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STREAMFLOW GAINS AND LOSSES IN THE NIOBRARA RIVER BASIN, NEBRASKA, 1980 AND 2009

Philip J. Soenksen[1]
Brandi B. Flyr[2]
Jason S. Alexander[1]
Nathan J. Schaepe[1]

[1]U.S. Geological Survey, Lincoln, Nebraska, USA
[2]Nebraska Department of Natural Resources, Lincoln, Nebraska, USA

A study was made to determine the locations and rates of groundwater gains and losses (seepage) in the roughly 350-mile lower reach of the Niobrara River in northern Nebraska, United States, including the 76 miles designated as a National Scenic River, using synoptic main-channel and tributary discharge measurements. Results were compared to those from a 1980 study, to groundwater and surface-water head measurements, and to alluvial thickness estimates along the main channel. For 2009, most tributary reaches west of Valentine had gains of about 0-2 cubic feet per second per mile (cfs/mi), but upper Minnechaduza Creek had losses of 5 cfs/mi. Eagle Creek, Long Pine Creek, Verdigre Creek, and the Snake River showed the largest tributary gains of >3 cfs/mi. The remainder of the study region showed a mix of gains and losses along tributaries. For the main stem, results from the 1980 and 2009 seepage studies indicated similar patterns of total flow, cumulative tributary inflow, and cumulative main-stem seepage gain/loss. Upstream from the confluence with the Snake River, Niobrara River flow increases were almost entirely from main-stem seepage gains; downstream from the confluence, the number of contributing tributaries increased substantially, and tributary inflows were the largest source of main-stem flow increases below Norden. For many individual main-stem reaches, seepage rates for this study did not agree with the results obtained during the 1980 study; but, for four longer reaches classified by their differing geology, there were increasing gains in the upper two reaches followed by losses in the third reach - rates were 1.8, 4.1, and -5.5 cfs/mi for 1980; and 2.6, 3.4, and -2.3 cfs/mi for 2009, respectively. In the fourth geologic reach, there were no data for 1980, but the 2009 results indicated that this reach had the largest rate of main-stem seepage gain, 8.5 cfs/mi. The broad-scale spatial patterns of main-stem flow gains and losses were coincident with similarly scaled patterns of bedrock and unconsolidated alluvial-aquifer thickness, and with reach-scale measurements of head differences between groundwater and surface water.

INTRODUCTION

The Niobrara River of northern Nebraska (Figure 1), United States, is a valuable water resource that sustains irrigated agriculture, recreation, and power generation, as well as a diverse array of ecosystem types (Johnsgard, 2001). A 76-mile reach from Borman Bridge near Valentine to State Highway 137 near Mariaville was designated as the Niobrara National Scenic River in 1991, part of which flows through the 19,000-acre Fort Niobrara National Wildlife Refuge. The availability of water for multiple uses is affected by both natural hydroclimatic processes and increasing human demands. Having identified the potential for conflict between groundwater and surface-water uses, the Nebraska Department of Natural Resources (NDNR) recently designated portions of the Niobrara River as fully appropriated for management purposes. This designation requires sustainable management of the hydrologically connected surface-water and groundwater resources by balancing variable water supply with competing demands, while considering near- and long-term benefits.

Effective management of the Niobrara River benefits from advancements in our understanding of the interactions between the surface-water and groundwater resources of the basin. In cooperation with the Nebraska Game and Parks Commission, the U.S. Geological Survey (USGS) undertook a collaborative seepage study with the NDNR and the National Park Service to investigate the broad-scale magnitudes and variation in groundwater contributions to streamflow in the Niobrara River from Box Butte Dam to the mouth, a distance of about 350 miles. The primary purpose of the study was to determine the locations and rates of groundwater gains and losses (seepage) using synoptic (during a brief period) main-channel and tributary discharge measurements. In this paper, seepage results are compared to those from a previous study (U.S. Geological Survey, 1981) as well as to hydraulic-head measurements and alluvial-thickness estimates along the main channel.

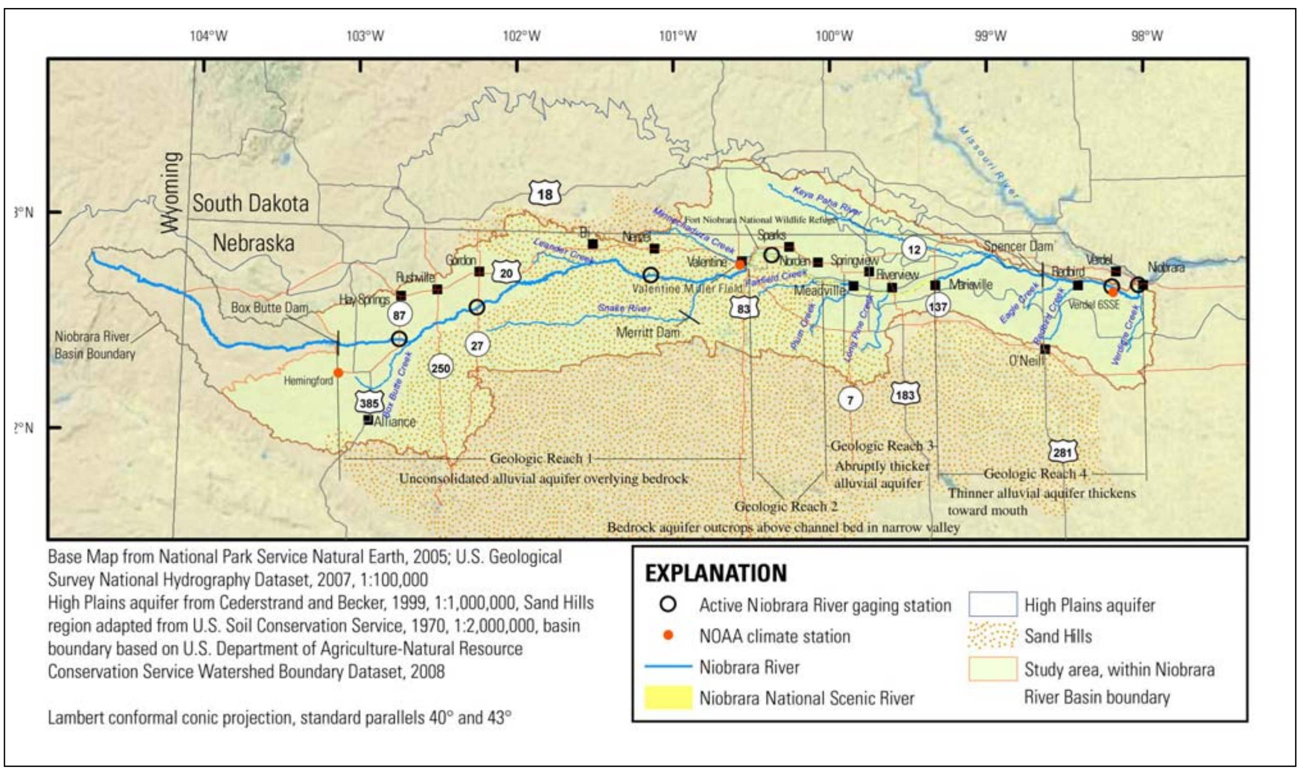

Figure 1. Study area and Niobrara River Basin boundary.

BACKGROUND

Streamflows in the Niobrara River are largely derived from groundwater inflows (Bentall and Schaffer, 1979). During dry periods, when runoff from rainfall or melting snow is reduced, the proportion of streamflow from groundwater inputs increases. The presence of seeps and springs are evidence of a groundwater-fed, gaining stream; however, most gains are not visible above ground, flowing through hydrologically connected alluvial sediments. The amount of inflow depends partly on the type and thickness of alluvial materials and on the height of the water table, which fluctuates in response to precipitation, evapotranspiration, drainage through stream channels, and groundwater pumpage. Under certain combinations of hydrologic conditions and geologic settings, streamflow can also re-enter the groundwater system, resulting in a losing reach of stream. Broad-scale geologic controls, such as the thinning and thickening of the alluvial aquifer, are also primary determinants of the locations of streamflow gains or losses respectively (Konrad, 2006).

Seepage studies—measurements of discharge during periods when streamflow is sustained primarily by groundwater—are one method to help understand and quantify the magnitudes and spatial variability of stream gains and losses. Measurements of hydraulic-head differences between the surface of the stream and the pressure head from the underlying groundwater also can be anecdotal indicators of groundwater inputs to a stream (Winter et al., 1988; Rosenberry and LaBaugh, 2008).

DESCRIPTION OF STUDY AREA

The Niobrara River originates in east-central Wyoming, and flows eastward approximately 560 miles before reaching its confluence with the Missouri River. The total drainage area is approximately 13,480 square miles and includes portions of Wyoming and South Dakota, but most of the basin is within Nebraska (Figure 1). Annual precipitation increases gradually from 14 inches in the semi-arid steppe of east-central Wyoming to 24 inches in the subhumid glacial-till terrain along the northeastern margin of Nebraska (Fenneman, 1928; Dugan and Zelt, 2000). The Niobrara River alternately flows through wide alluvial valleys, canyons, and valleys bounded by steep escarpments (University of Nebraska, 1986; Alexander et al., 2009).

Much of the Niobrara River Basin overlies the High Plains aquifer, a massive groundwater system extending from South Dakota to Texas, and the source of water for much of the irrigated agriculture in the region (McGuire and Peterson, 2008). Additionally, a large portion of the Niobrara River Basin lies in the Sand Hills, a vast region of vegetation-stabilized sand dunes (Soller and Reheis, 2004). The high infiltration capacity of the Sand Hills almost completely eliminates direct surface runoff from precipitation, and delivers water to the surrounding rivers by aquifer seepage (Bentall and Schaffer, 1979). The dominance of a groundwater-influenced streamflow regime is most evident west of Valentine, Nebraska, where the Niobrara River flow is steady and persistent. Eastward from Valentine, increased precipitation and storm-generated runoff progressively decrease the steady nature of the flow (Shaffer, 1975; Soenksen et al., 1999; Istanbulluoglu, University of Nebraska-Lincoln, unpub. data, 2009).

The Niobrara River Basin is relatively undeveloped compared to other large river basins of Nebraska, and local economies are dependent on a combination of cattle ranching, agriculture, recreation, and tourism (Schultz, 2009). Two large dams, Box Butte on the Niobrara River and Merritt on the Snake River, store surface water for large irrigation projects and affect the flow regime of the Niobrara River. Water released from Box Butte Dam is diverted at Dunlap Diversion Dam, and the channel below the diversion is almost entirely de-watered for a short distance before groundwater seepage produces substantial gains (Bentall and Schaffer, 1979). After its construction in 1964, the operation of Merritt Dam reduced the mean annual flow of the Niobrara below the confluence with the Snake River (Buchanan, 1981; Istanbulluoglu, University of Nebraska-Lincoln, unpub. data, 2009). The majority of irrigation wells in the basin are concentrated in two areas, one in the southwest region near Alliance and one in the southeast region near O'Neill (Alexander et al., 2009). The magnitude of effects from irrigation development on streamflow in the Niobrara River Basin has not been fully assessed.

PREVIOUS STUDIES AND STRATEGY FOR STUDY

The NDNR completed several seepage studies on portions of the Niobrara River Basin prior to this study. One of the studies extended from the Wyoming-Nebraska boundary to south of Springview, and included the main stem and tributaries on both sides of the river. Another study extended downstream to Mariaville for north side tributaries (and for the Keya Paha River sub-basin tributaries) during April 21–24 and 28–30, 1980 (U.S. Geological Survey, 1981). The south-side tributaries were measured from south of Springview to the mouth during October 3–4, 1980. The Long Pine Creek sub-basin was re-measured during October 28–29, 1987. The results of these measurements were examined by the USGS to aid in the site-selection strategy for the new seepage run. The NDNR streamflow discharge measurements showed relatively small inflows from tributary streams, and increasing or steady flow along the main-stem sites downstream to Bryan Bridge (old U.S. Hwy 20/83) south of Valentine, thus indicating that site-to-site increases in streamflow were probably greater that the uncertainty in the discharge measurements. For these reasons, it was decided that for the new study only single measurements were needed at main-stem sites throughout that reach. The abundance of sites and small proportion of streamflow added by individual tributaries indicated that single measurements generally were adequate for tributary sites.

Previous study measurements from Bryan Bridge to the USGS streamflow-gaging station near Sparks (station 06461500; at Berry Bridge) showed both gaining and losing stream segments. Farther downstream, there were both increases and decreases in streamflow to the last main-stem measurement site at U.S. Highway 183 south of Springview. Such apparent discharge changes raised questions concerning measurement uncertainty and its sources, including equipment, methods, conditions, and temporal variability. To verify the magnitude of actual site-to-site differences, previous results suggested that replicate measurements were necessary to reduce uncertainty at these sites.

To avoid problems caused by irrigation withdrawals and ice effects, the target period for the 2009 seepage study was set to follow the irrigation season and refilling of reservoir storage but before ice formation on streams. The generally cool fall temperatures and dormancy of most vegetation minimize effects from evapotranspiration. The late-October to mid-November period also coincides with the timeframe when surface runoff from storm events is generally minimal, thereby increasing chances for base-flow conditions.

METHODS

The primary source of data for this study consisted of streamflow measurements of the Niobrara River main stem and tributaries. USGS and National Park Service (NPS) staff measured the main-stem discharges; and NDNR staff measured tributary discharges. Additionally, USGS and NPS staff measured hydraulic-head differences between stream and aquifer, where possible, at discharge measurement sites along the main stem.

Streamflow Gain and Loss

Base flow is the part of streamflow that enters stream channels relatively slowly after precipitation or snowmelt. Generally, it is composed of groundwater flow, but can include delayed surface flow from interflow and return flow (Langbein and Iseri, 1960; Chow, 1964; Soenksen, 1996). As the time between precipitation events increases, the groundwater proportion of streamflow will increase. Streamflow measurements made during ideal base-flow conditions will be largely a measure of groundwater inflows to the streams. Such measurements made at various points along a stream, if made precisely, can then be used to determine aggregate groundwater gains or losses to the stream between those points. This assumes that artificial or natural modifications to streamflow are absent within the intervening drainage area. Modifications include irrigation withdrawals and return flows, and water entering ice and backwater storage during periods of freezing weather, followed by release of that water during warmer periods. If all tributary inflows in a reach are also measured, the groundwater inflows to the main-stem channel can be determined within the limits of streamflow measurement uncertainty.

Base-Flow Conditions and Temporal Variability

Under ideal base-flow conditions, streamflow would steadily recede as water drains from the groundwater system into the stream channel—unless affected by factors such as precipitation, snowmelt, evaporation, plant transpiration, or flow manipulation. If the maximum and minimum flows do not occur at the start and end of the day, respectively, base-flow conditions are not ideal. In such cases the maximum and minimum flows within given days can indicate the temporal variability that contributes to potential error in determining the site-to-site differences in streamflow discharge. Assuming no measurement error, if an upstream site were measured during the lower part of within-site range of flow variability and the next downstream site were measured on the higher part of the range of within-site flow variability, the computed difference (downstream minus upstream) would positively bias the estimated gain or loss between the adjacent sites. The converse relations between adjacent discharge measurements and the within-site range of temporal variability would negatively bias the estimated gain or loss from seepage. Where temporally continuous discharge data were available, this temporal variability range was determined and reported as a source of potential error in the gain-loss calculations.

The hydrologic conditions leading up to and during the study are shown for three main-stem streamflow-gaging stations and three National Oceanic and Atmospheric Administration climate stations (National Oceanic and Atmospheric Administration, 2010a and 2010b) on the upper, middle, and lower portions of the study area (Figure 2). The continuous discharge data shown for these sites were not available for all sites measured, but the data from these gaged sites can be used as a relative indicator of conditions for other sites along the main stem. Precipitation in northern Nebraska during middle-to-late October 2009 resulted in substantial increases in surface runoff to streams. Consequently, the seepage study timeline was rescheduled to allow for improvement of probability for base-flow conditions. Although conditions were not ideal—with limited time for surface runoff to exit the basin, probable high soil-moisture conditions on the lower part of the basin, and additional runoff possible because of lingering snow—the seepage study measurements were completed during the period of November 9–13, 2009, with main-stem measurements made during November 10–13.

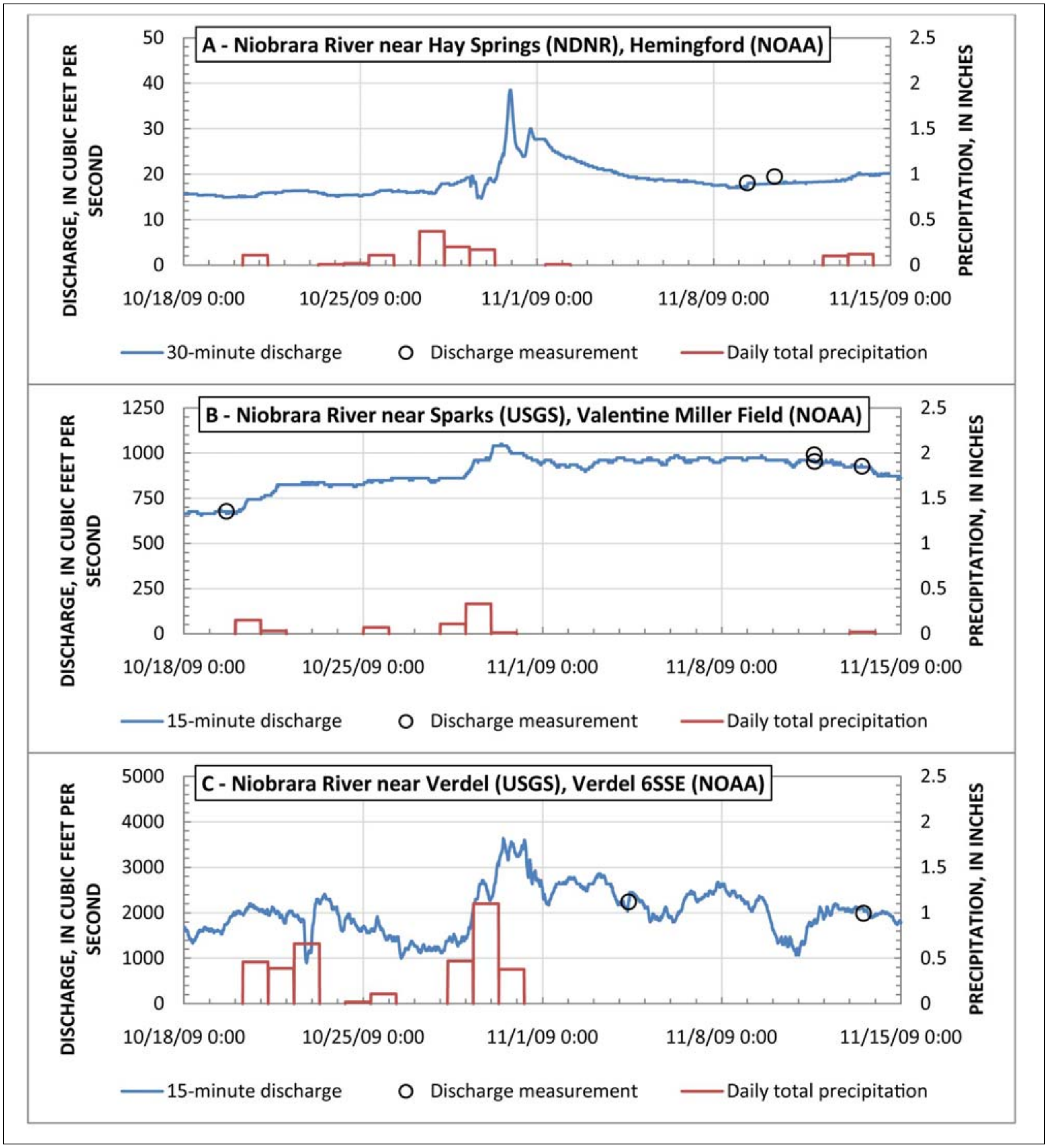

Figure 2. Gaging station discharge record, discharge measurements, and daily precipitation for locations on (A) upper, (B) middle, and (C) lower parts of the study area during October 18–November 14, 2009. (Discharge data from Nebraska Department of Natural Resources (NDNR) and U.S. Geological Survey (USGS) gaging stations; precipitation data from National Oceanic and Atmospheric Administration (NOAA) climate stations.)

Based on NDNR gaging station records, there were no flow changes from Box Butte Dam on the Niobrara River during the period Nov 9–13, 2009 (J. Ostdiek, NDNR, written comm., 2010), and there were no changes from Merritt Dam on the Snake River until the morning of Nov 13, 2009 (T. Klanecky, NDNR, written comm., 2010). The latter would not have affected the seepage results as data were collected in that area several days before the change. Power is produced by the flows through turbines at Spencer Dam with operations designed to match the inflows to the reservoir with corresponding outflows by adjusting the turbine and other gate openings as needed to keep the pool steady within certain limits. This cannot be done with absolute precision, and routine dam operations can create short-term artificial fluctuations in flow downstream, even though the general trend follows the natural flow. Other fluctuations can be caused by maintenance operations to bypass floating debris and to sluice sediment deposits. Records from the Nebraska Public Power District (NPPD), which operates the dam, indicate that normal operations were in effect November 12–13, 2009, except for some short-term bypassing of debris during late afternoon November 12, 2009 (D. Lauredsen, NPPD, oral comm., 2010). This would have created a temporary increase in outflow, as water was released from storage, followed by a decrease in outflow, as the pool was re-filled. The exact effect is unknown, but both the increase and decrease would have moderated with increasing distance downstream and probably did not substantially affect the downstream measurements of November 13, 2009.

Discharge Measurements and Estimated Uncertainty

For the main-stem Niobrara River, measurements were made in a downstream direction to "follow the flow" and to minimize general recessional differences that could otherwise occur. From Bryan Bridge downstream to near the mouth at State Highway 12 at Niobrara, at least two nearly concurrent measurements were planned, but this was not always possible due to time constraints. To the extent possible, tributary measurements were made on the same day as the corresponding main-stem measurements. Streamflow discharge measurements were made using standard methods of the USGS (P.J. Soenksen, unpublished, Surface-Water Quality Assurance Plan for the Nebraska Water Science Center of the U.S. Geological Survey, rev. 2007; Nolan and Shields, 2000; Rantz et al., 1982) as discussed in more detail below.

The gain-loss calculations were directly dependent on discharge measurements; therefore, every reasonable effort was made to measure discharge as precisely as practical, but measurement accuracy still varied based on individual site conditions. Streamflow measurements made in 2009 were assigned a subjective rating for measurement uncertainty in view of site conditions (Rantz et al., 1982). For example, a rating of "excellent" indicated that the measurement was considered to have 2 percent uncertainty at the time of the measurement. Other ratings included "good," "fair," and "poor," indicating presumed measurement uncertainties of 5, 8, or greater than 8 percent of the actual discharge. The uncertainty ratings were based on the professional judgment of the hydrographer, and incorporate consideration of a variety of environmental and hydraulic factors, including distribution of flow across the channel, channel geometry, channel hydraulic controls, and flow stability. Uncertainty ratings for the 1980 streamflow measurements were not readily available. For subsequent calculations, main-stem measurements from 1980 were arbitrarily assigned an uncertainty of 8 percent. Although uncertainty ratings were subjective at best, they are valuable as indicators of relative measurement imprecision where none can be objectively quantified directly from an instrument.

Midsection and Point-Velocity Method

Although several methods for measuring discharge were used during the study, almost all measurements were made using the midsection method, with velocity measurements made at prescribed points in the vertical profile of the section. In this method, the stream cross section is divided into partial areas (subsections) for which the hydraulic area and an average velocity are determined (Rantz et al., 1982; Buchanan and Somers, 1969). The total discharge is the summation of the products of area and mean velocity for all of the subsections. Widths were determined from a graduated tape or tagline stretched across the measured section.

Water depths were measured directly using either a graduated wading rod or by sounding with a streamlined weight attached to a cable raised and lowered from a portable crane by a reel with an integral depth indicator (Rantz et al., 1982; Buchanan and Somers, 1969). A few measurements made by different methods are discussed in "ADCP and Other Methods" below. If water depth was too shallow to "zero" the depth indicator when the velocity meter (connected above the sounding weight) was centered on the water surface, depths were estimated.

Several combinations of equipment and methods were used to measure velocity. On the tributary streams, all measurements were made by wading with Price vertical-axis meters (type AA or pygmy) (Rantz et al., 1982; Buchanan and Somers, 1969). On the main stem of the Niobrara River, wading measurements were made using SonTek FlowTracker® acoustic Doppler velocimeters (ADVs) (Blanchard, 2007, 2009; Rehmel, 2007), which use the measured Doppler shift of an acoustic signal reflected off of particles in the water to determine velocity. For all but three discharge measurements made from bridges on the Niobrara River main stem, velocities were measured using the Price AA meter. Standard USGS procedures were used to determine the depths in the water column where velocity measurements were made, which are dependent on the specific meter being used and the depth of the flow at the section (Blanchard, 2007, 2009; Rehmel, 2007; Rantz et al., 1982; Buchanan and Somers, 1969). In cases where water depth was less than 2.5 times the distance from the center of the meter to bottom of sounding weight, which occurred often at some sites, a velocity measurement was made as low in the vertical profile as possible and then adjusted on the basis of the typical vertical-velocity curve from Buchanan and Somers (1969, p. 36) to estimate the mean velocity for the subsection. If water depth was too shallow to submerge the meter into the flow, the velocity was estimated from the trends of adjacent subsections or from direct estimates at the subsection. At the interface of vertical obstructions (for example, piers), velocity was estimated from the adjacent section using the method from Rantz et al. (1982, p. 82).

Beam checks of the ADV transducers are routinely made in the office, and electronic files of the results are archived as part of the normal quality-assurance procedures. A less extensive beam check was made in the field before each measurement and automatically recorded in the electronic measurement file. For Price AA meters, spin tests of the mechanical bucket wheels were made before and after the field study and between most measurements. The results were manually recorded on the measurement notes and in office log books.

ADCP and Other Methods

Two types of acoustic Doppler current profiler (ADCP) units were used to make discharge measurements using standard USGS procedures (Mueller and Wagner, 2009). The RD Instruments (RDI, Poway, Calif.) StreamPro® (2.0 MHz) was used to make two measurements, and the RDI Rio Grande® (1.2 MHz) was used to make one measurement. Both units used were mounted under small portable boats that were tethered either from a bridge or from a line stretched across the stream, with a wireless communications link between the ADCP and a portable computer. Similar to the ADVs, the ADCPs use an acoustic signal to determine current velocity. In addition, ADCPs measure the depth and velocity throughout most of the vertical profile simultaneously while traversing the cross section. Standard procedure is to make several traverses in each direction until four consecutively measured discharges are within 5 percent of each other. For one-person operation, the StreamPro was used in section-by-section mode, which is similar to the standard midsection method, but depth and velocity were measured using the ADCP. Due to simultaneous measurements of depth and the velocity profile, the StreamPro measurements took less time than the concurrent Price AA measurements.

A limitation of the ADCP method is that excessive sediment or air bubbles entrained in the flow can scatter the acoustic signal to the extent that insufficient readings are obtained. Higher-frequency transducers are more susceptible to this signal loss than are lower-frequency transducers, but lower-frequency transducers require a larger minimum water depth. These limitations restricted the use of ADCPs to only a few sites on the Niobrara River.

At some tributary sites, where conditions were not favorable for streamflow measurement, discharge was estimated based on the hydrographer's judgment. Such estimates were only made when flows were of small magnitude (=0.33 cubic feet per second (cfs)). Knowledge of zero flow at a site is important information, and such observations were documented.

Sites Not Measured or Measurements Not Used

Along the main stem, several planned sites were not measured, and several discharge measurements were not used for analysis. No measurement was made at State Highway 61 near Merriman because of time and safety constraints with loss of daylight conditions. No measurement was attempted at Meadville because of debris in the measuring section and bridge construction just upstream. At the bridge at U.S. Highway 183 near Springview, depths were too great to wade at the edges, but too shallow to measure velocity from the bridge throughout most of the remaining wide cross section. At the bridge at State Highway 7 at Riverview, a malfunction (over-registering) in the depth indicator was discovered during the only measurement there. The same equipment had been used for a measurement downstream from Cornell Dam where two other measurements also had been made at about the same time—one with a different set of the same type of equipment, and one with an ADCP. A comparison of data for cross-sectional areas among those three measurements verified the malfunction and consequent overestimation of areas and discharges. Therefore, neither of the two measurements made with the malfunctioning instrument was used for analysis.

The measurements made with the StreamPro ADCP at the site downstream from Cornell Dam and at the Sparks gaging station (Berry Bridge) were also not used, because of a possible method bias. In both cases, the ADCP-measured discharge was larger than that measured with the Price AA meter. An independent, routine measurement at the Sparks gaging station, made by wading with an ADV 2 days after the seepage measurement (on November 15, 2009), was in close agreement with the Price AA seepage measurement (Figure 2) and confirmed the rationale for not using the StreamPro ADCP measurements. The Rio Grande ADCP measurement at Norden Bridge site did not meet the standard for four consecutive traverses within 5 percent of each other and was, therefore, not used for analysis. Air bubbles entrained into the flow about 200 feet (ft) upstream at a waterfall (Norden Chute) might have been a contributing factor.

Gain/Loss Calculations and Levels of Uncertainty

Calculations of streamflow gains or losses from seepage, for both the 1980 and 2009 seepage studies, were made from the inflow and outflow terms of a volume balance approach, that is, by combination of measured main-stem and tributary discharges. For any two sites along a given reach of stream, the stream inflows were summed (in other words, upstream discharge plus the discharges of any inflowing tributaries), and the total was then subtracted from the outflowing discharge at the downstream end of the reach. By assuming that (1) all tributary inflows were accounted for (measured or estimated), (2) the effects from temporal variability or measurement bias were negligible, and (3) change in storage was negligible, a positive difference would indicate a gain in streamflow from inflowing groundwater seepage, and a negative difference would indicate a loss in streamflow through seepage outflow from the reach.

Linear-average rates of gain or loss for total flow, tributary inflow, and main-stem seepage were computed for each reach between measurement sites by dividing the gain or loss by the length of the reach. To evaluate the reliability of the gain/loss for a given reach, the computed seepage gain/loss was compared to the estimated combined magnitude of the two sources of uncertainty affecting measured discharges, that is, potential temporal variability and measurement uncertainty related to site conditions. In reality, both sources of uncertainty affect the calculated gain/loss more where measured sites are close together and the magnitude of gain/loss is small compared to the combined uncertainty. This was evident along the main stem in the upper end of the Scenic River where the linear-average rates were most variable.

Longer reaches were selected for analysis to smooth or minimize site-specific measurement uncertainty and to provide greater comparability of results between 1980 and 2009. These longer reaches had (1) fairly consistent underlying geology; (2) gain/loss differences determined by double measurements that agreed within 5 percent (except at the first and last study sites, which only had single measurements); and (3) gain/loss differences greater than the measurement uncertainty. In a downstream direction, the breakpoints between the four longer geologic reaches were at Bryan Bridge south of Valentine, Norden Bridge, and State Highway 137 near Mariaville. Geologic reaches 1 and 2 are underlain by the High Plains aquifer, which here consists of an unconsolidated alluvial aquifer overlying a bedrock aquifer of consolidated sediments. In geologic reach 1 the alluvial aquifer generally thins in the downstream direction and is much thinner below about river mile 200. In geologic reach 2, the alluvial aquifer is mostly absent in the channel because the bedrock aquifer outcrops at elevations above the channel bed (McGuire and Peterson, 2008), resulting in springs, seeps, and waterfalls along the narrow valley walls. Geologic reach 3 is characterized by an abruptly thicker and wider unconsolidated alluvial aquifer overlying Cretaceous Pierre Shale, an aquitard. In geologic reach 4, the unconsolidated alluvial aquifer is much thinner in the upper part of the reach, but thickens again toward the mouth of the Niobrara River.

Uncertainty bars were computed for the main-stem discharge measurements based on the subjective uncertainty ratings of each measurement (see “Streamflow Discharge Measurements and Estimated Uncertainty”). For illustrative purposes only, uncertainty bars for measurements with conditions rated “poor” were arbitrarily set to 16 percent.

Cumulative tributary inflow, main-stem seepage, and total flow were computed in relation to distance along the channel in a downstream direction. For tributary inflows, this was a step increase along the main stem at the river mile of each contributing tributary confluence with the main stem. For main-stem seepage, the cumulative total changed gradually between each main-stem measurement site as the calculated gain or loss was prorated along the channel length between sites. The reconstructed total flow was the sum of the other two cumulative totals.

Uncertainty bands were then computed for the cumulative gain/loss totals using the measurement uncertainty bars. The high band was computed by subtracting the low-uncertainty-bar value of the measured discharge for the upstream site from the high-uncertainty-bar discharge for the downstream site of each reach. Conversely, the low uncertainty band was computed by subtracting the high-uncertainty-bar discharge for the upstream site from the low-uncertainty-bar discharge for the downstream site for each reach. Similarly, uncertainty bands were computed for the main-stem seepage rates in the geologic reaches. The uncertainty bars and bands reflect the subjective ratings of measurement uncertainty only and do not include the possible effects from short-term temporal variability in streamflow.

GROUNDWATER AND SURFACE-WATER HYDRAULIC-HEAD MEASUREMENTS

Measurements of relative difference between hydraulic head (that is, potentiometric difference) of groundwater and surface water were made at most main-stem sites to provide anecdotes of the potential for streamflow gains or losses. Head differences were measured using a hydraulic potentiomanometer (Winter et al., 1988; Rosenberry and LaBaugh, 2008). The potentiomanometer uses a screened probe to measure the head of groundwater in the shallow alluvium of the river, and a filter to measure the head of the surface water. The water from the surface water and the alluvium are pulled by suction into two parallel tubes of a glass manometer using a hand-operated vacuum pump. Once the pressures of the two tubes are equilibrated in the manometer, a precise measurement of head difference is made using a ruler or measuring tape (Rosenberry and LaBaugh, 2008). If groundwater head is greater than surface-water head, the stream at that location is considered to be gaining groundwater through the alluvium. If the groundwater head is less than surface-water head, the stream at that location is considered to be losing water to the shallow aquifer either horizontally or vertically.

At locations where the alluvium exceeded 2 ft of thickness, the probe of the potentiomanometer was driven 2 ft into the bed of the river at both the left and right bank, and a head difference was measured. At one location, a third measurement had to be made because substantial head differences were measured at the left and right bank. At the most downstream site, four measurements were made because the river had two primary channels separated by extensive vegetated islands. Relative head differences were not measured at sites that had thin alluvium (<2 ft) or outcropping bedrock lining the river channel. These sites were mainly limited to the central portion of the study area, and included sites where the bedrock is part of the High Plains aquifer system (McGuire and Peterson, 2008). Although the bedrock at these locations is part of an aquifer system and might coincide with stream-aquifer interactions, the potentiomanometer is not designed to penetrate consolidated material.

Alluvial Thickness Estimates

Differences in the thickness of alluvial material, and the composition and topography of the bedrock material which underlies it, are primary determinants of the locations of surface water and groundwater interactions (Konrad, 2006). These interactions occur over a variety of temporal and spatial scales (Bencala, 2000) and act as important biogeochemical pathways, heat sources and sinks, and drivers of aquatic and riparian ecosystem functioning in river systems (Boulton et al., 1998; Baxter and Hauer, 2000). Because this study focused on magnitudes of streamflow gains and losses over spatial scales of tens of kilometers, broad-scale patterns of alluvial thickness and bedrock topography along the main stem of the Niobrara River were evaluated. For the purposes of this paper a generalized differentiation was made between geologic units: (1) the unconsolidated alluvial aquifer, which is composed of modern valley fill deposits of fluvial origin, (2) the bedrock aquifer, which is composed of consolidated fluvial-lacustrine sediments of Tertiary age, and (3) a bedrock aquitard, which is primarily composed of shale of Cretaceous age. In the Niobrara River

Basin upstream from approximately Norden, the unconsolidated alluvial aquifer and the Tertiary consolidated bedrock formations are both considered part of the High Plains aquifer groundwater system as described by McGuire and Peterson (2008). Downstream from approximately Norden, the unconsolidated alluvial fill overlies Cretaceous Pierre Shale (Burchett, 1986), an aquitard.

Two primary datasets were used to construct the basic model of bedrock topography and unconsolidated alluvial thickness. First, structure contours of the elevation of the base of the High Plains aquifer (McGuire and Peterson, 2008) were used to evaluate the thickness of the bedrock aquifer below the river bed. The thickness of the bedrock aquifer was calculated by subtracting the base-of-aquifer elevation from the earth-surface elevation wherever a structure contour crossed the Niobrara River channel centerline. The elevation profile of the earth surface along the channel centerline (modified from Alexander et al., 2009) primarily was derived from the 10-meter grid of the USGS National Elevation Data Set. Second, borehole logs at bridge abutments were obtained from the Nebraska Department of Roads (NDOR) and were evaluated. In most cases, the borehole logs were available for both the left and right banks and included an elevation of the free water surface in the river. The unconsolidated alluvial aquifer thickness was calculated by subtracting the depth to bedrock in the borehole log from the elevation of the free water surface. The maximum of the two thicknesses (either left or right bank) was used as the primary measure of unconsolidated aquifer thickness. This dataset was supplemented with one additional borehole point from the Bureau of Reclamation (Buchanan, 1981).

RESULTS AND DISCUSSION

Discharge measurements, estimates, or observations of zero flow were made at 263 stream sites within the Niobrara River Basin downstream from Box Butte Dam during November 10–13, 2009 (Figure 3). Discharge measurements or estimates were made at 194 sites (appendix, Table A–1). Wet roads and lingering snowmelt from several storms in preceding weeks prevented additional measurements upstream from Box Butte Dam. Tributary flows were measured during November 9–13, 2009, at 161 sites and estimated at 15 sites; zero flow was observed at an additional 69 sites. On the main stem, 30 of 36 planned measurements of discharge were made at 18 out of 20 planned sites. Of the 30 main-stem discharge measurements, 25 measurements at 17 sites defined 16 reaches for which the gain/loss was calculated; 2 were not used for analysis because of equipment problems; 2 were not used for analysis because of possible method bias; and 1 was not used because of incomplete data caused by poor site conditions. Replicate measurements were made at nine sites.

Tributary Gains and Losses—November 2009

Discharge measurements, estimates, or observations were made on 78 tributary reaches within the Niobrara River Basin (Figure 3). Except for the observations of zero flow, the corresponding data are listed in the appendix (Table A–1). For selected tributary reaches, linear-average gain or loss computed from the discharge measurements are listed in Table 1. Data for three tributary reaches indicated loss of discharge to groundwater in the upper reach of Minnechaduza Creek, the lower reach of Leander Creek, and an unnamed tributary to Box Butte Creek. These reaches are all in the western portion of the study region, west of Valentine. Leander Creek and the tributary to Box Butte Creek showed minor losses, less than 1 cubic feet per second per mile (cfs/mi). These losses may be within the interval of measurement uncertainty, indicating inconclusive results with respect to their status as gaining/losing reaches. Along the upper reach of Minnechaduza Creek,

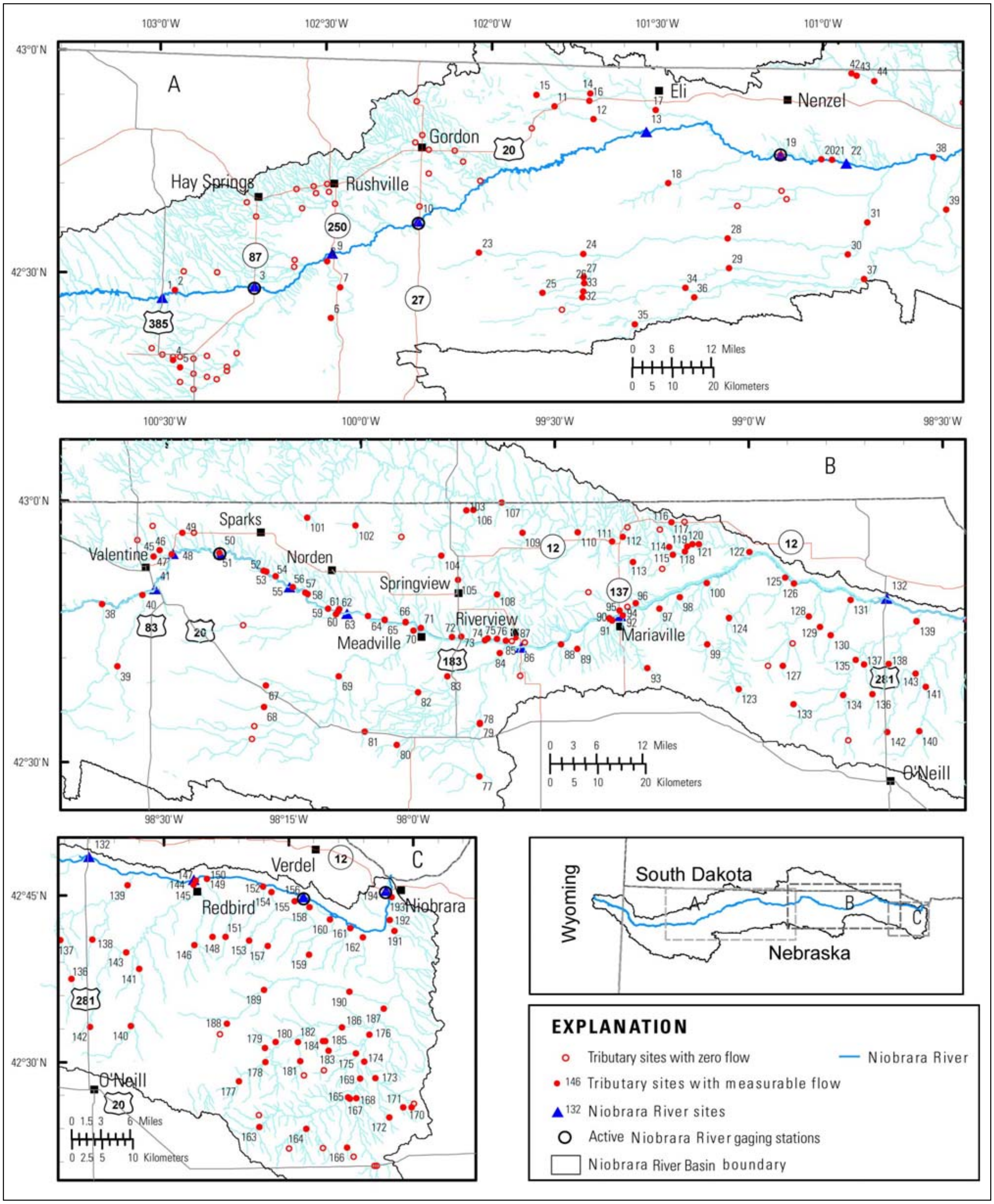

Figure 3. Locations of measurement sites. Label numbers correspond to map ID numbers in the appendix (Table A–1).

discharge losses averaged approximately 5 cfs/mi. Results for the remaining tributary reaches in the upper part of the basin indicated streamflow gains of approximately 0–2 cfs/mi.

The four tributaries where results indicated the largest gain rates (>3 cfs/mi) were Eagle Creek, Long Pine Creek, Verdigre Creek, and the Snake River (Table 1). The region of the study area between Meadville and Riverview contained a higher frequency of tributaries with larger rates of seepage, with four of the seven reaches that had the highest average rates of streamflow gain located within this area. The gaining tributaries within this region were Fairfield Creek, Sand Draw, Bone Creek, Plum Creek, and Long Pine Creek. The remainder of the study area contained a mixed distribution of reach-average gain/loss rates.

Main-Stem Gains and Losses—April 1980 and November 2009

Results from the 1980 and 2009 seepage studies are shown in Figure 4 and for 2009 in Table 2. Both studies indicated similar patterns of total flow, cumulative tributary inflow, and cumulative main-stem seepage gain/loss, with some differences apparently related to antecedent precipitation. The patterns of main-stem seepage gain/loss rates for individual measured reaches did not agree well between studies because of measurement uncertainty and the close proximity between some pairs of measurement sites (Figure 4). However, the patterns of main-stem seepage gain/loss rates averaged for the geologic reaches are similar, with increasing gains in the two upstream reaches followed by losses in the third reach, downstream from Norden Bridge (river mile 119.3). For those upper three geologic reaches, data for 1980 showed seepage rates of 1.8, 4.1 and -5.5 cfs/mi; and data for 2009 showed seepage rates of 2.6, 3.4, and -2.3 cfs/mi. There was no 1980 data

Table 1. Streamflow gain and loss rates per stream mile for selected tributary reaches within the Niobrara River Basin based on discharge measurements November 9–13, 2009.

Tributary reach	Streamflow gain/loss rate (cfs/mi)	
	Gain	Loss
Box Butte Creek tributary (unnamed) (Box Butte Creek enters Niobrara River at mile 312.1)	---	<1[a]
Leander Creek (lower reach) (enters Niobrara River at mile 223.6)	---	<1[a]
Snake River (enters Niobrara River at mile 173.2)	>3	---
Minnechaduza Creek (upper reach) (enters Niobrara River at mile 150.3)	---	5
Fairfield Creek (enters Niobrara River at mile 120.7)	1.7	---
Plum Creek (enters Niobrara River at mile 108.6)	1.6	---
Long Pine Creek (enters Niobrara River at mile 96.6)	>3	---
Bone Creek (tributary to Long Pine Creek)	2.2	---
Sand Draw (tributary to Bone Creek)	1.0	---
Eagle Creek (enters Niobrara River at mile 33.8)	>3	---
Verdigre Creek (enters Niobrara River at mile 5.0)	>3	---

[cfs/mi, cubic feet per second per mile; ---, no data or not computed]

[a] Reach could be gaining or losing based on uncertainty level of measurements.

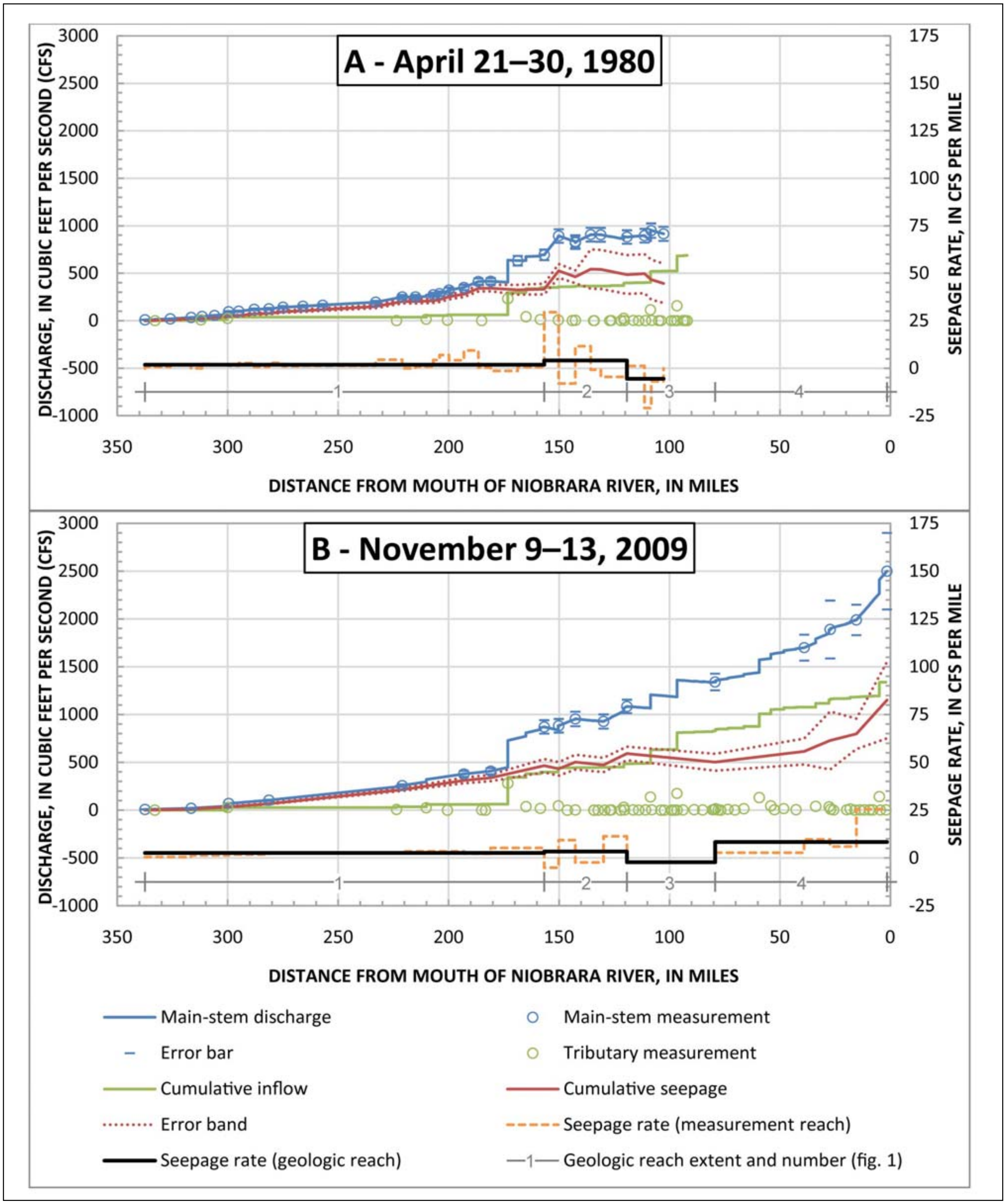

Figure 4. Niobrara River main-stem discharge and tributary inflow measurements, and computed main-stem gains and losses during base-flow seepage studies: (A) April 21–30, 1980, and (B) November 9–13, 2009.

for the fourth geologic reach, but the 2009 data show the largest rate of main-stem seepage at 8.5 cfs/mi. Except for the most upstream and downstream main-stem sites, the endpoints of the geologic reaches all had replicate measurements of discharge in 2009 that were within 5 percent of each other, increasing the confidence in those results. There were no main-stem data collected

Table 1. Rates of streamflow gain or loss in main stem summarized for total flow, tributary inflows, and main-stem seepage, with interval of uncertainty, for selected geologic reaches of Niobrara River, April 21–30, 1980, and November 9–13, 2009.

Geologic reach along Niobrara River	Total main-stem gain/loss of flow, mean rate (cfs/mi)		Tributary inflows, reach total, mean rate (cfs/mi)		Main-stem gain/loss from seepage, mean rate (cfs/mi)	
	1980	2009	1980	2009	1980	2009
U.S. Highway 385 (map ID 1) to Bryan Bridge (map ID 41) (river mile 337.5 to 156.7, geologic reach 1)	*4.1* **3.8** *3.5*	*5.2* **4.8** *4.4*	--- **1.9** ---	--- **2.2** ---	*2.2* **1.8** *1.5*	*3.0* **2.6** *2.2*
Bryan Bridge (map ID 41) to Norden Bridge (map ID 63) (river mile 156.7 to 119.3, geologic reach 2)	*8.7* **5.3** *2.0*	*9.5* **5.7** *2.0*	**1.2** ---	**2.3** ---	*7.5* **4.1** *0.7*	*7.2* **3.4** *-0.3*
Norden Bridge (map ID 63) to U.S. Highway 183 (1980, no map ID) and to State Highway 137 (2009, map ID 92) (river mile 119.3 to 102.7 and 79.4, geologic reach 3)	*10.6* **2.0** *-6.7*	*10.3* **6.4** *2.4*	--- **7.5** ---	--- **8.6** ---	*3.1* **-5.5** *-14.2*	*1.7* **-2.3** *-6.2*
State Highway 137 (map ID 92) to State Highway 12 (map ID 194) (river mile 79.4 to 1.5, geologic reach 4)	--- --- ---	*21.2* **14.9** *8.6*	--- --- ---	--- **6.5** ---	--- --- ---	*14.8* **8.5** *2.2*

[cfs/mi, cubic feet per second per mile; —, no data or not computed; values in bold are computed rates, and values in italics above and below computed values are estimated upper and lower uncertainty limits; river miles are curvilinear distance from river mouth; map IDs (identification numbers) can be found in Figure 3]

in 1980 downstream from U.S. Highway 183 near Springview (river mile 102.7), but the 2009 data indicated the largest rates of main-stem seepage gain in the most downstream geologic reach, below State Highway 137 (river mile 79.4, Table 2). Unfortunately, no replicate measurements of discharge were made for the two channels at State Highway 12.

In geologic reach 1 upstream from the Snake River (river mile 173.2), Niobrara River flow increases were almost entirely from main-stem seepage gains (Figure 4). Downstream from the Snake River confluence in geologic reach 1, and especially downstream from the gaging station near Sparks in geologic reach 2 (Berry Bridge, river mile 142.6), the number of contributing tributaries increased substantially, and their cumulative inflows became nearly equal to main-stem seepage gains. Farther downstream, in geologic reach 3 below Norden Bridge, the results for both 1980 and 2009 indicated main-stem seepage losses, and tributary inflows became the largest source of the overall gains in main-stem total flow. In geologic reach 4 between State Highways 137 (Mariaville) and 12 (Niobrara), the rates of main-stem seepage gains and total flow increases were larger than anywhere else along the main stem, although tributary inflows remained the largest source of increases in total flow.

The uncertainty of results for the lower part of the basin was magnified by the large differences in antecedent precipitation between the lower and upper parts of the basin in 2009, and between the two studies. Overall, main-stem flows were greater in 2009 than in 1980. At the climate stations on the upper, middle, and lower parts of the basin (Figure 2), the 2- and 3-week precipitation totals prior to the 2009 study were 0.85, 0.45, and 2.06 inches, and 1.00, 0.70, and 3.59 inches, respectively (National Oceanic and Atmospheric Administration, 2010a and 2010b). At the same or comparable stations in 1980, the 2- and 3-week prior precipitation totals were only 0.03, 0.27, and 0.10 inches, and 0.89, 0.46, and 0.83 inches, respectively (National Oceanic and Atmospheric Administration, 1980a and 1980b). The large amount of precipitation on the lower part of the basin in 2009 was likely a factor contributing to the relatively large average gains in main-stem seepage and total flow in geologic reach 4. Because the antecedent conditions were not uniform, comparisons between the upper and lower reaches for 2009 also are more difficult, and the results for the lower reach are considered less certain.

Groundwater and Surface-Water Interactions

The longitudinal pattern of streamflow gains and losses are in general agreement with the regional pattern of aquifer composition and topography, and local hydraulic-head measurements (Figure 5). In the upper part of the basin, the unconsolidated alluvial portion of the High Plains aquifer occupies a valley gouged into the bedrock portion of the aquifer, and both of these aquifers thin in an eastward direction (Figure 5). Seepage measurements from both studies indicate that the river is gaining substantial amounts of water in these reaches from groundwater seepage. NDOR borehole data indicate that the unconsolidated alluvial aquifer is thin-to-absent between river miles 210 to 120, but the river there is underlain by the High Plains aquifer and is gaining in most of the reach. Downstream from Norden (river mile 119), the Niobrara River is underlain by the Pierre Shale, an aquitard, but the unconsolidated alluvial aquifer thickens abruptly for a 20-mile reach, and the width of the alluvial valley and the river also substantially increases in the same reach (J.S. Alexander, USGS, unpub. data, 2010). This reach of river is coincident with main-stem seepage losses calculated both in this and the previous seepage study (Figure 5), indicating the river likely is losing water to the unconsolidated alluvial aquifer in the short transition zone from a bedrock bed to a zone of dramatic increase in alluvial thickness and width. Downstream from river mile 100, the unconsolidated alluvial aquifer thins and as a result the main stem gains flow from groundwater seepage. These gains continue downstream from Spencer Dam (river mile 39) to the mouth, even as the unconsolidated aquifer thickens as the river enters the Niobrara delta at the Missouri River. Although the thickening of the alluvial aquifer by itself might suggest this reach tends to lose water

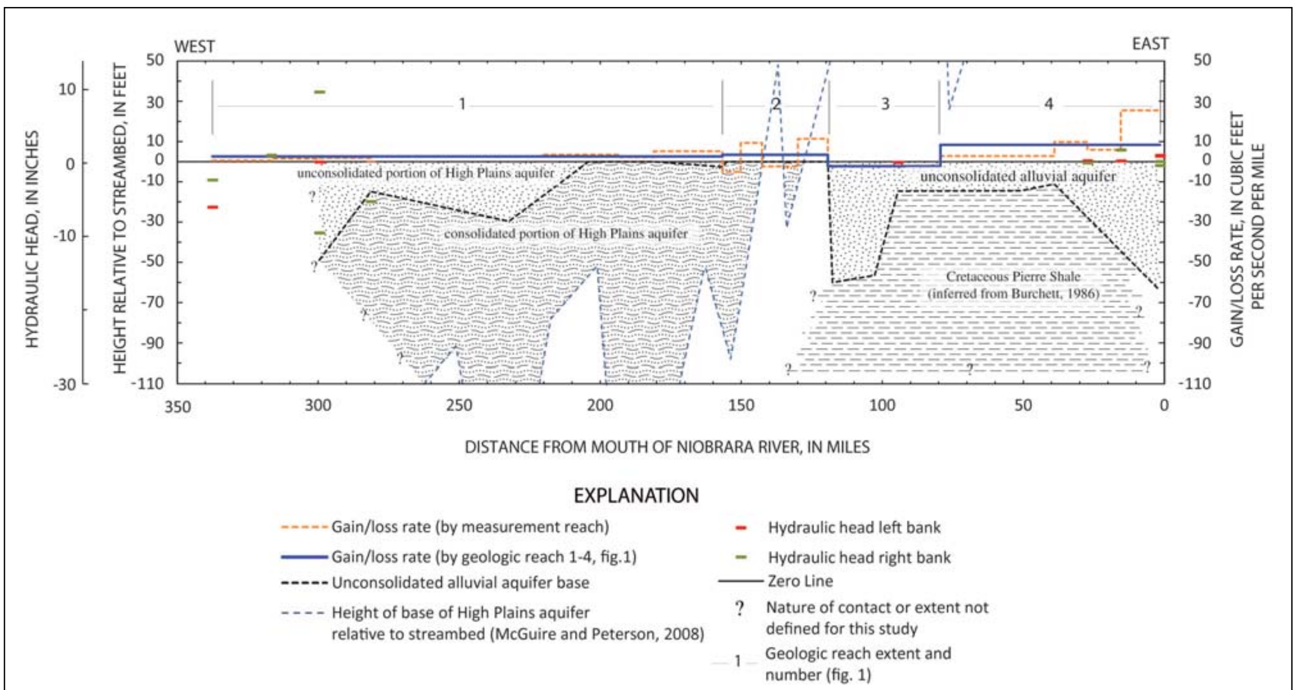

Figure 5. Hydraulic-head measurements and main-stem seepage gain/loss rate along Niobrara River during November 9–13, 2009, and geologic section showing base of unconsolidated alluvial aquifer and High Plains aquifer.

to the aquifer, we hypothesize that the seepage gains in the main stem calculated in this seepage study may be due in part to tributary losses to the aquifer. Nearly half of the tributary contributions to the main stem in the study area were posted downstream from river mile 100. Thus, the seepage gains in this reach of main stem could be linked to substantial tributary losses to the alluvial aquifer as tributaries enter the wide alluvial valley of the main stem from bedrock-floored side canyons. Additionally, although total unconsolidated aquifer storage capacity likely increases downstream from Spencer Dam as the thickness of alluvium increases, some of the increase is likely offset by the reduction in aquifer storage as the river enters the delta reach and backwater from the Missouri River intrudes on the alluvial aquifer.

Main-stem hydraulic-head measurements during this study are sparse relative to the scale of the river in a reach, and even more so for the study-area scale. Nonetheless, the results indicated some reasonable agreement with the patterns of the underlying geology, geomorphology, and river gains and losses (Table 3). In the upper region of the study area (> river mile 280), hydraulic-head differences were mixed and indicate frequent exchanges with the alluvial aquifer. This also is a region where the Niobrara River bed is alluvial, exhibits active meandering, some pool-riffle structuring, and is typically much narrower than the surrounding valley bottom (Alexander et al., 2009). Such reaches would be expected to have more hyporheic activity (aquifer exchange over short distances) resulting in a mix of upward and downward hydraulic gradients in each bank

Table 1. Summary of differences between hydraulic head in river and in alluvium along main stem of Niobrara River, Nebraska, November 9–13, 2009.

Map ID (fig. 3)	Station or stream name	Distance from mouth (river miles)	GW-SW average head difference (inches)	GW-SW left-bank head difference (inches)	GW-SW right-bank head difference (inches)	GW-SW third head difference (inches)
1	Niobrara River near Dunlap, Nebr (U.S. Highway 385)	337.5	-4.2	-6.0	-2.3	---
3	Niobrara River near Hay Springs, Nebr (State Highway 87)	316.6	1.0	1.0	1.1	---
9	Niobrara River near Rushville, Nebr (State Highway 250)	299.6	-4.7	0.1	-9.5	9.7[a]
10	Niobrara River near Gordon, Nebr (State Highway 27)	281.3	-5.3	0.2[b]	-5.3	---
86	Niobrara River at Riverview, Nebr (State Highway 7)	94.4	0.1	0.1	---	---
145	Niobrara River at Redbird, Nebr (Boyd/Holt County road)	27.2	0.2	0.3	0.0	---
156	Niobrara River near Verdel, Nebr (Knox County road)	15.4	1.0	0.3	1.8	---
194	Niobrara River at Niobrara, Nebr (left channel, State Highway 12)	1.5	0.6	0.9	0.2	---
194	Niobrara River at Niobrara, Nebr (right channel, State Highway 12)	1.5	0.3	1.0	-0.4	---

[Positive values indicate groundwater head is greater, negative values indicate surface-water head is greater; all differences calculated from potentiomanometer measurements; groundwater head measured at 2 feet below river bed except where otherwise indicated; GW-SW, groundwater-surface water; ---, no data]

[a] Measurement made on right bank approximately one-channel width upstream from primary transect.

[b] Measurement made at 1.4 feet below river bed because of indurated/hard subsurface layer.

(Bencala, 2000; Fernald et al., 2001; Kasahara and Wondzell, 2003). Downstream from river mile 100, hydraulic-head measurements, although sparse, generally indicated either equilibrium or slightly streamward gradients, a pattern that is in agreement with the broad-scale seepage gains for this reach.

SUMMARY AND CONCLUSIONS

The Niobrara River is a valuable water resource that sustains irrigated agriculture, recreation, power generation, as well as a diverse array of ecosystem types. A 76-mile stretch has been designated as the Niobrara National Scenic River. The Nebraska Department of Natural Resources (NDNR) recently designated portions of the Niobrara River as fully appropriated for management purposes, thus requiring sustainable management of the hydrologically connected surface-water and groundwater resources by balancing competing demands that consider all beneficial uses and stakeholder interests. To investigate the broad-scale magnitudes and variation in groundwater contributions to streamflow in a roughly 350-mile reach of the Niobrara River from below Box Butte Dam to the mouth, the U.S. Geological Survey (USGS), in cooperation with the Nebraska Game and Parks Commission, undertook a collaborative seepage study with the NDNR and the National Park Service. The purpose of the study was to determine the locations and rates of groundwater gains and losses (seepage) using synoptic main-stem and tributary discharge measurements. The results were compared to those from a previous study as well as to hydraulic-head measurements and alluvial thickness estimates along the main channel.

Discharges were measured using standard USGS methods. For the main stem of the Niobrara River, measurements were made in a downstream direction to minimize recessional differences; to the extent possible, tributary measurements were made on the same day as the corresponding main-stem measurements. Streamflow gains or losses, for both the 1980 and 2009 seepage runs, were computed directly from the combination of main-stem and tributary discharge measurements. For any two sites along a given reach of stream, the upstream discharge was added to the discharges of any tributaries flowing into the reach, and the total was then subtracted from the discharge at the downstream end of the reach. A positive difference indicates a gain in streamflow by groundwater seepage, and a negative difference indicates a loss in streamflow by seepage in the reach.

Average rates of gain/loss for total flow, tributary inflow, and main-stem seepage were then computed for each reach by dividing the gain/loss by the length of the reach. Temporal streamflow variability and the potential discharge measurement errors probably affected the calculations of streamflow gain/loss. This was especially true where sites were close together and the gain/loss was small in comparison, as was evident along the main stem in the upper end of the Scenic River where the average rates change back and forth between gains and losses. Therefore, four longer reaches, with fairly consistent underlying geology, were selected to compute gain/loss rates; breakpoints were at Bryan Bridge south of Valentine, Norden Bridge, and State Highway 137 near Mariaville. Geologic reaches 1 and 2 are underlain by the High Plains aquifer, which here consists of an unconsolidated alluvial aquifer overlying a bedrock aquifer of consolidated sediments. In geologic reach 1 the alluvial aquifer generally thins in the downstream direction and is much thinner below about river mile 200. In geologic reach 2, the alluvial aquifer is mostly absent in the channel because the bedrock aquifer outcrops at elevations above the channel bed (McGuire and Peterson, 2008), resulting in springs, seeps, and waterfalls along the narrow valley walls. Geologic reach 3 is characterized by an abruptly thicker and wider unconsolidated alluvial aquifer overlying Cretaceous Pierre Shale, an aquitard. In geologic reach 4, the unconsolidated alluvial aquifer is much thinner in the upper part of the reach, but thickens again toward the mouth of the Niobrara River. Cumulative totals of tributary flow, main-stem seepage, and total flow were computed in relation to distance along the centerline of the channel in a downstream direction. Error bars were computed for the main-stem discharge measurements based on the subjective accuracy ratings assigned to each measurement, but the error bars did not reflect the possible effects from temporal variability in streamflow.

Head differences between groundwater and surface water were made at most main-stem sites using a hydraulic potentiomanometer. Exceptions were sites that had shallow alluvium (<2 feet) or outcropping bedrock in the river channel, which were located mainly in the central portion of the study area. If the groundwater head was greater than the surface-water head, the location was considered to be gaining groundwater, but it was considered to be losing water to the shallow aquifer if the head difference was reversed. Data for computation of alluvial thickness along the main stem Niobrara River were compiled from USGS reports and data sets and from borehole logs from the Nebraska Department of Roads and the Bureau of Reclamation. The unconsolidated alluvial aquifer thickness was calculated by subtracting the depth to bedrock in the borehole log from the elevation of the earth surface. The maximum of the two thicknesses was used as the primary measure of unconsolidated aquifer thickness.

Discharge measurements, estimates, or observations of zero flow were made at 263 sites in the Niobrara River Basin downstream of Box Butte Dam during November 10–13, 2009. For the main stem, 25 measurements at 17 sites defining 16 reaches were used in the gain/loss calculations. Eagle Creek, Long Pine Creek, Verdigre Creek, and the Snake River showed the largest tributary gains (>3 cfs/mi). Most tributary reaches west of Valentine had gains of about 0–2 cfs/mi, but a tributary to Box Butte Creek and lower Leander Creek showed possible minor losing reaches (<1 cfs/mi), and upper Minnechaduza Creek had losses of 5 cfs/mi. The region between Meadville and Riverview showed the highest frequency of tributaries with gaining reaches, including Fairfield Creek, Sand Draw, Bone Creek, Plum Creek, and Long Pine Creek. The remainder of the study region showed a mix of gains and loss.

For the main stem, results from the 1980 and 2009 seepage studies indicated similar patterns of total flow, cumulative tributary inflow, and cumulative main-stem seepage gain/loss. Upstream from the Snake River (geologic reach 1), Niobrara River flow increases were almost entirely from main-stem seepage gains; downstream from there, the number of contributing tributaries increased substantially, and their flows became the largest source of main-stem flow below Norden Bridge. Seepage rates for many individual reaches (between measurement sites) do not agree well, probably due to measurement uncertainty and the close proximity of some of the sites, but the seepage rates for the longer geologic reaches are similar, with increasing gains in the upper two reaches followed by losses in the third reach between Norden Bridge and State Highway 137. For those upper three reaches, data for 1980 showed seepage rates of 1.8, 4.1 and -5.5 cfs/mi; and data for 2009 showed seepage rates of 2.6, 3.4, and -2.3 cfs/mi. There was no 1980 data for the fourth geologic reach, but the 2009 data show the largest rate of main-stem seepage at 8.5 cfs/mi. The larger magnitude of that rate could be from antecedent precipitation differences —about 1.0, 0.7, and 3.6 inches of precipitation at climate stations on the upper, middle, and lower parts of the basin in the 3 weeks prior to the study in 2009, compared to about 0.9, 0.5, and 0.8 inches in 1980.

The longitudinal pattern of streamflow gains and losses are in general agreement with the regional pattern of aquifer topography and local hydraulic-head measurements. In the upper part of the basin (geologic reach 1), the unconsolidated alluvial aquifer occupies a valley gouged into the bedrock portion of the High Plains aquifer, both aquifers thin in the eastward direction, and streamflow measurements indicated groundwater seepage gains. Hydraulic-head measurements were mixed, but indicate exchange with the alluvial aquifer. Downstream, from river miles 210 to 120 (geologic reaches 1 and 2), the unconsolidated alluvial aquifer is thin-to-absent, but the river is underlain by the High Plains aquifer, and was gaining in most of the reach. Downstream from Norden (river mile 119, geologic reach 3), the unconsolidated alluvial aquifer thickens abruptly, river and alluvial valley widths increase, and streamflow measurements showed seepage losses indicating the river may be losing water to the now larger aquifer. Downstream from river mile 100 (transition to geologic reach 4), the unconsolidated alluvial aquifer thins, and the river again begins to post groundwater gains, which continue downstream even as the unconsolidated aquifer again thickens to the mouth. Groundwater gains in this reach may be a result of tributary losses to the alluvial aquifer as they enter the wide alluvial valley floor from bedrock-floored side canyons and by the reduction in aquifer storage as the river enters the delta reach and the backwater effect from the Missouri River.

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REFERENCES

Alexander, J.S., R.B. Zelt, and N.A. Schaepe. 2009. Geomorphic segmentation, hydraulic geometry, and hydraulic microhabitats of the Niobrara River, Nebraska—Methods and initial results. U.S. Geological Survey Scientific Investigations Report 2009–5008.

Baxter, C.V., and F.R. Hauer. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout. Can. J. Fish. Aquat. Sci., Vol. 57, pp. 1470–1481.

Bencala, K.E. 2000. Hyporheic zone hydrological processes. Hydrol. Process., Vol. 14, pp. 2797–2798.

Bentall, R., and F.B. Shaffer. 1979. Availability and use of water in Nebraska, 1975. University of Nebraska, Conservation Survey Division, Nebraska Water Survey Paper 48.

Blanchard, S.F. 2007. SonTek/YSI FlowTracker firmware version 3.10 and software version 2.11 upgrades and additional policy on the use of FlowTrackers for discharge measurements. U.S. Geological Survey Office of Surface Water Technical Memorandum 2007.01, http://water.usgs.gov/admin/memo/SW/sw07.01.html.

Blanchard, S.F. 2009 Application of FlowTracker firmware and software mounting correction factor for potential bias. U.S. Geological Survey Office of Surface Water Technical Memorandum 2009.04, http://water.usgs.gov/admin/memo/SW/sw09.04.html.

Boulton, A.J., S. Findlay, P. Marmonier, E.H. Stanley, and H.M. Valett. 1998. The functional significance of hyporheic zone in streams and rivers. Annu. Rev. Ecol. and Syst., Vol. 29, pp. 59–81.

Buchanan, J.P. 1981. Channel morphology and sedimentary facies of the Niobrara River, north-central Nebraska. Fort Collins, Colorado State University, M.S. Thesis.

Buchanan, T.J., and W.P. Somers. 1969. Discharge measurements at gaging stations. U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A8.

Burchett, R.R., comp. 1986. Geologic bedrock map of Nebraska. Lincoln, University of Nebraska, Conservation Survey Division, Institute of Agriculture and Natural Resources, scale 1:1,000,000.

Cederstrand, J.R., and M.F. Becker. 1999. Digital map of aquifer boundary for the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. U.S. Geological Survey, http://water.usgs.gov/GIS/metadata/usgswrd/XML/ofr99-267.xml.

Chow, V.T. 1964. Runoff, in Chow, V.T., ed., Handbook of applied hydrology, Section 14. New York; McGraw-Hill.

Dugan, J.T., and R.B. Zelt. 2000. Simulation and analysis of soil-water conditions in the Great Plains and adjacent areas, Central United States, 1951–80. U.S. Geological Survey Water-Supply Paper 2427.

Fenneman, N.M. 1928 Physiographic divisions of the United States. Ann. Assoc. Am. Geogr., Vol. 18, pp. 261-353.

Fernald, A.G., P.J. Wigington, and D.H. Landers. 2001. Transient storage and hyporheic flow along the Willamette River, Oregon—Field measurements and model estimates. Water Resour. Res. Vol. 37, pp. 1681–1694.

Johnsgard, P.A. 2001. The nature of Nebraska—Ecology and biodiversity. Lincoln, University of Nebraska Press.

Kasahara, T., and S.W. Wondzell. 2003. Geomorphic controls on hyporheic exchange flow in mountain streams. Water Resour. Res, Vol. 39(1), 1005, doi:10.1029/2002WR001386.

Konrad, C.P. 2006. Location and timing of river-aquifer exchanges in six tributaries to the Columbia River in the Pacific Northwest of the United States. J. Hydrol., Vol. 329, pp. 444–470.

Langbein, W.B., and K.T. Iseri. 1960. General introduction and hydrologic definitions, Part 1 of manual of hydrology—General surface-water techniques. U.S. Geological Survey Water-Supply Paper 1541–A.

McGuire, V.L., and S.M. Peterson. 2008. Base of principal aquifer for the Elkhorn-Loup model area, north-central Nebraska. U.S. Geological Survey Scientific Investigations Map 3042, http://pubs.usgs.gov/sim/3042.

Mueller, D.S., and C.R. Wagner. 2009. Measuring discharge with acoustic Doppler current profilers from a moving boat. U.S. Geological Survey Techniques and Methods 3A–22, http://pubs.water.usgs.gov/tm3a22.

National Oceanic and Atmospheric Administration. 1980a. Climatological data—Nebraska, March 1980. National Oceanic and Atmospheric Administration, Vol. 85(3).

National Oceanic and Atmospheric Administration. 1980b. Climatological data—Nebraska, April 1980. National Oceanic and Atmospheric Administration, Vol. 85(4).

National Oceanic and Atmospheric Administration. 2010a. Climatological data—Nebraska, October 2009. National Oceanic and Atmospheric Administration, Vol. 114(10), http://www7.ncdc.noaa.gov/IPS/cd/cd.html.

National Oceanic and Atmospheric Administration. 2010b. Climatological data—Nebraska, November 2009. National Oceanic and Atmospheric Administration, Vol. 114(11), http://www7.ncdc.noaa.gov/IPS/cd/cd.html.

National Park Service. 2005. Natural Earth. U.S. National Park Service, http://resources.esri.com/arcgisdesktop/index.cfm?fa=content&tab=layers from cache within ESRI ArcGIS Resource Center, "US Topo Maps".

Nolan, M.K., and R.R. Shields. 2000. Measurement of stream discharge by wading. U.S. Geological Survey Water-Resources Investigations Report 2000–4036 CD-ROM, http://pubs.er.usgs.gov/usgs/usgspubs/wri/wri20004036.

Rantz, S.E., and others. 1982. Measurement and computation of streamflow. U.S. Geological Survey Water-Supply Paper 2175, Vol. 1 and 2.

Rehmel, M.S. 2007. Applications of acoustic Doppler velocimeters for streamflow measurement. J. Hydraul. Eng.-ASCE, Vol. 133(12).

Rosenberry, D.O., and J.W. LaBaugh. 2008. Field techniques for estimating water fluxes between surface water and ground water. U.S. Geological Survey Techniques and Methods 4–D2, http://pubs.usgs.gov/tm/04d02/.

Schultz, S. 2009. Economic and social studies of recreational floating on the Niobrara National Scenic River. Omaha, University of Nebraska, final report to Nebraska Game and Parks Commission.

Shaffer, F.B. 1975. History of irrigation and characteristics of streamflow in northern Nebraska. U.S. Geological Survey Open-File Report 75-01.

Soenksen, P.J. 1996. Transport of agricultural chemicals in surface flow, tileflow, and streamflow of Walnut Creek watershed near Ames, Iowa, April 1991–September 1993. U.S. Geological Survey Water-Resources Investigations Report 96–4017.

Soenksen, P.J., L.D. Miller, J.B. Sharpe, and J.R. Watton. 1999. Peak-flow frequency relations and evaluation of the peak-flow gaging network in Nebraska. U.S. Geological Survey Water-Resources Investigations Report 99–4032.

Soller, D.R., and M.C. Reheis. 2004. Surficial materials in the conterminous United States. United States Geological Survey Open-File Report 2003–275.

U.S. Department of Agriculture–Natural Resources Conservation Service. 2008. Watershed boundary dataset for HUC 101500, Nebraska. Natural Resources Conservation Service digital data, http://datagateway.nrcs.usda.gov.

U.S. Geological Survey. 1981. Water resources data for Nebraska—Water Year 1980. U.S. Geological Survey Water-Data Report NE–80–1.

U.S. Geological Survey. 2007. National Hydrography Dataset. U.S. Geological Survey, http://nhd.usgs.gov/data.html.

U.S. Soil Conservation Service. 1970. Major land resource areas (MLRA). Adapted from the U.S. Soil Conservation Service by the U.S. Geological Survey, scale 1:2,000,000, http://water.usgs.gov/GIS/metadata/usgswrd/XML/mlra.xml.

University of Nebraska-Lincoln, Conservation and Survey Division. 1986. The ground water atlas of Nebraska. Lincoln, University of Nebraska, Conservation and Survey Division, Resource Atlas No. 4.

Winter, T.C., J.W. LaBaugh, and D.O. Rosenberry. 1988. The design and use of a hydraulic potentiomanometer for direct measurement of differences in hydraulic head between groundwater and surface water. Limnol. Oceanogr., Vol. 33(5), pp. 1209-1214.

APPENDIX A

Table A–1. Streamflow discharge for selected Niobrara River tributary and main-stem sites downstream from Box Butte Dam, Nebraska, November 9–13, 2009.

[ADV, acoustic Doppler velocimeter; Cr, Creek; cfs, cubic feet per second; Hwy, Highway; ID, identification number; nr, near; MU, measurement uncertainty; NDNR, Nebraska Department of Natural Resources; NPS, National Park Service; R, River; trib, tributary; USGS, U.S. Geological Survey; >, greater than; %, percent; —, not assigned or no data; underlined values in body of table indicate estimates; river miles given for tributaries that directly enter the Niobrara River and used in gain/loss computations, value represents distance to confluence; tributary stream or sites names are indented based on stream order]

Map ID (fig. 3)	USGS station ID number	Stream or site name	Latitude north (degrees)	Longitude west (degrees)	River miles up-stream from mouth	Day of month, Nov 2009	Discharge (cfs)	MU (%)	Foot-note by map ID
1	---	Niobrara R nr Dunlap (U.S. Hwy 385)	42.4510	102.9690	337.5	10	8.24	5	yes
2	---	Cottonwood Cr	42.4674	102.9311	333.0	9	0.14	---	---
3	06456500	Niobrara R nr Hay Springs (State Hwy 87)	42.4830	102.6940	316.6	10	19.5	5	yes
4	---	Box Butte Cr	42.3100	102.9291	---	9	0.53	---	---
5	---	Box Butte Cr	42.2942	102.9079	---	9	1.32	---	---
6	---	Pine Cr	42.4161	102.4614	---	9	5.79	---	yes
7	---	Pine Cr	42.4858	102.4362	---	9	22.1	---	---
8	---	Pine Cr	42.5436	102.4777	300.1	9	27.5	---	---
9	---	Niobrara R nr Rushville (State Hwy 250)	42.5620	102.4650	299.6	10	71.0	5	yes
10	06457500	Niobrara River nr Gordon (State Hwy 27)	42.6400	102.2110	281.3	10	104	5	yes
11	---	Leander Cr	42.9042	101.8060	---	9	9.50	>8	---
12	---	Leander Cr	42.8775	101.6880	223.6	9	7.60	8	---
13	---	Niobrara R nr Eli	42.8520	101.5290	221.0	10	258	5	yes
14	---	Bear Cr	42.9354	101.6990	---	9	8.70	8	---
15	---	Dry Cr	42.9297	101.8616	---	9	6.49	8	---
16	---	Dry Cr	42.9185	101.7005	---	9	8.16	8	---
17	---	Bear Cr	42.9001	101.5001	210.1	9	25.0	8	---
18	---	Medicine Cr	42.7360	101.4593	200.5	9	0.02	---	---
19	06459025	Niobrara R nr Nenzel	42.8040	101.1230	193.1	10	380	8	yes
20	---	McCann Canyon Cr	42.7942	100.9986	---	9	1.48	5	---
21	---	Mercham Canyon Cr	42.7938	100.9672	183.3	9	0.40	8	---
22	---	Niobrara R at Anderson Bridge SWMA	42.7870	100.9260	181.0	10	408	8	yes
23	---	Snake R	42.5715	102.0229	---	9	1.87	---	---
24	---	Snake R	42.5737	101.7104	---	9	55.3	5	---
25	---	Clifford Cr	42.4842	101.8297	---	9	0.05	---	---
26	---	Clifford Cr	42.5075	101.7049	---	9	3.17	>8	---
27	---	Willow Cr	42.5212	101.7077	---	9	2.42	8	---
28	---	Snake R	42.6140	101.2774	---	9	168	5	---
29	---	Boardman Cr	42.5472	101.2724	---	9	0.13	>8	---
30	---	Boardman Cr	42.5815	100.9158	---	9	20.7	5	---
31	---	Snake R	42.6535	100.8583	173.2	9	281	5	---

Table A–1 (continued). Streamflow discharge for selected Niobrara River tributary and main-stem sites downstream from Box Butte Dam, Nebraska, November 9–13, 2009.

[ADV, acoustic Doppler velocimeter; Cr, Creek; cfs, cubic feet per second; Hwy, Highway; ID, identification number; nr, near; MU, measurement uncertainty; NDNR, Nebraska Department of Natural Resources; NPS, National Park Service; R, River; trib, tributary; USGS, U.S. Geological Survey; >, greater than; %, percent; —, not assigned or no data; underlined values in body of table indicate estimates; river miles given for tributaries that directly enter the Niobrara River and used in gain/loss computations, value represents distance to confluence; tributary stream or sites names are indented based on stream order]

Map ID (fig. 3)	USGS station ID number	Stream or site name	Latitude north (degrees)	Longitude west (degrees)	River miles up-stream from mouth	Day of month, Nov 2009	Discharge (cfs)	MU (%)	Foot-note by map ID
32	---	Sand Cr	42.4753	101.7097	---	9	0.92	8	---
33	---	Arkansas Flats	42.4893	101.7073	---	9	0.93	>8	---
34	---	Gordon Cr	42.5012	101.4022	---	9	15.2	5	---
35	---	Betsy Carver Cr	42.4174	101.5515	---	9	2.82	8	---
36	---	Betsy Carver Cr	42.4803	101.3753	---	9	8.20	8	---
37	---	Gordon Cr	42.5258	100.8676	---	9	32.6	>8	---
38	---	Gordon Cr	42.8024	100.6628	165.0	10	37.0	5	---
39	---	Schlagel Cr	42.6836	100.6227	---	9	0.07	---	---
40	---	Schlagel Cr	42.8203	100.5589	158.4	10	18.5	5	---
41	---	Niobrara R at Bryan Bridge nr Valentine (old U.S. Hwys 20/83)	42.8320	100.5280	156.7	11	872	8	yes
42	---	Minnechaduza Cr	42.9890	100.9104	---	10	8.00	>8	---
43	---	Minnechaduza Cr	42.9835	100.8950	---	10	0.69	>8	---
44	---	Bull Cr	42.9724	100.8421	---	10	0.59	8	---
45	---	Fishberry Cr	42.8943	100.5312	---	10	1.03	5	---
46	---	Spring Cr	42.9061	100.5166	---	10	1.23	5	---
47	---	Minnechaduza Cr	42.8985	100.4844	150.3	10	44.3	8	---
48	---	Niobrara R below Cornell Dam (Cornell Bridge)	42.9000	100.4820	150.2	11	883	8	yes
49	---	Big Beaver Cr	42.9402	100.4575	146.2	10	0.19	8	---
50	06461500	Niobrara R nr Sparks (Berry Bridge)	42.9020	100.3630	142.6	11	954	8	yes
51	---	Trout Springs	42.9017	100.3627	142.6	10	2.22	8	---
52	---	Niobrara R trib 1	42.8675	100.2484	134.3	10	0.36	8	---
53	---	Kuskie Cr	42.8661	100.2414	134.1	10	0.80	8	---
54	---	Clapp Cr	42.8577	100.2177	132.3	10	0.18	8	---
55	---	Niobrara R at Sunny Brook Campground nr Norden	42.8360	100.1800	129.9	11	928	8	yes
56	---	Niobrara R trib 2	42.8366	100.1737	129.3	10	0.42	8	---
57	---	Coleman Cr	42.8263	100.1417	127.0	10	0.72	8	---
58	---	Muleshoe Cr	42.8233	100.1357	126.3	10	2.51	5	---
59	---	McGuire Cr	42.7949	100.0827	122.0	10	0.85	8	---
60	---	Fairfield Cr	42.7851	100.0634	120.7	11	31.2	5	---
61	---	East Middle Cr	42.7940	100.0550	---	10	0.83	>8	---
62	---	Middle Cr	42.7907	100.0565	120.4	10	1.99	8	---
63	06462000	Niobrara R nr Norden (Norden Bridge)	42.7870	100.0360	119.3	12	1080	6.5	yes

Table A–1 (continued). Streamflow discharge for selected Niobrara River tributary and main-stem sites downstream from Box Butte Dam, Nebraska, November 9–13, 2009.

[ADV, acoustic Doppler velocimeter; Cr, Creek; cfs, cubic feet per second; Hwy, Highway; ID, identification number; nr, near; MU, measurement uncertainty; NDNR, Nebraska Department of Natural Resources; NPS, National Park Service; R, River; trib, tributary; USGS, U.S. Geological Survey; >, greater than; %, percent; —, not assigned or no data; underlined values in body of table indicate estimates; river miles given for tributaries that directly enter the Niobrara River and used in gain/loss computations, value represents distance to confluence; tributary stream or sites names are indented based

Map ID (fig. 3)	USGS station ID number	Stream or site name	Latitude north (degrees)	Longitude west (degrees)	River miles up-stream from mouth	Day of month, Nov 2009	Discharge (cfs)	MU (%)	Foot-note by map ID
64	---	Turkey Cr	42.7815	99.9803	116.4	10	2.67	8	---
65	---	Chimney Cr	42.7741	99.9378	113.9	10	1.24	8	---
66	---	Cub Cr	42.7698	99.8838	110.9	10	2.81	8	---
67	---	Evergreen Cr	42.6483	100.2422	---	10	7.67	8	---
68	---	Rush Cr	42.6073	100.2466	---	10	0.45	---	---
69	---	Plum Cr	42.6667	100.0554	---	11	98.9	5	---
70	---	Plum Cr	42.7538	99.8646	108.6	11	138	8	---
71	---	Rock Cr	42.7596	99.8449	108.0	10	3.60	8	---
72	---	Bear Cr	42.7414	99.7656	103.9	10	0.62	8	---
73	---	Dry Cr	42.7424	99.7422	102.3	10	0.31	>8	---
74	---	Thomas Cr	42.7355	99.6816	99.1	10	0.28	8	---
75	---	Barnard (Lucky) Cr	42.7384	99.6733	98.9	10	0.24	>8	---
76	---	Rickman Cr	42.7376	99.6507	97.8	10	0.76	8	---
77	---	Long Pine Cr	42.4741	99.6966	---	11	11.3	5	---
78	---	Long Pine Cr	42.5751	99.6945	---	11	70.9	5	---
79	---	Willow Cr	42.5767	99.6946	---	11	6.00	5	---
80	---	Bone Cr	42.5352	99.9070	---	11	0.004	---	---
81	---	Sand Draw Cr	42.5602	99.9888	---	11	0.91	8	---
82	---	Sand Draw Cr	42.6359	99.8531	---	11	13.0	8	---
83	---	Bone Cr	42.6662	99.7773	---	11	53.6	8	---
84	---	Long Pine Cr	42.7102	99.6427	96.6	11	176	8	---
85	---	Beeman Cr	42.7344	99.6270	96.6	10	1.08	8	---
86	---	Niobrara R at Riverview (State Hwy 7)	42.7217	99.5892	---	12	---	---	yes
87	---	Wyman Cr	42.7304	99.5793	93.9	10	2.24	8	---
88	---	Laughing Water Cr	42.7264	99.4857	88.8	11	4.48	5	---
89	---	Rock Cr	42.7174	99.4442	85.0	11	3.35	5	---
90	---	Willow Cr	42.7749	99.3615	80.5	11	4.09	8	---
91	---	Oak Cr	42.7713	99.3549	79.8	11	3.77	8	---
92	06463720	Niobrara R at Mariaville (State Hwy 137)	42.7809	99.3346	79.4	12	1340	6.5	yes
93	---	Ash Cr	42.6796	99.2650	---	12	0.28	---	---
94	---	Ash Cr	42.7802	99.3276	79.1	11	16.0	5	---
95	---	Big Ann Cr	42.7896	99.3357	77.9	12	2.00	8	---

Table A–1 (continued). Streamflow discharge for selected Niobrara River tributary and main-stem sites downstream from Box Butte Dam, Nebraska, November 9–13, 2009.

[ADV, acoustic Doppler velocimeter; Cr, Creek; cfs, cubic feet per second; Hwy, Highway; ID, identification number; nr, near; MU, measurement uncertainty; NDNR, Nebraska Department of Natural Resources; NPS, National Park Service; R, River; trib, tributary; USGS, U.S. Geological Survey; >, greater than; %, percent; —, not assigned or no data; underlined values in body of table indicate estimates; river miles given for tributaries that directly enter the Niobrara River and used in gain/loss computations, value represents distance to confluence; tributary stream or sites names are indented based on stream order]

Map ID (fig. 3)	USGS station ID number	Stream or site name	Latitude north (degrees)	Longitude west (degrees)	River miles up-stream from mouth	Day of month, Nov 2009	Discharge (cfs)	MU (%)	Foot-note by map ID
96	---	Simpson Cr	42.8035	99.2939	76.8	12	1.00	8	---
97	---	Otter Cr	42.7928	99.2338	73.5	12	8.68	8	---
98	---	Clay Cr	42.8143	99.1806	70.4	12	1.49	8	---
99	---	Beaver Cr	42.7247	99.1121	---	12	7.07	5	---
100	---	Beaver Cr	42.8408	99.1117	66.3	12	16.0	5	---
101	---	Shadley Cr	42.9697	100.1375	---	12	0.08	8	---
102	---	Lost Cr	42.9545	100.0132	---	12	0.52	>8	---
103	---	Jimmie Cr	42.9835	99.7270	---	11	0.25	8	---
104	---	Holt Cr	42.8967	99.7920	---	12	0.95	8	---
105	---	East Holt Cr	42.8499	99.7492	---	12	0.21	8	---
106	---	Holt Cr	42.9839	99.7099	---	11	8.42	8	---
107	---	Keya Paha R	42.9979	99.6364	59.3	11	70.2	8	---
108	---	Burton Cr	42.8221	99.6502	---	12	0.17	>8	---
109	---	Burton Cr	42.9404	99.5837	---	11	6.19	8	---
110	---	Spring Cr	42.9406	99.4410	---	11	12.5	8	---
111	---	Coon Cr	42.9223	99.3530	---	11	3.18	8	---
112	---	Spotted Tail Cr	42.9306	99.3259	---	11	1.61	8	---
113	---	Oak Cr	42.8830	99.3002	---	11	0.45	8	---
114	---	Meglin Cr	42.9111	99.2064	---	11	0.76	8	---
115	---	Big Cr	42.8962	99.1976	---	11	0.67	8	---
116	---	Morse Cr	42.9586	99.1998	---	11	0.21	5	---
117	---	Dry Cr	42.9583	99.1999	---	11	0.01	---	---
118	---	Morse Cr	42.9018	99.1664	---	11	2.41	5	---
119	---	Keya Paha R trib	42.9119	99.1607	---	11	0.12	>8	---
120	---	Lost Cr	42.9156	99.1467	---	11	0.24	5	---
121	---	Dry Cr	42.9156	99.1305	---	11	0.41	8	---
122	---	Keya Paha R	42.8996	99.0008	59.3	11	132	5	---
123	---	Big Sandy Cr	42.6378	99.0326	---	12	0.33	---	---
124	---	Big Sandy Cr	42.7738	99.0552	---	12	27.7	5	---
125	---	Big Sandy Cr	42.8497	98.9091	54.1	12	45.1	8	---
126	---	Little Sandy Cr	42.8386	98.8870	52.5	12	3.77	8	---
127	---	Brush Cr trib	42.6819	98.9183	---	12	0.12	---	---

Table A–1 (continued). Streamflow discharge for selected Niobrara River tributary and main-stem sites downstream from Box Butte Dam, Nebraska, November 9–13, 2009.

[ADV, acoustic Doppler velocimeter; Cr, Creek; cfs, cubic feet per second; Hwy, Highway; ID, identification number; nr, near; MU, measurement uncertainty; NDNR, Nebraska Department of Natural Resources; NPS, National Park Service; R, River; trib, tributary; USGS, U.S. Geological Survey; >, greater than; %, percent; —, not assigned or no data; underlined values in body of table indicate estimates; river miles given for tributaries that directly enter the Niobrara River and used in gain/loss computations, value represents distance to confluence; tributary stream or sites names are indented based on stream order]

Map ID (fig. 3)	USGS station ID number	Stream or site name	Latitude north (degrees)	Longitude west (degrees)	River miles up-stream from mouth	Day of month, Nov 2009	Discharge (cfs)	MU (%)	Foot-note by map ID
128	---	Brush Cr	42.7751	98.8498	48.3	12	16.4	8	---
129	---	Spring Branch Cr	42.7548	98.8220	---	12	0.99	8	---
130	---	Turkey Cr	42.7395	98.7950	---	12	1.45	8	---
131	---	Turkey Cr	42.8053	98.7432	42.7	12	5.74	8	---
132	06465000	Niobrara R nr Spencer (U.S. Hwy 281)	42.8080	98.6509	39.0	13	1700	8	yes
133	---	East Branch Eagle Cr	42.6076	98.8928	---	12	0.22	---	---
134	---	Middle Branch Eagle Cr	42.6242	98.7649	---	12	7.29	5	---
135	---	Eagle Cr	42.6911	98.7314	---	12	31.0	5	---
136	---	Honey Cr	42.6246	98.6902	---	12	0.002	---	---
137	---	Honey Cr	42.6825	98.7112	---	12	1.69	5	---
138	---	Camp Cr	42.6825	98.6473	---	12	0.004	---	---
139	---	Eagle Cr	42.7633	98.5745	33.8	12	39.4	8	---
140	---	Redbird Cr	42.5523	98.5726	---	12	4.30	5	---
141	---	Redbird Cr	42.6375	98.5536	---	12	18.6	5	---
142	---	Blackbird Cr	42.5520	98.6541	---	12	0.07	---	---
143	---	Blackbird Cr	42.6630	98.5795	---	12	9.58	5	---
144	---	Redbird Cr	42.7626	98.4427	27.8	12	35.7	5	---
145	---	Niobrara R at Redbird	42.7709	98.4421	27.2	13	1890	>8	yes
146	---	Louse Cr	42.6719	98.4425	---	12	3.62	8	---
147	---	Louse Cr	42.7685	98.4373	27.0	12	10.8	5	---
148	---	Niobrara R trib nr Dorsey	42.6836	98.4063	---	12	0.006	---	---
149	---	Niobrara R trib nr Redbird	42.7712	98.4154	---	12	1.66	>8	---
150	---	Niobrara R trib nr Redbird	42.7713	98.4154	25.7	12	1.93	5	---
151	---	Squaw Cr nr Dorsey	42.6834	98.3803	---	12	0.62	>8	---
152	---	Squaw Cr nr Pishelville	42.7578	98.3030	19.7	12	4.37	5	---
153	---	Steel Cr at Dorsey	42.6773	98.3327	---	12	0.48	5	---
154	---	Steel Cr nr Pishelville	42.7497	98.2859	18.2	12	12.1	5	---
155	---	Niobrara R trib nr Pishelville	42.7347	98.2400	16.0	13	0.90	8	---
156	06465500	Niobrara R nr Verdel	42.7420	98.2230	15.4	13	1990	8	yes
157	---	Pishel Cr nr Dorsey	42.6688	98.2959	---	12	0.02	---	---
158	---	Pishel Cr nr Pishelville	42.7258	98.2104	13.8	12	2.66	5	---
159	---	Soldier Cr	42.6544	98.2136	---	13	0.048	>8	---

Table A–1 (continued). Streamflow discharge for selected Niobrara River tributary and main-stem sites downstream from Box Butte Dam, Nebraska, November 9–13, 2009.

[ADV, acoustic Doppler velocimeter; Cr, Creek; cfs, cubic feet per second; Hwy, Highway; ID, identification number; nr, near; MU, measurement uncertainty; NDNR, Nebraska Department of Natural Resources; NPS, National Park Service; R, River; trib, tributary; USGS, U.S. Geological Survey; >, greater than; %, percent; —, not assigned or no data; underlined values in body of table indicate estimates; river miles given for tributaries that directly enter the Niobrara River and used in gain/loss computations, value represents distance to confluence; tributary stream or sites names are indented based on stream order]

Map ID (fig. 3)	USGS station ID number	Stream or site name	Latitude north (degrees)	Longitude west (degrees)	River miles up-stream from mouth	Day of month, Nov 2009	Discharge (cfs)	MU (%)	Foot-note by map ID
160	---	Soldier Cr	42.7064	98.1697	11.8	13	2.78	>8	---
161	---	Niobrara R trib nr Verdigre	42.6931	98.1293	9.4	12	2.82	5	---
162	---	Schindler Cr nr Verdigre	42.6788	98.1048	7.9	13	2.66	5	---
163	---	South Branch Verdigre Cr	42.3976	98.3199	---	13	0.32	>8	---
164	---	Big Spring Cr	42.3931	98.2264	---	13	8.30	8	---
165	---	South Branch Verdigre Cr	42.4390	98.1420	---	13	27.6	8	---
166	---	Hay Cr	42.3640	98.1458	---	13	0.42	>8	---
167	---	East Branch Verdigre Cr	42.4371	98.1384	---	13	26.7	5	---
168	---	Cottonwood Cr	42.4373	98.1251	---	13	0.16	>8	---
169	---	Verdigre Cr	42.4666	98.1164	---	12	58.8	5	---
170	---	Merriman Cr	42.4222	98.0156	---	13	0.40	>8	---
171	---	Merriman Cr trib 1	42.4223	98.0319	---	13	0.32	>8	---
172	---	Merriman Cr trib 2	42.4076	98.0603	---	13	0.46	>8	---
173	---	Merriman Cr	42.4668	98.0858	---	12	7.78	8	---
174	---	Merriman Cr	42.4919	98.1079	---	12	10.2	8	---
175	---	Verdigre Cr trib	42.5044	98.1236	---	13	1.74	8	---
176	---	Verdigre Cr	42.5323	98.0958	---	12	74.8	5	---
177	---	Middle Branch Verdigre Cr	42.4662	98.3586	---	13	1.90	>8	---
178	---	Middle Branch Verdigre Cr	42.4942	98.3053	---	13	9.66	>8	---
179	---	Middle Branch Verdigre Cr trib 1	42.5159	98.3053	---	13	0.53	>8	---
180	---	Lamb Cr	42.5240	98.2842	---	13	1.63	8	---
181	---	Middle Branch Verdigre Cr trib2	42.4949	98.2353	---	13	0.82	>8	---
182	---	Middle Branch Verdigre Cr trib 2	42.5238	98.2391	---	13	2.84	5	---
183	---	Middle Branch Verdigre Cr trib 3	42.5096	98.1787	---	13	0.46	5	---
184	---	Middle Branch Verdigre Cr trib 3	42.5240	98.1893	---	13	0.48	8	---
185	---	Middle Branch Verdigre Cr trib 3	42.5242	98.1842	---	13	0.75	>8	---
186	---	Middle Branch Verdigre Cr	42.5445	98.1503	---	12	29.2	5	---
187	---	Verdigre Cr nr Verdigre	42.5710	98.0666	---	12	94.9	5	---
188	---	North Branch Verdigre Cr nr Page	42.5530	98.3809	---	12	0.94	>8	---
189	---	North Branch Verdigre Cr	42.6028	98.3053	---	12	22.1	5	---
190	---	North Branch Verdigre Cr nr Verdigre	42.5974	98.1345	---	13	29.0	5	---
191	06465700	Verdigre Cr nr Verdigre	42.6870	98.0410	5.0	13	142	8	---

Table A–1 (continued). Streamflow discharge for selected Niobrara River tributary and main-stem sites downstream from Box Butte Dam, Nebraska, November 9–13, 2009.

[ADV, acoustic Doppler velocimeter; Cr, Creek; cfs, cubic feet per second; Hwy, Highway; ID, identification number; nr, near; MU, measurement uncertainty; NDNR, Nebraska Department of Natural Resources; NPS, National Park Service; R, River; trib, tributary; USGS, U.S. Geological Survey; >, greater than; %, percent; —, not assigned or no data; underlined values in body of table indicate estimates; river miles given for tributaries that directly enter the Niobrara River and used in gain/loss computations, value represents distance to confluence; tributary stream or sites names are indented based on stream order]

Map ID (fig. 3)	USGS station ID number	Stream or site name	Latitude north (degrees)	Longitude west (degrees)	River miles up-stream from mouth	Day of month, Nov 2009	Discharge (cfs)	MU (%)	Foot-note by map ID
192	---	Bingham Cr	42.7037	98.0497	4.5	12	1.52	5	---
193	---	Burgess Cr	42.7382	98.0457	2.0	12	1.96	>8	---
194	06466000	Niobrara R at Niobrara (State Hwy 12, two channels)	42.7480	98.0580	1.5	13	2510	>8	yes

Footnotes referenced by map ID

1	Discharge from single wading measurement made with ADV.
3	Discharge from single wading measurement made with ADV. Discharge varied from 17.8 to 18.3 cfs during the day, based on the NDNR gaging station record.
6	Discharge measurement made at new location from previous study.
9	Discharge from single wading measurement made with ADV.
10	Discharge from single wading measurement made with ADV.
19	Discharge from mean of two non-concurrent wading measurements made with Price AA meter (399 cfs, NDNR) and with ADV (360 cfs, USGS).
22	Discharge from single wading measurement made with ADV.
41	Discharge from mean of two concurrent bridge measurements made with Price AA meters (860 and 883 cfs)
48	Discharge from single bridge measurement made with Price AA meter. Concurrent bridge measurement made with StreamPro ADCP (986 cfs) not used because of possible method bias; and subsequent bridge measurement made with Price AA meter not used because of equipment malfunction.
50	Discharge from single bridge measurement made with Price AA meter. Concurrent bridge measurement made with StreamPro ADCP (992 cfs) not used because of possible method bias. Flow varied from 961 to 935 cfs during the day, based on the USGS gaging station record.
55	Discharge from mean of two concurrent wading measurements made with ADVs (945 and 910 cfs).
63	Discharge from mean of two concurrent bridge measurements made with Price AA meters (1,060 and 1,110 cfs). Concurrent measurement made with Rio Grande ADCP (tethered bank to bank) not used because of poor measuring conditions.
86	Discharge measurement made from bridge with Price AA meter was not used because of equipment malfunction. Hydraulic-head measurements reported in table 3.
92	Discharge from mean of two concurrent bridge measurements made with Price AA meters (1,350 and 1,330 cfs)
132	Discharge from mean of two concurrent bridge measurements made with Price AA meters (1,710 and 1,690 cfs)
145	Discharge from mean of two non-concurrent bridge measurements made with Price AA meters (2,050 and 1,730 cfs)
156	Discharge from single bridge measurement made with Price AA meter. Discharge varied from 2,130 to 1,890 cfs during the day, based on the USGS gaging station record.
194	Discharge from the sum of nearly concurrent bridge measurement made with Price AA meters on the west (2,180 cfs) and east (333 cfs) channels.

ADDRESS FOR CORRESPONDENCE
Philip J. Soenksen
U.S. Geological Survey
Nebraska Water Science Center
5231 South 19th Street
Lincoln, NE 68512-1271
USA

Email: pjsoenks@usgs.gov