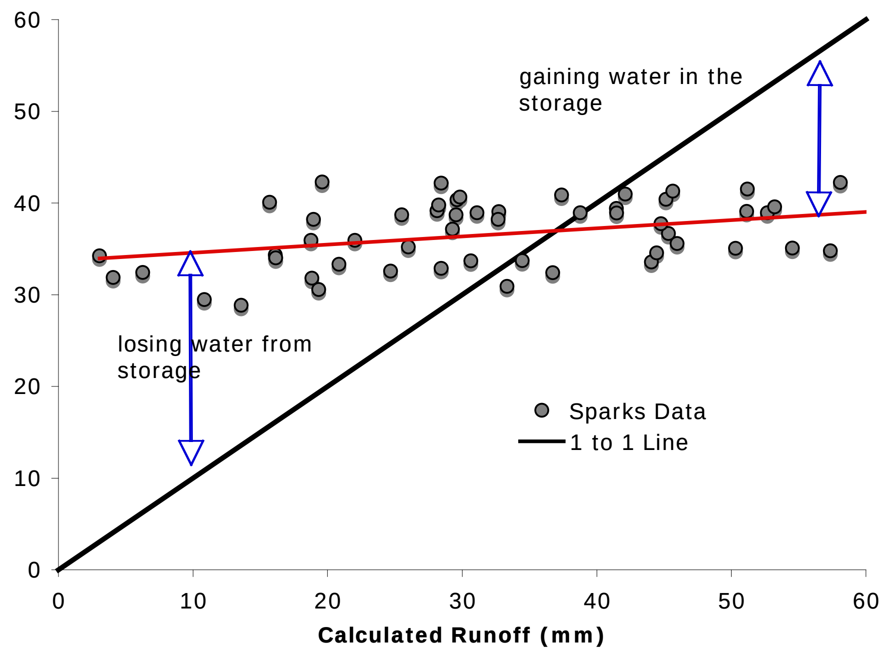



**Figure 34.** Calculated versus observed annual runoff in the Niobrara River.

Next runoff for each year is calculated using equation 13b for the Niobrara River basin above Sparks and plotted against observed annual runoff at Sparks (Figure 34). The poor prediction of the model is evident as the observed runoff deviates very significantly from the 1-to-1 curve. This led to the hypothesis that, to the extent that the actual evapotranspiration estimates are correct, a positive deviation from the 1-to-1 line in Figure 34 suggest that river is loosing water from storage, and a negative deviation suggests that the river is gaining water to storage. This hypothesis will need to be further elaborated with more field and modeling research.

**Storage-Dependent Annual Model**

A simplistic lumped annual water balance model was developed by adding a storage and water diversion terms to an earlier annual scale lumped model that predicts basin water yield (e.g., Budyko, 1951; Zhang et al., 2001). The model is calibrated using actual spatially averaged precipitation and water diversion data for the basin area above the Sparks gage. The model can be used to simulate annual runoff, evapotranspiration, and recharge to the Niobrara River. The only forcing term in the model is annual precipitation. The model allows self calibration.

The rate of change in the storage of water S (L) available for seeping into the channel from channel banks can be written as:

$$\frac{dS}{dt} = P + D - ET - R \qquad (16)$$

where P is annual precipitation, ET is annual actual evapotranspiration, and R is annual runoff, and D is diverted flow from the river. Runoff is calculated as the sum of runoff that is generated on the saturated portions of the landscape during rainfall events (i.e., saturation excess or direct runoff), and runoff generated by seepage along the channel banks and topographic depressions. The latter mechanism is conceptualized as a function of the storage term itself, as more water is stored in the basin the higher hydraulic head that storage will cause. Basin runoff may be written as:

$$R = \beta P + \kappa S - D \qquad (17)$$

where $\beta$ is the saturated fraction of the basin, which generally corresponds to topographically low elevations around the channel network; and $\kappa$ is an empirical drainage constant. The second term on the right hand side of this equation resembles the Darcy law as S can be considered as a basin averaged hydraulic head along the channel banks. Theoretically κ lumps physical parameters such as hydraulic conductivity and drainage density.

Actual evapotranspiration is calculated using the aridity-index based model of Zhang as described above. The model is coded in MATLAB and forced with randomly generated annual precipitation representative of the observed annual precipitation regime of the Niobrara River. The basin is assumed to be "empty" (i.e., no storage, S=0) in the beginning. The model is run for 3000 years for spin-up (Figure 35).

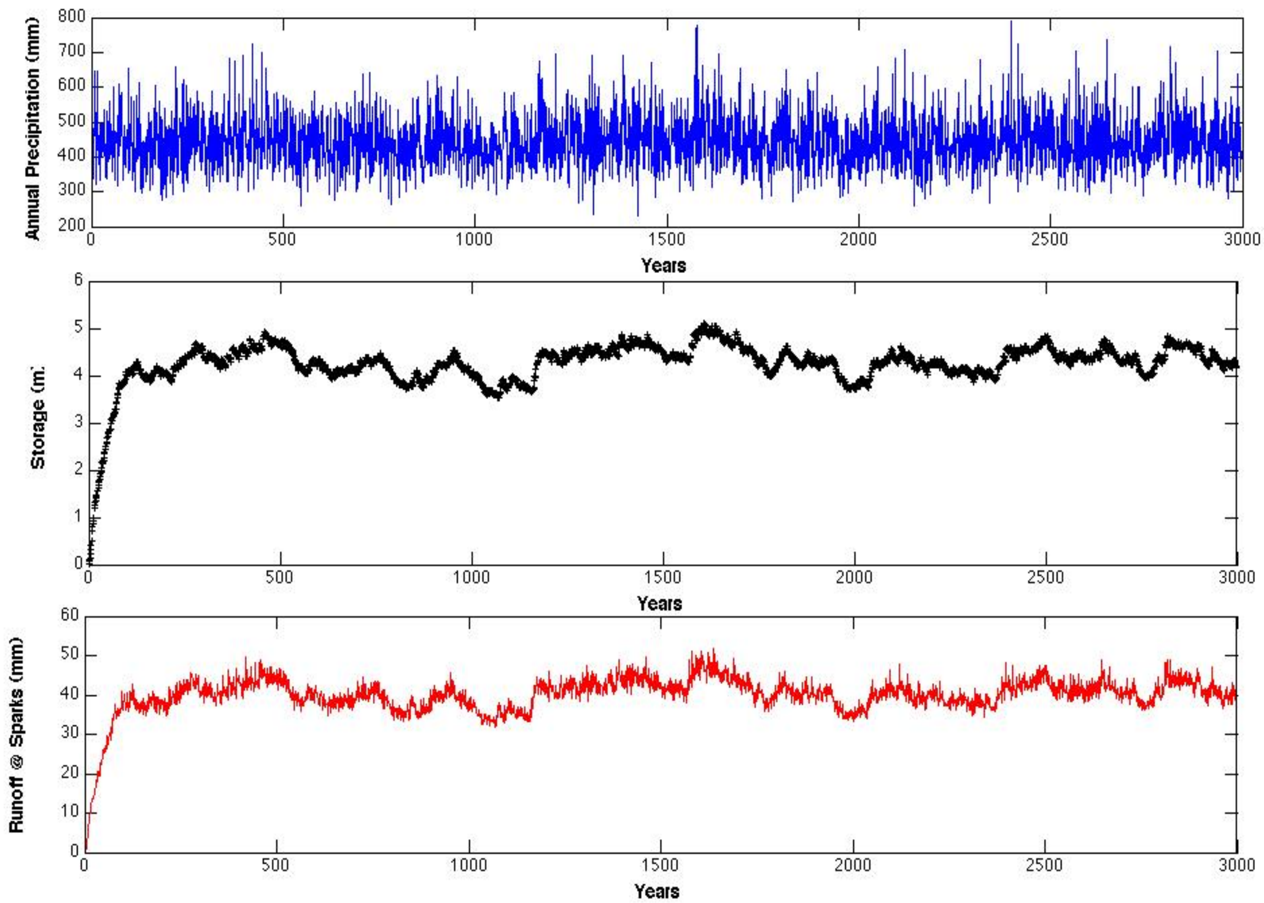



**Figure 35.** Spin-up of the model for 3000 years using randomly generated precipitation data. In the figure generated annual precipitation (top); modeled basin water storage (middle), and runoff (bottom panel) are plotted.

During the spin-up period, storage adjusts such that annual runoff attains close to the mean annual runoff rate observed at the Sparks gage. Following the spin-up the model is used to predict observed runoff in the Niobrara River @ the Sparks gage from 1948 to end of 2006, using the measured diversion data as source of outflux from the stream. To simulate the impact of irrigation, the diverted water is added on annual precipitation (Figure 36 and Figure 37). Despite the relatively low $R^2$ the model represent hydrology much better than the runoff calculated using the model of Zhang et al. (2001) (Compare Figure 33 with Figure 31). This suggests that the storage term incorporated in the model improved runoff estimates significantly. Interestingly in both the long-term simulation and the simulation conducted using actual precipitation, the storage and runoff shows lower-frequency fluctuations and some periodicity. To examine the influence of water diversion in the basin, the model was run without any water diversion (Figure 38).

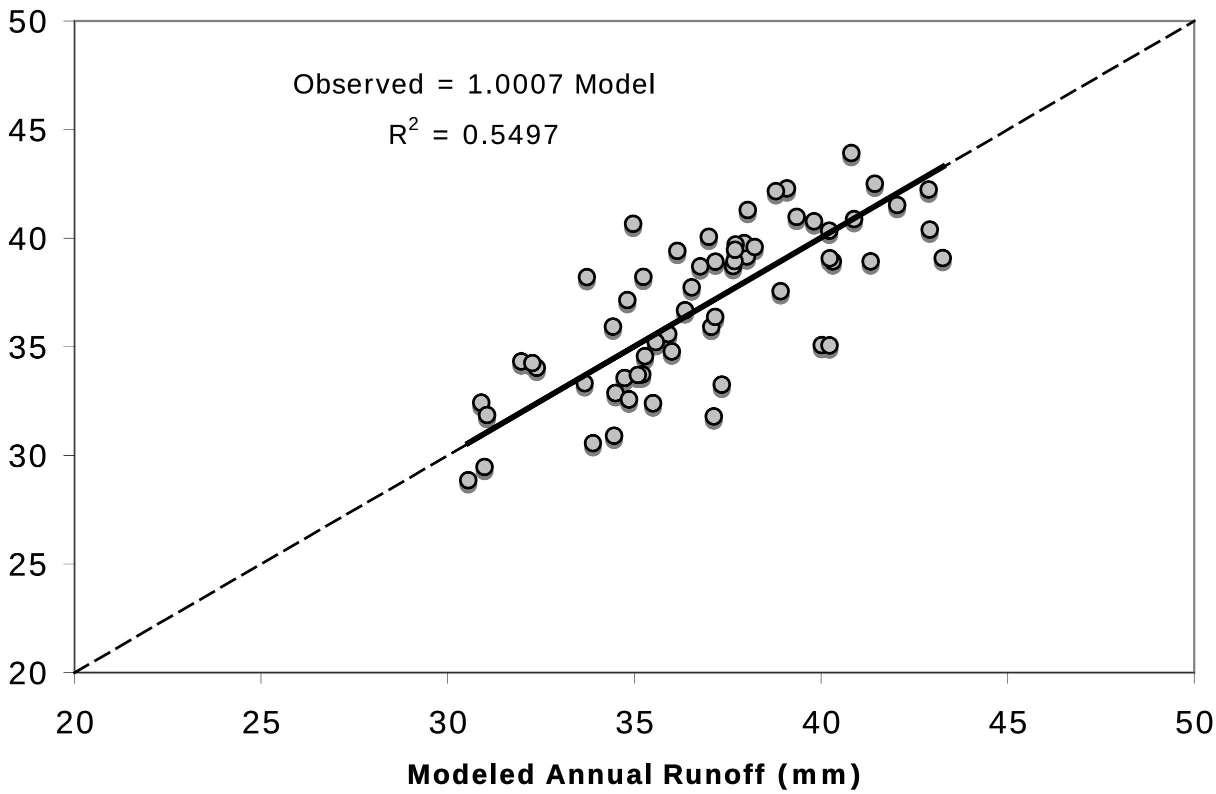



**Figure 36.** Comparison of calculated versus observed flow in the Niobrara River at the Sparks gage.

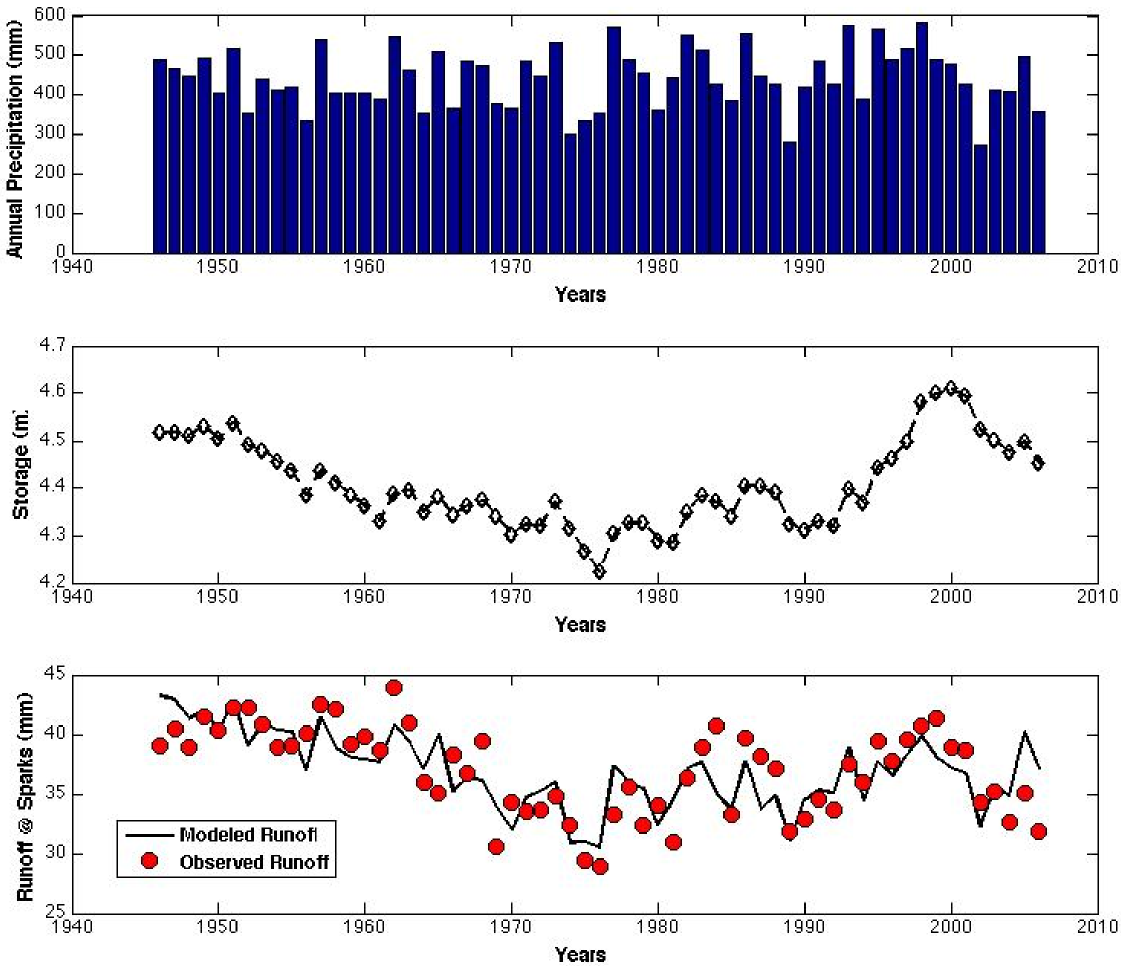



**Figure 37.** Annual time series of observed annual precipitation (top panel), modeled basin water storage (middle panel), and modeled runoff versus observed runoff at the Sparks gage (bottom panel).

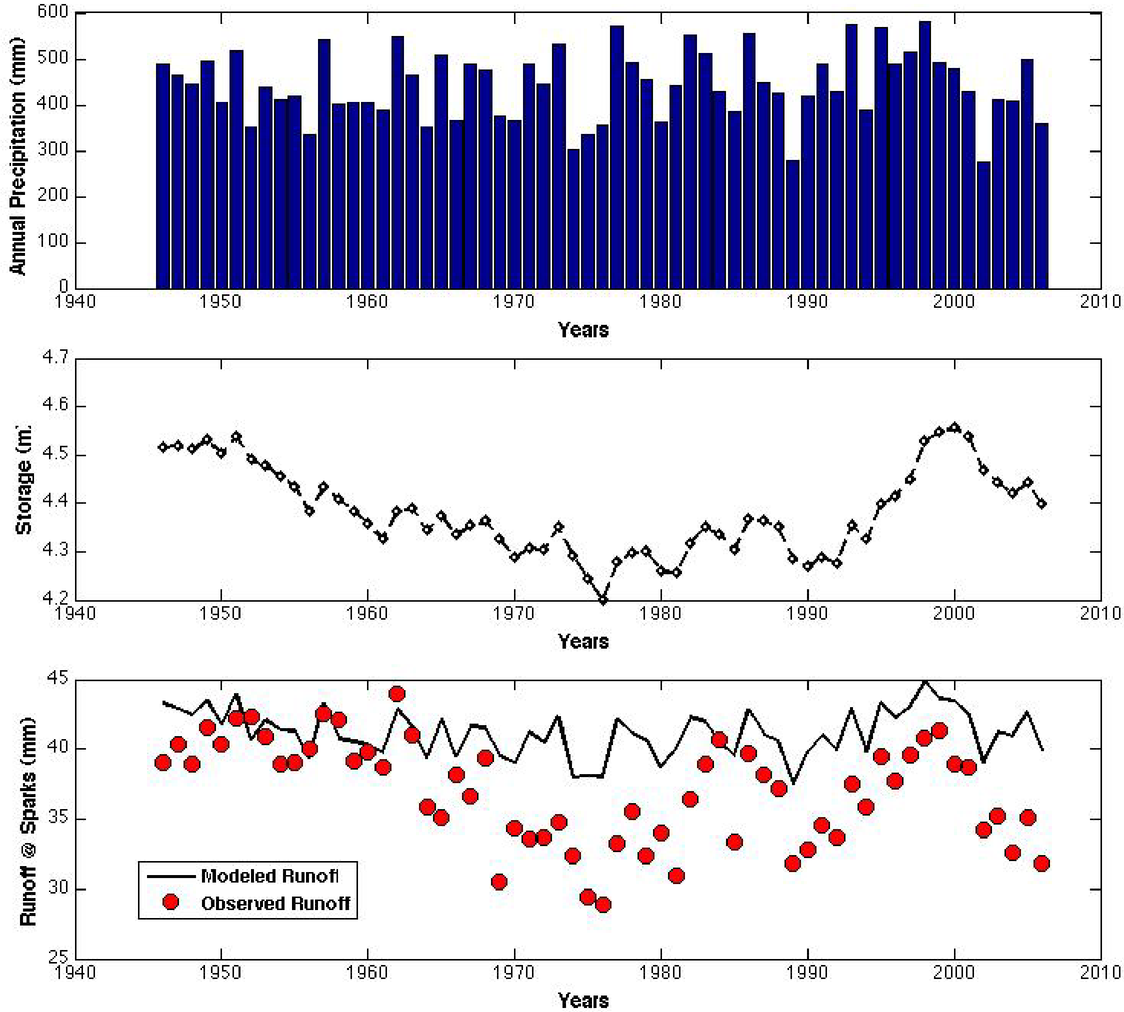



**Figure 38.** Annual time series of observed annual precipitation (top panel), modeled basin water storage (middle panel), and modeled runoff versus observed runoff at the Sparks gage (bottom panel). Irrigation water diversions is not included in the model.

The difference between observed and predicted runoff grew when water is not taken out of the stream in the model that started around 1965. When water diversion is not implemented in the model the annual river runoff went back to its original regime that looked similar to before 1965.

Although the limitations of the model are significant, the model was able to predict approximately 55% of the variability in the annual runoff in the Niobrara River at the Sparks gage (Figure 3). For a basin in which there is significant storage, this prediction is promising for future model developments along the lines presented here. Currently a monthly version of this model is being developed. The model results echo the influence of river water use on the annual balance. When the observed water diversion is not simulated in the basin, annual runoff increased as high as ~25%.

## 7. Conclusions

In this work some climate and hydrological data were analyzed to examine the hydrology of the Nibrara River especially at the USGS Sparks and Verdel gages, and a simplistic annual water balance model developed. Below a summary of the major findings of this study are presented with respect to climate, hydrology, and flow frequencies in the Niobrara River.

Climate: Average annual temperatures of the last 10 years were approximately 2$^{o}$F higher than the mean annual temperature of the last ~110 years of the instrumented data in the panhandle and north central climate regions of Nebraska. Annual precipitation was below the mean annual precipitation in 3 out of the last 10 years. The Palmer Drought Severity Index (PDSI) calculated using measured climate variables in the last ~110 years shows significant periodicity, with moderate to severe droughts occurring on average every 8 to >10 years. According to this, especially years 2002, 2003, 2004 were drier than average. The long-term observed data as well as the paleo-PDSI data shows that recent droughts experienced in the region were typical of the long-term (~1200 years) climatic trends in the region and they were not exceptional.

Annual Hydrology:

Annual runoff at the Sparks and Verdel gages were analyzed by separating the data before and after 1964. In the region water diversions rose rapidly after 1964 following the construction of the Merritt dam and diversions to the Ainsworth and Mirage Flats canals. The ratio of annual runoff to annual precipitation (often known as the runoff ratio) at the Sparks gage was reduced 12.95% after 1964 likely due to increased water diversions. For a given amount of annual precipitation, the fraction of that precipitation forming runoff after 1964 was 12.95% (on average) less than what it was before 1964. Our analysis showed a statistically significant difference in annual runoff before and after 1964 at the Sparks gage, while no statistically significant change in annual precipitation after 1964 was detected in the analysis. Because of limited data prior to 1964 at the Verdel streamflow gage, the annual hydrology analysis for this gage are largely inconclusive.

Change in mean annual runoff along the main stem of the Niobrara River was examined for the periods of before and after 1964 using information from 9 streamflow gages that contained data for both periods. Except the Dunlop and Verdel gages, all other gages showed declines in mean annual runoff between 10% to slightly higher than 20% (Figure 22).

Monthly Hydrology: The mean daily runoff in each month in the periods before and after 1964 showed that in all of the months except January, in which only 0.75% increase was observed, mean daily flows at the Sparks gage declined. The highest decline (up to 25%) occurred in summer months as follows: June 9.5%, July 24.4%, August 25%, September 24.7%, October 23.6%. March flows were also reduced significantly up to 13.3%. Standard deviations of the mean daily flows in each month were also altered after 1964. In July, standard deviation of the mean daily flows was lower 23%, followed by 22.7% in September and 22.1% in August. In March the standard deviation was also reduced 35%, marking the highest reduction on record. Consistent with the mean daily flows in each month, mean daily flows calculated for each calendar day also showed marked reductions especially in summer months. From July to the end of September mean daily flows were, on average, 30% lower than the pre-development period. There was also a significant reduction in March.

Flow Frequency: Significant differences were found in the frequency of flows before and after 1965 at the Sparks gage. The number of days any given flow is exceeded in the river was higher in the before 1965 period than in the after 1965 period. The difference became more pronounced in summer months. Flow discharge for a given number of days of exceedance was on average 17.8%, and as high as 29% lower in the post 1965 period. The results suggest that high flows become less frequent at the Sparks gage with water diversion for irrigation. At the Verdel gage, the low flows were not altered significantly with increased water diversions. However, the magnitude of the flows that occur less than 10 days a year decreased very significantly. For the flows that are observed one day a year the mean daily discharge decreased up to 50%.

Change in the 20$^{th}$ and 80$^{th}$ percentile of the mean daily flows along the main stem of the Niobrara River was examined for the periods before and after 1964 using information from 9 streamflow gages that contained data for both periods. Except Agate, Above Box Butte, and Verdel other gages experienced reduced 20$^{th}$ percentile mean daily flows after 1964. Regarding the 80$^{th}$ percentile flows, stations showed 10% to 20% reductions, excluding the station below Box Butte. In that station (ID: 06455500) the 80$^{th}$ percentile of mean daily discharge dramatically decreased from 56.8 to 1.3 cfs. This reduction might be caused by the Box Butte Reservoir.

Modeling: Our modeling study illustrated the dominant influence of baseflow in the Niobrara River annual hydrology. Most notably, when runoff calculated using a model that assumes no interannual change in basin water storage, predicted values of annual runoff as a closure term to water balance deviated significantly from observed annual runoff. To enhance model predictive performance, a basin water storage term that changes with time is added, and baseflow is assumed to be a function of this storage. This model revision improved the prediction of the model significantly. The model explained approximately 55% of the variability observed in annual runoff. When the model was run excluding the surface water diversion, the annual runoff increased as high as ~25%.

The data analyses presented in this report clearly show significant reductions in the mean annual, monthly, and mean daily low and high flows after the 1964-1965 water year in the Niobrara River especially in the portion of the basin at the Sparks gage. This time period corresponds to the development of man made structures and growing water diversions form the river. Our results suggest no significant change in annual precipitation and the climatic trends in general in the periods before and after 1964. Neither of the two periods seemed to be different from the long-term climatic trends in this region. As such, data analysis suggests that man-made changes and water diversions in the system are responsible for reduced flows. The numerical model developed for annual runoff also corroborates this finding. When water diversions are not included as a sink in the model, the annual runoff increased as high as 25%.

## 8. Future Work

The findings of this work are based on the limited data available for analyses. Baseflow dominated river systems typically have a longer hydrological memory than those dominated by surface overland and subsurface flows. This suggests that the impact of any man-made developments in the basin or climate change may be seen in the river much later than surface water driven systems. Given the Niobrara system is mostly dominated by baseflow, especially the region above the Sparks gage, longer time periods of data is crucial to understand the system behavior. In predicting and forecasting the future of the Niobrara system, research simulation models that are simple enough to run for long periods of times under a statistical climate regime would be critical. Given the uncertainty in the system due to unknown initial conditions, and physical processes, ensemble forecast models should be developed in an attempt to represent system behavior probabilistically. The annual model developed in this study was an initial attempt to develop a simplistic numerical representation of the system to learn more about the system behavior. Models like this would be crucial for planning water allocations. For example data analysis showed in this work that when diversion is larger than 200 cfs in the water diversions above the Sparks gage, variability of mean monthly streamflow is reduced and most values converge to a constant lower-end flow rate. This point requires both climatological and hydrological considerations using models.

**Acknowledgements:**

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## 8. References


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**APPENDIX:**

**Table 1.** AWDN Stations Located Within/Vicinity of the Niobrara Basin.

| Name | Lat(deg) | Long(deg) | Elev(m) | Data Period |
|---|---|---|---|---|
| Ainsworth | 42.55 | 99.82 | 765 | 1984-2008 |
| AllianceNorth | 42.18 | 102.92 | 1213 | 1988-2008 |
| AllianceWest | 42.02 | 103.13 | 1213 | 1988-2008 |
| Barta | 42.23 | 99.65 | 777 | 2000-2008 |
| Beresford | 43.07 | 96.93 | 389 | 1988-2008 |
| Brunswick | 42.35 | 97.92 | 548 | 1998-2008 |
| Buffalo gap | 43.48 | 103.32 | 981 | 1984-1986 |
| Elgin | 41.93 | 98.18 | 619 | 1988-2008 |
| Gordon | 42.73 | 102.17 | 1109 | 1984-2008 |
| Gudmundsens | 42.07 | 101.43 | 1049 | 1982-2008 |
| Higgins Ranch | 42.83 | 99.25 | 619 | 2004-2008 |
| Martin | 43.17 | 101.72 | 1007 | 2005-2008 |
| Merritt | 42.45 | 100.9 | 948 | 2004-2008 |
| Newport | 42.58 | 99.38 | 699 | 2004-2008 |
| Oneill | 42.47 | 98.75 | 625 | 1985-2008 |
| Oral | 43.4 | 103.27 | 960 | 2002-2008 |
| Panhandle | 41.93 | 103.7 | 1244 | 1982-1992 |
| Parkston | 43.38 | 97.97 | 450 | 2006-2008 |
| Pinebluffs | 41.18 | 104.1 | 1554 | 1985-1994 |
| Sparks | 42.98 | 100.2 | 772 | 2004-2008 |
| Torrington | 42.03 | 104.18 | 1216 | 1996-2008 |
| Wheatland | 42.08 | 104.95 | 1417 | 1985-1994 |
| White River | 43.55 | 100.73 | 600 | 2006-2008 |

**Table 2.** NWS/COOP Stations in the Niobrara River Basin.

| Name | Lat(deg) | Long(deg) | Elev(m) | Data Period |
|---|---|---|---|---|
| Agate 3 E | 42.42 | 103.73 | 1423 | 1948-2008 |
| Ainsworth | 42.55 | 99.85 | 765 | 1890-2008 |
| Atkinson | 42.53 | 98.97 | 643 | 1906-2008 |
| Butte | 42.9 | 98.85 | 552 | 1948-2008 |
| Chadron | 42.82 | 103 | 1070 | 1948-2008 |
| Gross | 42.95 | 98.55 | 533 | 2001-2008 |
| Harrison | 42.68 | 103.88 | 1478 | 1893-2008 |
| Haysprings | 42.67 | 102.68 | 1175 | 1886-2008 |
| Haysprings,12s | 42.5 | 102.68 | 1160 | 1951-2008 |
| Hemingford | 42.32 | 103.07 | 1301 | 1964-2008 |
| Kilgore | 42.95 | 100.93 | 927 | 1997-2008 |
| Plainview | 42.33 | 97.78 | 512 | 1978-2008 |
| Spenser 5 SSE | 42.8 | 98.65 | 466 | 1948-2008 |
| Valentine 4 SSE | 42.88 | 100.5 | 742 | 1998-2008 |
| Valentine Lks game | 42.57 | 100.68 | 893 | 1948-2008 |
| Valentine Wso AP | 42.87 | 100.55 | 789 | 1948-2008 |

**Table 3.** Current and discontinued flow gaging records for USGS and NDNR stations on the Niobrara River.

**USGS Existing stations**

| USGS Station name | Station Number | Drainage Area (mi$^2$) | Period of Record |
|---|---|---|---|
| NR near Sparks | 06461500 | 7,150 | 1945-2007 |
| NR near Verdel | 06465500 | 11,580 | 1957-2007 |
| NR at Niobrara | 06466000 | 4660 | 1954-1958 |
| Long Pine Creek near Riverview NE | 06463500 | 458 | 1948-2007 |
| Verdigre Creek near Verdigre NE | 06465700 | 470 | 2002-2007 |

**N-DNR Stations** (Appended Data with the USGS stations using the NHAT software)

| NDNR Station name | Station Number | Drainage Area (mi$^2$) | Period of Record |
|---|---|---|---|
| NR above Box Butte Reservoir | 6454500 | 1400 | 1946-2004 |
| NR below Box Butte Reservoir | 6455500 | 1460 | 1946-2004 |
| NR WY-NE state boarder | 6454000 | 455 | 1955-2004 |
| NE near Gordon | 6457500 | 4290 | 1945-1994 |
| Snake River at Doughboy | 6459175 | 405 | 1981-2004 |
| Snake river near Burge | 6459500 | 660 | 1947-2004 |
| Minnechaduza Creek at Valentine | 6461000 | 390 | 1949-1994 |
| Keya Paha River near Naper | 6464900 | 1690 | 1957-2004 |

**USGS Discontinued gages**

| **USGS Station name** | **Station #** | **Drainage Area (mi$^2$)** | **Period of Record** |
|---|---|---|---|
| NR at WY-NE state line* | 4540 | 455 | 1956-94 |
| NR at Agate | 4541 | 840 | 1957-1991 |
| NR above Box Butte Reservoir* | 4545 | 1,400 | 1947-1994 |
| NR below Box Butte Reservoir* | 4555 | 1,460 | 1947-1991 |
| NR near Dunlap | 4559 | 1,580 | 1931-1942, 1962-1971 |
| NR near Hay Springs | 4565 | 1,790 | 1950-1964, 2004- |
| NR near Colclesser | 4570 | 2,220 | 1948 |
| NR near Gordon* | 4575 | 4,290 | 1929-32; 46-91; 2004- |
| Antelope Creek, near Gordon | 4580 | 160 | *1948 |
| Bear Creek near Eli | 4585 | 360 | 1948-1953 |
| NR at Cody | 4590 | 5,570 | 1948-1957 |
| Snake River at Doughboy* | 459175 | 405 | 1982-1993 |
| Snake river above Merritt Res. | 4592 | 440 | 1963-1981 |
| Snake River near Burge* | 4595 | 646 | 1947-1994 |
| Gordon Creek near Simeon | 4600 | --- | *1948 |
| NR near Valentine | 4605 | 6,160 | 1901-06, 1928-1932 |
| Minnechaduza Creek near Kilgore | 4609 | 85 | 1958-1974 |
| Minnechaduza Creek at Valentine* | 4610 | 390 | 1948-1993 |
| NR near Norden | 4620 | 8,390 | 1953-1983 |
| Plum Creek at Meadville | 4625 | 536 | 1948-1975, 1977-1994 |
| NR at Meadville | 4630 | -- | 1951-1952 |
| Long Pine Creek near Long Pine | 463080 | 246 | 1980-1991 |
| NR at Mariaville | 463720 | 9,810 | 1986-1991 |
| Keya Paha River near Naper* | 4649 | 1,690 | 1958-1994 |
| Eagle Creek near Redbird | 465310 | 206 | 1979-1991 |
| Redbird Creek at Redbird | 465440 | 157 | 1981-1994 |
| North Branch Verdigre Creek near Verdigre | 465680 | 137 | 1980-1992 |
| NR at Niobrara | 4660 | -- | 1954-1958 |

* Data later appended with the NDNR data using the NHAT software.

**Table 4.** Diversion Data of the Niobrara River at County Level

| Station Name County Name | Station ID | Begin Date | End Date | Latitude | Longitude | Basin | NRD | Legal Desc |
|---|---|---|---|---|---|---|---|---|
| CIRCLE PUMP FROM NIOBRARA RIVER | | | | | | | | |
| Box Butte | 26000 | 1970 | 1985 | 42-25-50 | 103-17-53 | 12 | 12 | 28N51W05 |
| | | | | | | | | |
| EXCELSIOR CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Box Butte | 46000 | 1956 | 2004 | 42-24-57 | 103-22-33 | 12 | 11 | 28N52W10 |
| | | | | | | | | |
| GEO HITSHEW CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Box Butte | 63000 | 1956 | 2004 | 42-25-49 | 103-26-02 | 12 | 11 | 28N52W06 |
| | | | | | | | | |
| HITSHEW PUMP NO. 2 FROM NIOBRARA RIVER | | | | | | | | |
| Box Butte | 64000 | 1956 | 1985 | 42-25-49 | 103-26-02 | 12 | 12 | 28N52W06 |
| | | | | | | | | |
| HOMRIGHAUSEN PUMP FROM NIOBRARA RIVER | | | | | | | | |
| Box Butte | 66000 | 1970 | 1973 | 42-24-57 | 103-23-43 | 12 | 12 | 28N52W09 |
| | | | | | | | | |
| HUGHES CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Box Butte | 69000 | 1956 | 2004 | 42-25-49 | 103-20-14 | 12 | 11 | 28N52W01 |
| | | | | | | | | |
| MCLAUGHLIN CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Box Butte | 86000 | 1956 | 2004 | 42-24-57 | 103-23-43 | 12 | 11 | 28N52W09 |

| Station Name County Name | Station ID | Begin Date | End Date | Latitude | Longitude | Basin | NRD | Legal Desc |
|---|---|---|---|---|---|---|---|---|
| AINSWORTH CANAL FROM SNAKE RIVER AND MERRITT RESERVOIR (15-FOOT PARSHALL FLUME) | | | | | | | | |
| Cherry | 1000 | 1965 | 2004 | 42-38-04 | 100-51-53 | 12 | 13 | 31N30W29 |

| Station Name County Name | Station ID | Begin Date | End Date | Latitude | Longitude | Basin | NRD | Legal Desc |
|---|---|---|---|---|---|---|---|---|
| DELSING PUMP FROM NIOBRARA RIVER | | | | | | | | |
| **Dawes** | 37200 | 1983 | 1987 | 42-26-39 | 103-02-00 | 12 | 12 | 29N49W35 |
| | | | | | | | | |
| ENTERPRISE CANAL PUMP FROM NIOBRARA RIVER | | | | | | | | |
| Dawes | 45000 | 1956 | 1985 | 42-27-35 | 103-10-36 | 12 | 12 | 29N50W27 |
| | | | | | | | | |
| MIRAGE FLATS CANAL FROM NIOBRARA RIVER (10-FOOT PARSHALL FLUME) | | | | | | | | |
| Dawes | 100000 | 1948 | 2004 | 42-27-37 | 102-55-12 | 12 | 11 | 29N48W26 |
| | | | | | | | | |
| MONTAGUE CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Dawes | 102000 | 1956 | 2004 | 42-27-37 | 102-56-24 | 12 | 11 | 29N48W27 |
| | | | | | | | | |
| MONTAGUE PUMP FROM NIOBRARA RIVER | | | | | | | | |
| Dawes | 103000 | 1956 | 1987 | 42-27-37 | 102-57-36 | 12 | 12 | 29N48W28 |
| | | | | | | | | |
| PIONEER CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Dawes | 123000 | 1956 | 2004 | 42-26-28 | 103-15-21 | 12 | 11 | 29N51W36 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| PIONEER PUMP FROM NIOBRARA RIVER | | | | | | | | |
| Dawes | 123500 | 1981 | 1987 | 42-27-16 | 103-14-01 | 12 | 12 | 29N50W30 |
| | | | | | | | | |
| POTMESIL CANAL FROM NIOBRARA RIVER 3 FOOT (PARSHALL FLUME) | | | | | | | | |
| Dawes | 124000 | 1956 | 2004 | 42-27-37 | 102-55-12 | 12 | 11 | 29N48W26 |
| | | | | | | | | |
| SNOW CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Dawes | 135000 | 1956 | 1976 | 42-26-28 | 103-16-32 | 12 | 12 | 29N51W35 |

| Station Name County Name | Station ID | Begin Date | End Date | Latitude | Longitude | Basin | NRD | Legal Desc |
|---|---|---|---|---|---|---|---|---|
| ARMSTRONG PUMP FROM NIOBRARA RIVER | | | | | | | | |
| **Sioux** | 4000 | 1970 | 1984 | 42-24-57 | 103-30-41 | 12 | 12 | 28N53W09 |
| | | | | | | | | |
| BEISER CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Sioux | 8000 | 1968 | 1974 | 42-31-00 | 103-54-02 | 12 | 12 | 29N56W04 |
| | | | | | | | | |
| BENNETT-KAY CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Sioux | 13000 | 1956 | 2004 | 42-25-39 | 103-34-09 | 12 | 11 | 28N54W01 |
| | | | | | | | | |
| BIGELOW-SEYMOUR CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Sioux | 15000 | 1956 | 1985 | 42-38-50 | 104-01-57 | 12 | 12 | 31N57W19 |
| | | | | | | | | |
| BOURETT CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Sioux | 18000 | 1967 | 1974 | 42-31-52 | 103-54-02 | 12 | 12 | 30N56W33 |
| | | | | | | | | |
| COOK CANAL NO. 1 FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Sioux | 29000 | 1956 | 2004 | 42-25-47 | 103-49-26 | 12 | 11 | 28N56W02 |
| | | | | | | | | |
| COOK PUMP FROM NIOBRARA RIVER | | | | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 29200 | 1981 | 1987 | 42-25-47 | 103-48-16 | 12 | 12 | 28N56W01 |

DAVISON PUMP FROM NIOBRARA RIVER

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 36000 | 1956 | 1985 | 42-24-48 | 103-34-09 | 12 | 12 | 28N54W12 |

EARNEST CANAL (COMBINED FLOW-NORTH & SOUTH) FROM NIOBRARA RIVER (RATING FLUME)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 38000 | 1956 | 1985 | 42-30-08 | 103-54-02 | 12 | 12 | 29N56W09 |

EARNEST CANAL NO. 1 (SOUTH) FROM NIOBRARA RIVER (THROUGH RATING FLUME)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 38100 | 1956 | 2004 | 42-30-08 | 103-54-02 | 12 | 11 | 29N56W09 |

EARNEST CANAL NO. 2 (NORTH) FROM NIOBRARA RIVER (THROUGH RATING FLUME)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 38200 | 1956 | 2004 | 42-30-08 | 103-54-02 | 12 | 11 | 29N56W09 |

HARRIS-NEECE CANAL FROM NIOBRARA RIVER (RATING FLUME)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 62000 | 1955 | 2004 | 42-25-46 | 103-43-34 | 12 | 11 | 28N55W03 |

HOFFMAN PUMP FROM NIOBRARA RIVER

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 65000 | 1956 | 1987 | 42-25-46 | 103-43-34 | 12 | 12 | 28N55W03 |

HOOVER PUMP FROM NIOBRARA RIVER

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 68000 | 1956 | 1985 | 42-38-50 | 104-01-02 | 12 | 12 | 31N57W21 |

JOHNSON CANAL FROM NIOBRARA RIVER (1 1/2-FOOT PARSHALL FLUME)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 72000 | 1956 | 2004 | | | 12 | 11 | 30N57W01 |

LABELLE CANAL FROM NIOBRARA RIVER (RATING FLUME)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 78000 | 1956 | 2004 | 42-25-39 | 103-40-02 | 12 | 11 | 28N54W06 |

LAKOTAH CANAL FROM NIOBRARA RIVER (2-FOOT PARSHALL FLUME)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sioux | 79000 | 1956 | 2004 | | | 12 | 11 | 30N57W12 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MCGINLEY-STOVER CANAL (NORTH) FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Sioux | 83000 | 1956 | 1978 | 42-27-31 | 103-50-36 | 12 | 12 | 29N56W25 |
| | | | | | | | | |
| MCGINLEY-STOVER CANAL (SOUTH) FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Sioux | 84000 | 1957 | 2004 | 42-27-31 | 103-50-36 | 12 | 11 | 29N56W25 |
| | | | | | | | | |
| METTLEN CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Sioux | 89000 | 1956 | 2004 | 42-25-39 | 103-37-41 | 12 | 11 | 28N54W04 |
| MOORE-KAY CANAL FROM NIOBRARA RIVER (RATING FLUME) | | | | | | | | |
| Sioux | 104000 | 1956 | 2004 | 42-24-57 | 103-30-41 | 12 | 11 | 28N53W09 |

## NHAT Indices of Hydrologic Variability

**MA5**

The skewness of the entire flow record is computed as the mean for the entire flow record (MA1) divided by the median (MA2) for the entire flow record (dimensionless).

**MA6**

**Range in daily flows** is the ratio of the 10% to 90% exceedence values for the entire flow record. Compute the 5% to 95% exceedence values for the entire flow record. Exceedence is computed by interpolating between the ordered (descending) flow values. Divide the 10% exceedence value by the 90% value (dimensionless).

**MA9**

**Spread in daily flows** is the ratio of the difference between the 90th and 10th percentile of the flow data to median of the entire flow record. Compute the 5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th, 50th, 55th, 60th, 65th, 70th, 75th, 80th, 85th, 90th, and 95th percentiles for the entire flow record. Percentiles are computed by interpolating between the ordered (ascending) logs of the flow values. Compute MA9 as (90th - 10th) /MA2 (dimensionless).

**MA37**

Variability across monthly flows. Compute the first (25th percentile) and the third (75th percentile) quartiles (every month in the flow record). MA37 is the third quartile minus the first quartile divided by the median of the monthly means (dimensionless).

**MA38**

Variability across monthly flows. Compute the 10th and 90th percentiles for the monthly means (every month in the flow record). MA38 is the 90th percentile minus the 10th percentile divided by the median of the monthly means (dimensionless).

**MA43**

Variability across annual flows. Compute the first (25th percentile) and third (75th percentile) quartiles and the 10th and 90th percentiles for the annual means (every year in the flow record). MA43 is the third quartile minus the first quartile divided by the median of the annual means (dimensionless).

**ML1 – ML12**

Mean (or median - Use Preference option) minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. For example, ML1 is the mean of the minimums of all January flow values over the entire record (cubic feet per second - temporal).

**ML 13**

Variability (coefficient of variation) across minimum monthly flow values. Compute the mean and standard deviation for the minimum monthly flows over the entire flow record. ML13 is the standard deviation times 100 divided by the mean minimum monthly flow for all years (percent).

**ML 15**

**Low flow index.** ML15 is the mean (or median - Use Preference option) of the ratios of minimum annual flows to the mean flow for each year (dimensionless).

**ML 17**

**Base flow.** Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median – Use Preference option) of those ratios (dimensionless).

## MATLAB CODES FOR FLOW FREQUENCY ANALYSIS

<u>Annual analysis:</u>

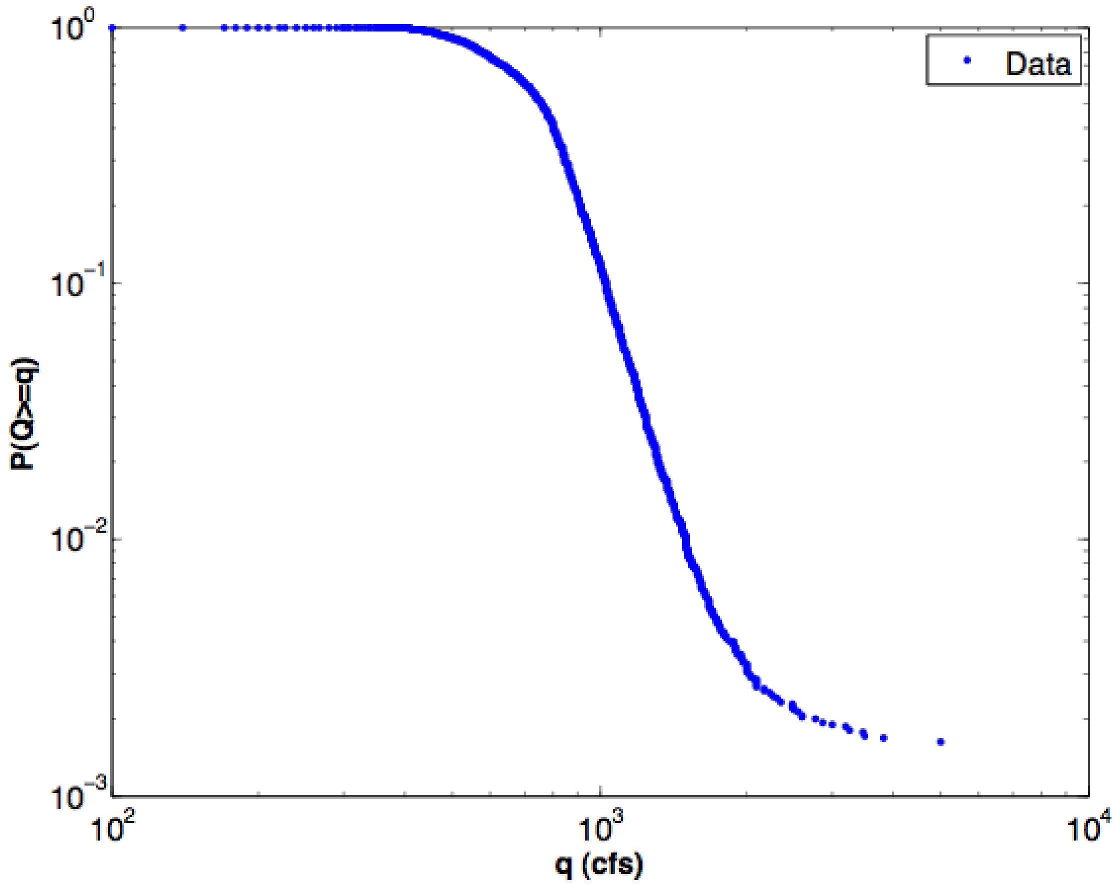
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This Matlab code calculates exceedance probabilities and expected number of
%%  exceedances of mean daily flows provided in an array X=[ ], and develops log-log
%% plots for both statistics. For selected periods given in S=[ ], the code also finds the
%% probabilities corresponding to those periods.

NDays=0;
Nd=0;
S=0;
Nx=0;
Xsort=0;
Yx=0;
Pexceedance=0;
Avg=0;
Nd=365;  %%  The number of days in the period analyzed.
S=[1, 2, 5, 7, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 150, 160, 180, 200, 220, 250, 270,
300, 340];

Nx=max(size(X));
Xsort=sort(X);
Yx=(1:Nx)./(Nx+1);
NDays=(1-Yx)*Nd;
Pexceedance=(1-Yx);

j=1;
while(j<=max(size(S)))
  for i= 1:(Nx-1)
    if  ((S(j) <= NDays(i))  & (S(j) >= NDays(i+1)))
          Avg(j) =(Xsort(i)+Xsort(i+1))/2
    end;
  end;
  j=j+1
end;

for i=1:max(size(S));
    fprintf('%f   %f\n',S(i),Avg(i));
end;

loglog(Xsort,NDays,'.');
xlabel('q (cfs)','fontsize',15,'FontWeight','bold');
ylabel('NDays(Q>=q)','fontsize',15,'FontWeight','bold');
figure
loglog(Xsort,Pexceedance,'.');
xlabel('q (cfs)','fontsize',15,'FontWeight','bold');
ylabel('P(Q>=q)','fontsize',15,'FontWeight','bold');
hold
legend('Data','fitted power-law')
```

Analysis of the flows during the 6 month (May-October) spring-summer period:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This Matlab code calculates exceedance probabilities and expected number of
%%  exceedances of mean daily flows provided in an array X=[ ], and develops log-log
%% plots for both statistics. For selected periods given in S=[ ], the code also finds the
%% probabilities corresponding to those periods.

NDays=0;
Nd=0;
S=0;
Nx=0;
Xsort=0;
Yx=0;
Pexceedance=0;
Avg=0;

Nd=184;  %% The number of days in the period analyzed

S=[1, 2, 5, 7, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 150, 160, 180];
Nx=max(size(X));
Xsort=sort(X);
Yx=(1:Nx)./(Nx+1);
NDays=(1-Yx)*Nd;
Pexceedance=(1-Yx);

j=1;
while(j<=max(size(S)))
  for i= 1:(Nx-1)
    if  ((S(j) <= NDays(i))  & (S(j) >= NDays(i+1)))
          Avg(j) =(Xsort(i)+Xsort(i+1))/2
    end;
  end;
  j=j+1
end;

for i=1:max(size(S));
    fprintf('%f   %f\n',S(i),Avg(i));
end;

loglog(Xsort,NDays,'.');
xlabel('q (cfs)','fontsize',15,'FontWeight','bold');
ylabel('NDays(Q>=q)','fontsize',15,'FontWeight','bold');

figure

loglog(Xsort,Pexceedance,'.');
xlabel('q (cfs)','fontsize',15,'FontWeight','bold');
ylabel('P(Q>=q)','fontsize',15,'FontWeight','bold');
hold
legend('Data','fitted power-law')
```

Analysis of the flows during the 3 month (June-August) summer period:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This Matlab code calculates exceedance probabilities and expected number of
%%  exceedances of mean daily flows provided in an array X=[ ], and develops log-log
%% plots for both statistics. For selected periods given in S=[ ], the code also finds the
%% probabilities corresponding to those periods.

NDays=0;
Nd=0;
S=0;
Nx=0;
Xsort=0;
Yx=0;
Pexceedance=0;
Avg=0;

Nd=92;  %% The number of days in the period analyzed

S=[0.1, 1, 2, 5, 7, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90];
Nx=max(size(X));
Xsort=sort(X);
Yx=(1:Nx)./(Nx+1);
NDays=(1-Yx)*Nd;
Pexceedance=(1-Yx);

j=1;
while(j<=max(size(S)))
  for i= 1:(Nx-1)
    if  ((S(j) <= NDays(i))  & (S(j) >= NDays(i+1)))
          Avg(j) =(Xsort(i)+Xsort(i+1))/2
    end;
  end;
  j=j+1
end;

for i=1:max(size(S));
    fprintf('%f   %f\n',S(i),Avg(i));
end;

loglog(Xsort,NDays,'.');
xlabel('q (cfs)','fontsize',15,'FontWeight','bold');
ylabel('NDays(Q>=q)','fontsize',15,'FontWeight','bold');

figure

loglog(Xsort,Pexceedance,'.');
xlabel('q (cfs)','fontsize',15,'FontWeight','bold');
ylabel('P(Q>=q)','fontsize',15,'FontWeight','bold');
hold
legend('Data','fitted power-law')
```




Example Probability of Exceedance Plot for mean daily flows at Sparks.

# GIS DATA

## Shapefiles of the Niobrara River Basin

- Stream Gages of Niobrara River Basin
- Groundwater Wells on State of Nebraska Site of Niobrara River Basin
- Dams Along Niobrara River
- Niobrara Stream and Tributaries
- Niobrara River Basin Borders and Subbasins Borders
- Niobrara River Basin National Land Cover Data (NLCD) year 2001
- Digital Elevation Model of Niobrara River Basin

**Stream Gages of the Niobrara River Basin**
The shapefile is downloaded from USGS web site and modified some of the percentile and date data based on recent USGS stream gages observations. The shapefile included the data below;

- First date (year, month, day) of streamflow data
- Last date (year, month, day) of streamflow data
- Number of days of streamflow data
- Number of days of non-zero streamflow data
- Minimum and maximum daily flow for the period of record (cubic feet per second)
- Percentiles (1, 5, 10, 20, 25, 50, 75, 80, 90, 95, 99) of daily flow for the period of record (cubic feet per second)
- Average and standard deviation of daily flow for the period of record (cubic feet per second)
- Mean annual base-flow index (BFI) computed for the period of record (fraction, ranging from 0 to 1)
- Year-to-year standard deviation of the annual base-flow index computed for the period of record (fraction)
- Number of years of data used to compute the base-flow index (years)

**Groundwater Wells on State of Nebraska Site of the Niobrara River Basin**
The shapefile is downloaded from Nebraska Department of natural Resources web site

| Use Code | Water Use |
|---|---|
| A | Aquaculture |
| C | Commercial/Industrial |
| D | Domestic |
| E | Pit (Excavation) |

G Ground Heat Exchanger
H Heat Pump (Ground Water Source)
I Irrigation
J Injection
L Observation (Ground Water Levels)
O Other - Lake Supply, Fountain, Geothermal,
Wildlife, Wetlands, Recreation,
Plant & Lagoon, Sprinkler, Test,
Vapor Monitoring
P Public Water Supply with Spacing Protection
Q Monitoring (Ground Water Quality)
R Recovery
S Livestock
T Geothermal
U Public Water Supply without Spacing Protection
W Dewatering (Over 90 Days)

Registration Number (example G81537A)
Prefix of well registration number ('A' or 'G')
Well registration number (3-5 digits) (#81537 in above example)
This number is assigned by Nebraska Department of Natural Resources.
Suffix of well registration number (A-Z, AA-ZZ) (A in above example)
Status Status of the well

A Active
I Inactive
S Suspense (Replacement well, original well not yet decommissioned or modified)
U Unregistered Decommissioned
X Decommissioned
Z Inactive Suspense (Pump Not installed, Replacement well,
original well not yet decomissioned or modified)

Times Replace Number of times well has been replaced
Well Location refers to township (North), range (East or West), section and sub section
Sub Section Examples:

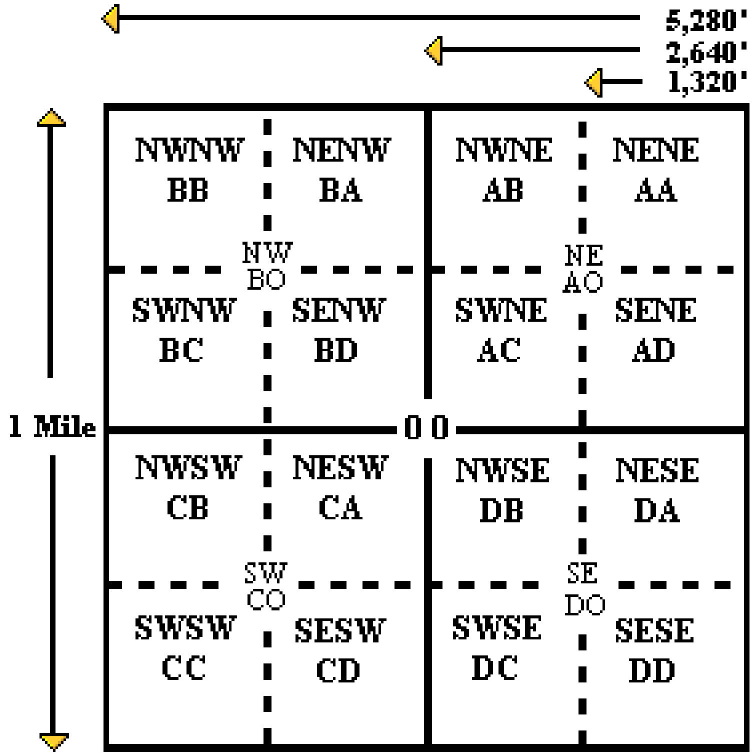
AA = NE 1/4 of NE 1/4
AB = NW 1/4 of NE 1/4
AC = SW 1/4 of NE 1/4
AD = SE 1/4 of NE 1/4
AO = Center of NE 1/4
BA = NE 1/4 of NW 1/4
BB = NW 1/4 of NW 1/4
BC = SW 1/4 of NW 1/4
BD = SE 1/4 of NW 1/4
BO = Center of NW 1/4
CA = NE 1/4 of SW 1/4
CB = NW 1/4 of SW 1/4
CC = SW 1/4 of SW 1/4
CD = SE 1/4 of SW 1/4

6 Miles

| | | | | | |
|---|---|---|---|---|---|
| 6 | 5 | 4 | 3 | 2 | 1 |
| 7 | 8 | 9 | 10 | 11 | 12 |
| 18 | 17 | 16 | 15 | 14 | 13 |
| 19 | 20 | 21 | 22 | 23 | 24 |
| 30 | 29 | 28 | 27 | 26 | 25 |
| 31 | 32 | 33 | 34 | 35 | 36 |

6 Miles

CO = Center of SW 1/4
DA = NE 1/4 of SE 1/4
DB = NW 1/4 of SE 1/4
DC = SW 1/4 of SE 1/4
DD = SE 1/4 of SE 1/4
DO = Center of SE 1/4
OO = Center of the Section




Footage Gives feet from section line. Examples: 2100N 100E = 2100 feet North from south section line and 100 feet East from west section line. 200S 400W = 200 feet South of north section line and 400 feet West of east section line.
See "Map It" from well location. Wells are mapped in following order:
1. GPS
2. Footage
3. Legal description location. If no GPS or footage is available, well will be mapped in center of legal description provided.

Filing Date (Registration Date) is the registration filing date
Completion Date is the date when the well completed construction
Decommissioned Date is the year and month when the well was decommissioned in format yy/mm
Gallons/Min is the pumping rate in gallons per minute
Well Depth is the total depth of the well in feet
Static Water Level and Pumping water level are in feet
Pump Col Diameter (Pump Column Diameter) is the column size in inches
Pump Depth is the depth to the pump in feet
Footage is the number of feet from section line to well location
Permit Number is the management area permit code. This number is assigned by the individual Natural Resources Districts.

**Dams along the Niobrara River**
The shapefile is downloaded from http://www.nationalatlas.gov/ web site

**Niobrara Stream and Tributaries**
The shapefile is downloaded from Nebraska Department of Natural Resources web site

**Niobrara River Basin National Land Cover Data (NLCD) year 2001**
The shapefile is downloaded from USGS web site. Explanations of the fields are below;

**Water** - All areas of open water or permanent ice/snow cover.
11. *Open Water* - all areas of open water, generally with less than 25% cover of vegetation/land cover.
12. *Perennial Ice/Snow* - all areas characterized by year-long surface cover of ice and/or snow.
**Developed** Areas characterized by a high percentage (30 percent or greater) of constructed materials (e.g. asphalt, concrete, buildings, etc).
21. *Low Intensity Residential* - Includes areas with a mixture of constructed materials and vegetation. Constructed materials account for 30-80 percent of the cover. Vegetation may account for 20 to 70 percent of the cover. These areas most commonly include single-family housing units. Population densities will be lower than in high intensity residential areas.
22. *High Intensity Residential* - Includes highly developed areas where people reside in high numbers. Examples include apartment complexes and row houses. Vegetation accounts for less than 20 percent of the cover. Constructed materials account for 80 to100 percent of the cover.
23. *Commercial/Industrial/Transportation* - Includes infrastructure (e.g. roads, railroads, etc.) and all highly developed areas not classified as High Intensity Residential.
**Barren** - Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material, with little or no "green" vegetation present regardless of its inherent ability to support life. Vegetation, if present, is more widely spaced and scrubby than that in the "green" vegetated categories; lichen cover may be extensive.
31. *Bare Rock/Sand/Clay* - Perennially barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, beaches, and other accumulations of earthen material.
32. *Quarries/Strip Mines/Gravel Pits* - Areas of extractive mining activities with significant surface expression.
33. *Transitional* - Areas of sparse vegetative cover (less than 25 percent of cover) that are dynamically changing from one land cover to another, often because of land use activities. Examples include forest clearcuts, a transition phase between forest and agricultural land, the temporary clearing of vegetation, and changes due to natural causes (e.g. fire, flood, etc.).
**Forested Upland** - Areas characterized by tree cover (natural or semi-natural woody vegetation, generally greater than 6 meters tall); tree canopy accounts for 25-100 percent of the cover.
41. *Deciduous Forest* - Areas dominated by trees where 75 percent or more of the tree species shed foliage simultaneously in response to seasonal change.
42. *Evergreen Forest* - Areas dominated by trees where 75 percent or more of the tree species `maintain their leaves all year. Canopy is never without green foliage.
43. *Mixed Forest* - Areas dominated by trees where neither deciduous nor evergreen species represent more than 75 percent of the cover present.
**Shrubland** - Areas characterized by natural or semi-natural woody vegetation with aerial stems, generally less than 6 meters tall, with individuals or clumps not touching to interlocking. Both evergreen and deciduous species of true shrubs, young trees, and trees or shrubs that are small or stunted because of environmental conditions are included.
51. *Shrubland* - Areas dominated by shrubs; shrub canopy accounts for 25-100 percent of the cover. Shrub cover is generally greater than 25 percent when tree cover is less than 25 percent. Shrub cover

may be less than 25 percent in cases when the cover of other life forms (e.g. herbaceous or tree) is less than 25 percent and shrubs cover exceeds the cover of the other life forms.
**Non-Natural Woody** - Areas dominated by non-natural woody vegetation; non-natural woody vegetative canopy accounts for 25-100 percent of the cover. The non-natural woody classification is subject to the availability of sufficient ancillary data to differentiate non-natural woody vegetation from natural woody vegetation.
61. *Orchards/Vineyards/Other* - Orchards, vineyards, and other areas planted or maintained for the production of fruits, nuts, berries, or ornamentals.
**Herbaceous Upland** - Upland areas characterized by natural or semi-natural herbaceous vegetation; herbaceous vegetation accounts for 75-100 percent of the cover.
71. *Grasslands/Herbaceous* - Areas dominated by upland grasses and forbs. In rare cases, herbaceous cover is less than 25 percent, but exceeds the combined cover of the woody species present. These areas are not subject to intensive management, but they are often utilized for grazing.
**Planted/Cultivated** - Areas characterized by herbaceous vegetation that has been planted or is intensively managed for the production of food, feed, or fiber; or is maintained in developed settings for specific purposes. Herbaceous vegetation accounts for 75-100 percent of the cover.
81. *Pasture/Hay* - Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops.
82. *Row Crops* - Areas used for the production of crops, such as corn, soybeans, vegetables, tobacco, and cotton.
83. *Small Grains* - Areas used for the production of graminoid crops such as wheat, barley, oats, and rice.
84. *Fallow* - Areas used for the production of crops that do not exhibit visable vegetation as a result of being tilled in a management practice that incorporates prescribed alternation between cropping and tillage.
85. *Urban/Recreational Grasses* - Vegetation (primarily grasses) planted in developed settings for recreation, erosion control, or aesthetic purposes. Examples include parks, lawns, golf courses, airport grasses, and industrial site grasses.
**Wetlands** - Areas where the soil or substrate is periodically saturated with or covered with water as defined by Cowardin et al.
91. *Woody Wetlands* - Areas where forest or shrubland vegetation accounts for 25-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water.
92. *Emergent Herbaceous Wetlands* - Areas where perennial herbaceous vegetation accounts for 75-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water.

**Digital Elevation Model of Niobrara River Basin**
The shapefile is downloaded from USGS web site.