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Hydrogeologic Framework Studies of Portions of the Niobrara River

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Project Completion Report:

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Nebraska Geological Survey
Report of Investigations No. 12

Conservation and Survey Division
School of Natural Resources
Institute of Agriculture and Natural Resources
University of Nebraska-Lincoln
Lincoln, Nebraska

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CONSERVATION AND SURVEY DIVISION
School of Natural Resources

REPORT OF INVESTIGATION

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Executive Summary

The Nebraska Department of Natural Resources (NeDNR) and Upper Niobrara-White Natural Resources District (UNWNRD) expressed interest in improving understanding and their ability to effectively manage water resources in and around a particular reach of the Niobrara River. Aquifer-thickness contours mapped by the Conservation and Survey Division (CSD) indicate that the principle aquifer has zero thickness in this area. Additionally, the statewide geologic bedrock map produced by CSD shows non-aquifer strata of the White River Group along the same reach, and this setting is consistent with the designation of an "aquifer absent area," as in the present document. Water-management policy development and decisions are complicated by the apparently conflicting presence of registered irrigation wells in the aquifer absent area. This apparent conflict warranted a detailed review of local hydrogeology to improve the available science on which the UNWNRD and NeDNR will base any controls within an integrated water management plan.

Previous work in the region including the aquifer absent area was completed at a watershed scale (e.g., the Niobrara watershed in Nebraska) and, therefore, the present study is a more spatially detailed examination of available information in and along the reach between USGS stream gages at Agate and near Dunlap. We conclude that:

- The observation of outcrops of the White River Group along the margins of the Niobrara River Valley has led to the misconception that the reach lacks any hydraulic connection between surface water and groundwater. Our results, however, indicate that there are local hydrologic connections between the two.
- There is sufficient alluvium within this this portion of the valley to conduct water between the stream and groundwater wells. Transmissivity is limited by the relative thinness of alluvial sediments and/or the fineness of sandy sediments in the subsurface.
- Transmissivity in the reach is spatially variable, due primarily to significant irregularity in thickness of sediments capable of conducting water in significant volumes.
- Irrigation wells in the aquifer absent area near the Niobrara River are hydraulically connected to the High Plains Aquifer and/or alluvial fill of the Niobrara River valley.
- It is still appropriate to consider the reach in question as an aquifer absent area at a regional scale of observation because of the comparatively slight thickness of alluvial aquifer materials and our uncertainty regarding their distribution, Any study that telescopes from generalized regional to more specific localized questions will experience challenges created as scale-related uncertainty is magnified. Interestingly, however, smaller scale multi-state maps of the High Plains Aquifer do not include an aquifer absent area in the reach.
- It is apparent that the reach is in contact with alluvial sediments capable of conducting water, and that the ability to conduct water will likely be affected by the local thicknesses of hydraulically conductive sediments and their overall geometries.
- At points, such as individual irrigation well locations, uncertainties regarding the nature and proportion of hydraulic connection among the High Plains Aquifer, the respective

well, and the Niobrara River (including associated alluvium) are high. Thus, the direct relationship of every individual well is not defined at the scale of this investigation.

Additional investigations and/or remote sensing methods outlined in this report may improve understanding and mitigate limitations at refined spatial resolution.

Regional Setting and Site Geology

The study includes the area along and adjacent to the Niobrara River between and near to the USGS stream gages at Agate [06454100] and near Dunlap [06455900] (Table 1). It includes portions of Sioux, Dawes, Box Butte and Sheridan Counties in the Nebraska Panhandle, and lies within the UNWNRD (Figure 1). The area includes a relatively narrow valley bottom, a low terrace, and extensive dissected plains in the uplands (Figure 2). Beyond the watershed boundary of the Niobrara River, the breaks of the Pine Ridge fall off to the north, toward the White River. The Box Butte Table to the south includes sand dunes, dry tributary valleys (the confluences of are downstream of the study reach), and extensive agricultural land on a gently rolling plain - (Figure 3). Sources for the elevation hillshade (Figure 3) include orthophoto collections conducted in 1939, 1946-1949, 1970-1979, and 1980-1985. Detailed local analysis of topography in the study area will be vastly improved after the Hat Creek/White River and Sandhills LiDAR collections of 2016-2017 are available.

Oligocene and Miocene bedrock of the Ogallala, Arikaree, and White River groups in the study area include strata of gravel, sand, sandstone, siltstone, and claystone (Figure 4). The Ogallala Group includes the Ash Hollow, Valentine, Sheep Creek and Runningwater formations. The Arikaree Group includes the Harrison, Monroe Creek and Gering formations. The White River Group includes the Sharps, Brule, Chadron, and Chamberlain Pass formations. The Brule Formation is subdivided into the Whitney and Orella Members. Cretaceous sedimentary rocks underlie all primary and secondary aquifers in the region (Figure 5); the Pierre Shale is widespread under at the base of Cenozoic succession (Swinehart, et. al., 1985, p219).

Seven 7.5 minute STATEMAP quadrangles were used in this study (Figure 6) to provide the most detailed maps of surface geology available (Figure 7). Quaternary surface deposits of the study area include alluvium, colluvium, residuum, peat, and eolian sand. Detailed descriptions of these sediments for each quadrangle are included in Appendix 2. These sediments were deposited mostly by streams and winds. Alluvium occurs primarily in local valleys where water has re-worked and transported much of the material. Eolian sand was deposited by winds as broad shallow sheets where source material was limited.

Colluvium is common on the valley margins and in the transition zone to uplands. Residuum often occurs where indurated sediments have been weathered in place and moved little. Peat is present locally where lush masses of vegetation are rapidly buried and preserved by saturated and anoxic conditions.

The study reach is at the western margin of the Ogallala Group strata in the northern panhandle, and is typically underlain by Arikaree Group strata except in specific locations, including portions of the study reach where it is underlain by White River Group sediments (Figure 4). This lithostratigraphic configuration is the justification for mapping a zero thickness contour (aquifer absent area) in the reach when aquifer thickness contours were created for the statewide map (Figure 8). Note that the contour correlates imperfectly with the presence of White River Group as bedrock, indicating differing levels of detail relating to various scales of analysis.

Surface Water and Hydrogeology

The study reach includes 108 river miles (174 kilometers) of the Niobrara River in a project domain about 46 miles (74 kilometers) east to west and about 6 miles (10 kilometers) north to south. The major surface water feature of the reach is the Box Butte Reservoir, which was completed in 1948. It provides storage water for the Mirage Flats irrigation project downstream of the study reach (Nebraska Department of Natural Resources, 2014) and provides a regionally significant recreation and fishery resource. The study reach includes 55 active points of diversion with priority dates between 1887 and 1987, 39 of which predate the completion of Box Butte Reservoir (Nebraska Department of Natural Resources Surface Water Rights Database). Points of diversion and canals (Table 2) are actively monitored by NeDNR stream gages (Table 3). Water rights in the study reach total 76,182 acre-feet (94 million cubic meters) for the Box Butte Reservoir and Mirage Flats Canal, and 238 cubic feet per second (cfs) (6.7 cubic meters per second) for the remaining appropriators. Historical flow in the reach was about 15 cfs (425 liters per second) at the Agate gage, about 30 cfs (850 liters per second) above Box Butte Reservoir, and about 40 cfs (1133 liters per second) at the downstream gage near Dunlap (US Geological Survey National Water Information System, 2017).

Development of groundwater for irrigation in northwest Nebraska began in the 1950's and reached a peak in the 1970's (Korus et. al., 2013). The overall rate of well development in the study reach has been less dense than much of the remainder of Nebraska. While groundwater levels have been relatively constant around the Niobrara River in the study reach, the area in proximity to the reach is characterized by a lack of consistently distributed observations (Figure 9). Groundwater observations in the developed area south of the study reach show that Box Butte County has experienced significant groundwater declines (Figure 10). While extensive drawdown has occurred to the south of the river, the groundwater level has been stable near the Niobrara River, potentially indicating a hydraulic connection between groundwater and surface water in the Niobrara River Valley (Conservation and Survey Division, 2017).

Szilagyi et. al. (2003) computed base flow indices statewide, and estimated that the Niobrara River is dependent on groundwater for 70 to 90% of its stream flow, indicating a hydraulic connection between the river and local groundwater. The Nebraska Department of Natural Resources estimates that flows above Box Butte Reservoir have been impacted by groundwater pumping by approximately 6 cfs (170 liters per second) when comparing the years 1956-1960 to 1996-2000 (2014), and others have proposed that these reductions are due to groundwater pumping and falling groundwater levels in Box Butte County. While groundwater pumping in the region has undoubtedly impacted flow in various tributary streams, the relative effect on the Niobrara River of pumping in Box Butte County, when compared with other areas, such as the main part of the Niobrara River Valley, Sioux County, or even Wyoming, is less well understood.

Ogallala and Arikaree Group strata are usually considered to be parts of the High Plains Aquifer, while the White River Group is not generally considered as part of the aquifer, except in specific locales where it is known to have significant networks of interconnected fractures. In much of the study reach, fine grained Arikaree Group sediments (Harrison Formation) occur adjacent to the upper White River Group (Sharps Formation). Distinguishing these units in the field can be extremely difficult, as they are both fine-grained with similar appearance. Because of these similarities, in this part of Nebraska, the Sharps and Harrison formations may have similar hydraulic characteristics. If this is the case, the degree to which the Sharps Formation serves as a marginal aquifer and the Harrison Formation as an aquiclude may confound the use of the enclosed aquifer configurations and hydraulic characteristics for building water-accounting tools.

Methods

Since the goals of the integrated management process are to ensure a balance between water supplies and uses and to protect the rights of existing users of surface water and groundwater, the hydrogeologic and hydrostratigraphic refinement is needed because there are irrigation wells located in the area of interest where existing hydrostratigraphic unit maps show little or no aquifer material present. The objective of this project is to improve the understanding of hydrostratigraphic units in the area of interest and better define the hydrogeologic relationship between producing wells and the adjacent stream reach. The added detail sought may influence, or be incorporated into, water accounting tools used for integrated management purposes in the region, at the discretion of the NeDNR and/or the UNWNRD.

Our initial work included a review and assessment of existing studies and data relevant to the reach. These included documents relating to local and regional stratigraphy, geology, modeling, and hydrology. The project requires mapping of aquifer units, which are defined for this study as Quaternary alluvium (Qal), Ogallala Group sediments (No), and Arikaree Group sediments (Na). Additional discussion and an associated map are provided to illustrate areas where the White River Group (PEw) likely produces some water for the local supplies. This study does not include analysis or discussion of the Chadron aquifer and its associated Chamberlain Pass Formation, a known minor aquifer that is hydraulically distinct from the High Plains aquifer in the study area. A small number of registered wells analyzed for this study are completed in the Chadron and Chamberlain Pass Formations, and while their cuttings descriptions are useful for distinguishing Groups, pumping information for these locations was ignored.

Local results of this work are reported utilizing Public Land Survey System (PLSS) subdivisions to describe specific areas of the study area. PLSS subdivisions are shown in Figure 11.

Twenty-two test holes were selected to provide a basic framework around the reach as shown in Figure 12 (Table 4, Appendix 3). Test-hole attributes, including formation tops and surface elevations, were extracted from Conservation and Survey Divisions statewide test-hole database and incorporated into the project databases. To refine the spatial resolution, the regions between the test holes were populated with available data from the NeDNR's registered wells database. One hundred sixty-one registered wells were selected in and around the mapped occurrence of White River Group on the statewide bedrock map and the aquifer absent area (Figure 13) for this analysis. The wells were selected such that each could help the authors better understand the nature of the previously mapped aquifer absent area boundary, as well as potentially refining their understanding of the lithostratigraphic distribution of bedrock in the study area. Filtering of the selected wells was conducted to remove inactive wells and wells without recorded values for pumping rate, static water level (SWL), pumping water level (PWL), and a level of detail in their cuttings descriptions sufficient to identify the various aquifer units of this study. This filtering resulted in 106 wells used in this analysis (Figure 14, Table 5). The selected registered wells were attributed with the surface elevation corresponding to their mapped locations from the 10-meter digital elevation model from the National Elevation Dataset using the ArGIS Spatial Analyst tool "Extract Values to Points". The extraction was quality checked by manually comparing approximately 25% of the elevations extracted with the digital elevation model values using the identify tool. Maps were prepared illustrating the number of acres served by each registered well (Figure 15) and the specific capacity of each registered well (Figure 16).

Test holes and registered wells were reviewed and depths recorded relating to the base of Quaternary sediments, top and base of Ogallala Group sediments, top and base of Arikaree Group sediments, and top of White River Group sediments. The SWL field in the registration database was used to calculate the saturated thickness and estimate the likely extent of saturated Quaternary (Figures 17), Ogallala Group (Figure 18), and Arikaree Group sediments (Figure 19), as well as to estimate the total saturated thickness of all groups (Figure 20). The calculations for each well and test hole were qualitatively analyzed with the topography, land cover, surface and bedrock geology data to estimate the horizontal extent of saturated sediments in each aquifer unit. Additionally, calculations were made to determine the depth of penetration for registered wells into the White River Group, and to highlight areas in the study reach where White River Group sediments may be producing water (Figure 21).

Test holes and registered wells not containing a defined land surface elevation were attributed with the value from the USGS 1/3 arc-second digital elevation model obtained from the National Elevation Dataset based on their mapped locations (Figure 22). Depth values relating to the bases of Quaternary, Ogallala Group, and Arikaree Group sediments (the base of Arikaree Formation represents the local base of the principal aquifer) were calculated and converted to elevation for each of the test holes and registered wells. Elevation calculations for test holes and registered wells, as well as contours of the land surface, base of Quaternary sediment, base of Ogallala Group strata, and the base of Arikaree Group strata were interpolated across the study area by kriging. The kriging data were then overlaid on and compared to land surface, surface geology, and bedrock maps of the area. Contour intervals representing the contacts between geologic groups were manually digitized at 100 foot intervals from this view. The contours were then attributed with the appropriate elevations and used along with the data points to create the deliverable raster datasets using the "topo to raster" function in the 3D Analyst toolbox of ArcGIS. The results of these computations are shown in Figures 23-25.

The digital elevation models of each surface were subtracted using the "Minus" tool in 3D Analyst toolbox of ArcGIS to calculate the stratigraphic thickness of each of the aquifer units shown in Figures 26-28 and the total stratigraphic thickness of all principal aquifer sediments as shown in Figure 29.

Various methods for estimating specific yield were researched and available data examined to determine the feasibility of conducting quantitative calculations of specific yield (Fetter, 1980, Johnson, 1963, Ramsahoye and Lang, 1993, Robson, 1993). Specific yield for this study was estimated qualitatively and mapped subjectively based on available sediment descriptions that inferred grain size (Johnson, 1966, Souders, 1981, Souders et. al., 1980) and previous work containing estimates of specific yield in the region (Ayers, 2007, McGuire, et. al., 2012, NeDNR, 2014), as shown in Figures 30-32.

Results

Quaternary alluvium (Qal)

Saturated alluvium is present through the entire length of the Niobrara River valley and possibly limited areas in the Whistle Creek and Willow Creek drainages (Figures 17 and 26). Saturated thickness is relatively thin and highly variable. Maximum saturated thickness approaches 70 feet (21 meters) while the average thickness is less than 40 feet (12 meters).

Hydraulic conductivity is very high and specific yield (Figure 30) is relatively high while overall transmissivity is limited by the thinness of the aquifer. Specific capacity and transmissivity are limited by the thinness of the aquifer. Specific capacity and transmissivity are highest in the wells with the greatest saturated thickness. Due to the thinness of the aquifer, irrigation wells are often drilled into the underlying, less permeable White River Group and Arikaree Group strata to avoid problems with drawdown. Specific yield is likely around 0.2 on average across the study area and is locally variable, likely ranging between 0.12 and 0.30. It may be somewhat lower to the east end of the reach (0.12 to 0.2) and higher to the west end of the reach (0.15 to 0.3) as shown in Figure 30, since the stream valley is wider in the east and more incised in the west. Due to the high hydraulic conductivity of the sand and gravels of this aquifer, the hydraulic connection with the surface water of the Niobrara River is excellent.

Ogallala Group (No)

The distribution of likely saturated Ogallala Group sediment is limited in the Niobrara River valley but is more widespread in the upland areas in the Box Butte table lands and the Pine Ridge (Figures 18 and 27). The greatest saturated thickness of the Ogallala Group aquifer is east of Box Butte reservoir in T. 28 N., R. 48 W. The Ogallala aquifer in the Niobrara river valley may extend through T. 29 N., R. 50 W. into section 36 T. 29 N., R. 51 W. Based on our evaluation of driller's logs, there appears to be an Ogallala Group or Arikaree Group gravel channel fill in the north part of T. 28 N., R. 53 W. which connects with the alluvial aquifer in the valley (Figure 18). Maximum saturated thickness in this channel is approximately 160 feet (49 meters). Another saturated channel connects laterally to saturated Arikaree Group sediments in the north portion of T. 27 N., R. 55 W. and the southernmost sections of T. 28 N., R. 55 W.

Although the Ogallala Group sediments are widespread in the upland areas, there are large areas where they have little or no saturation (Figure 27). Irrigation wells are usually found in those areas where there are channels cut into strata of the underlying Arikaree or White River groups. Maximum saturated thickness in these areas approaches 200 feet (61 meters), but is typically in the range of 100 to 150 feet (30-46 meters).

The sediments of the Ogallala Group are variable, resulting in varying hydraulic conductivity and specific yield. The sandy gravel beds are similar to the Quaternary alluvium and have hydraulic conductivities that exceed 60 m/day while the clayey silts probably average less than 1 m/day (Souders, 1981). Likewise, specific yield may vary from around 0.3 down to approximately 0.05. Souders estimated transmissivity for two test holes drilled in the Ogallala Group in Sheridan County. One test hole near Rushville, NE (northeast of the study area) had a calculated transmissivity of 248 m^2/day while a test hole in section 24, T. 29 N., R. 46 W. (about 10 miles (16 kilometers) east of our study area, and one mile (1.6 kilometers) north of Niobrara River) had a calculated transmissivity of 1,860 m^2/day. Specific yield is likely slightly lower on average than the values for Quaternary alluvium. McGuire et. al. (2012) shows values between 0.1 and 0.2 for the study area, which is consistent with values used previously in NeDNR's management model for the region. Specific yield of the channel in the northern portion of T. 27 N., R. 55 W. and the southernmost sections of T. 28 N., R. 55 W. is likely high (0.2 to 0.3), as is the channel north of the river in the middle sections (13-24) of T. 29 N., R. 49 W. and T. 29 N., R. 50 W. Other portions of the study area are less certain and may have spatially varying specific yield values between 0.05 and 0.3 (Figure 31). Specific capacity values in the study area indicate that hydraulic connection between the surface water in the Niobrara River valley and the Ogallala aquifer is probably good where the Ogallala Group is saturated in the valley.

Arikaree Group (Na)

The formations of the Arikaree Group are largely absent or have low hydraulic conductivity in the Niobrara River Valley in the study area. The Arikaree Group formations were removed by erosion prior to deposition of the Ogallala Group in most of the eastern part of the study area. As a consequence, the Ogallala Group directly overlies the White River Group in the eastern part of the study area along the Niobrara River. In the western part of the study area, the Arikaree Group formations and Ogallala Group formations were removed by the more recent erosion during the development of the present day Niobrara river valley. In the far western part of the study area, the Harrison Formation of the Arikaree Group underlies the Quaternary alluvium. Souders et al (1980) noted that the Harrison Formation is very similar to the Sharps Formation (previously known as the Brown Siltstone Member of the Brule Formation) These two formations can only be distinguished by looking for volcanic glass shards under the microscope. The Sharps Formation has a much higher percentage of volcanic glass. The Harrison Formation does contain some permeable fine sand and sandstone beds and can transmit enough water to support a domestic or stock well but cannot transmit enough water for an irrigation well. Nevertheless, specific yield for Arikaree Group sediments (including the Harrison Formation) likely averages around 0.15 and varies between 0.05 and 0.2. Various studies (Bradley, 1956, Cady and Scherer, 1946), assigned values around 0.15 for specific yield of the Harrison Formation. The Box Butte model study prepared for NeDNR (Ayers, 2007) also used a uniform value of 0.15. It is likely that specific yield in much of the area varies between 0.1 and 0.2, with Souders (1981) indicating that the northeast quadrant may be somewhat lower, ranging from 0.05 to 0.15 (Figure 32). The Whistle Creek Northwest, Whistle Creek Northeast, Marsland Northwest, and Marsland 7.5 Minute Quadrangles from the USGS (1997) indicate that the Harrison Formation crops out along the margins of the Niobrara River Valley in the western part of the area but due to its similarity to the Sharps Formation, it would be impossible to tell these two formations apart in the subsurface using drillers' descriptions of cuttings. In general, Souders (1981) did not consider the Arikaree Group to be an important aquifer in southern Dawes County. In contrast, the Arikaree Group is an important aquifer in Box Butte County and in parts of northern Sheridan County.

White River Group (PEw)

The White River Group consists of four formations in the study area. The Sharps Formation is the youngest formation and consists of brown siltstone, very fine sand, and sandstone which can yield water sufficient to support stock and domestic wells. The Brule Formation is composed of brown siltstone and is considered an aquitard. The Chadron Formation consists of multicolored (green to red) bentonitic clays which form a regional confining unit that separates the underlying Chadron sands and Chamberlain Pass Formation from the shallower units of the High Plains aquifer (Quaternary alluvium, Ogallala Group, and Arikaree Group). Regionally, the top of the White River Group is considered the base of the High Plains aquifer system even though some water is produced from the Sharps Formation. In the study area, we have noted there are three areas where there are wells with significant screened intervals in this unit. In the eastern area in the southwest corner of T. 29 N., R. 50 W. (Figure 21), there is an irrigation well (ID # 23442, Figure 13) that produces from both the Ogallala Group and the Sharps Formation. In the center area (at the intersection of T. 28-29 N., R. 52-53 W.), there are wells which may produce from this unit, the Ogallala Group and possibly from the Arikaree Group. In the western area (T. 28 & 29 N., R. 53 & 54 W.), there are irrigation wells that produce largely from the Quaternary alluvium that are also screened in the Sharps Formation or possibly the Harrison Formation of the Arikaree Group. Well # 112600 produces 50 gallons per minute from the White River Group in this area (Figure 13).

Summary of Results

Surface water in the Niobrara river valley is well connected to Quaternary sediments and the Ogallala Group. Quaternary sediments with high hydraulic conductivity but variable thickness are the most important aquifer in this area, while the Ogallala Group with highly variable conductivity is also important in some areas. The Arikaree Group is largely absent near the river or has relatively low hydraulic conductivity except in localized pebbly/gravelly channels, and the

White River Group can also yield small quantities of water. Quaternary age aquifer materials cover much of the study area, representing a potential hydraulic connection along the reach.

Finally, other investigations have reached similar conclusions regarding the significance of unconsolidated local materials creating a connection between stream water and groundwater in the study area, including the Nebraska Department of Environmental Quality study of percolation rates (Figure 33) and a study by the Center for Advanced Land Management Information Technologies (CALMIT) on groundwater contamination potential using the DRASTIC model (Figure 34). The high percolation rates shown in the NDEQ study area are anecdotal of areas where surface water and groundwater should be hydraulically well connected. Similarly, the DRASTIC method evaluates seven factors that represent an anecdotal proxy of the degree of connection (through movement of contaminants) between groundwater and the land surface, including adjacent surface water.

Limitations and Uncertainties

Limitations and uncertainties in this study include:

1. Conclusions made on the basis of driller's descriptions of cuttings are highly interpretational.
2. Saturated thickness should not be contoured in the study reach because data are limited and the results may be misleading. Some data points are from test holes which penetrate the entire section, but many of the irrigation wells do not, creating significant uncertainty relating to the Transmissivity at those locations. This is especially true of the Arikaree Group (Na) penetrations. Limitation #3 may also contribute significantly to this limitation.
3. The hydraulic information contained in the project deliverables is limited by the spatial density of wells and test holes, as well as the time when the information was collected. Water levels were recorded over many years, making uncertain the extent that they are affected by precipitation, drought or other climate variability, and/or seasonal variations.
4. Well locations may be inexact, influencing the map results, Group elevations, and saturated thickness estimates.
5. Registered well logs contain only the most basic descriptions of sediments encountered, therefore distinguishing between certain portions of the Arikaree and White River groups that occur together represents a particular challenge when interpreting the logs. Further confounding this uncertainty is the fact that portions of the Arikaree Group vary in their ability to transmit water, influencing the reported specific yield. In some instances, the Sharps Formation (White River Group) may transmit water nearly as well as the Harrison Formation of the Arikaree Group.
6. Descriptions of White River Group strata from a few test holes suggests fracturing and resultant secondary porosity. Therefore, using the top of the White River Group as the base of aquifer may not be an ideal assumption in those places.

7. Source materials for the elevation hillshade in Figure 3 include orthophoto collections conducted between 1939 and 1985, representing a long timeframe for data collection in a changing landscape.
8. LiDAR derived elevation data was recently delivered to USGS for the study area. Differences between newly collected elevation data and the 1/3 arc-second digital elevation model obtained from the National Elevation Dataset will directly influence the results of this study.
9. Stratigraphic thicknesses mapped in the study area are inherently uncertain for the same reasons as the saturated thicknesses (see #2 above).

Recommendations for Improvements

Spatial conceptualizations of aquifer frameworks are simple to improve by collecting an increasing density of data and continually evaluating new information, whether the data are anecdotal or comprehensive. Each new piece of data and information collected represents a qualitative improvement in our understanding of a local system, and often more importantly, improves our understanding of the relationship between the local and regional systems as we move our attention upstream or downstream from the reach.

Designing water management models requires a balance among detailed local knowledge, regional data and interpretations, and the data consistency necessary to build a robust and stable accounting tool at the desired scale, as well as spatial and temporal resolutions. Knowing the best approach requires experience, judgement, and a fundamental understanding of the uncertain and imperfect nature of all manner of simulation, as well as the uncertain and imperfect nature of available data and information. Given the relative small scale of the water accounting model employed by NeDNR and UNWNRD, locally refined investigation is probably not necessary, and would not likely provide significant substantive benefits to the regional water accounting models currently in use.

The authors' interpretations of the aquifer framework and hydraulic properties of the reach could be improved in a number of ways, including:

- Conduct and expand detailed surface mapping (STATEMAP) in adjacent areas of interest.
- Conduct aquifer tests in the reach to improve estimates of hydraulic properties.
- Conduct additional test-hole drilling combined with aerial electromagnetic (AEM) surveys to verify the extent of the mapped channel containing Ogallala Group sediments. Use this work to determine if AEM techniques can be used to discern the Arikaree and White River groups in the study area.
- Conduct additional test holes in the area around the mapped channel filled with Ogallala Group sediments, including: the north part of T. 28 N., R. 52 W. the south part of T. 29 N., R. 51 W., and Whistle Creek areas to help improve the local aquifer framework.
- Conduct additional test holes to better assess possible spatial variability and identify locations where the Arikaree Group may contain coarser sediment.

- Complete a detailed analysis of the elevated bedrock surface along the right bank of the reach, to help define limits to the hydraulic relationship with irrigated lands of Box Butte County.
- Establish a network of recording wells to determine the transfer of hydraulic stress through the aquifer to the south of the reach.
- Conduct modal type analyses of grain sizes found in cuttings and/or grain size distribution to improve estimates of specific yield.
- Conduct pebble analyses of gravel channel deposits to differentiate gravels in the Ogallala Group from those in the Arikaree Group.
- Reexamine the reach when LiDAR derived elevation data is available - detailed local analysis of topography and corresponding formation bottoms (including saturated thickness of uppermost units) in the study area could be improved when the Hat Creek/White River and Sandhills LiDAR collections are available.
- Examine existing test-hole cuttings under a microscope to better assess possible spatial variability and identify locations where the White River Group sediments may be a marginal source of water.
- Include new test holes that were drilled in 2017 into the analysis.
- Investigate to determine if any of the wells with significant screened intervals in the White River Group were hydraulically fractured to enhance groundwater recovery.
- Investigate the history of dam building along and above the study area to determine if it is possible to build a temporal relationship between installation of flow control structures and changes in the observed flow regime.
- Complete a detailed examination of geophysical logs collected during mineral exploration activities in the reach and compare with the closest available geophysical logs from CSD test holes.

Disclaimer

The views, conclusions, and/or opinions expressed in this work are solely those of the authors and not the University of Nebraska, State of Nebraska, or any political subdivision thereof.

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APPENDIX 1 – Report Figures and Tables

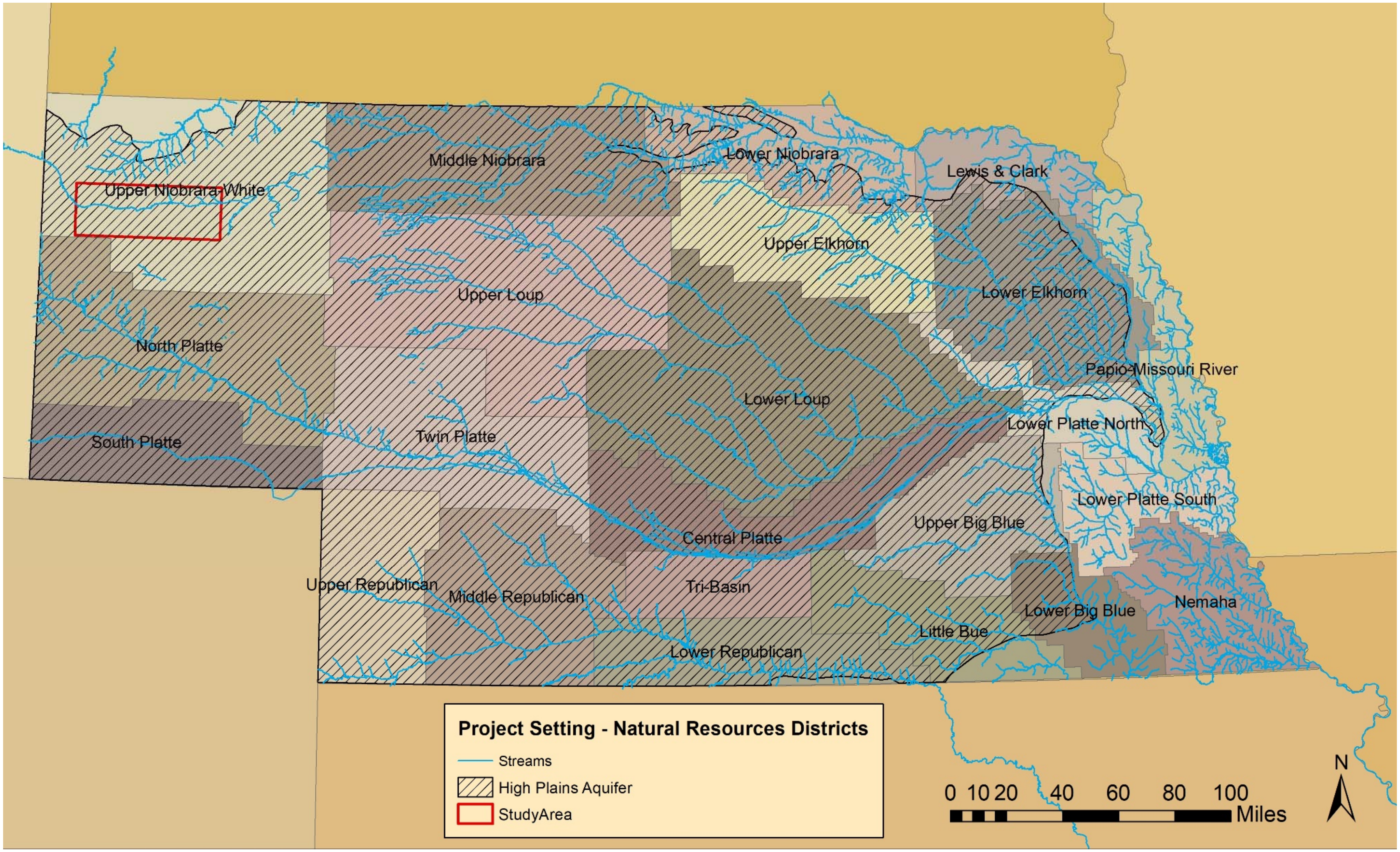


Figure 1. Map showing the extent of the High Plains Aquifer system in Nebraska, the Nebraska Natural Resources Districts, and configuration of major streams. The area of interest in this study is outlined in red.

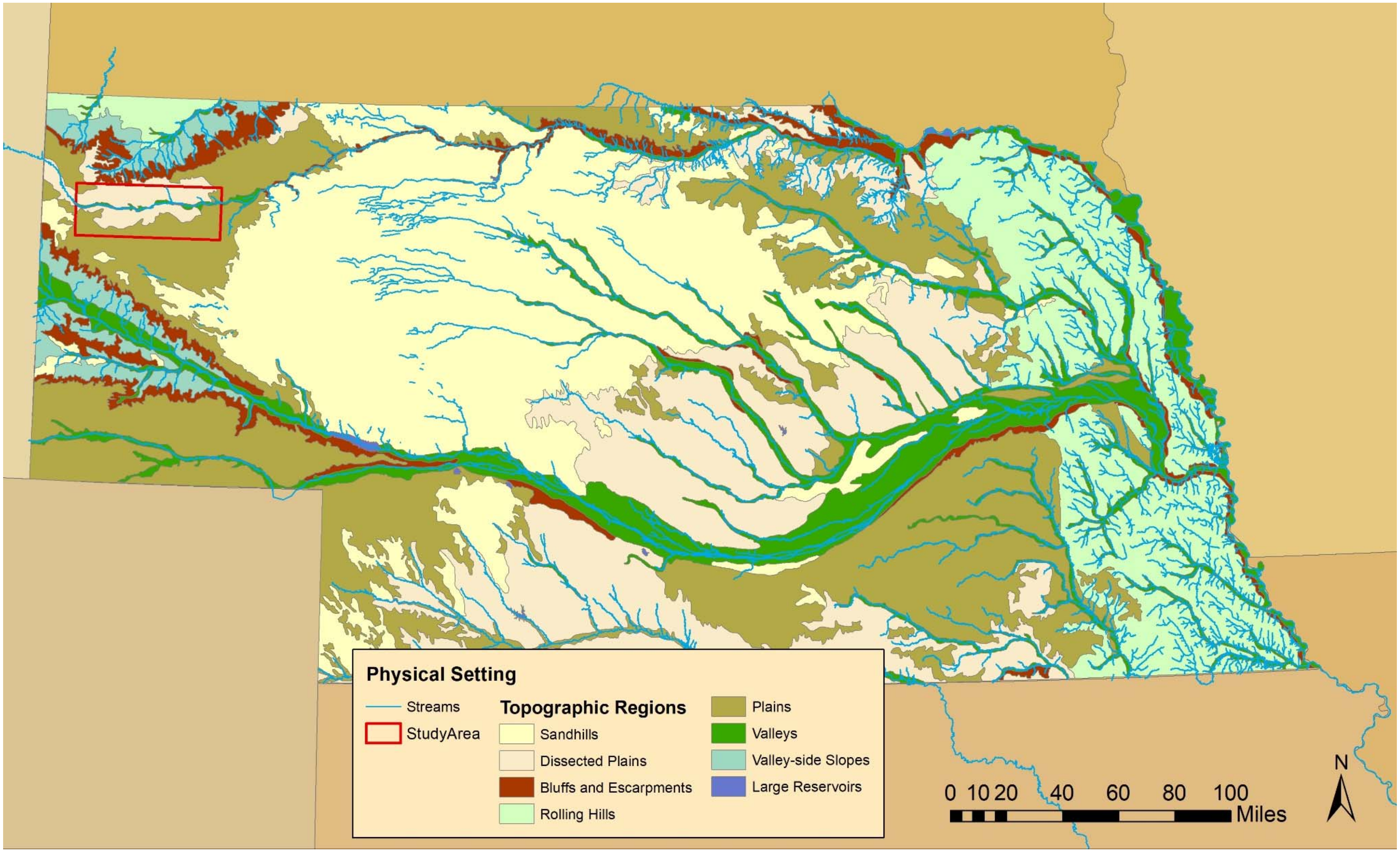


Figure 2. Map of Nebraska showing topographic regions. The area of interest in this study is outlined in red.

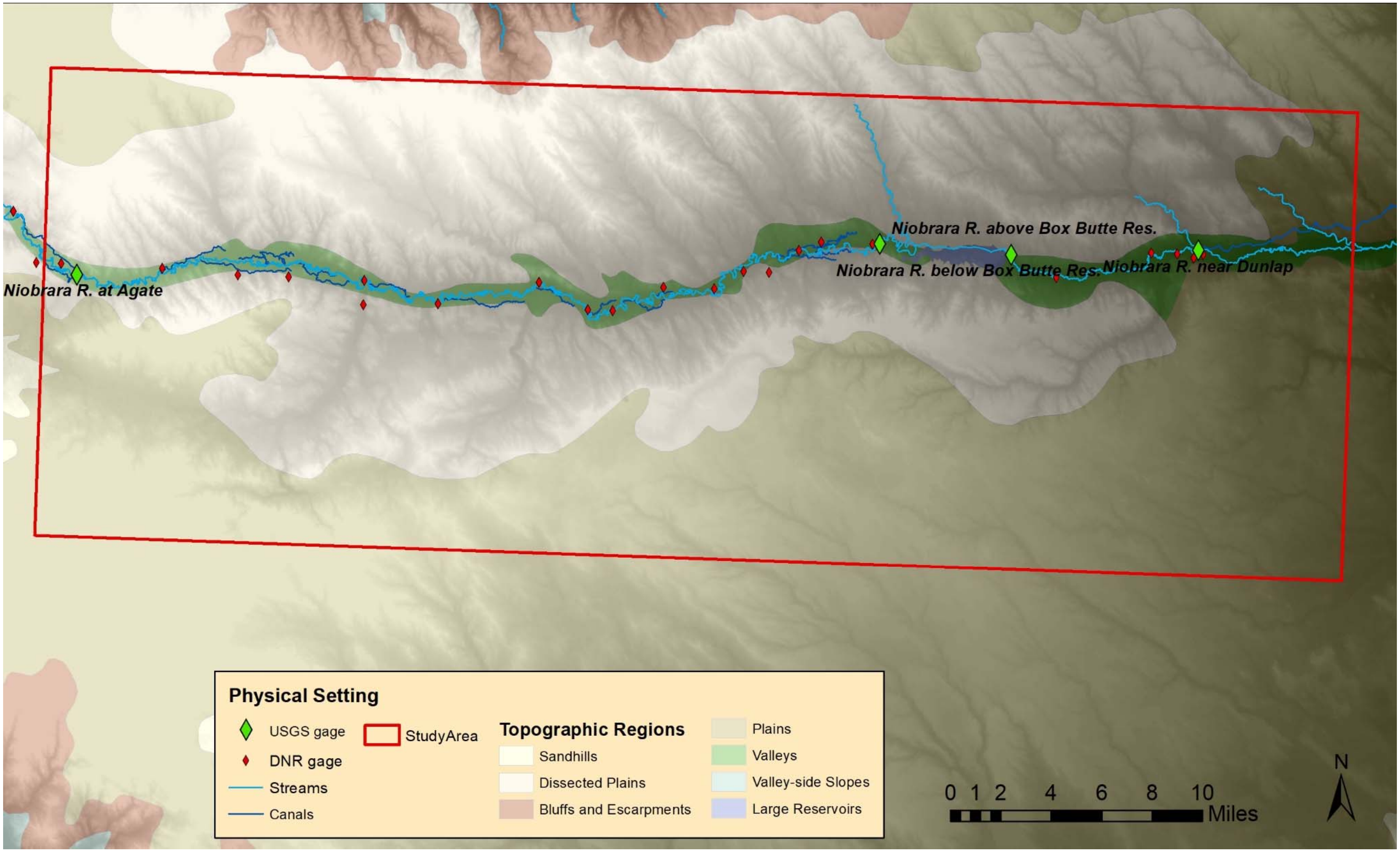


Figure 3. Map showing study area in south-central portion of the Upper Niobrara-White NRD, showing topographic regions and Stream/Canal gages used to define the study area on a hillshade of the photogrammetrically derived 1/3 arc-second digital elevation model provided in the National Elevation Dataset.

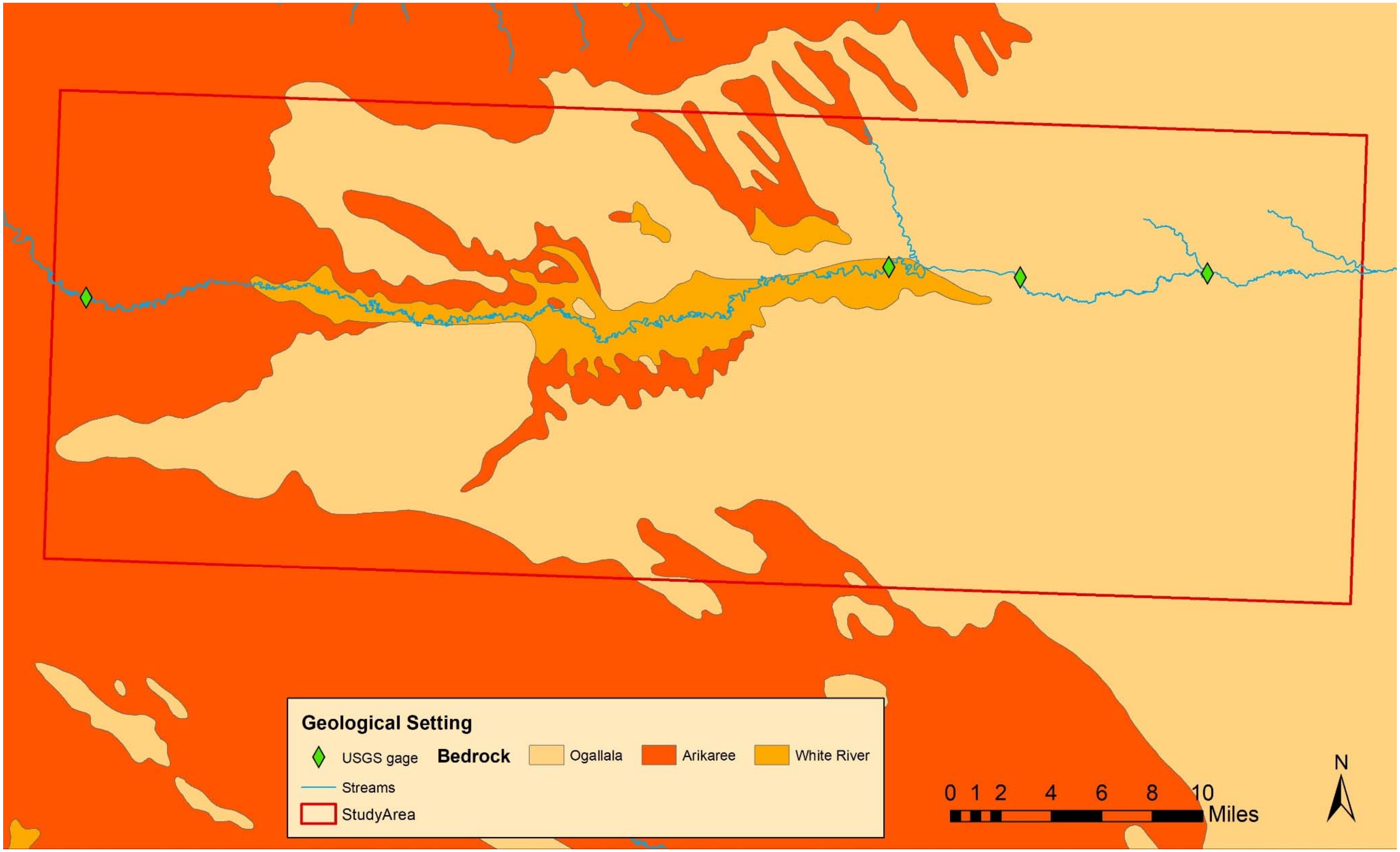


Figure 4. Map showing the general occurrence of Ogallala, Arikaree and Whiter River Group sediments in the study area.

PERIOD	EPOCH	GROUP	FORMATION
QUATERNARY	Holocene and Pleistocene		Undifferentiated
NEOGENE	Miocene	Ogallala	Ash Hollow
			Valentine
			Sheep Creek
			Runningwater
		Arikaree	Harrison
			Monroe Creek
PALEOGENE	Oligocene		Gering
		White River	Sharps
			Brule
			Chadron
	Eocene		Chamberlain Pass
CRETACEOUS	Late Cretaceous		Laramie
			Fox Hills
		Montana	Pierre Shale

Figure 5. Chart illustrating a generalized geologic framework of western Nebraska.

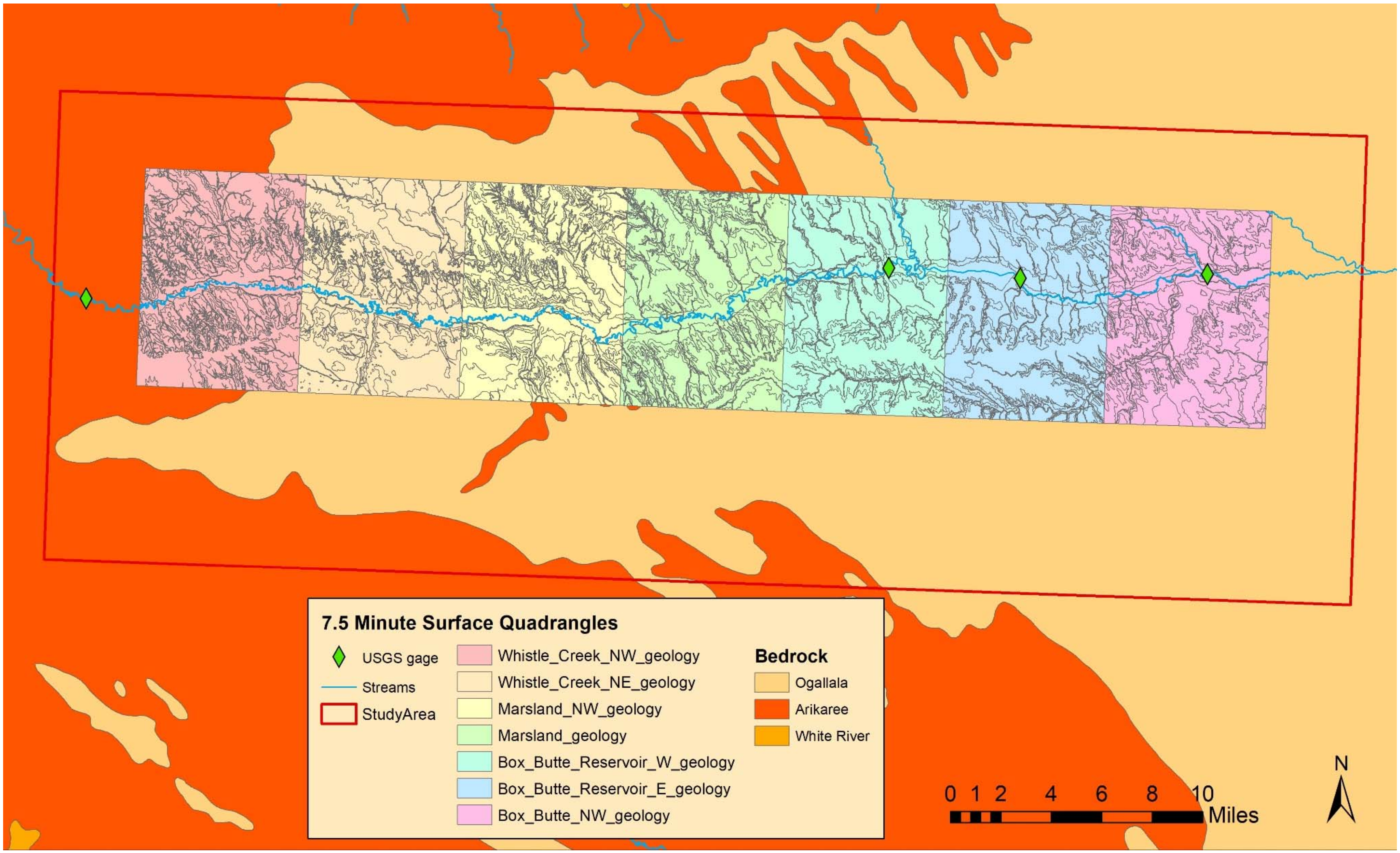


Figure 6. Map showing study area and USGS 7.5 Minute quadrangles (1997) that were analyzed as part of this study.

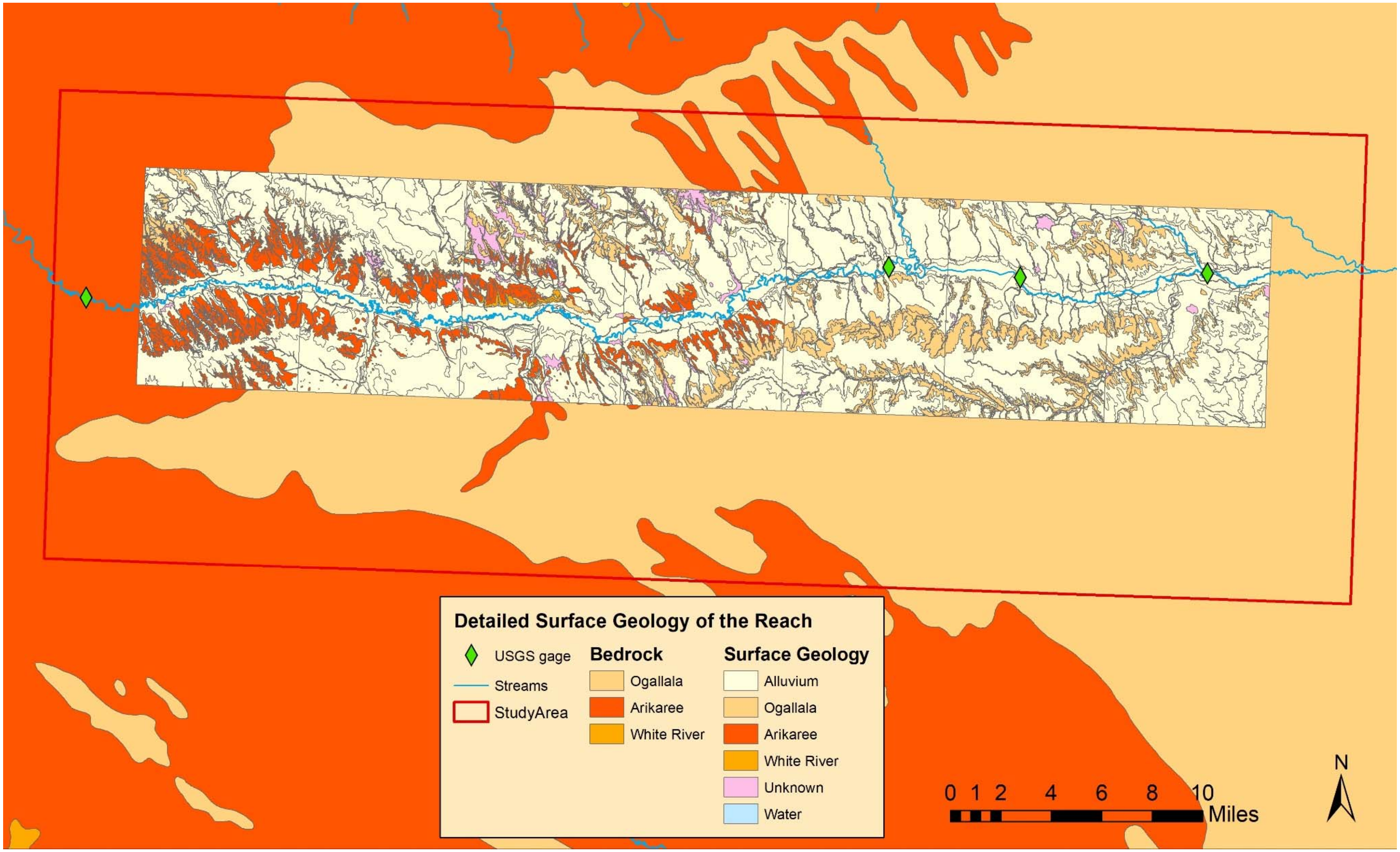


Figure 7. Map illustrating typical sediments of the surface geology show by the USGS 7.5 Minute quadrangles (1997) that were analyzed as part of this study.

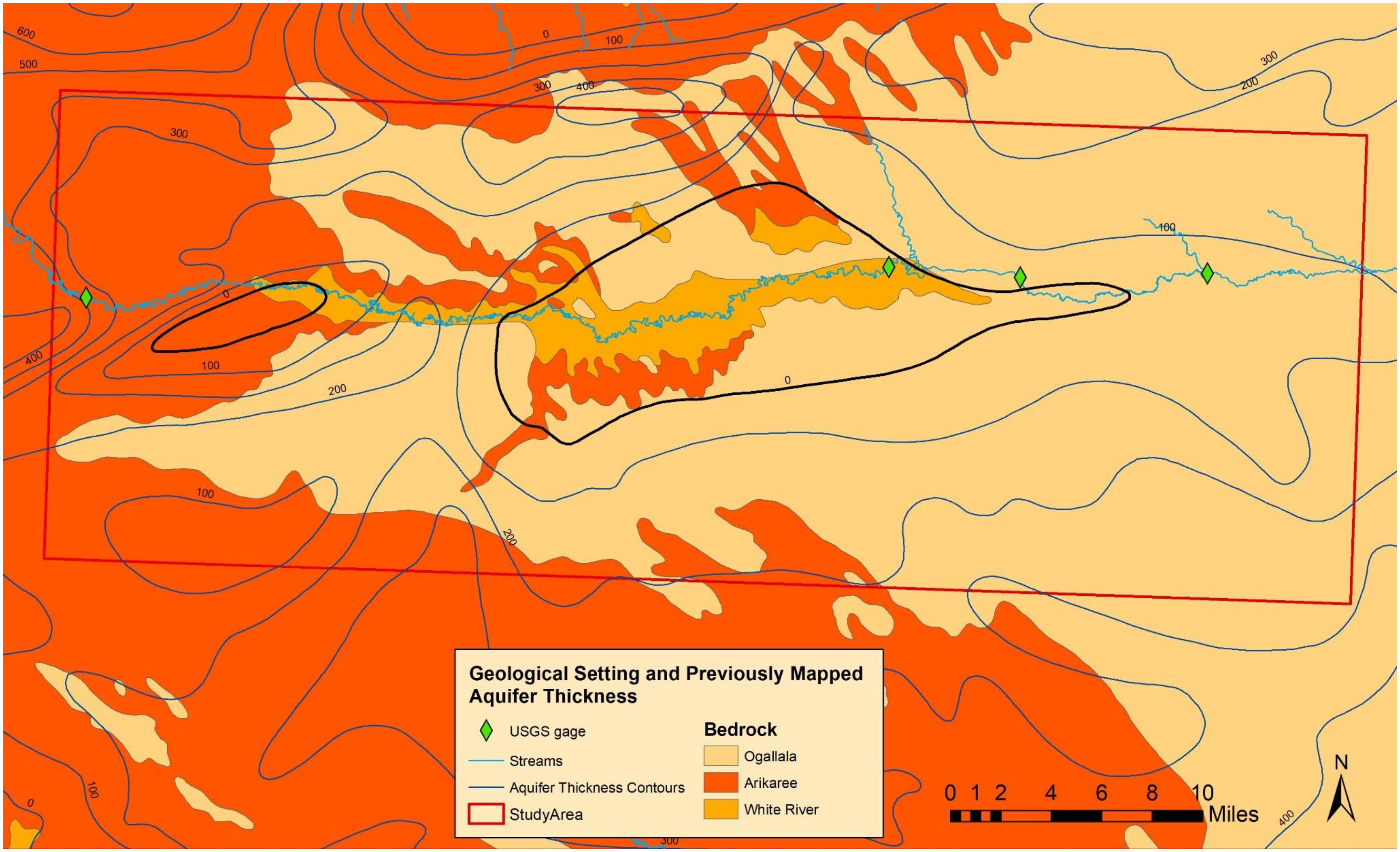


Figure 8. Map showing study area and previously mapped aquifer thickness contours. The contour representing the aquifer absent area is bold black.

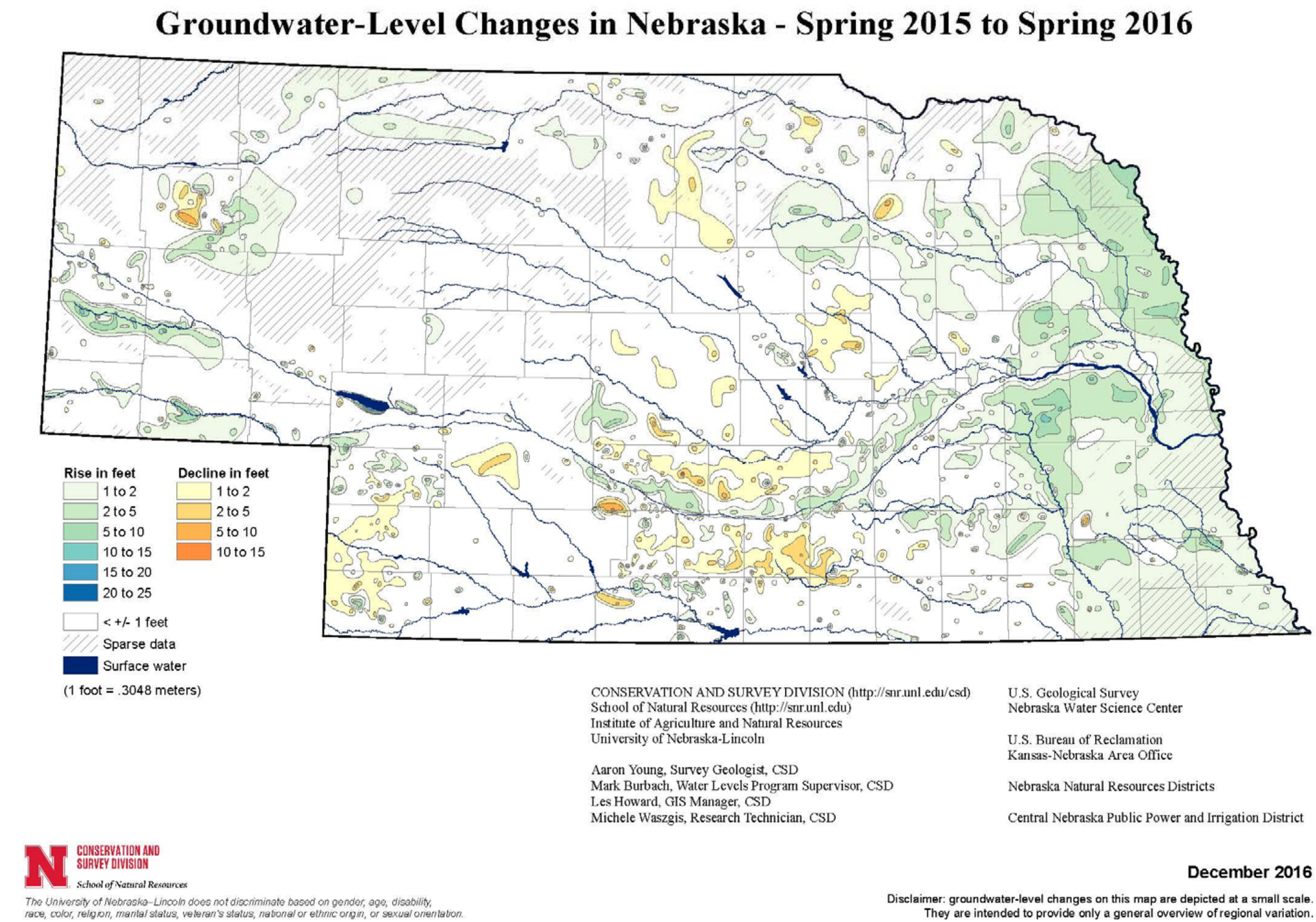


Figure 9. Statewide map showing water level changes between 2015 and 2016, indicating sparse data in the project area (Conservation and Survey Division, 2017.)

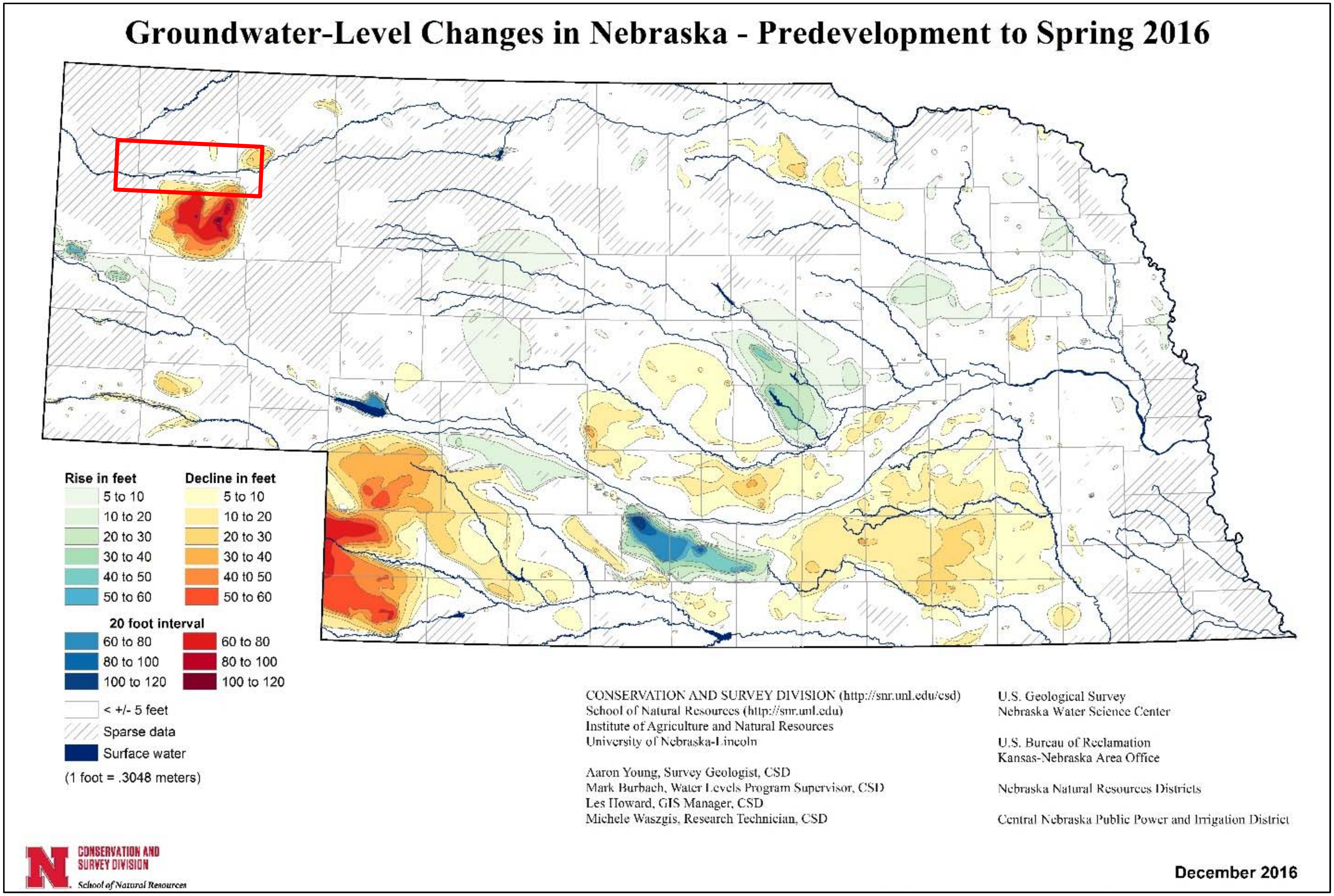


Figure 10. Statewide map showing water level changes between predevelopment and 2016. The area of interest in this study is outlined in red.

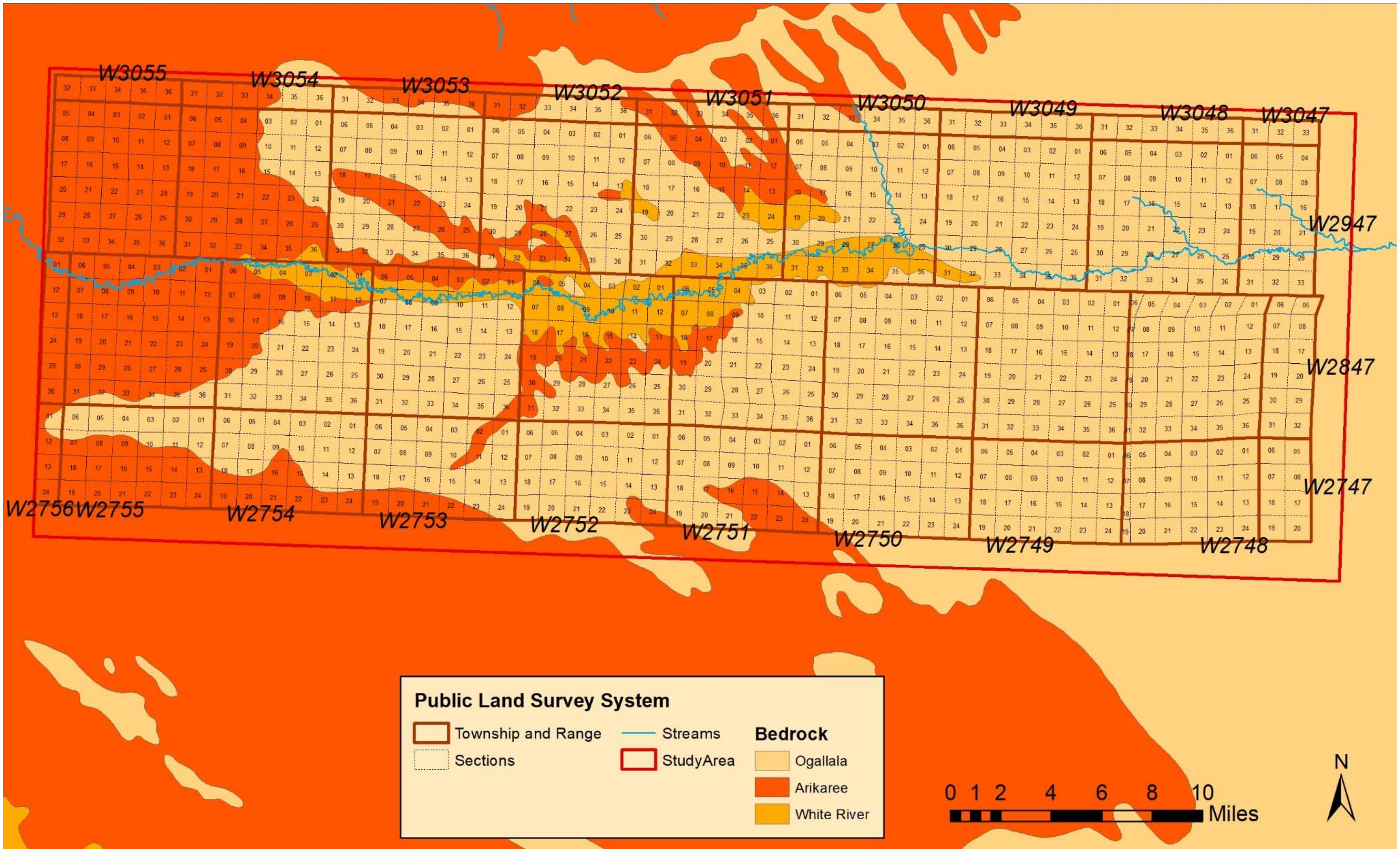


Figure 11. Map showing Public Land Survey System subdivisions of the study area.

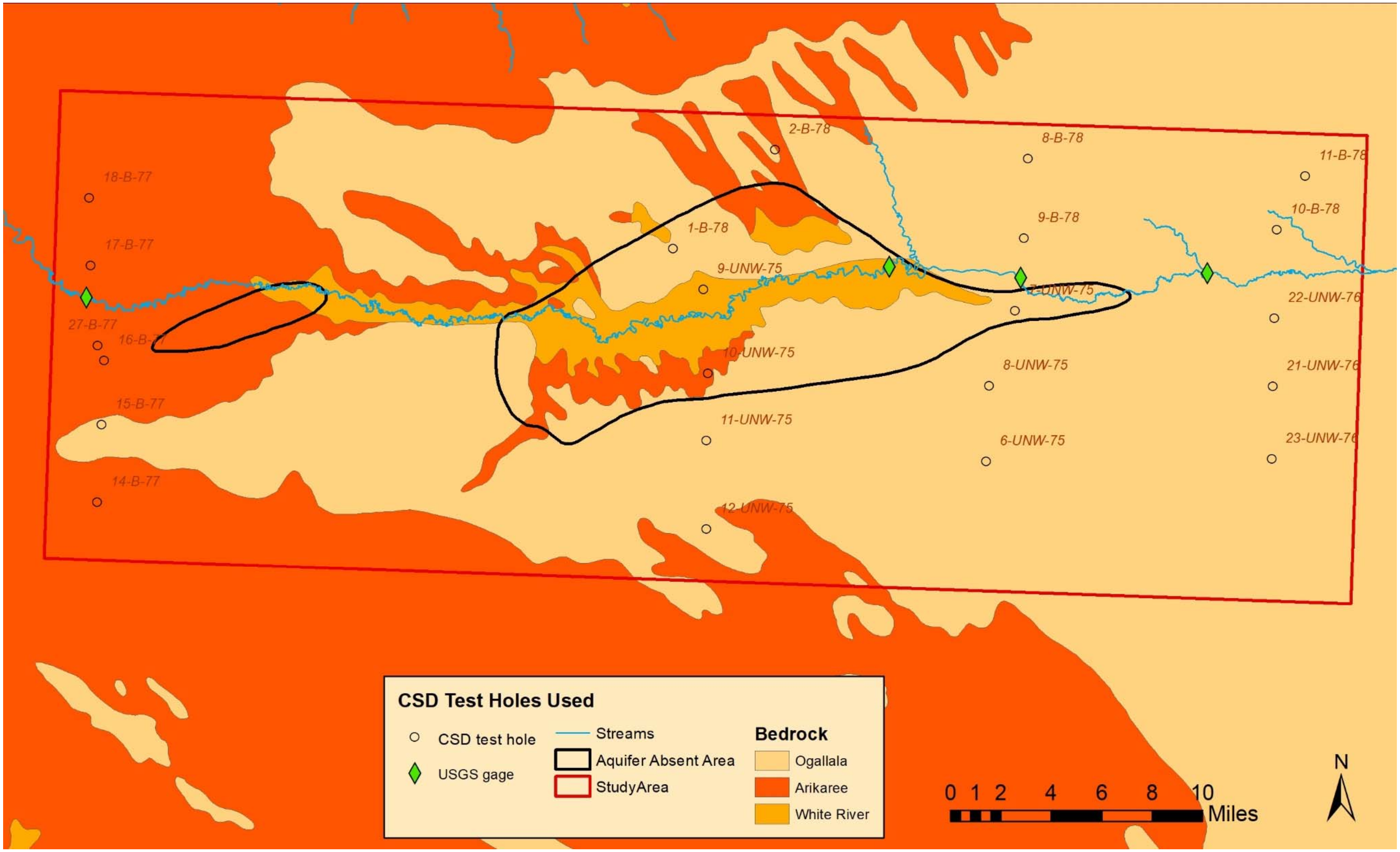


Figure 12. Map showing study area and CSD test holes used in this analysis. Test holes are also listed in Table 3.

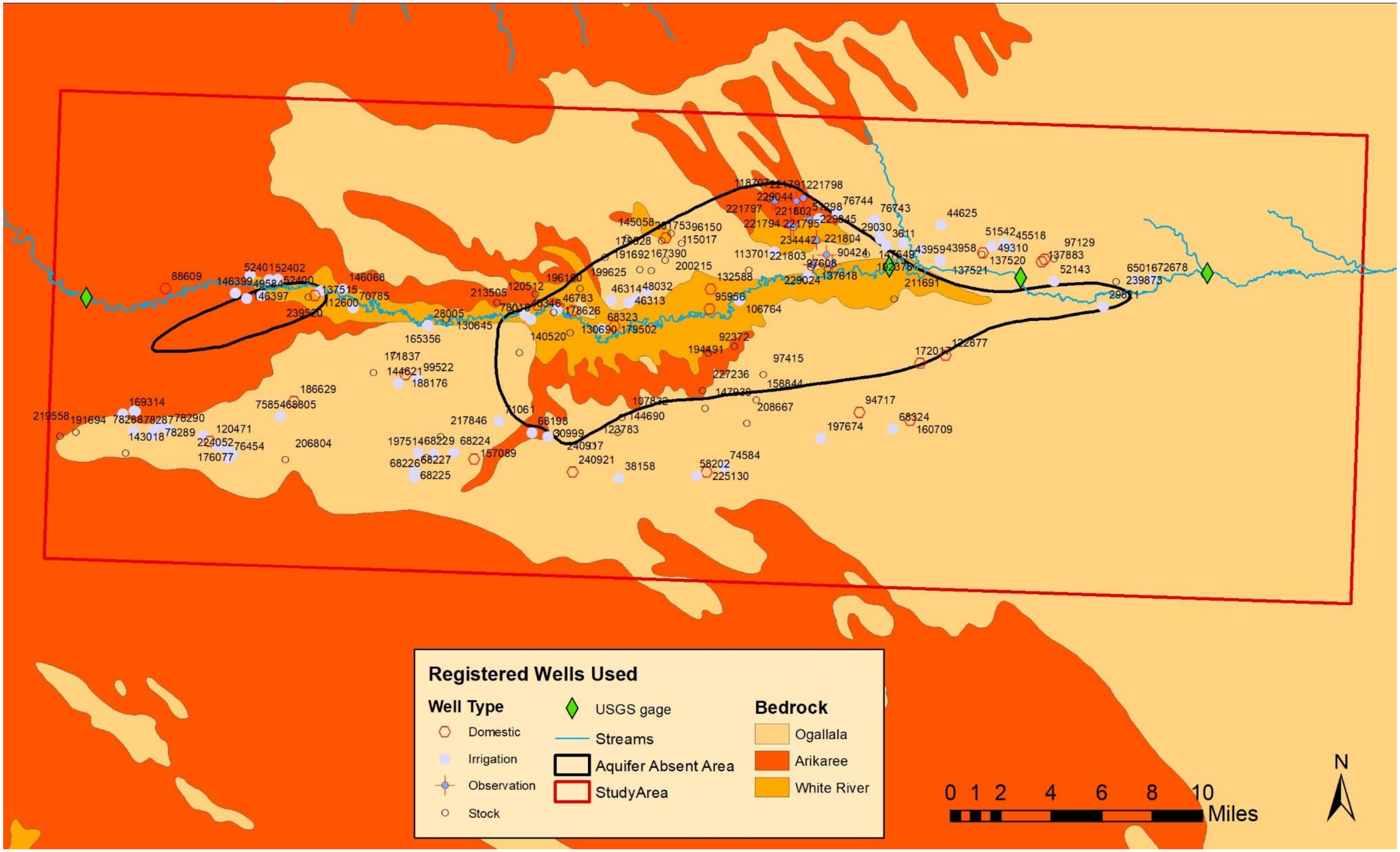


Figure 13. Map showing study area and registered wells selected for analysis under this study. The wells were selected to enhance our understanding of the area of White River Group bedrock, and aquifer areas mapped with zero thickness.

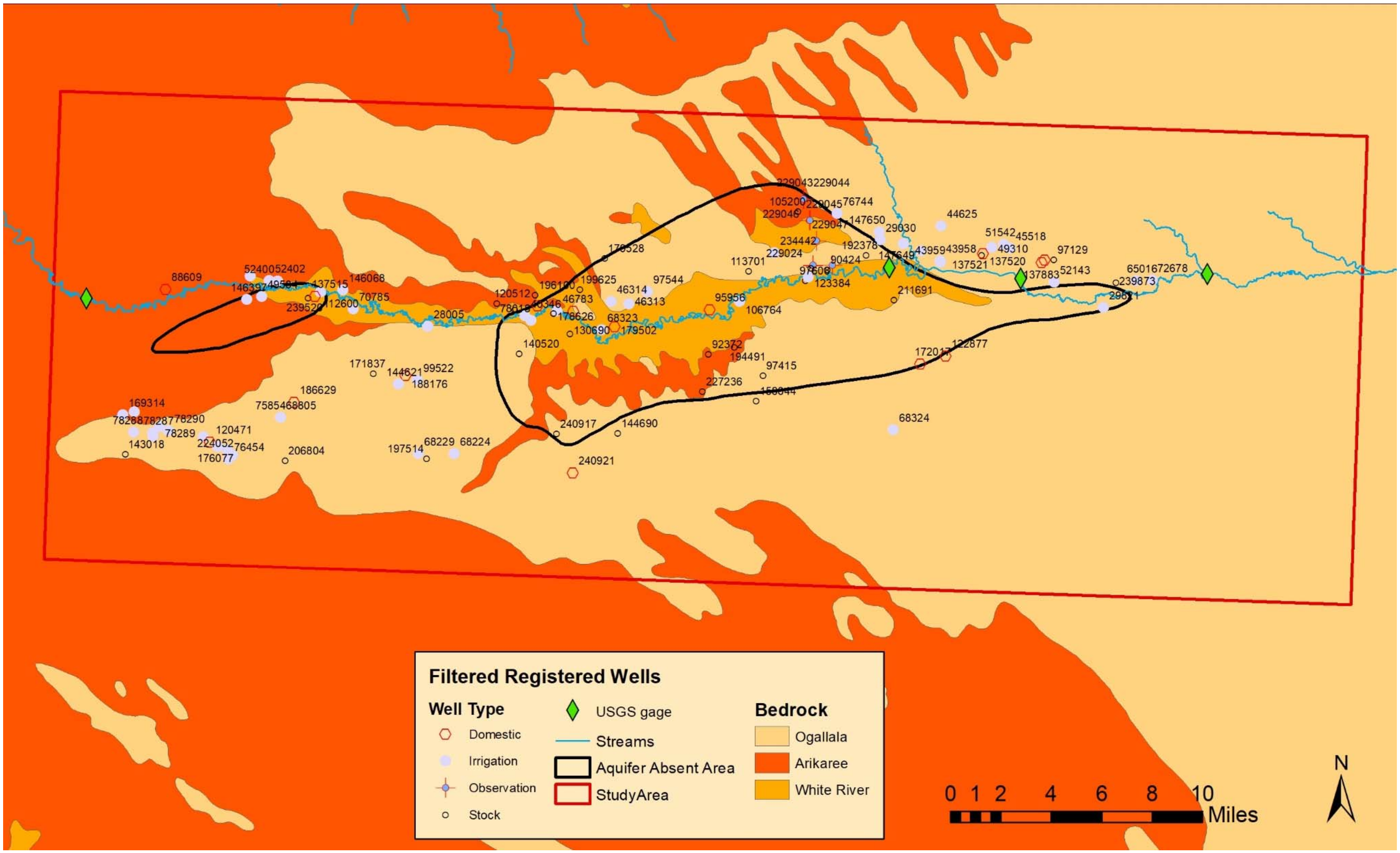


Figure 14. Map showing study area and registered wells used in this analysis after filtering to remove inactive wells and wells without needed values, and a sufficient level of detail in their cuttings descriptions. Registered wells used in the study are listed in Table 5.

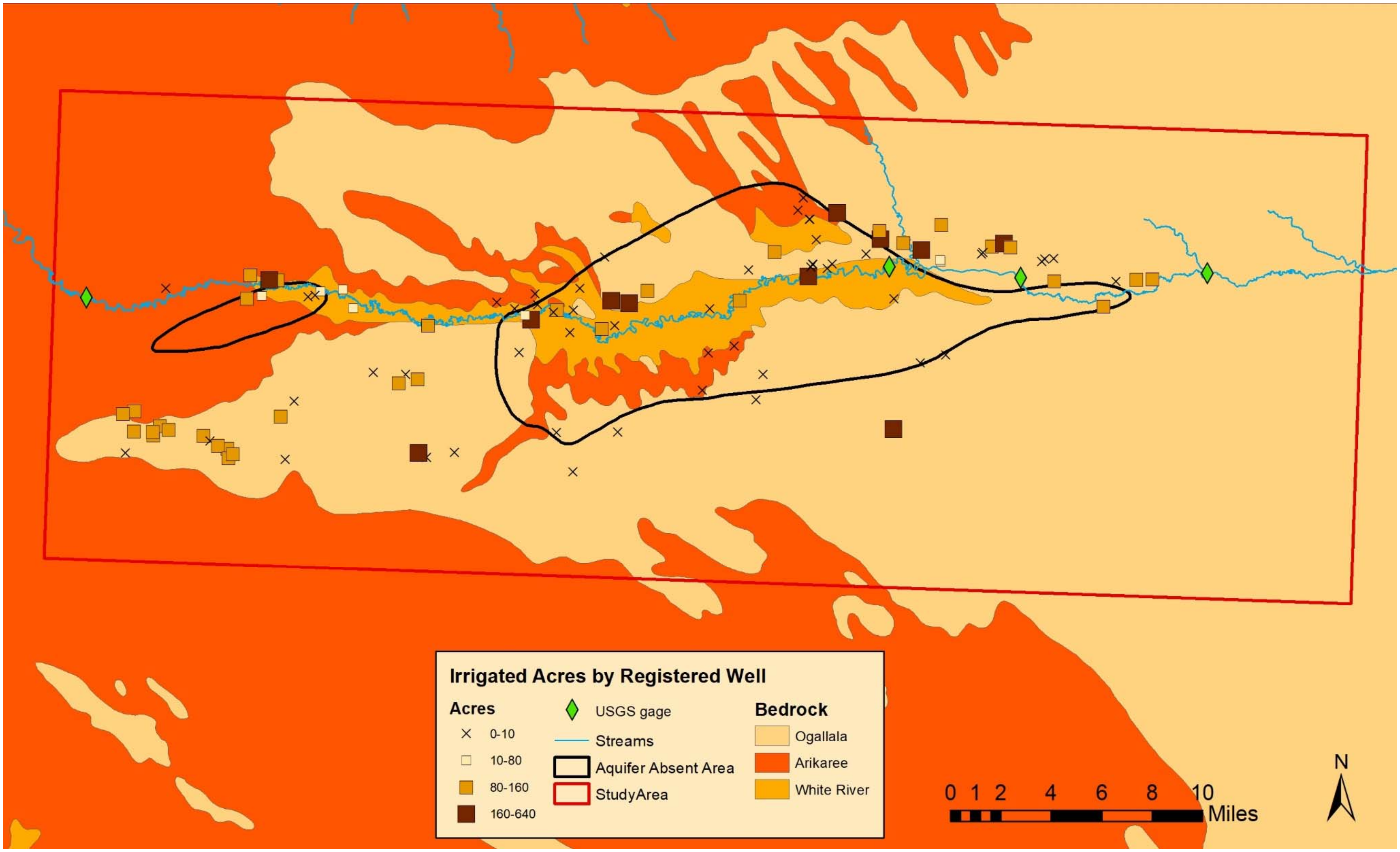


Figure 15. Map showing study area and acres irrigated for registered wells selected for analysis under this study.

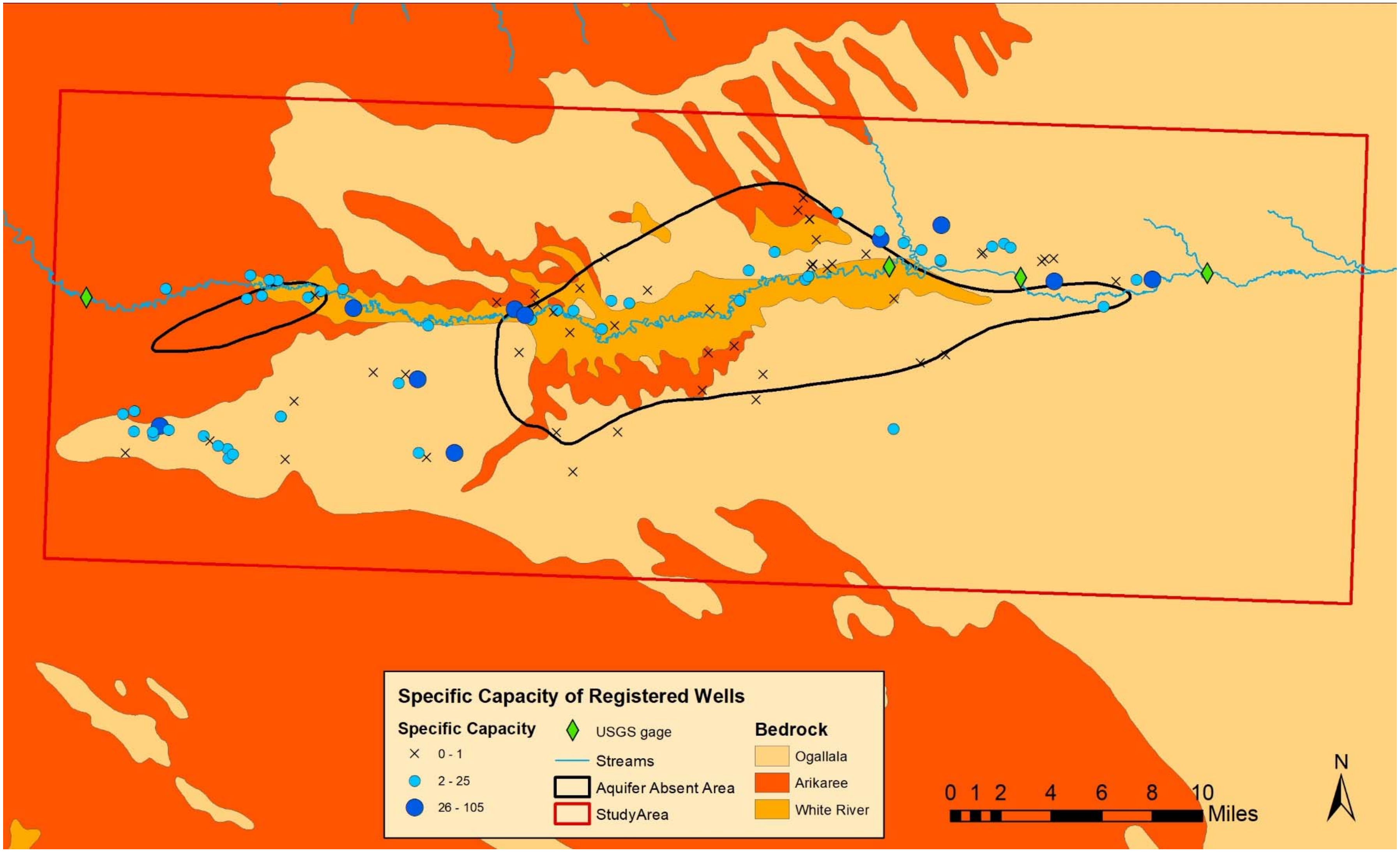


Figure 16. Map showing study area and specific capacity of registered wells (gallons per minute per foot of drawdown) selected for analysis under this study.

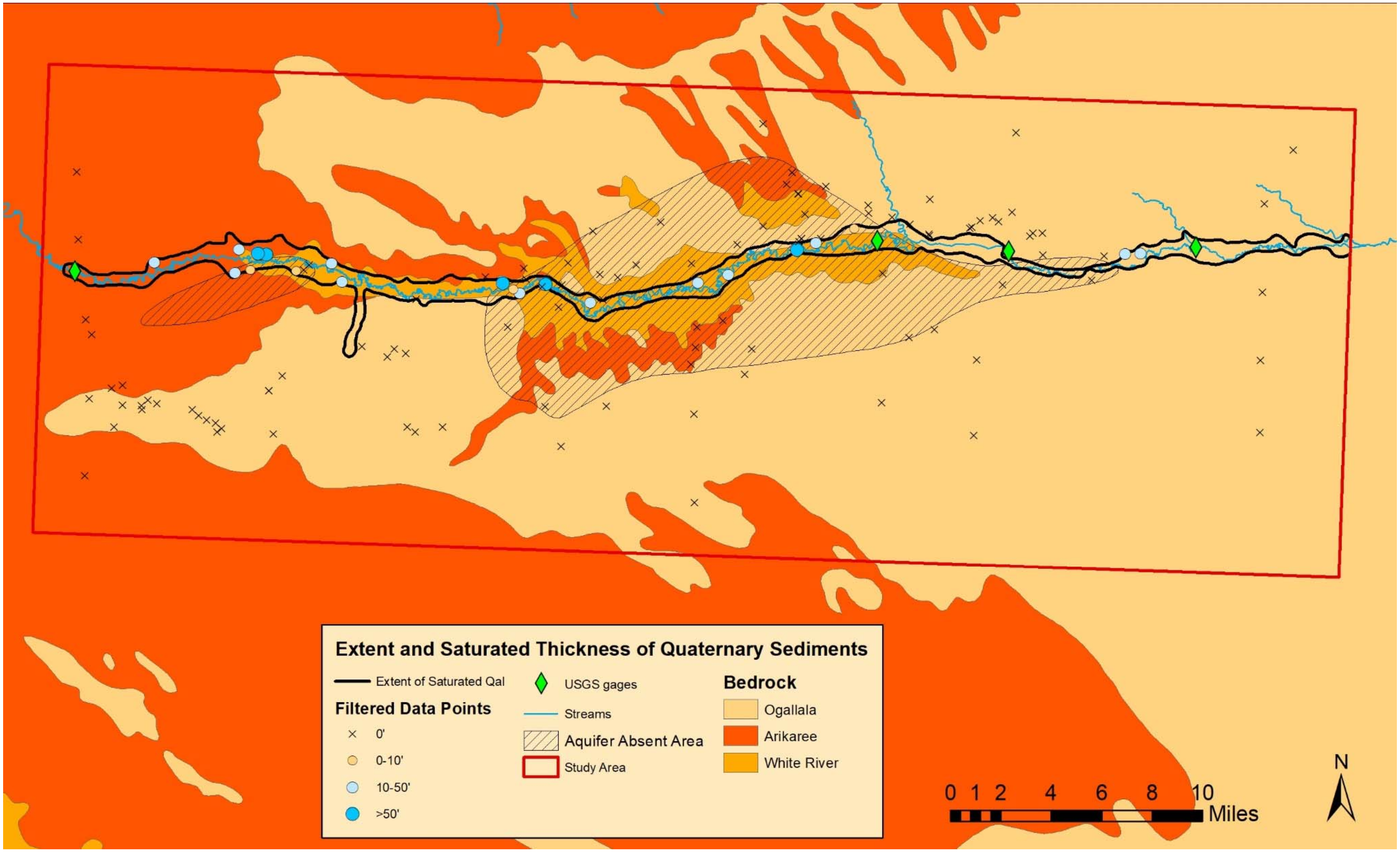


Figure 17. Map showing extent of saturated Quaternary sediments and saturated thickness of Quaternary sediments at the Filtered Data Points for analysis under this study.

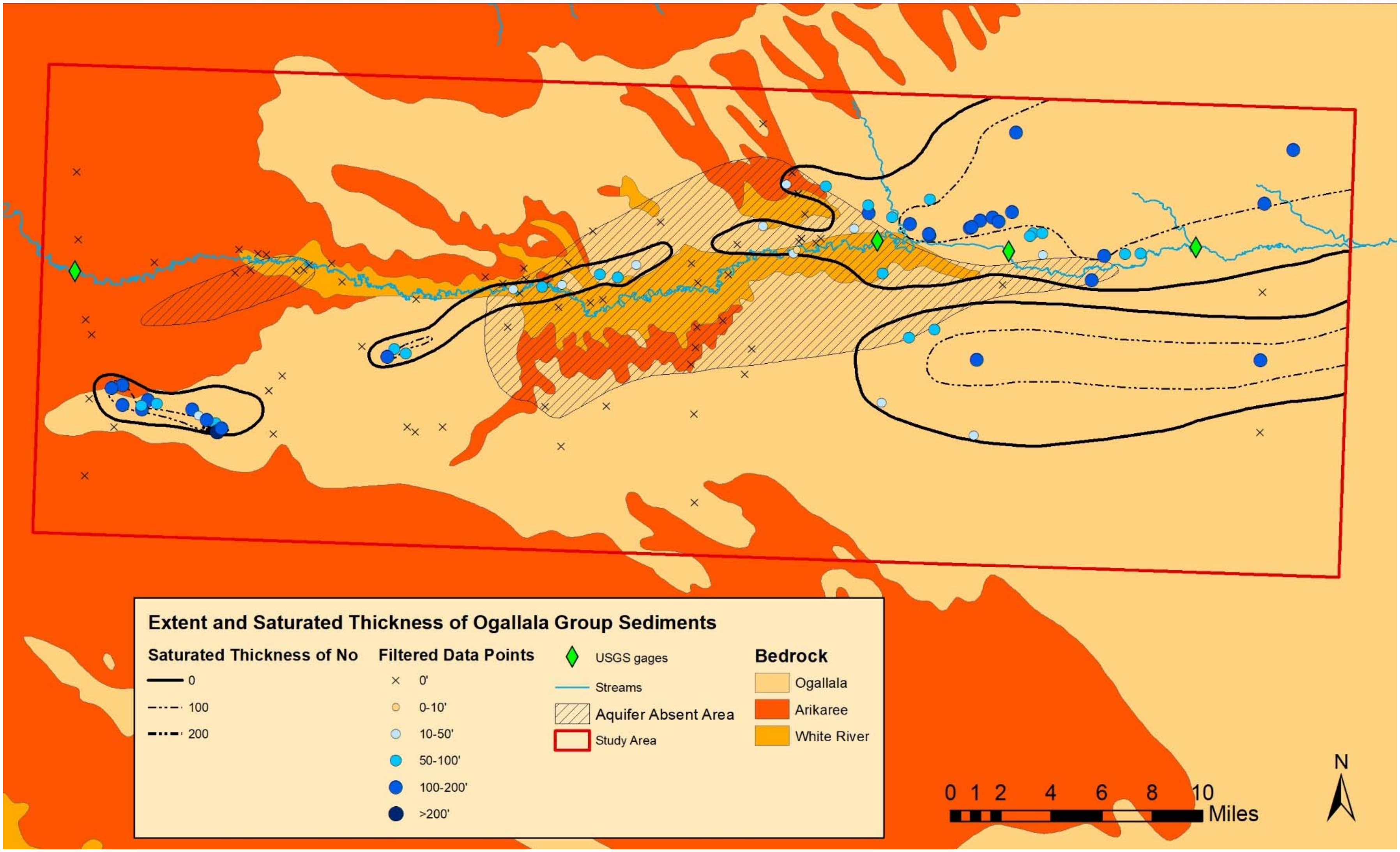


Figure 18. Map showing study area and saturated thickness contours of Ogallala Group sediments from calculations at registered wells and test holes (Filtered Data Points) used in this study.

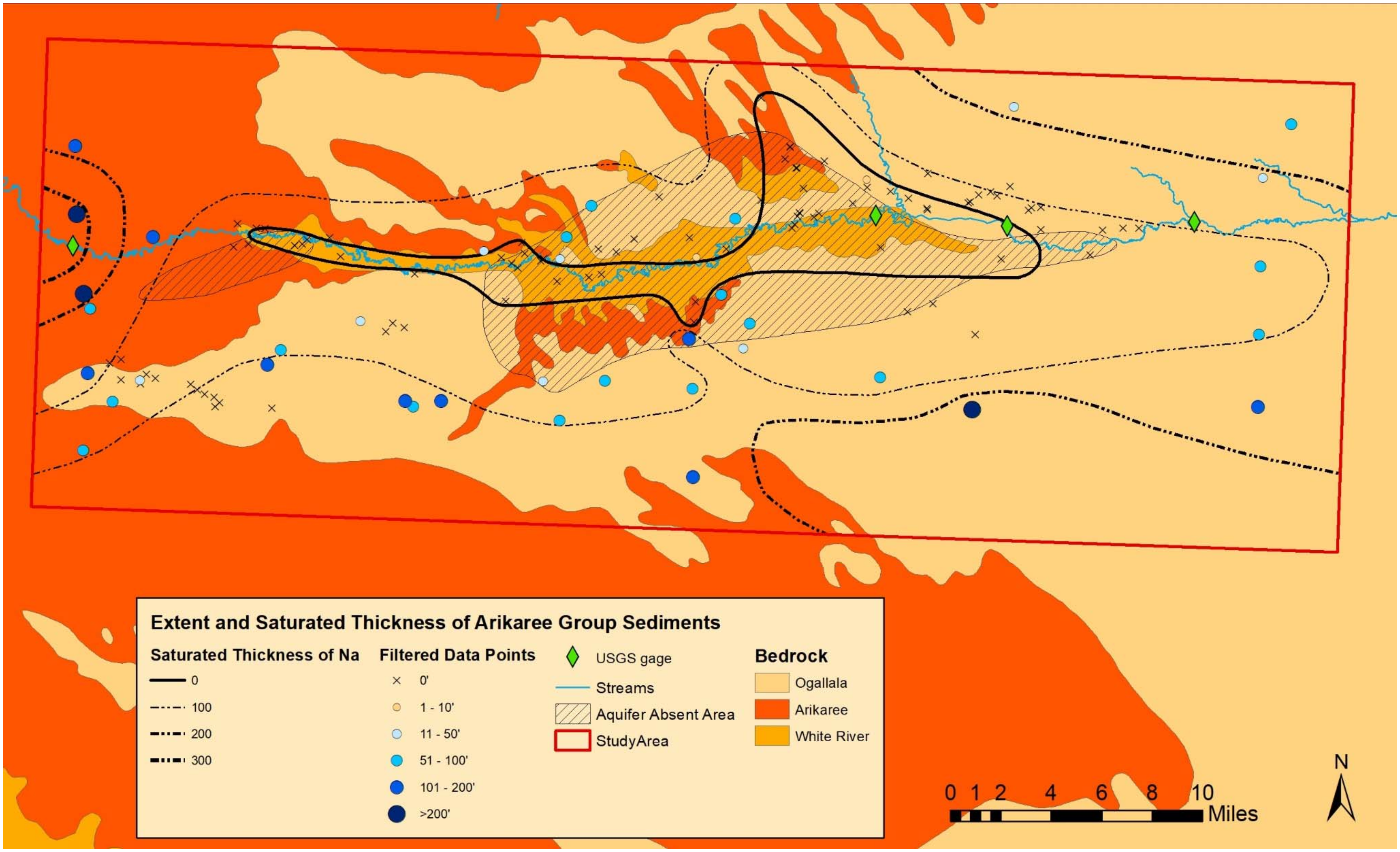


Figure 19. Map showing study area and saturated thickness of Arikaree Group sediments in registered wells and test holes (Filtered Data Points) selected for analysis under this study.

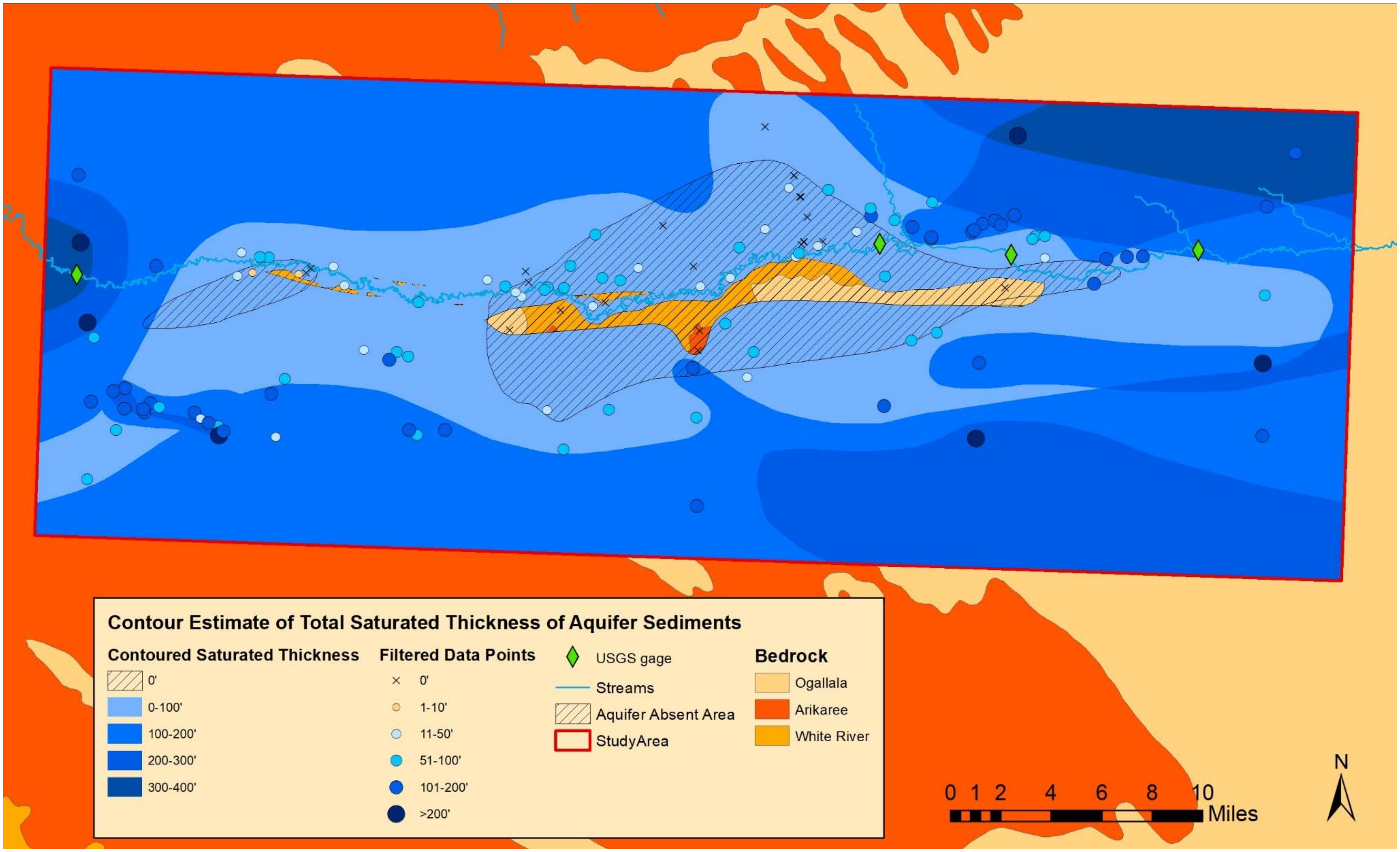


Figure 20. Map showing study area and total thickness of saturated sediments in registered wells and test holes (Filtered Data Points) selected for analysis under this study.

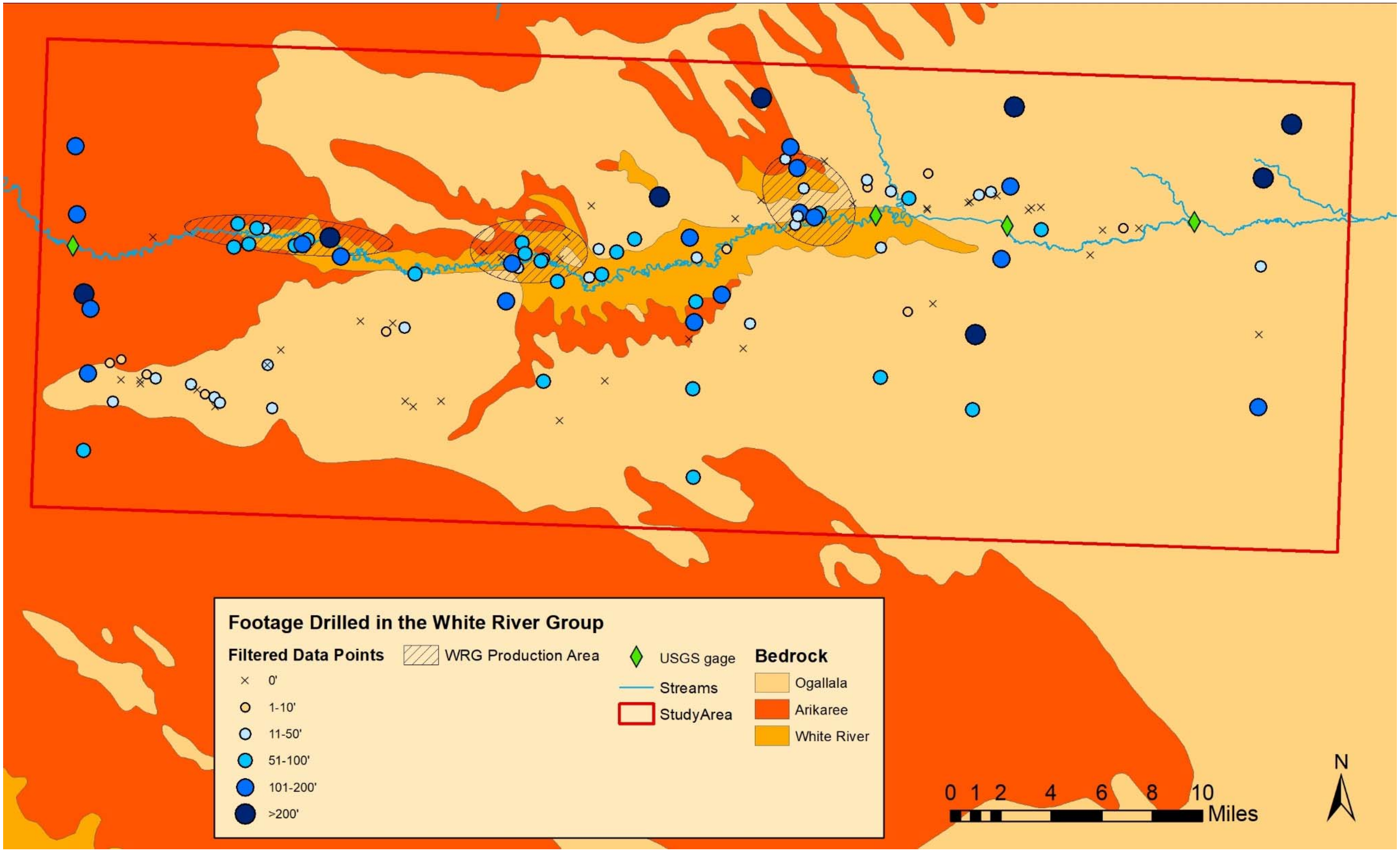


Figure 21. Map showing the depth of White River Group sediment penetration at filtered data points and areas where White River Group (WRG) sediments may be producing significant quantities of water in the study area (WRG Production Area).

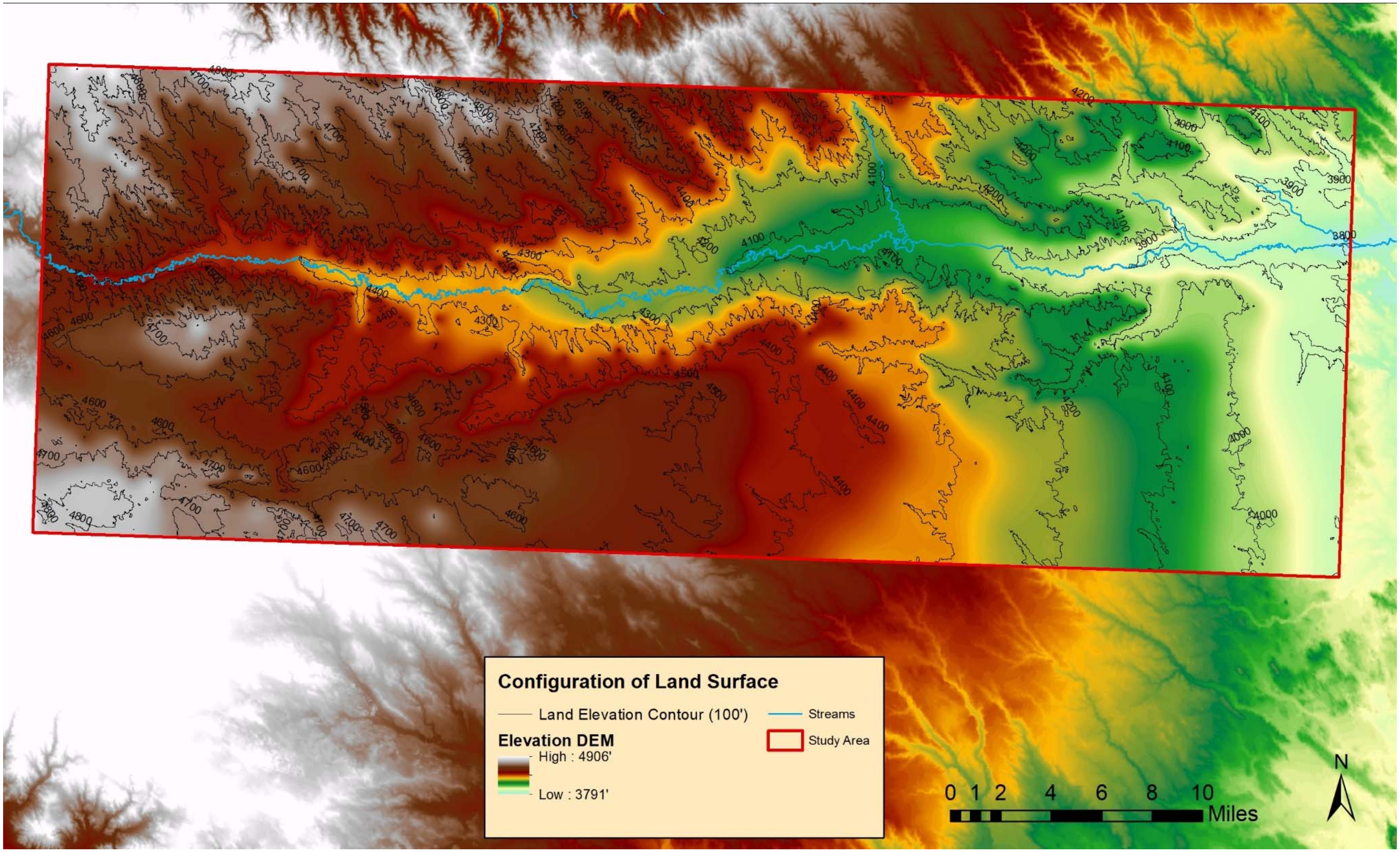


Figure 22. Map showing configuration of the land surface.

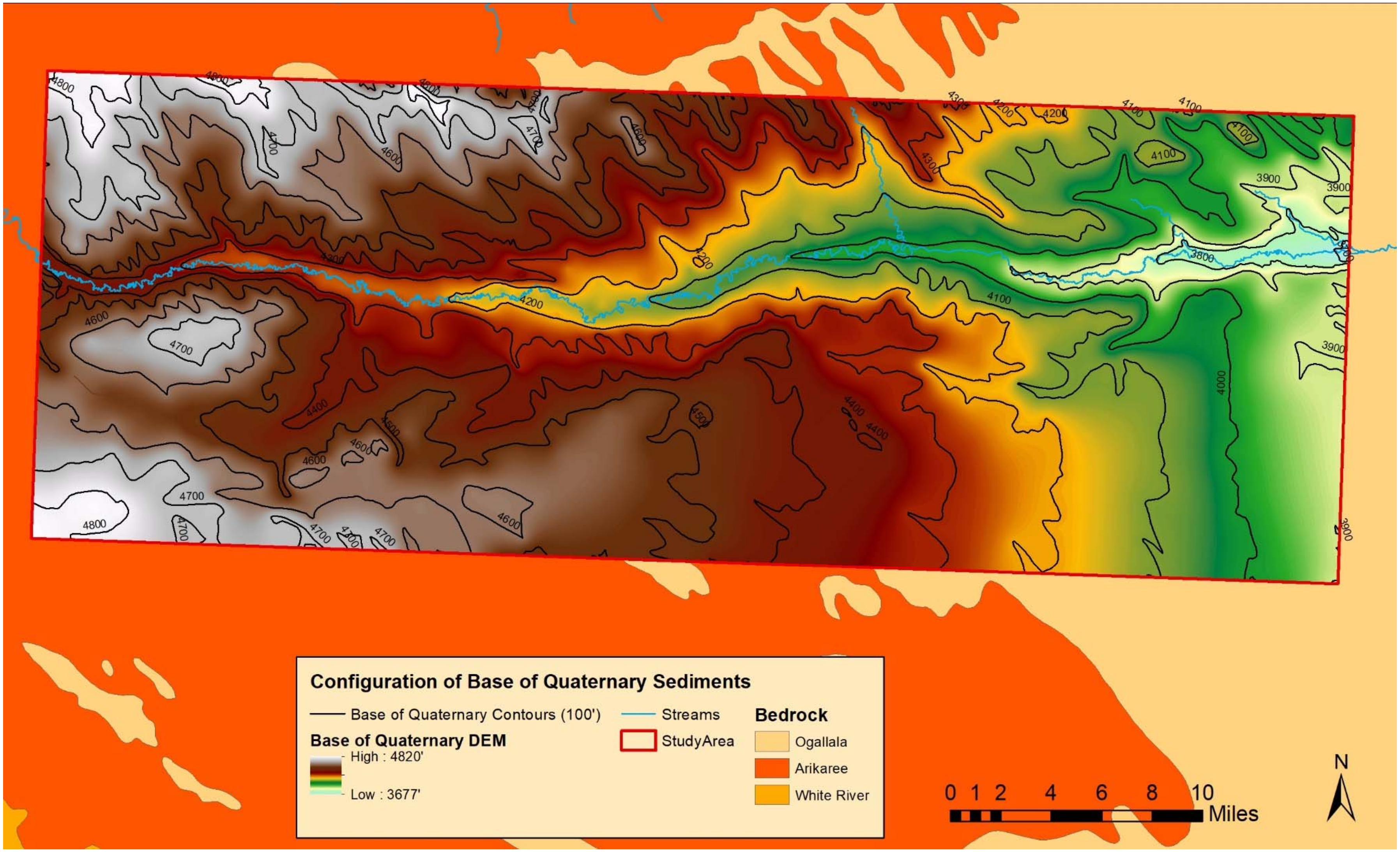


Figure 23. Map showing configuration of the base of Quaternary sediments.

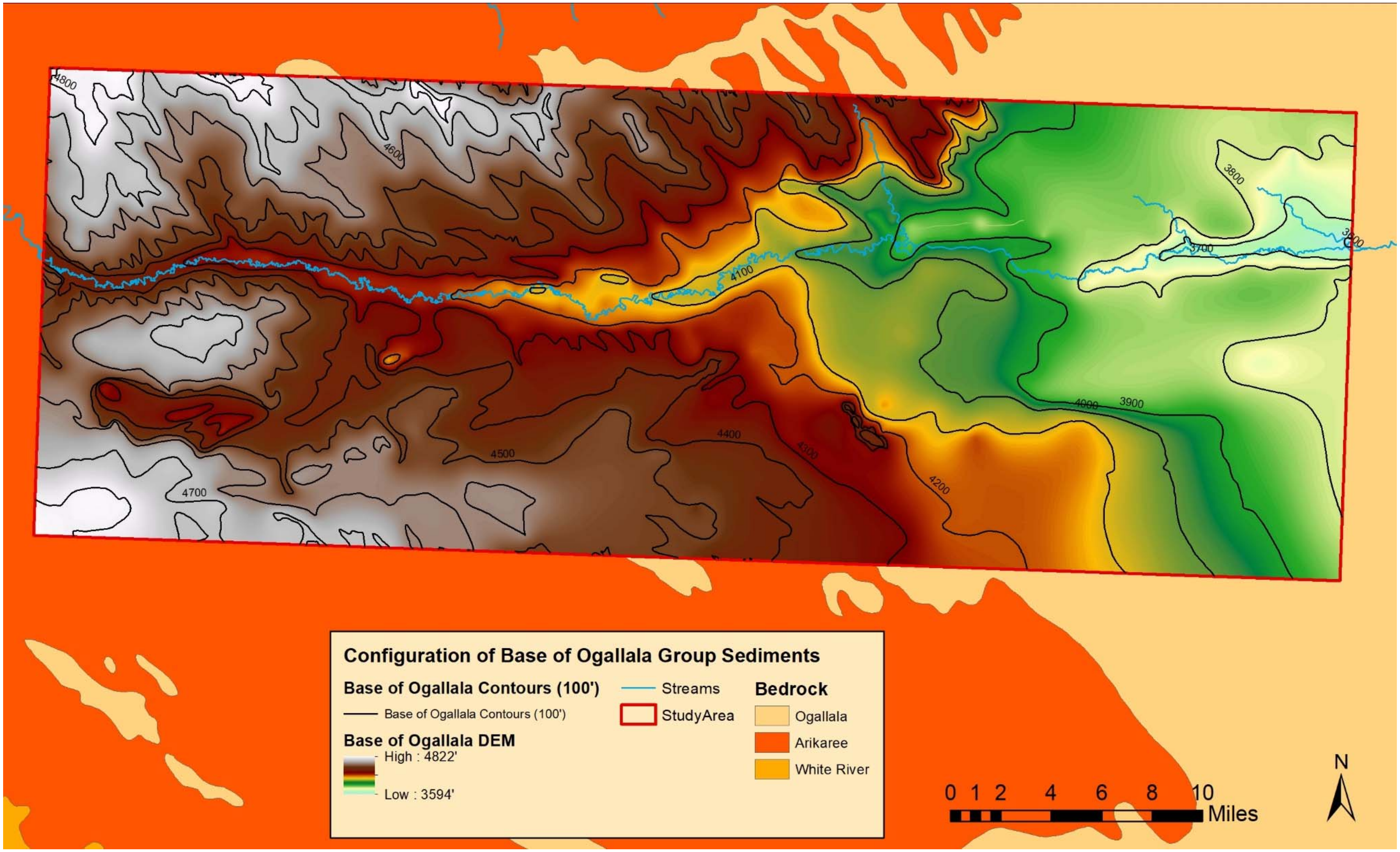


Figure 24. Map showing configuration of the base of Ogallala Group sediments.

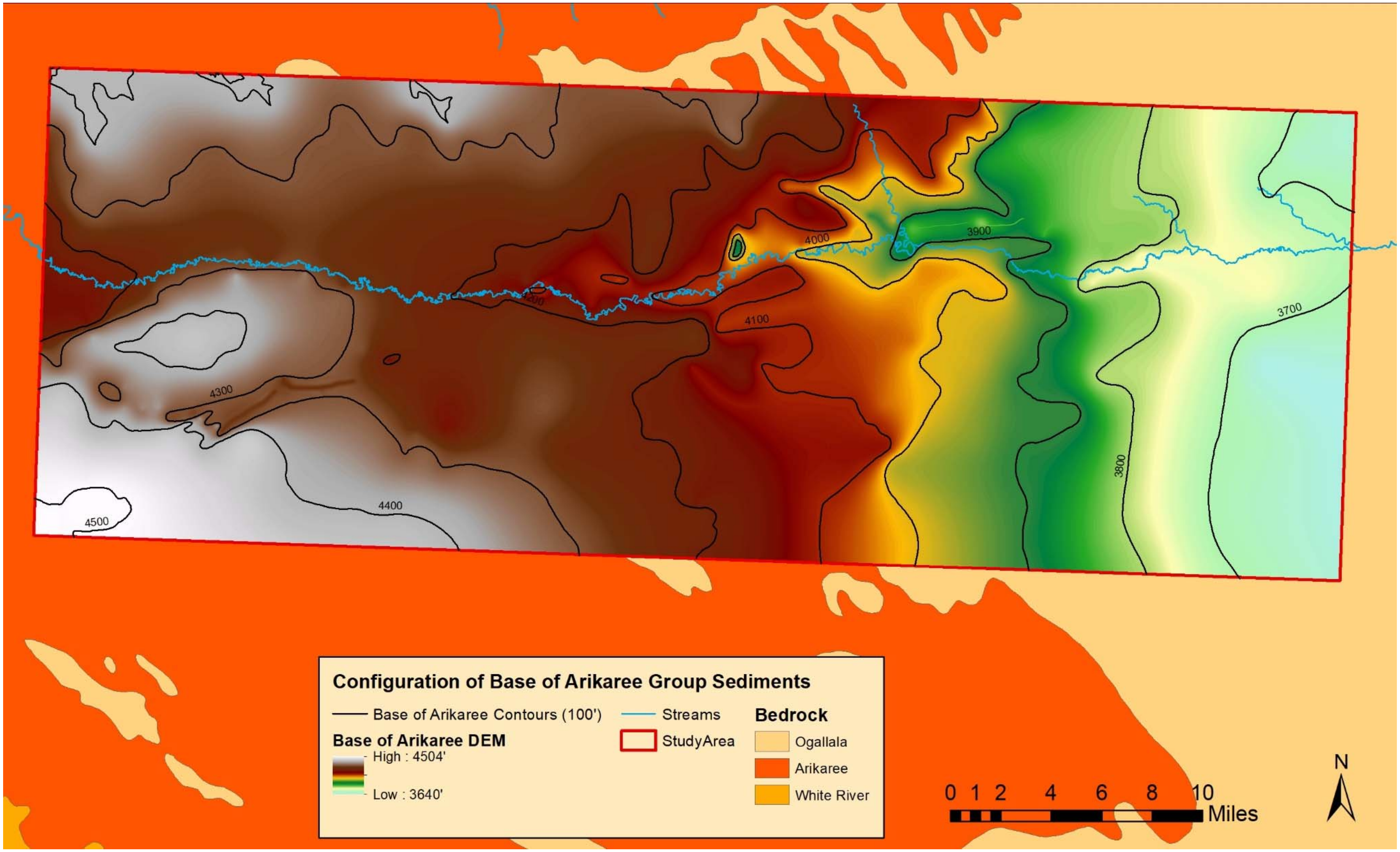


Figure 25. Map showing configuration of the base of Arikaree Group sediments, or the top of White River Group sediments.

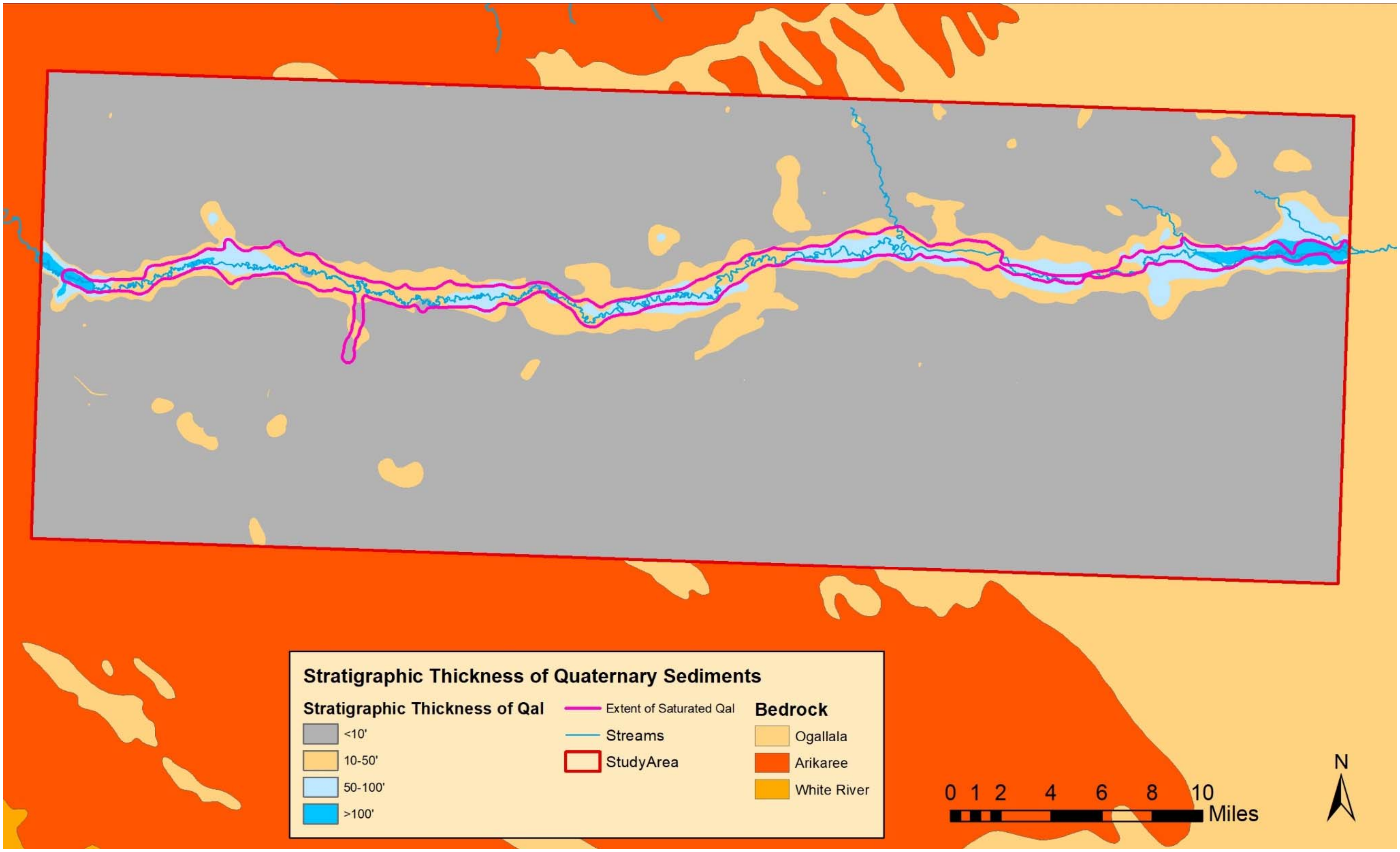


Figure 26. Map showing the stratigraphic thickness and saturated extent of Quaternary sediments.

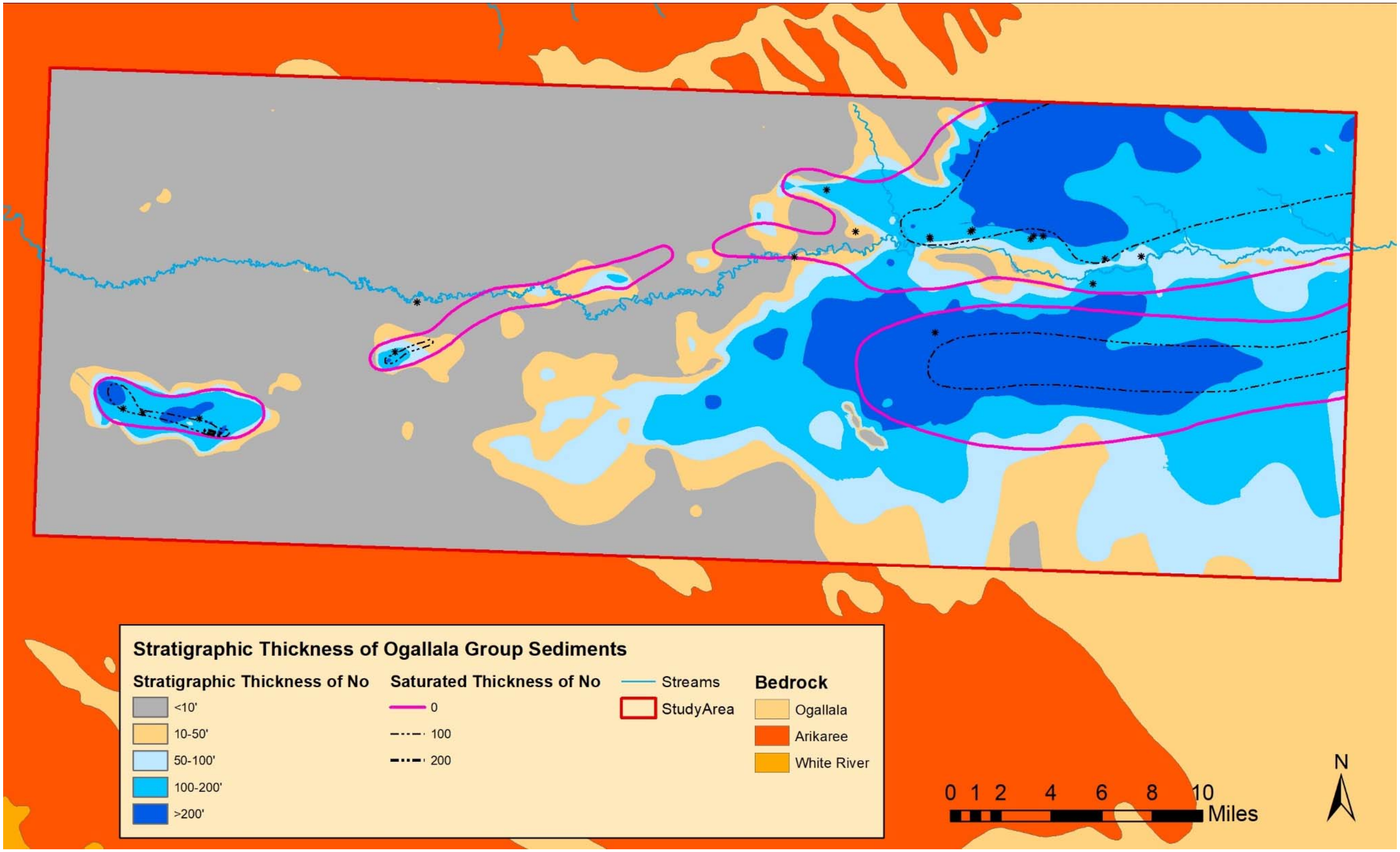


Figure 27. Map showing the stratigraphic and saturated thickness of Ogallala Group sediments. Asterisks show analysis point locations where the wells or test holes partially penetrated the Group, so values mapped in proximity to the respective points likely represent minimum thicknesses.

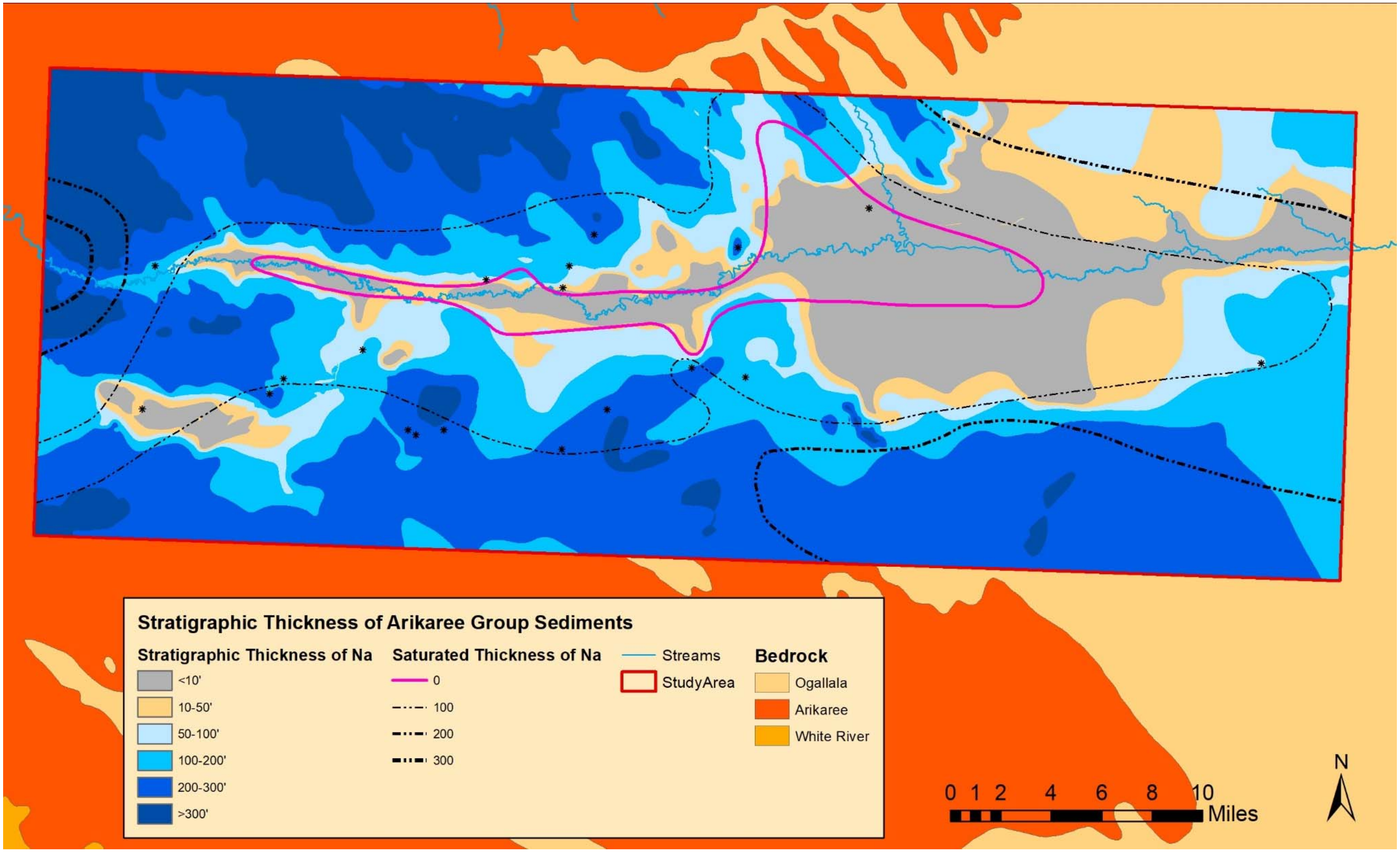


Figure 28. Map showing the stratigraphic thickness of Arikaree Group sediments. Asterisks show analysis point locations where the wells or test holes partially penetrated the group, so values mapped in proximity to the respective points likely represent minimum thicknesses.

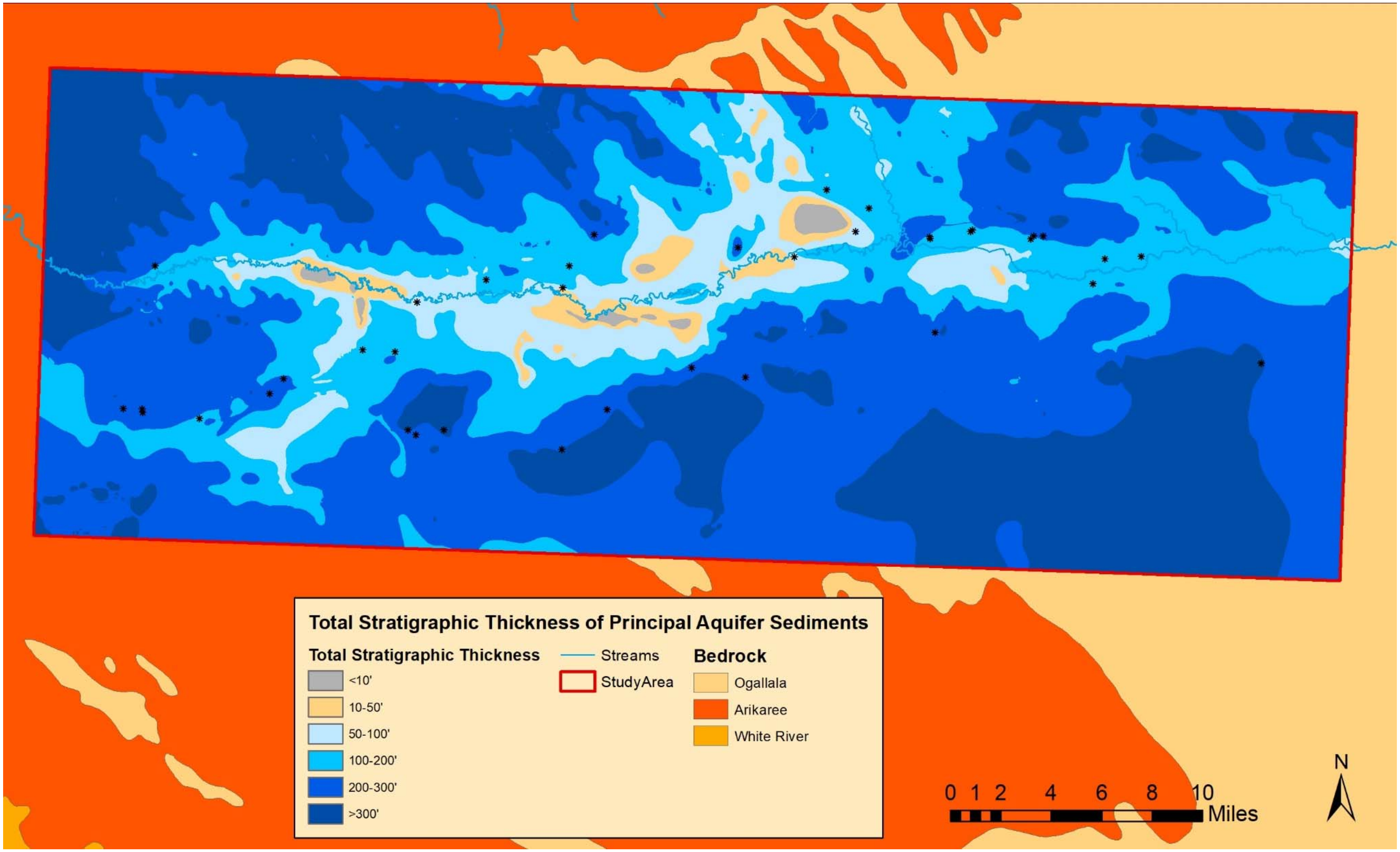


Figure 29. Map showing the total stratigraphic thickness of principal aquifer sediments. Asterisks show analysis point locations where the wells or test holes partially penetrated High Plains aquifer sediments, so values mapped in proximity to the respective points likely represent minimum thicknesses.

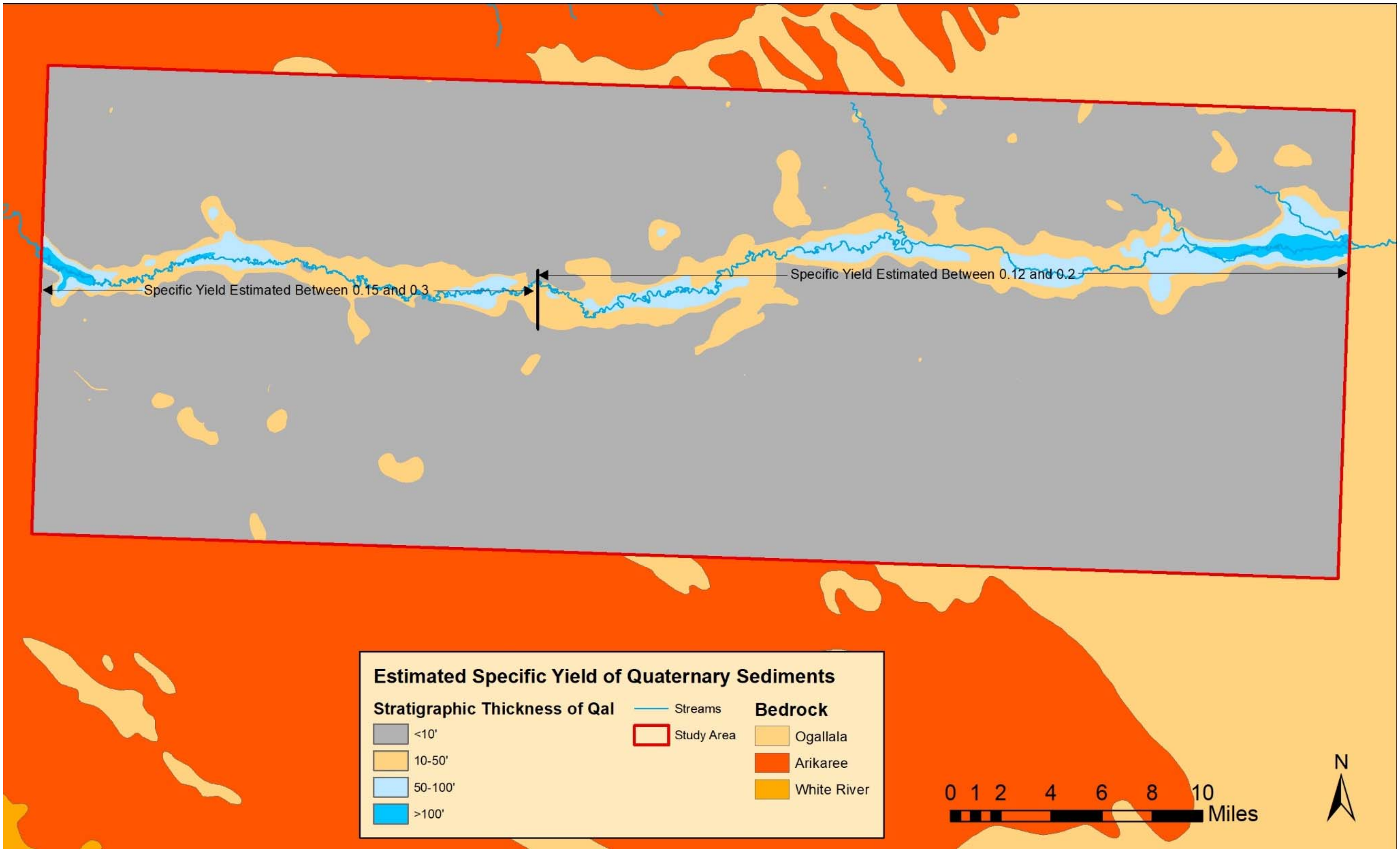


Figure 30. Map showing specific yield of Quaternary sediments.

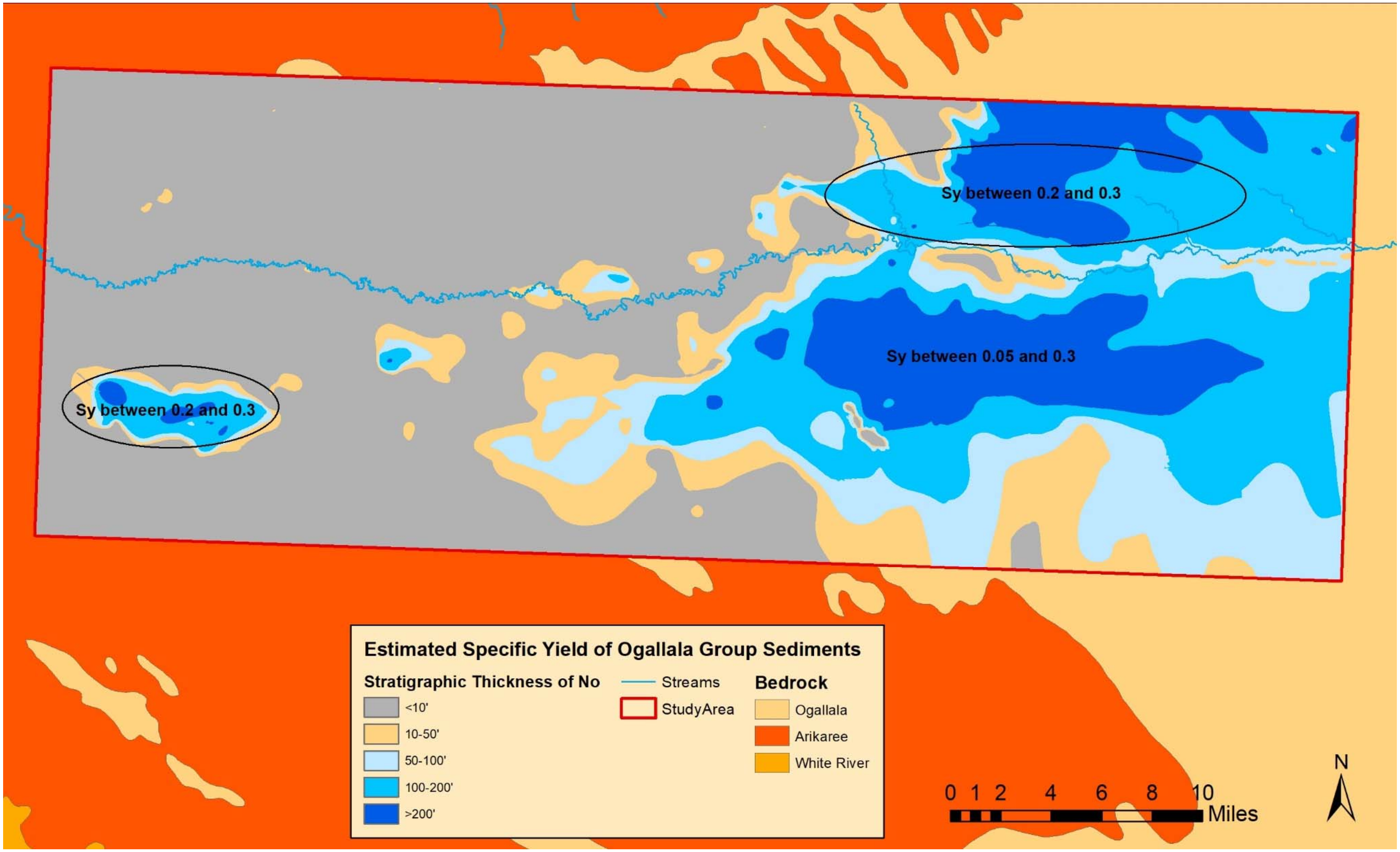


Figure 31. Map showing specific yield of Ogallala Group sediments.

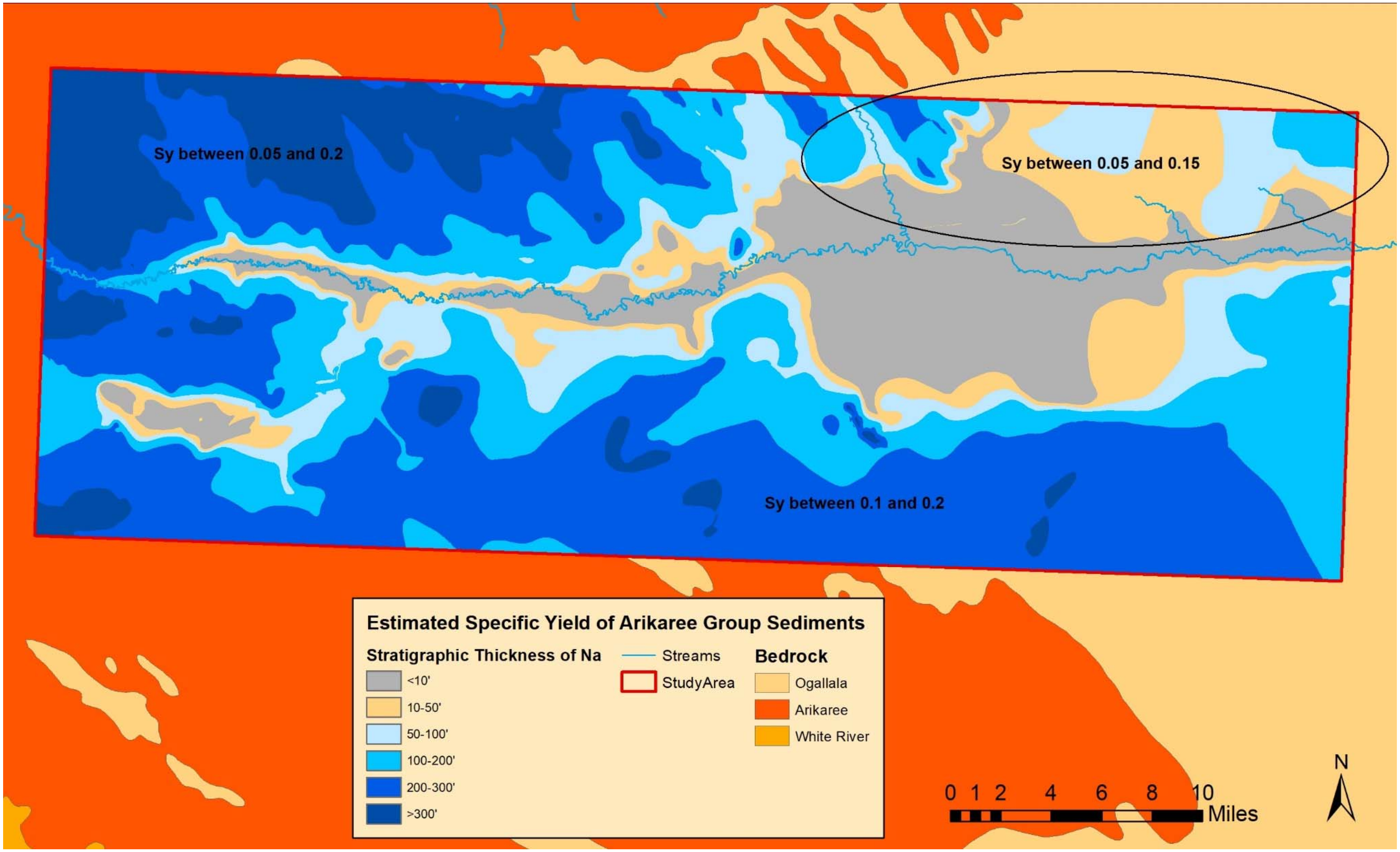


Figure 32. Map showing specific yield of Arikaree Group sediments.

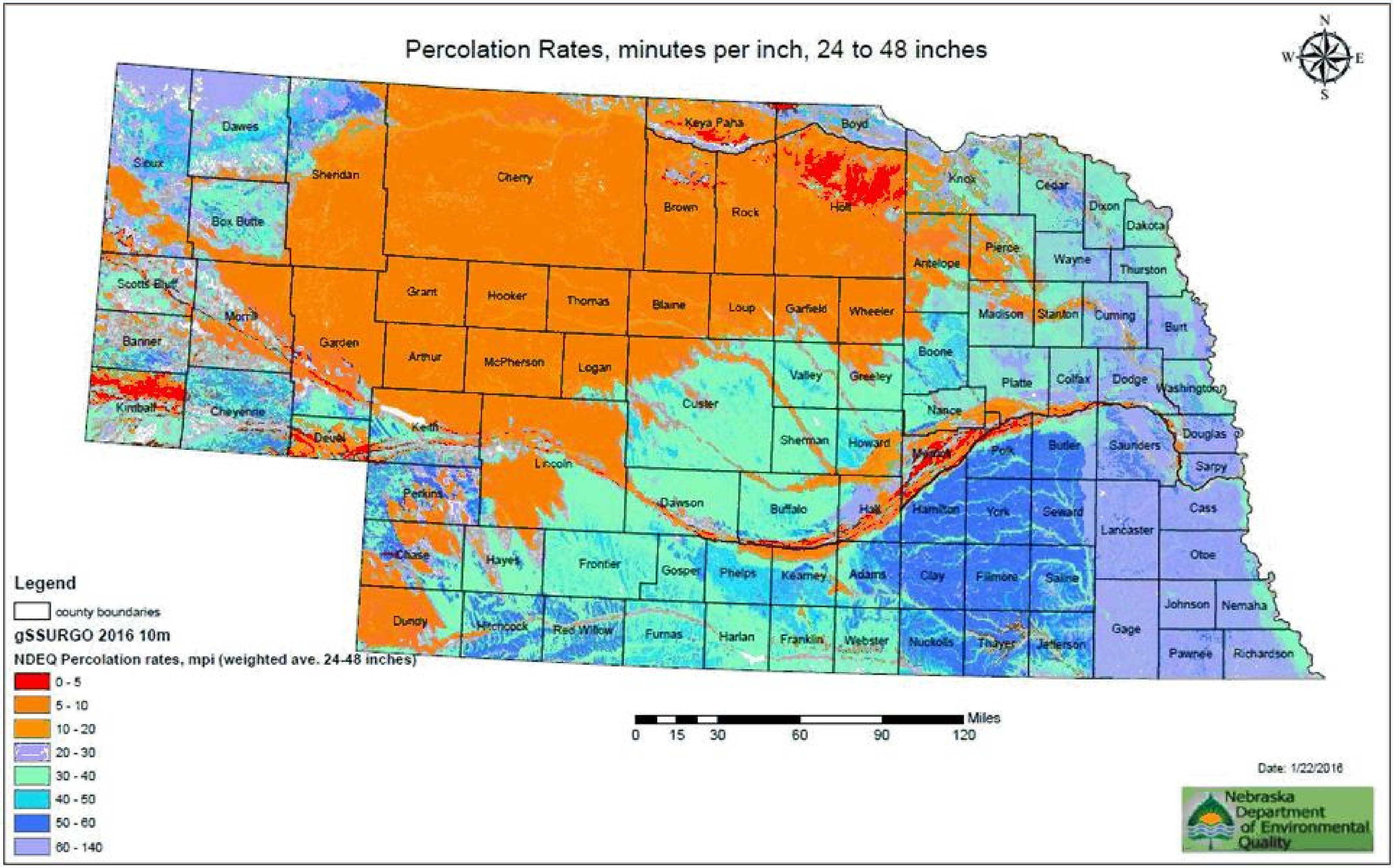


Figure 33. Statewide map showing low near surface percolation rates in Sioux County and higher near surface percolation rates in Dawes and Box Butte Counties in the study area (Nebraska Department of Environmental Quality, 2016).

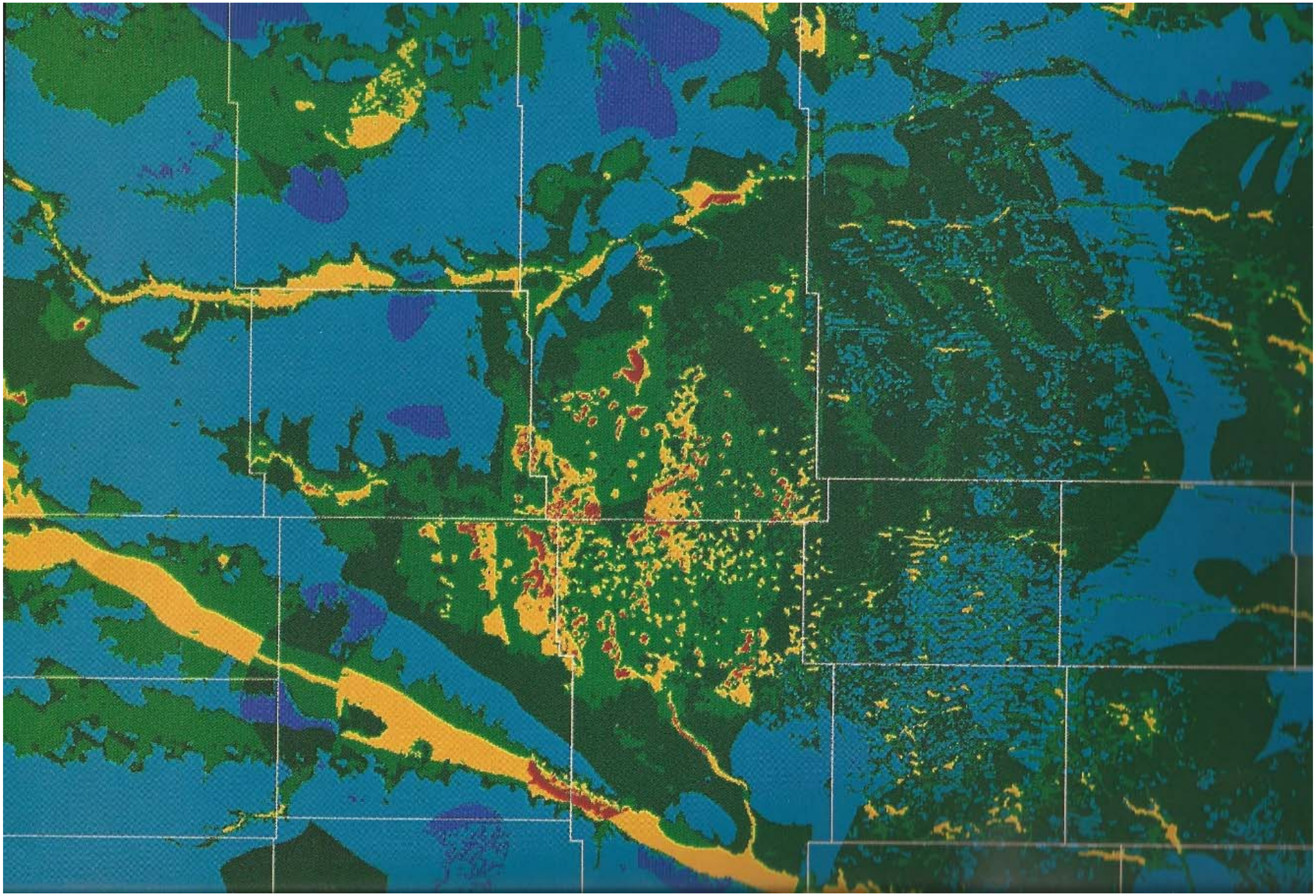


Figure 34. Regional map showing groundwater vulnerability to contamination using the DRASTIC method (CALMIT, 1991). Low vulnerability areas are show by cool colors (like gray and blue), while high vulnerability areas are shown in warm colors (like red and yellow).

Table 1. US Geological Survey stream gages in the study area.

Site ID	Station Name
6454100	NIOBRARA RIVER AT AGATE, NEBR.
6454500	NIOBRARA RIVER ABOVE BOX BUTTE RESERVOIR, NE
6455500	NIOBRARA RIVER BELOW BOX BUTTE RESERVOIR NEBR
6455900	NIOBRARA RIVER NEAR DUNLAP, NEBR.

Table 2. List of mapped canal segments along the study reach.

ReachCode	**Canal_System**
10150002000527	Unnamed Niobrara River Canals
10150002000451	Harris Neece Canal
10150002000167	Unnamed Niobrara River Canals
10150002000525	Unnamed Niobrara River Canals
10150002000437	Harris Neece Canal
10150002000509	Harris Neece Canal
10150002000160	Unnamed Niobrara River Canals
10150002003129	Unnamed Niobrara River Canals
10150002000506	Harris Neece Canal
10150002000528	Unnamed Niobrara River Canals
10150002000503	Harris Neece Canal
10150002000407	Unnamed Niobrara River Canals
10150002000510	Harris Neece Canal
10150002000169	Unnamed Niobrara River Canals
10150002000413	Unnamed Niobrara River Canals
10150002000168	Unnamed Niobrara River Canals
10150002000169	Unnamed Niobrara River Canals
10150002000504	Harris Neece Canal
10150002000529	Unnamed Niobrara River Canals
10150002000172	Unnamed Niobrara River Canals
10150002000524	????
10150002000167	Unnamed Niobrara River Canals
10150002003128	Unnamed Niobrara River Canals
10150002000451	Harris Neece Canal
10150002000419	Unnamed Niobrara River Canals
10150002000167	Unnamed Niobrara River Canals

10150002000526	Unnamed Niobrara River Canals
10150002000507	Harris Neece Canal
10150002000502	Harris Neece Canal
10150002000160	Unnamed Niobrara River Canals
10150002000172	Unnamed Niobrara River Canals
10150002000451	Harris Neece Canal
10150002000505	Harris Neece Canal
10150002000164	Sandoz Ditch
10150002000156	Harris Neece Canal
10150002000170	Unnamed Niobrara River Canals
10150002000164	Sandoz Ditch
10150002000166	Sandoz Ditch
10150002000158	Harris Neece Canal
10150002000421	Unnamed Niobrara River Canals
10150002000173	Unnamed Niobrara River Canals
10150002000167	Unnamed Niobrara River Canals
10150002000167	Unnamed Niobrara River Canals
10150002000165	Sandoz Ditch
10150002000171	Unnamed Niobrara River Canals
10150002000162	Mentlen Ditch
10150002000524	Mentlen Ditch

Table 3. Nebraska NeDNR stream gages in the study area.

Site ID	Station Name
135000	SNOW CANAL FROM NIOBRARA RIVER (RATING FLUME)
100000	MIRAGE FLATS CANAL FROM NIOBRARA RIVER (10-FOOT PARSHALL FLUME)
102000	MONTAGUE CANAL FROM NIOBRARA RIVER (RATING FLUME)
103000	MONTAGUE PUMP FROM NIOBRARA RIVER
104000	MOORE-KAY CANAL FROM NIOBRARA RIVER (RATING FLUME)
123000	PIONEER CANAL FROM NIOBRARA RIVER (RATING FLUME)
123500	PIONEER PUMP FROM NIOBRARA RIVER
124000	POTMESIL CANAL FROM NIOBRARA RIVER 3 FOOT (PARSHALL FLUME)
13000	BENNETT-KAY CANAL FROM NIOBRARA RIVER (RATING FLUME)
26000	CIRCLE PUMP FROM NIOBRARA RIVER
36000	DAVISON PUMP FROM NIOBRARA RIVER
37200	DELSING PUMP FROM NIOBRARA RIVER
4000	ARMSTRONG PUMP FROM NIOBRARA RIVER
45000	ENTERPRISE CANAL PUMP FROM NIOBRARA RIVER
46000	EXCELSIOR CANAL FROM NIOBRARA RIVER (RATING FLUME)
55000	FURMAN CANAL (COMBINED FLOW, NORTH & SOUTH) FROM NIOBRARA RIVER
55100	FURMAN CANAL (NORTH) FROM NIOBRARA RIVER
55200	FURMAN CANAL (SOUTH) FROM NIOBRARA RIVER
62000	HARRIS-NEECE CANAL FROM NIOBRARA RIVER (RATING FLUME)
63000	GEO HITSHEW CANAL FROM NIOBRARA RIVER (RATING FLUME)
64000	HITSHEW PUMP NO. 2 FROM NIOBRARA RIVER
65000	HOFFMAN PUMP FROM NIOBRARA RIVER
66000	HOMRIGHAUSEN PUMP FROM NIOBRARA RIVER
69000	HUGHES CANAL FROM NIOBRARA RIVER (RATING FLUME)
78000	LABELLE CANAL FROM NIOBRARA RIVER (RATING FLUME)
81000	LICHTE CANAL FROM NIOBRARA RIVER 3 FOOT (PARSHALL FLUME)
86000	MCLAUGHLIN CANAL FROM NIOBRARA RIVER (RATING FLUME)
89000	METTLEN CANAL FROM NIOBRARA RIVER (RATING FLUME)

Table 4. List of CSD Test Holes along the study reach showing the total measured depth of each hole.

LogID	Year	Long.	Lat.	Elev. (ft)	DTW (ft)	TD (ft)
27-B-77	1977	-103.7816853	42.39649033	4567	138	640
10-B-78	1978	-102.8712491	42.48901216	3907	Unknown	560
10-UNW-75	1975	-103.3083706	42.3946986	4293	120	320
11-B-78	1978	-102.8505243	42.52048194	3927	Unknown	680
11-UNW-75	1975	-103.3076228	42.35631105	4498	237	420
12-UNW-75	1975	-103.3046363	42.30542598	4502	186	400
17-B-77	1977	-103.7898709	42.44211772	4658	113	570
14-B-77	1977	-103.7769356	42.30656702	4772	188	360
15-B-77	1977	-103.7761303	42.35101132	4571	94	390
16-B-77	1977	-103.7762726	42.38800791	4671	219	490
18-B-77	1977	-103.7934738	42.48099813	4682	201	580
21-UNW-76	1976	-102.8703544	42.39893035	3950	15	300
1-B-78	1978	-103.3389925	42.46587564	4272	93	500
22-UNW-76	1976	-102.8707648	42.43811427	3929	83	200
23-UNW-76	1976	-102.8690993	42.3573265	3973	Unknown	420
2-B-78	1978	-103.2627396	42.52480434	4335	178	410
9-B-78	1978	-103.0670298	42.47926752	4175	160	450
6-UNW-75	1975	-103.0904983	42.3501496	4272	50	420
7-UNW-75	1975	-103.0721164	42.43730462	4053	81	220
8-B-78	1978	-103.0662588	42.52504386	4145	78	500
8-UNW-75	1975	-103.0900863	42.39352322	4229	139	460
9-UNW-75	1975	-103.3142075	42.44292755	4154	40	220

Table 5. List of registered wells examined in this study.

Well ID	Use ID	Acres	Pump Rate (gpm)	SWL (ft)	PWL (ft)	Lat.	Long.
49310	I	133	480	45	239	42.473612	-103.091717
114192	I	130	400	42	100	42.340171	-103.677801
199625	S	0	3	65	65	42.44055556	-103.41
178769	D	0	10	125	150	42.4675	-103.0505556
229046	Q	0	2	75	95	42.4853	-103.2340556
51298	I	140	1300	78	171	42.485984	-103.226403
137521	S	0	8	49	80	42.46899	-103.099691
240917	S	0	11	128	149	42.35719444	-103.4236389
97608	S	0	20	18	25	42.450708	-103.235564
229047	Q	0	2	72	90	42.47372222	-103.2280083
76744	I	176.1	900	115	174	42.48999432	-103.2125771
229048	Q	0	1	87	95	42.48123333	-103.2484278
140313	S	0	10	125	135	42.46972222	-103.3480556
115017	S	0	8	152	160	42.474392	-103.340999
68228	I	231.2	1700	123	210	42.34227778	-103.5176889
221797	Q	0	2	50	75	42.49548611	-103.2630333
78018	I	177	420	12	47	42.42179678	-103.4467911
158844	S	0	15	255	270	42.380458	-103.269894
142792	I	160	700	30	94	42.440511	-103.665542
224055	I	105.7	500	72	140	42.34722222	-103.6964722
240921	D	0	13	242	251	42.33486111	-103.4098889
197514	S	0	12	176	193	42.339726	-103.523337
105200	S	0	3	106	147	42.490274	-103.243036
29821	I	120	600	36	129	42.441472	-103.003665
113701	S	0	3	178	180	42.45475	-103.279742
38158	I	137	450	215	222	42.3325137	-103.373798
224341	I	122.44	800	90	90	42.35947222	-103.7504167
229043	Q	0	1	113	130	42.49742222	-103.2393806
107047	I	125	750	77	120	42.346057	-103.735383
46783	I	124.49	550	15	55	42.42765468	-103.4270521
65016	I	110	1207	10	65	42.457394	-102.978825
78288	I	130	700	72	134	42.34798	-103.750586
224496	I	122.4	700	82	160	42.35958333	-103.7511111
118707	S	0	10	150	160	42.496068	-103.265376
41876	I	172	675	35	145	42.470195	-103.146165
68323	I	142	500	21	65	42.41794746	-103.3916212
165356	S	0	10	50	65	42.39803333	-103.55185
186629	D	0	10	180	210	42.36888889	-103.6277778
145058	S	0	3	198	198	42.47055556	-103.3752778
146397	I	100	600	12	64	42.426928	-103.667734

107832	S	0	3	183	185	42.367594	-103.373707
49584	I	50	660	30	97	42.42903	-103.656211
229025	Q	0	10	35	50	42.45946389	-103.2299944
229006	Q	0	10	20	50	42.45995278	-103.2150028
192378	S	0	10	24	24	42.46638889	-103.1891667
120471	D	0	10	90	125	42.344045	-103.691368
194491	S	0	7	118	133	42.410852	-103.288498
88609	D	0	300	26	69	42.430814	-103.730713
160709	D	0	12	148	170	42.371908	-103.150077
51542	I	180	575	65	180	42.475612	-103.082417
97544	I	130	500	80	70	42.440853	-103.357401
239520	S	0	18	33	39	42.42936111	-103.6203889
176077	I	142	850	80	118	42.341648	-103.685201
197674	I	251.8	700	202	230	42.35977778	-103.2185833
229044	Q	0	15	113	138	42.49733611	-103.2393722
179528	S	0	12	201	228	42.45916667	-103.3916667
30999	I	634	860	85	110	42.354774	-103.430192
123384	I	200	850	8	54	42.452852	-103.233204
221803	Q	0	5	72	122	42.47373056	-103.227925
52400	I	90	448	10	100	42.438295	-103.644155
221795	Q	0	25	324	375	42.47364444	-103.2279222
206804	S	0	5	14	14	42.33527778	-103.6327778
29030	I	400	840	71	79	42.475693	-103.178485
68324	I	320	1253	165	244	42.36687	-103.162996
137883	D	0	10	125	160	42.46583333	-103.0527778
144690	S	0	10	260	260	42.35888889	-103.3761111
179502	D	0	15	105	135	42.42	-103.3819444
43959	I	68	200	28	80	42.464046	-103.130965
229024	Q	0	15	38	65	42.45956667	-103.2300111
172017	D	0	15	178	240	42.405035	-103.143773
78289	I	130	700	68	82	42.351624	-103.731033
52401	I	0	350	10	60	42.438787	-103.644448
44625	I	130	825	74	88	42.484927	-103.131576
217846	S	0	10	179	200	42.35222222	-103.5133333
147650	I	130	600	63	140	42.48011111	-103.1792222
3611	I	130	500	60	125	42.472124	-103.173543
239873	S	0	15	24	50	42.45583333	-102.9947222
43958	I	68	150	29	90	42.464866	-103.131341
97415	S	0	10	200	216	42.395044	-103.265484
68224	I	9.07	1600	92	150	42.34333611	-103.5021
219558	S	0	15	155	165	42.34583333	-103.7958333
196100	S	0	3	190	200	42.43638889	-103.4444444
137520	D	0	10	50	100	42.469711	-103.098216

123783	S	0	3	270	280	42.350402	-103.395669
213505	S	0	15	17.5	18	42.42722222	-103.46
221794	Q	0	25	360	412	42.48121667	-103.248525
95956	D	0	10	12	12	42.431755	-103.308813
46313	I	251	275	60	168	42.43322271	-103.3711521
191694	S	0	2	180	185	42.34333333	-103.8080556
137618	S	0	10	14	45	42.45777778	-103.2316667
147649	I	130	330	44	110	42.47380556	-103.16025
68225	I	265.99	1000	95	200	42.32808333	-103.5319167
96150	S	0	3	160	200	42.468821	-103.332557
221804	Q	0	5	50	100	42.46546667	-103.219825
99522	I	90	550	75	95	42.384735	-103.532941
76454	I	120	750	56	138	42.334928	-103.676662
94717	D	0	25	190	260	42.37545	-103.18947
112600	I	80	50	31	60	42.433139	-103.610796
224052	I	130	700	69	200	42.33722222	-103.6733056
191692	S	0	10	168	210	42.4525	-103.3552778
140520	S	0	3	92	92	42.40222222	-103.455
171837	S	0	4	62	62	42.3875	-103.5672222
208667	S	0	15	217	265	42.36675	-103.2767222
28005	I	90.41	620	9	90	42.41601348	-103.5265563
52402	I	416	700	17	85	42.438477	-103.650804
169314	I	130	800	80	180	42.35752778	-103.7597778
227236	S	0	20	135	160	42.38478333	-103.312
68226	I	265.99	1000	90	210	42.32969444	-103.5323611
146399	I	50	130	40	80	42.429714	-103.676805
52143	I	160	750	80	90	42.455091	-103.042507
120503	D	0	18	22	30	42.427831	-103.414342
147930	S	0	10	251	274	42.37444444	-103.3097222
68229	I	640	1700	105	210	42.34241111	-103.5296917
122877	D	0	13	201	220	42.410156	-103.124358
97129	S	0	3	150	180	42.467792	-103.043288
90424	S	0	20	42	60	42.457382	-103.218809
75854	I	89.2	1159	88	135	42.36008342	-103.6377594
72678	I	130	1253	12	48	42.457952	-102.966612
76743	I	135.8	1000	105	140	42.48652746	-103.1834015
115023	D	0	10	32	32	42.430037	-103.442096
40346	I	63	580	13	35	42.424158	-103.45167
188176	D	0	25	45	65	42.38702778	-103.5420833
45518	I	130	500	72	172	42.4735	-103.077495
200215	S	0	10	185	205	42.458611	-103.344728
106764	I	100	550	7	40	42.4372	-103.285702
70785	I	77	500	12	22	42.42418056	-103.5846222

68805	I	89.2	747	94	169	42.36008342	-103.6377594
221791	Q	0	25	44.3	54.8	42.49548056	-103.2613583
143018	S	0	10	137	150	42.33527778	-103.7563889
167390	S	0	10	150	180	42.45277778	-103.3641667
211691	S	0	5	92	117	42.44136667	-103.1661167
234442	I	106.6	300	48	171	42.46598889	-103.2602139
201753	D	0	10	168	200	42.47166667	-103.3447222
46314	I	251	275	58	134	42.43448591	-103.3850806
92372	S	0	20	154	180	42.406345	-103.308308
130690	S	0	10	44	90	42.414881	-103.416212
120512	S	0	4	52	58	42.430546	-103.47384
130645	S	0	10	6	40	42.419736	-103.512879
225130	D	0	10	225	285	42.33805556	-103.3061111
229045	Q	0	15	74	99	42.48533056	-103.2335889
71061	I	106.6	600	72	108	42.36234444	-103.4681
78287	I	130	700	72	106	42.348155	-103.735914
221798	Q	0	5	50	95	42.49558889	-103.2445361
178626	S	0	18	40	100	42.42611111	-103.4294444
157089	D	0	13	104	140	42.340118	-103.486371
68227	I	265.99	1000	92	210	42.33161111	-103.5317778
221802	Q	0	5	93	143	42.48041389	-103.2463639
48032	I	251	550	60	108	42.43648807	-103.3655919
137515	D	0	16	28	50	42.430299	-103.614717
132588	D	0	10	90	100	42.443292	-103.308409
68198	I	634	700	74	85	42.356495	-103.442357
146068	I	70	500	23	49	42.43471944	-103.5935306
58202	I	130	900	240	259	42.335576	-103.313859
78290	I	130	700	66	130	42.34975	-103.7239444
74584	I	130	800	216	239	42.341097	-103.292561
144621	I	125	750	59	140	42.38219444	-103.54725

APPENDIX 2 – Mapping unit descriptions of surface geology from 7.5 Minute Quadrangles (listed from west to east) of Figure 6

Whistle Creek Northwest 7.5 Minute Quadrangle

Qa1 - Youngest alluvium (Holocene) - [Map Key - Alluvium], Commonly sand and pebbly gravel, minor thin sandy silt beds: yellowish-gray and yellowish-orange; unit underlies the modern stream channels and floodplain. Sands are trough and planar bedded. Most clasts are derived from local bedrock. Commonly 1-4 m thick.

Qa3 - Older alluvium 1 (Pleistocene) - [Map Key - Alluvium], *Clays to cobble sized sediment deposited in modern and ancient stream channels and floodplains.*

Qac2 - Sandy alluvium and colluvium (Holocene and upper Pleistocene)- [Map Key - Alluvium], Sand and silt residuum and colluvium derived from the weathering of sandy siltstones and sandstones, primarily of the Arikaree and Ogallala groups; brown to yellowish-gray. Upland occurrences are primarily colluvium (locally derived gravels or conglomerates) and typically grades into alluvium. The unit includes the Tassel-Ashollow-Rock soil association. Commonly 2–15 m thick

<u>Qalc</u> – Unknown [Map Key - Alluvium]

Qr3 Sandy residuum (Pleistocene) [Map Key - Alluvium] *Residuum and soils derived from the weathering of sandy siltstones and sandstones of the White River and Arikaree groups and minor amounts (10-15%) of alluvial and colluvial silt and sand sediments.*

Naar – Unknown [Map Key - Arikaree]

Nah – Harrison Formation: [Map Key - Arikaree], This unit consists of brown and gray, fine to medium grained, massive or weakly bedded, often poorly indurated volcaniclastic sandstones having prominent, rhizolithic silcretes 2-10 m thick in its upper 75 m. Fine siliceous and calcareous rhizoliths, root molds, and voids suggesting subterranean insect galleries are common within the upper part. These beds are well exposed along the flank and top of the Pine Ridge Escarpment. The upper boundary is an abrupt contact with overlying yellowish or grayish brown fine grained sandstones of the Upper Harrison Formation. This contact is a regional unconformity overlying a widespread silcrete that weathers into a prominent, flat bench that can be traced across the region. Hunt's (1985) disconformable contact between this unit and the underlying Monroe Creek Formation was observed within Monroe Canyon [Warbonnet Buttes (Nebraska) 7.5'quadrangle], but no discernable lithologic change occurs at this disconformity and it could not be traced outside of the Monroe Canyon. In most areas no recognizable lithologic contact between this unit and the underlying Monroe Creek Formation was observed, in which case these units were combined (Nah/Nam) following Swinehart and others (1985). Alternately, the contact was placed at the base of the lowest rhizolithic silcrete, giving this unit an overall thickness of 75-95 m. Below this alternate contact the sandstones are gray or buff rather than brown and were assigned to the underlying Monroe Creek Formation. Daimonelix are present throughout the uppermost 75 m of this unit, and vertebrate fossils, while present as isolated occurrences or local concentrations (Hunt, 1985), were not observed during this study.

Nor – Unknown - [Map Key - Ogallala]

Whistle Creek Northeast 7.5 Minute Quadrangle

Qa1 Youngest alluvium (Holocene) - [Map Key - Alluvium], Commonly sand and pebbly gravel, minor thin sandy silt beds: yellowish-gray and yellowish-orange; unit underlies the modern stream channels and floodplain. Sands are trough and planar bedded. Most clasts are derived from local bedrock. Commonly 1-4 m thick.

Qa3 Older alluvium 1 (Pleistocene) - [Map Key - Alluvium], *Clays to cobble sized sediment deposited in modern and ancient stream channels and floodplains.*

Qac2 Sandy alluvium and colluvium (Holocene and upper Pleistocene) - [Map Key - Alluvium], Sand and silt residuum and colluvium derived from the weathering of sandy siltstones and sandstones, primarily of the Arikaree and Ogallala groups; brown to yellowish-gray. Upland occurrences are primarily colluvium (locally derived gravels or conglomerates) and typically grades into alluvium. The unit includes the Tassel-Ashollow-Rock soil association. Commonly 2–15 m thick

Qalc - Unknown- [Map Key - Alluvium]

Qr3 Sandy residuum (Pleistocene) - [Map Key - Alluvium], *Residuum and soils derived from the weathering of sandy siltstones and sandstones of the White River and Arikaree groups and minor amounts (10-15%) of alluvial and colluvial silt and sand sediments.*

Naar – Unknown [Map Key - Arikaree]

Nah – Harrison Formation: [Map Key - Arikaree], This unit consists of brown and gray, fine to medium grained, massive or weakly bedded, often poorly indurated volcaniclastic sandstones having prominent, rhizolithic silcretes 2-10 m thick in its upper 75 m. Fine siliceous and calcareous rhizoliths, root molds, and voids suggesting subterranean insect galleries are common within the upper part. These beds are well exposed along the flank and top of the Pine Ridge Escarpment. The upper boundary is an abrupt contact with overlying yellowish or grayish brown fine grained sandstones of the Upper Harrison Formation. This contact is a regional unconformity overlying a widespread silcrete that weathers into a prominent, flat bench that can be traced across the region. Hunt's (1985) disconformable contact between this unit and the underlying Monroe Creek Formation was observed within Monroe Canyon [Warbonnet Buttes (Nebraska) 7.5'quadrangle], but no discernable lithologic change occurs at this disconformity and it could not be traced outside the of Monroe Canyon. In most areas no recognizable lithologic contact between this unit and the underlying Monroe Creek Formation was observed, in which case these units were combined (Nah/Nam) following Swinehart and others (1985). Alternately, the contact was placed at the base of the lowest rhizolithic silcrete, giving this unit an overall thickness of 75-95 m. Below this alternate contact the sandstones are gray or buff rather than brown and were assigned to the underlying Monroe Creek Formation. Daimonelix are present throughout the uppermost 75 m of this unit, and vertebrate fossils, while present as isolated occurrences or local concentrations (Hunt, 1985), were not observed during this study.

Nor – Unknown [Map Key - Arikaree]

PEwbs Sharps Member (upper Oligocene) - [Map Key – White River], Sandy siltstone and silty sandstone; volcaniclastic, brown and yellowish-brown. Massive to weakly stratified. Carbonate-cemented nodular concretions, typically 5 to 15 cm in diameter, are locally abundant. A small group of exposures up to 12 m thick, in section 10, T 24N, R55W contain 3 m of trough cross-bedded fine- to medium sandstone overlain by 4 m of ripple-laminated fine sandstone. These beds appear to be the basal strata of a paleovalley deposit (informally named the Schomp Ranch Channel) eroded as much as 50 m into the Whitney Member. At least one very light gray, biotitic volcanic ash bed, up to 70 cm thick, occurs in this unit. Vertebrate fossils are uncommon; fragments of oreodont jaws and limbs were recovered during the mapping. Commonly 50 m thick.

Marsland Northwest 7.5 Minute Quadrangle

Qa1 Youngest alluvium (Holocene) - [Map Key - Alluvium], Commonly sand and pebbly gravel, minor thin sandy silt beds: yellowish-gray and yellowish-orange; unit underlies the modern stream channels and floodplain. Sands are trough and planar bedded. Most clasts are derived from local bedrock. Commonly 1-4 m thick.

Qa3 Older alluvium 1 (Pleistocene) - [Map Key - Alluvium], *Clays to cobble sized sediment deposited in modern and ancient stream channels and floodplains.*

Qa4 Older alluvium (lower Pleistocene) - [Map Key - Alluvium], Pebbly gravel and sand; pale orange and grayish orange; occurs 75 to 115 m above the North Platte River. Commonly 5-20 m thick

Qac2 Sandy alluvium and colluvium (Holocene and upper Pleistocene) - [Map Key - Alluvium], Sand and silt residuum and colluvium derived from the weathering of sandy siltstones and sandstones, primarily of the Arikaree and Ogallala groups; brown to yellowish-gray. Upland occurrences are primarily colluvium (locally derived gravels or conglomerates) and typically grades into alluvium. The unit includes the Tassel-Ashollow-Rock soil association. Commonly 2–15 m thick

Qalc – Unknown - [Map Key - Alluvium]

Qp Peat (Holocene) - [Map Key - Alluvium], *Fibrous organic matter, dark brown, deposited in wetlands.*

It is between 0.5 and 2 m thick.

Qr3 Sandy residuum (Pleistocene) - [Map Key - Alluvium], *Residuum and soils derived from the weathering of sandy siltstones and sandstones of the White River and Arikaree groups and minor amounts (10-15%) of alluvial and colluvial silt and sand sediments.*

Qr4 Clayey residuum (Pleistocene) - [Map Key - Alluvium], *Clay and silt residuum (including fragments of calcareous nodules) and soils derived from the Dawes Clay Member of the Box Butte Formation.*

Naar - Unknown [Map Key - Arikaree]

Nah – Harrison Formation: [Map Key - Arikaree], This unit consists of brown and gray, fine to medium grained, massive or weakly bedded, often poorly indurated volcaniclastic sandstones having prominent, rhizolithic silcretes 2-10 m thick in its upper 75 m. Fine siliceous and calcareous rhizoliths, root molds, and voids suggesting subterranean insect galleries are common within the upper part. These beds are well exposed along the flank and top of the Pine Ridge Escarpment. The upper boundary is an abrupt contact with overlying yellowish or grayish brown fine grained sandstones of the Upper Harrison Formation. This contact is a regional unconformity overlying a widespread silcrete that weathers into a prominent, flat bench that can be traced across the region. Hunt's (1985) disconformable contact between this unit and the underlying Monroe Creek Formation was observed within Monroe Canyon [Warbonnet Buttes (Nebraska) 7.5'quadrangle], but no discernable lithologic change occurs at this disconformity and it could not be traced outside of the Monroe Canyon. In most areas no recognizable lithologic contact between this unit and the underlying Monroe Creek Formation was observed, in which case these units were combined (Nah/Nam) following Swinehart and others (1985). Alternately, the contact was placed at the base of the lowest rhizolithic silcrete, giving this unit an overall thickness of 75-95 m. Below this alternate contact the sandstones are gray or buff rather than brown and were assigned to the underlying Monroe Creek Formation. Daimonelix are present throughout the uppermost 75 m of this unit, and vertebrate fossils, while present as isolated occurrences or local concentrations (Hunt, 1985), were not observed during this study.

Nobd - Unknown [Map Key - Ogallala]

Nor - Unknown [Map Key - Ogallala]

Nors – Unknown [Map Key - Ogallala]

Noss – Unknown [Map Key - Ogallala]

PEwbs Sharps Member (upper Oligocene) - [Map Key – White River], Sandy siltstone and silty sandstone; volcaniclastic, brown and yellowish-brown. Massive to weakly stratified. Carbonate-cemented nodular concretions, typically 5 to 15 cm in diameter, are locally abundant. A small group of exposures up to 12 m thick, in section 10, T 24N, R55W contain 3 m of trough cross-bedded fine- to medium sandstone overlain by 4 m of ripple-laminated fine sandstone. These beds appear to be the basal strata of a paleovalley deposit (informally named the Schomp Ranch Channel) eroded as much as 50 m into the Whitney Member. At least one very light gray, biotitic volcanic ash bed, up to 70 cm thick, occurs in this unit. Vertebrate fossils are uncommon; fragments of oreodont jaws and limbs were recovered during the mapping. Commonly 50 m thick.

PEwss – Unknown [Map Key – White River]

Marsland 7.5 Minute Quadrangle

Qa1 Youngest alluvium (Holocene) - [Map Key - Alluvium], Commonly sand and pebbly gravel, minor thin sandy silt beds: yellowish-gray and yellowish-orange; unit underlies the modern stream channels and floodplain. Sands are trough and planar bedded. Most clasts are derived from local bedrock. Commonly 1-4 m thick.

Qa2 Older alluvium (upper Pleistocene) - [Map Key - Alluvium], Pebbly gravel and sand and local beds of silt. Deposit underlies a terrace in the southwest corner of the quadrangle about 25-30 m above the North Platte River.

Qa3 Older alluvium 1 (Pleistocene) - [Map Key - Alluvium], *Clays to cobble sized sediment deposited in modern and ancient stream channels and floodplains.*

Qa4 Older alluvium (lower Pleistocene) - [Map Key - Alluvium], Pebbly gravel and sand; pale orange and grayish orange; occurs 75 to 115 m above the North Platte River. Commonly 5-20 m thick

Qac2 Sandy alluvium and colluvium (Holocene and upper Pleistocene) - [Map Key - Alluvium], Sand and silt residuum and colluvium derived from the weathering of sandy siltstones and sandstones, primarily of the Arikaree and Ogallala groups; brown to yellowish-gray. Upland occurrences are primarily colluvium (locally derived gravels or conglomerates) and typically grades into alluvium. The unit includes the Tassel-Ashollow-Rock soil association. Commonly 2–15 m thick

Qac4 – Unknown - [Map Key - Alluvium]

Qalc – Unknown - [Map Key - Alluvium]

Qr3 Sandy residuum (Pleistocene) - [Map Key - Alluvium], *Residuum and soils derived from the weathering of sandy siltstones and sandstones of the White River and Arikaree groups and minor amounts (10-15%) of alluvial and colluvial silt and sand sediments.*

Qr4 Clayey residuum (Pleistocene) - [Map Key - Alluvium], *Clay and silt residuum (including fragments of calcareous nodules) and soils derived from the Dawes Clay Member of the Box Butte Formation.*

Naar – Unknown [Map Key - Arikaree]

Nah – Harrison Formation: - [Map Key - Arikaree], This unit consists of brown and gray, fine to medium grained, massive or weakly bedded, often poorly indurated volcaniclastic sandstones having prominent, rhizolithic silcretes 2-10 m thick in its upper 75 m. Fine siliceous and calcareous rhizoliths, root molds, and voids suggesting subterranean insect galleries are common within the upper part. These beds are well exposed along the flank and top of the Pine Ridge Escarpment. The upper boundary is an abrupt contact with overlying yellowish or grayish brown fine grained sandstones of the Upper Harrison Formation. This contact is a regional unconformity overlying a widespread silcrete that weathers into a prominent, flat bench that can be traced across the region. Hunt's (1985) disconformable contact between this unit and the underlying Monroe Creek Formation was observed within Monroe Canyon [Warbonnet Buttes (Nebraska) 7.5'quadrangle], but no discernable lithologic change occurs at this disconformity and it could not be traced outside of the Monroe Canyon. In most areas no recognizable lithologic contact between this unit and the underlying Monroe Creek Formation was observed, in which case these units were combined (Nah/Nam) following Swinehart and others (1985). Alternately, the contact was placed at the base of the lowest rhizolithic silcrete, giving this unit an overall thickness of 75-95 m. Below this alternate contact the sandstones are gray or buff rather than brown and were assigned to the underlying Monroe Creek Formation. Daimonelix are present throughout the uppermost 75 m of this unit, and vertebrate fossils, while present as isolated occurrences or local concentrations (Hunt, 1985), were not observed during this study.

Nobd – Unknown [Map Key - Ogallala]

Nor – Unknown [Map Key - Ogallala]

Norr – Unknown [Map Key - Ogallala]

Noss – Unknown [Map Key - Ogallala]

PEwbs Sharps Member (upper Oligocene)- [Map Key – White River], Sandy siltstone and silty sandstone; volcaniclastic, brown and yellowish-brown. Massive to weakly stratified. Carbonate-cemented nodular concretions, typically 5 to 15 cm in diameter, are locally abundant. A small group of exposures up to 12 m thick, in section 10, T 24N, R55W contain 3 m of trough cross-bedded fine- to medium sandstone overlain by 4 m of ripple-laminated fine sandstone. These beds appear to be the basal strata of a paleovalley deposit (informally named the Schomp Ranch Channel) eroded as much as 50 m into the Whitney Member. At least one very light gray, biotitic volcanic ash bed, up to 70 cm thick, occurs in this unit. Vertebrate fossils are uncommon; fragments of oreodont jaws and limbs were recovered during the mapping. Commonly 50 m thick.

Box Butte Reservoir West 7.5 Minute Quadrangle

Qa1 Youngest alluvium (Holocene) - [Map Key - Alluvium], Commonly sand and pebbly gravel, minor thin sandy silt beds: yellowish-gray and yellowish-orange; unit underlies the modern stream channels and floodplain. Sands are trough and planar bedded. Most clasts are derived from local bedrock. Commonly 1-4 m thick.

Qa3 Older alluvium 1 (Pleistocene) - [Map Key - Alluvium], *Clays to cobble sized sediment deposited in modern and ancient stream channels and floodplains.*

Qa4 Older alluvium (lower Pleistocene) - [Map Key - Alluvium], Pebbly gravel and sand; pale orange and grayish orange; occurs 75 to 115 m above the North Platte River. Commonly 5-20 m thick

Qac2 Sandy alluvium and colluvium (Holocene and upper Pleistocene) - [Map Key - Alluvium], Sand and silt residuum and colluvium derived from the weathering of sandy siltstones and sandstones, primarily of the Arikaree and Ogallala groups; brown to yellowish-gray. Upland occurrences are primarily colluvium (locally derived gravels or conglomerates) and typically grades into alluvium. The unit includes the Tassel-Ashollow-Rock soil association. Commonly 2–15 m thick

Qac4 – Unknown [Map Key - Alluvium]

Qalc – Unknown [Map Key - Alluvium]

Qr3 Sandy residuum (Pleistocene) - [Map Key - Alluvium], *Residuum and soils derived from the weathering of sandy siltstones and sandstones of the White River and Arikaree groups and minor amounts (10-15%) of alluvial and colluvial silt and sand sediments.*

Qr4 Clayey residuum (Pleistocene) - [Map Key - Alluvium], *Clay and silt residuum (including fragments of calcareous nodules) and soils derived from the Dawes Clay Member of the Box Butte Formation.*

Nob – Unknown [Map Key - Ogallala]

Nobd – Unknown [Map Key - Ogallala]

Nor – Unknown [Map Key - Ogallala]

Box Butte Reservoir East 7.5 Minute Quadrangle

Qa1 Youngest alluvium (Holocene) - [Map Key - Alluvium], Commonly sand and pebbly gravel, minor thin sandy silt beds: yellowish-gray and yellowish-orange; unit underlies the modern stream channels and floodplain. Sands are trough and planar bedded. Most clasts are derived from local bedrock. Commonly 1-4 m thick.

Qa3 Older alluvium 1 (Pleistocene) - [Map Key - Alluvium], *Clays to cobble sized sediment deposited in modern and ancient stream channels and floodplains.*

Qa4 Older alluvium (lower Pleistocene) - [Map Key - Alluvium], Pebbly gravel and sand; pale orange and grayish orange; occurs 75 to 115 m above the North Platte River. Commonly 5-20 m thick

Qac2 Sandy alluvium and colluvium (Holocene and upper Pleistocene) - [Map Key - Alluvium], Sand and silt residuum and colluvium derived from the weathering of sandy siltstones and sandstones, primarily of the Arikaree and Ogallala groups; brown to yellowish-gray. Upland occurrences are primarily colluvium (locally derived gravels or conglomerates) and typically grades into alluvium. The unit includes the Tassel-Ashollow-Rock soil association. Commonly 2–15 m thick

Qac4 – Unknown [Map Key - Alluvium]

Qalc – Unknown [Map Key - Alluvium]

Qr3 Sandy residuum (Pleistocene) - [Map Key - Alluvium], *Residuum and soils derived from the weathering of sandy siltstones and sandstones of the White River and Arikaree groups and minor amounts (10-15%) of alluvial and colluvial silt and sand sediments.*

Qr4 Clayey residuum (Pleistocene) - [Map Key - Alluvium], *Clay and silt residuum (including fragments of calcareous nodules) and soils derived from the Dawes Clay Member of the Box Butte Formation.*

Nmr Runningwater Formation (Miocene) - [Map Key - Ogallala], *Medium-to fine-grained sandstones, coarse sands, sandy siltstones, and gravels, and locally occurring clayey silts and volcanic ash beds; gray, greenish-gray, and brown.*

The gravels contain abundant Rocky Mountain-source clasts. Calcareous-cemented zones from 0.2 to 1.5 m thick are locally common. The unit occurs in a generally eastward trending paleovalley and is up to 100 m thick.

Noar – Unknown [Map Key - Ogallala]

Nobd – Unknown [Map Key - Ogallala]

Nor – Unknown [Map Key - Ogallala]

Noss – Unknown [Map Key - Ogallala]

Nowc Wolf Creek beds - [Map Key - Ogallala], *White, calcareous, medium to coarse-grained sandstones.*

Generally medium-bedded to massive, contains may calcareous root traces and nodules of various morphologies. Contains a prominent silver-gray volcanic ash 0.5-1 m thick near top; used to correlate exposures from Belmont to Observation Quarry (Barstovian) to Whiteclay vicinity to Porcupine Butte, S. D. Formerly considered Ash Hollow by Skinner & Johnson (1984) and Skinner & others (1988).

Box Butte Northwest 7.5 Minute Quadrangle

Qa1 Youngest alluvium (Holocene) - [Map Key - Alluvium], Commonly sand and pebbly gravel, minor thin sandy silt beds: yellowish-gray and yellowish-orange; unit underlies the modern stream channels and floodplain. Sands are trough and planar bedded. Most clasts are derived from local bedrock. Commonly 1-4 m thick.

Qa3   Older alluvium 1 (Pleistocene) - [Map Key - Alluvium], *Clays to cobble sized sediment deposited in modern and ancient stream channels and floodplains.*

Qa4 Older alluvium (lower Pleistocene) - [Map Key - Alluvium], Pebbly gravel and sand; pale orange and grayish orange; occurs 75 to 115 m above the North Platte River. Commonly 5-20 m thick

Qa5 Older alluvium (lower Pleistocene) - [Map Key - Alluvium], Pebbly to cobble gravel and sand; pale orange; occurs 105 to 140 m above the North Platte River and may represent the remnants of an alluvial apron eroded from the Broadwater Formation. Commonly 5-15 m thick

Qac1 Undifferentiated silty alluvium and colluvium (Pleistocene) - [Map Key - Alluvium], *Silt and clay derived from the weathering of clayey siltstones and silty claystones of the white River Group.*

Qac2   Sandy alluvium and colluvium (Holocene and upper Pleistocene) - [Map Key - Alluvium], Sand and silt residuum and colluvium derived from the weathering of sandy siltstones and sandstones, primarily of the Arikaree and Ogallala groups; brown to yellowish-gray. Upland occurrences are primarily colluvium (locally derived gravels or conglomerates) and typically grades into alluvium. The unit includes the Tassel-Ashollow-Rock soil association. Commonly 2–15 m thick

Qalc – Unknown [Map Key - Alluvium]

Qes2   Eolian sand Quaternary undifferentiated - [Map Key - Alluvium], *Very fine to medium sand deposited by the wind into sand dunes or sand sheets.* The sand dunes are typically transverse dunes with southeast facing slip faces and are up to 70 m thick. The sand sheets have no recognizable dune forms and are between 1 and 5 m thick.

Qr3 Sandy residuum (Pleistocene) - [Map Key - Alluvium], *Residuum and soils derived from the weathering of sandy siltstones and sandstones of the White River and Arikaree groups and minor amounts (10-15%) of alluvial and colluvial silt and sand sediments.*

Qt1 Unknown [Map Key - Alluvium]

Qt2 Unknown [Map Key - Alluvium]

Nmr Runningwater Formation (Miocene) - [Map Key - Ogallala], *Medium-to fine-grained sandstones, coarse sands, sandy siltstones, and gravels, and locally occurring clayey silts and volcanic ash beds; gray, greenish-gray, and brown.*

The gravels contain abundant Rocky Mountain-source clasts. Calcareous-cemented zones from 0.2 to 1.5 m thick are locally common. The unit occurs in a generally eastward trending paleovalley and is up to 100 m thick.

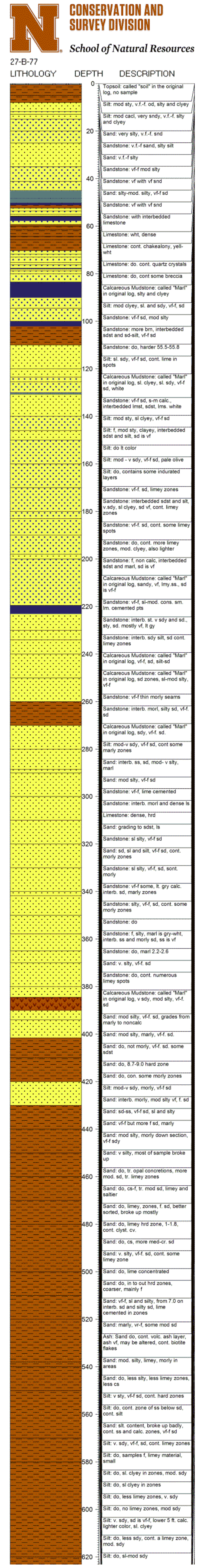
Nmr2 – Unknown [Map Key - Ogallala]

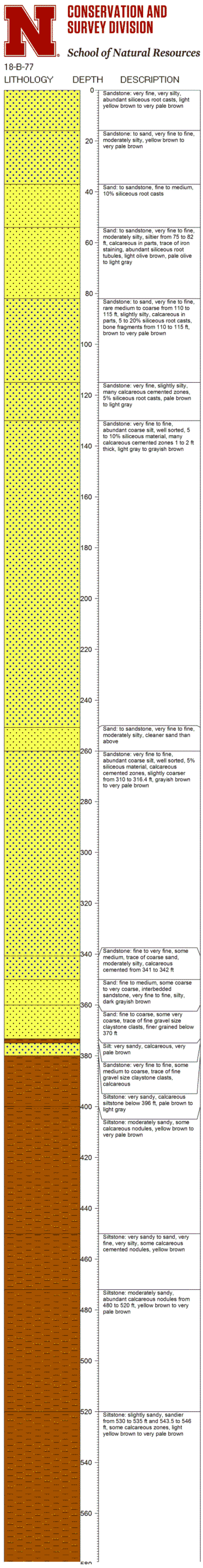
Nor1 - Starvation Gulch beds - [Map Key - Ogallala], Consists of up to 25 m of medium to thickly bedded orange-brown overbank sandstone and pedogenic carbonate horizons of early Miocene age. Occurs as large valley fill along Niobrara River Valley and under the Hartville table. Contains abundant vertebrate fossils.

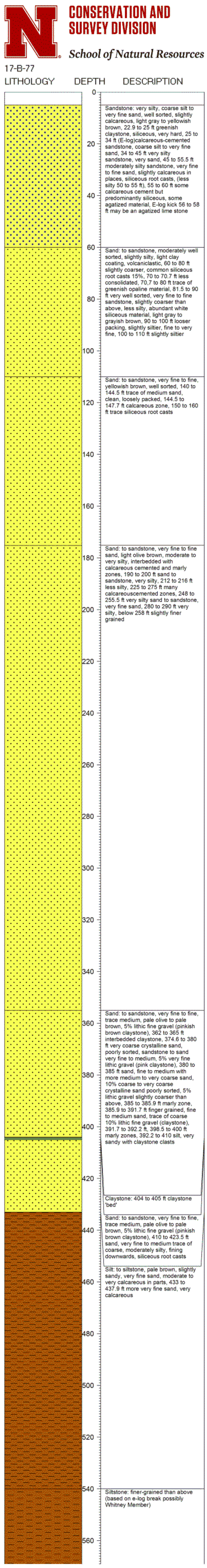
Nor2 - Rushville beds - [Map Key - Ogallala], Consists of up to 50 m of intermixed and interbedded olive sandstone and gravel of early Miocene age. Occurs as large valley fill along Niobrara River and under the Hartville table. Contains abundant vertebrate fossils.

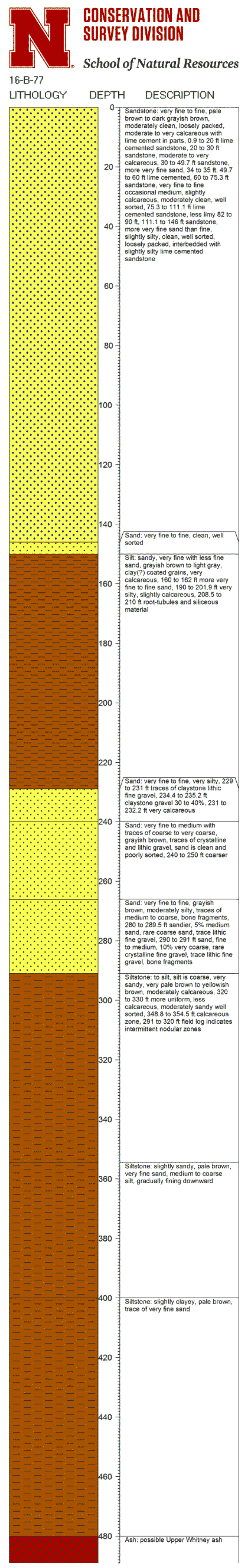
Nosg - Sand Canyon beds of Galusha - [Map Key - Ogallala], Consists of up to 5 m olive green fluvial sandstone and gravel with a prominent calcareous paleosol of early Miocene age. Occurs as broad sheets of sediment along the Niobrara River, as isolated valley fills along the Pine Ridge, and the interbedded hard grey sandstones hold up conical hills along the highest points of the Pine Ridge.

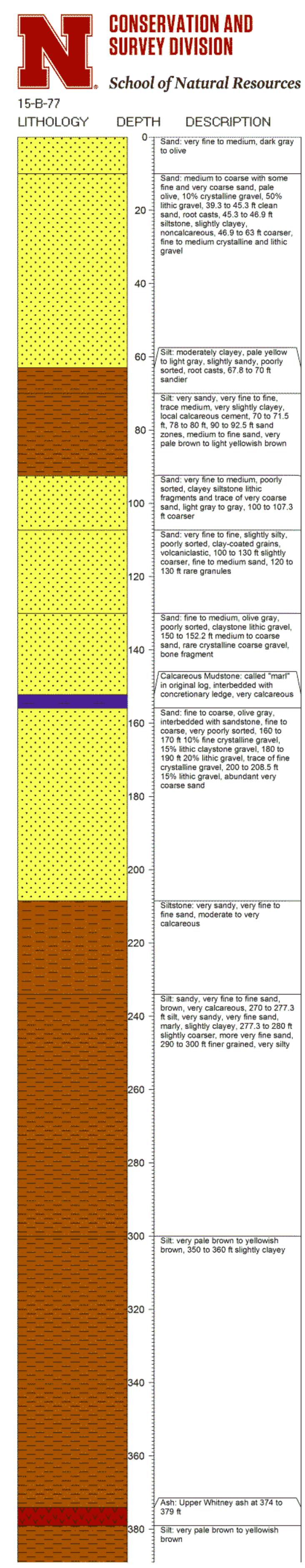
APPENDIX 3 – Test holes and other logs used for the study

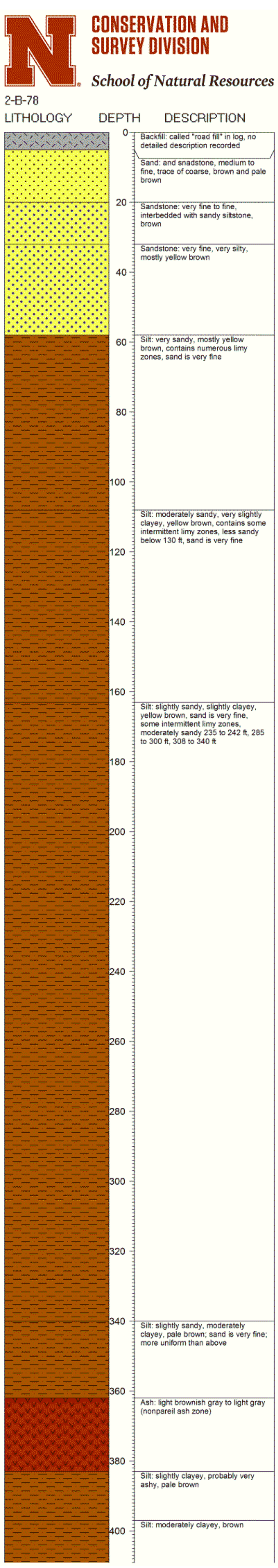


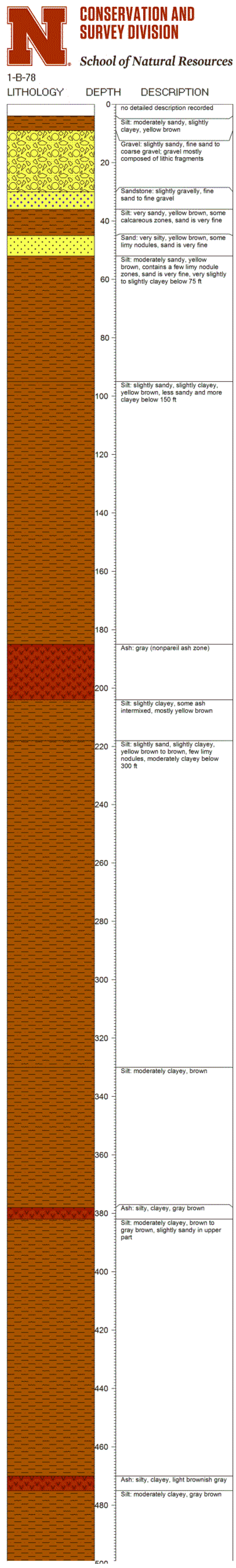


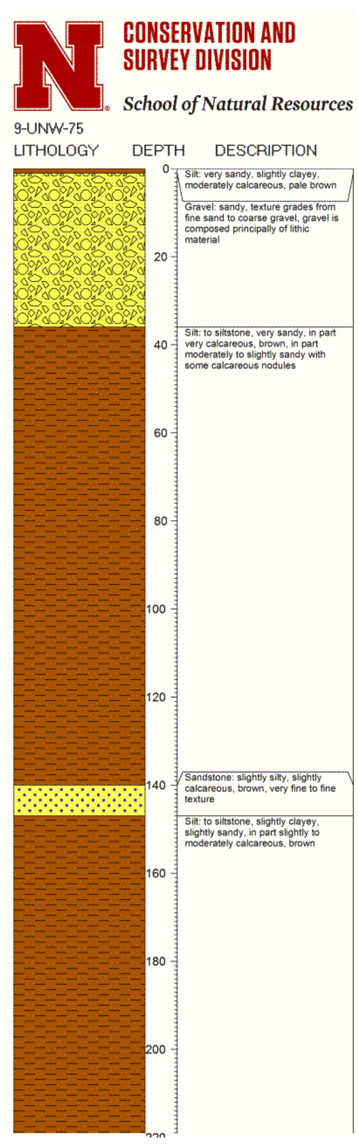


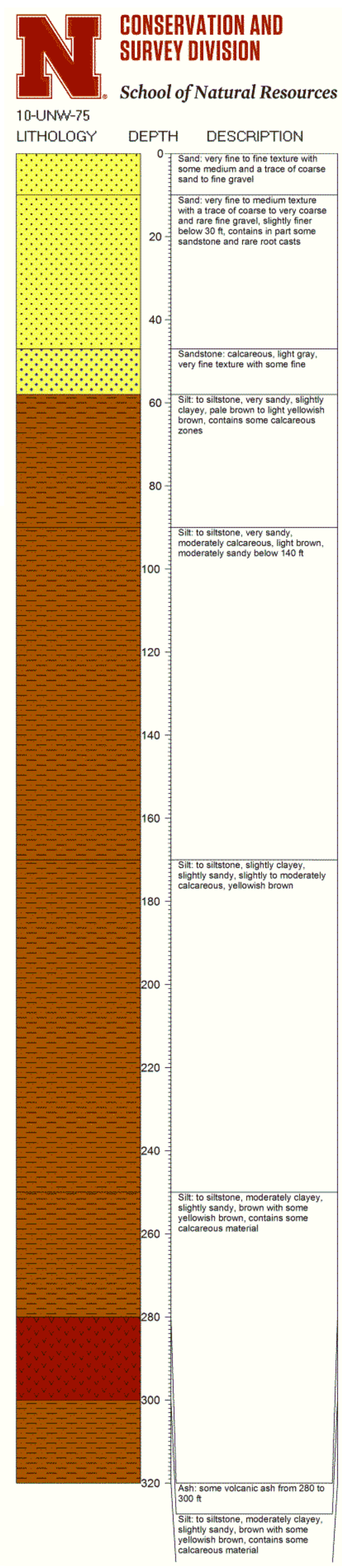


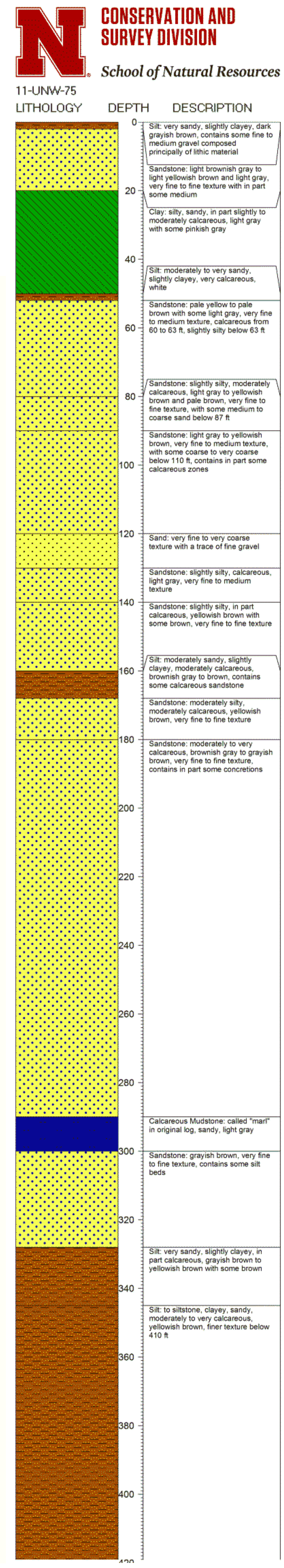


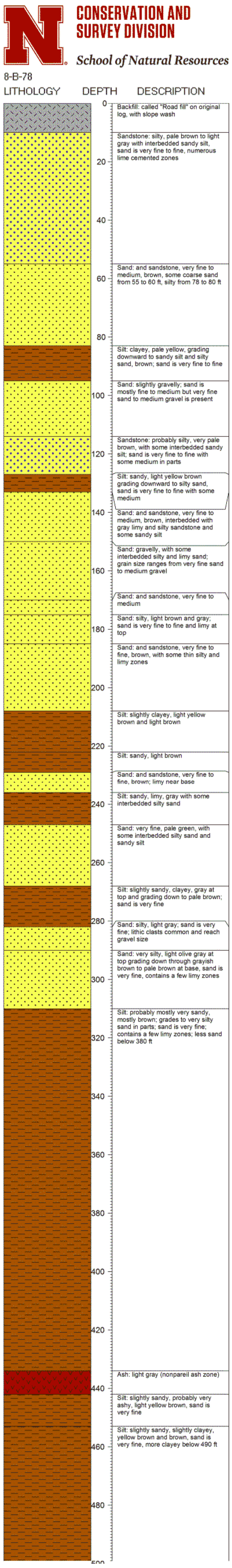

CONSERVATION AND SURVEY DIVISION
School of Natural Resources
2-B-78
LITHOLOGY
DEPTH
DESCRIPTION
Backfill: called "road fill" in log, no detailed description recorded
Sand: and snadstone, medium to fine, trace of coarse, brown and pale brown
Sandstone: very fine to fine, interbedded with sandy siltstone, brown
Sandstone: very fine, very silty, mostly yellow brown
Silt: very sandy, mostly yellow brown, contains numerous limy zones, sand is very fine
Silt: moderately sandy, very slightly clayey, yellow brown, contains some intermittent limy zones, less sandy below 130 ft, sand is very fine
Silt: slightly sandy, slightly clayey, yellow brown, sand is very fine, some intermittent limy zones, moderately sandy 235 to 242 ft, 285 to 300 ft, 308 to 340 ft
Silt: slightly sandy, moderately clayey, pale brown; sand is very fine; more uniform than above
Ash: light brownish gray to light gray (nonpareil ash zone)
Silt: slightly clayey, probably very ashy, pale brown
Silt: moderately clayey, brown

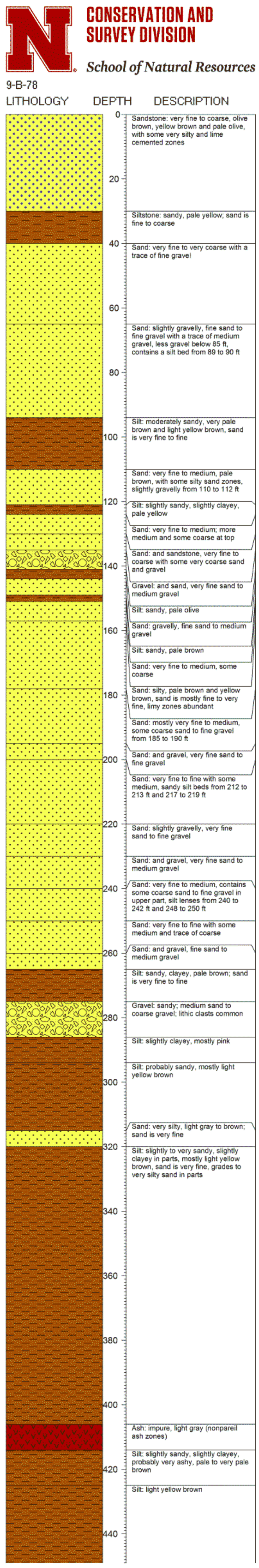

CONSERVATION AND SURVEY DIVISION
School of Natural Resources
1-B-78
LITHOLOGY
DEPTH
DESCRIPTION
no detailed description recorded
Silt: moderately sandy, slightly clayey, yellow brown
Gravel: slightly sandy, fine sand to coarse gravel; gravel mostly composed of lithic fragments
Sandstone: slightly gravelly, fine sand to fine gravel
Silt: very sandy, yellow brown, some calcareous zones, sand is very fine
Sand: very silty, yellow brown, some limy nodules, sand is very fine
Silt: moderately sandy, yellow brown, contains a few limy nodule zones, sand is very fine, very slightly to slightly clayey below 75 ft
Silt: slightly sandy, slightly clayey, yellow brown, less sandy and more clayey below 150 ft
Ash: gray (nonpareil ash zone)
Silt: slightly clayey, some ash intermixed, mostly yellow brown
Silt: slightly sand, slightly clayey, yellow brown to brown, few limy nodules, moderately clayey below 300 ft
Silt: moderately clayey, brown
Ash: silty, clayey, gray brown
Silt: moderately clayey, brown to gray brown, slightly sandy in upper part
Ash: silty, clayey, light brownish gray
Silt: moderately clayey, gray brown

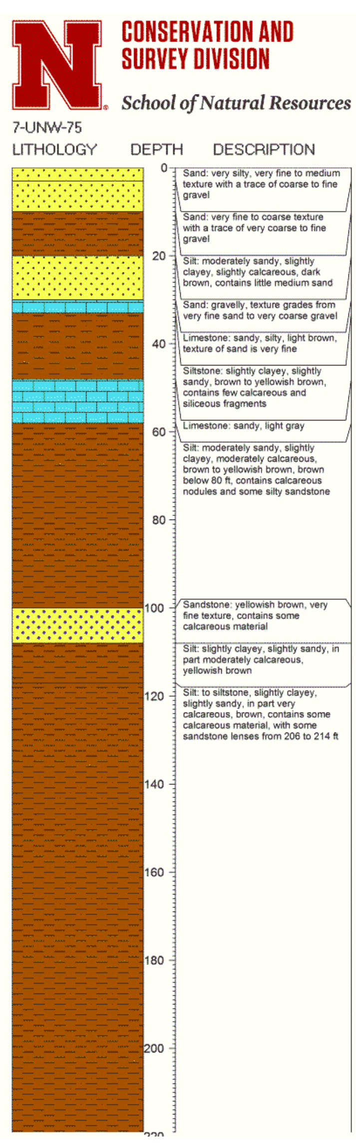

CONSERVATION AND SURVEY DIVISION
School of Natural Resources
9-UNW-75
LITHOLOGY
DEPTH
DESCRIPTION
Silt: very sandy, slightly clayey, moderately calcareous, pale brown
Gravel: sandy, texture grades from fine sand to coarse gravel, gravel is composed principally of lithic material
Silt: to siltstone, very sandy, in part very calcareous, brown, in part moderately to slightly sandy with some calcareous nodules
Sandstone: slightly silty, slightly calcareous, brown, very fine to fine texture
Silt: to siltstone, slightly clayey, slightly sandy, in part slightly to moderately calcareous, brown

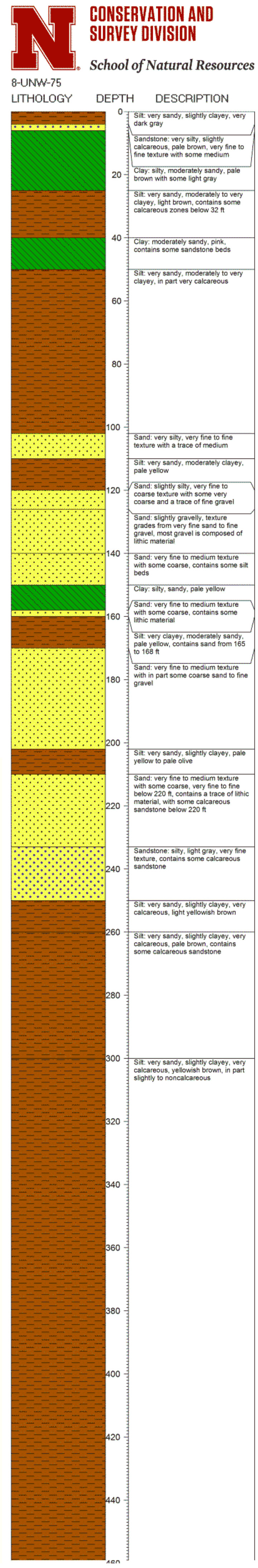

CONSERVATION AND SURVEY DIVISION
School of Natural Resources
10-UNW-75
LITHOLOGY
DEPTH
DESCRIPTION
Sand: very fine to fine texture with some medium and a trace of coarse sand to fine gravel
Sand: very fine to medium texture with a trace of coarse to very coarse and rare fine gravel, slightly finer below 30 ft, contains in part some sandstone and rare root casts
Sandstone: calcareous, light gray, very fine texture with some fine
Silt: to siltstone, very sandy, slightly clayey, pale brown to light yellowish brown, contains some calcareous zones
Silt: to siltstone, very sandy, moderately calcareous, light brown, moderately sandy below 140 ft
Silt: to siltstone, slightly clayey, slightly sandy, slightly to moderately calcareous, yellowish brown
Silt: to siltstone, moderately clayey, slightly sandy, brown with some yellowish brown, contains some calcareous material
Ash: some volcanic ash from 280 to 300 ft
Silt: to siltstone, moderately clayey, slightly sandy, brown with some yellowish brown, contains some calcareous material

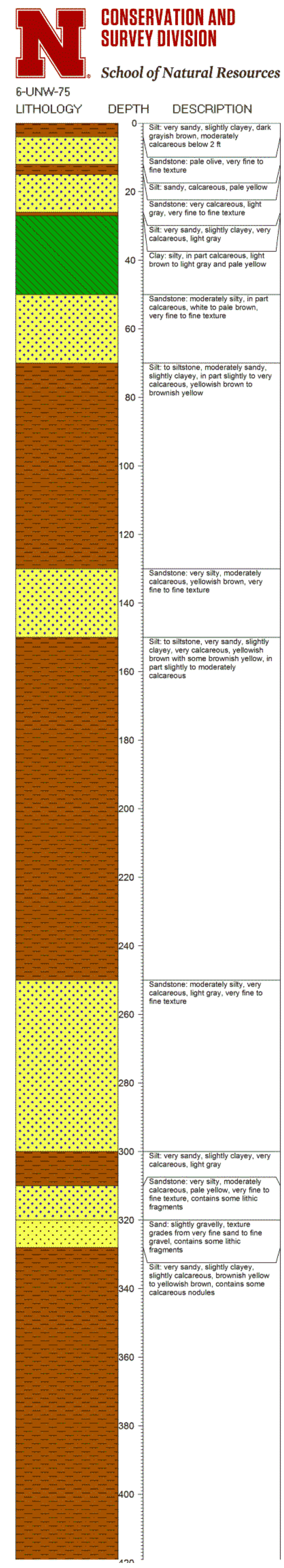

CONSERVATION AND SURVEY DIVISION
School of Natural Resources
11-UNW-75
LITHOLOGY
DEPTH
DESCRIPTION
Silt: very sandy, slightly clayey, dark grayish brown, contains some fine to medium gravel composed principally of lithic material
Sandstone: light brownish gray to light yellowish brown and light gray, very fine to fine texture with in part some medium
Clay: silty, sandy, in part slightly to moderately calcareous, light gray with some pinkish gray
Silt: moderately to very sandy, slightly clayey, very calcareous, white
Sandstone: pale yellow to pale brown with some light gray, very fine to medium texture, calcareous from 60 to 63 ft, slightly silty below 63 ft
Sandstone: slightly silty, moderately calcareous, light gray to yellowish brown and pale brown, very fine to fine texture, with some medium to coarse sand below 87 ft
Sandstone: light gray to yellowish brown, very fine to medium texture, with some coarse to very coarse below 110 ft, contains in part some calcareous zones
Sand: very fine to very coarse texture with a trace of fine gravel
Sandstone: slightly silty, calcareous, light gray, very fine to medium texture
Sandstone: slightly silty, in part calcareous, yellowish brown with some brown, very fine to fine texture
Silt: moderately sandy, slightly clayey, moderately calcareous, brownish gray to brown, contains some calcareous sandstone
Sandstone: moderately silty, moderately calcareous, yellowish brown, very fine to fine texture
Sandstone: moderately to very calcareous, brownish gray to grayish brown, very fine to fine texture, contains in part some concretions
Calcareous Mudstone: called "marl" in original log, sandy, light gray
Sandstone: grayish brown, very fine to fine texture, contains some silt beds
Silt: very sandy, slightly clayey, in part calcareous, grayish brown to yellowish brown with some brown
Silt: to siltstone, clayey, sandy, moderately to very calcareous, yellowish brown, finer texture below 410 ft

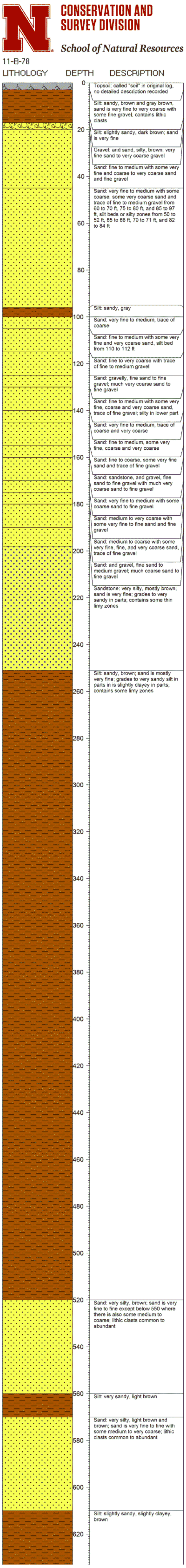

CONSERVATION AND SURVEY DIVISION
School of Natural Resources
8-B-78
LITHOLOGY DEPTH DESCRIPTION
Backfill: called "Road fill" on original log, with slope wash
Sandstone: silty, pale brown to light gray with interbedded sandy silt, sand is very fine to fine, numerous lime cemented zones
Sand: and sandstone, very fine to medium, brown, some coarse sand from 55 to 60 ft, silty from 78 to 80 ft
Silt: clayey, pale yellow, grading downward to sandy silt and silty sand, brown; sand is very fine to fine
Sand: slightly gravelly; sand is mostly fine to medium but very fine sand to medium gravel is present
Sandstone: probably silty, very pale brown, with some interbedded sandy silt; sand is very fine to fine with some medium in parts
Silt: sandy, light yellow brown grading downward to silty sand, sand is very fine to fine with some medium
Sand: and sandstone, very fine to medium, brown, interbedded with gray limy and silty sandstone and some sandy silt
Sand: gravelly, with some interbedded silty and limy sand; grain size ranges from very fine sand to medium gravel
Sand: and sandstone, very fine to medium
Sand: silty, light brown and gray; sand is very fine to fine and limy at top
Sand: and sandstone, very fine to fine, brown, with some thin silty and limy zones
Silt: slightly clayey, light yellow brown and light brown
Silt: sandy, light brown
Sand: and sandstone, very fine to fine, brown; limy near base
Silt: sandy, limy, gray with some interbedded silty sand
Sand: very fine, pale green, with some interbedded silty sand and sandy silt
Silt: slightly sandy, clayey, gray at top and grading down to pale brown; sand is very fine
Sand: silty, light gray; sand is very fine; lithic clasts common and reach gravel size
Sand: very silty, light olive gray at top grading down through grayish brown to pale brown at base, sand is very fine, contains a few limy zones
Silt: probably mostly very sandy, mostly brown; grades to very silty sand in parts; sand is very fine; contains a few limy zones; less sand below 380 ft
Ash: light gray (nonpareil ash zone)
Silt: slightly sandy, probably very ashy, light yellow brown, sand is very fine
Silt: slightly sandy, slightly clayey, yellow brown and brown, sand is very fine, more clayey below 490 ft

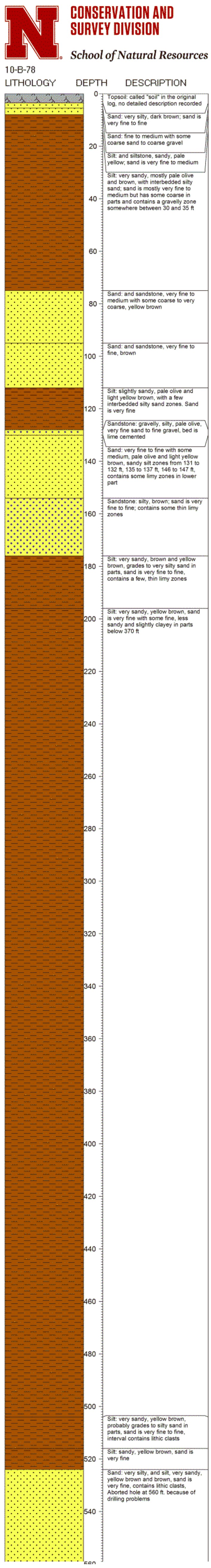

CONSERVATION AND SURVEY DIVISION
School of Natural Resources
9-B-78
LITHOLOGY DEPTH DESCRIPTION
Sandstone: very fine to coarse, olive brown, yellow brown and pale olive, with some very silty and lime cemented zones
Siltstone: sandy, pale yellow; sand is fine to coarse
Sand: very fine to very coarse with a trace of fine gravel
Sand: slightly gravelly, fine sand to fine gravel with a trace of medium gravel, less gravel below 85 ft, contains a silt bed from 89 to 90 ft
Silt: moderately sandy, very pale brown and light yellow brown, sand is very fine to fine
Sand: very fine to medium, pale brown, with some silty sand zones, slightly gravelly from 110 to 112 ft
Silt: slightly sandy, slightly clayey, pale yellow
Sand: very fine to medium; more medium and some coarse at top
Sand: and sandstone, very fine to coarse with some very coarse sand and gravel
Gravel: and sand, very fine sand to medium gravel
Silt: sandy, pale olive
Sand: gravelly, fine sand to medium gravel
Silt: sandy, pale brown
Sand: very fine to medium, some coarse
Sand: silty, pale brown and yellow brown, sand is mostly fine to very fine, limy zones abundant
Sand: mostly very fine to medium, some coarse sand to fine gravel from 185 to 190 ft
Sand: and gravel, very fine sand to fine gravel
Sand: very fine to fine with some medium, sandy silt beds from 212 to 213 ft and 217 to 219 ft
Sand: slightly gravelly, very fine sand to fine gravel
Sand: and gravel, very fine sand to medium gravel
Sand: very fine to medium, contains some coarse sand to fine gravel in upper part, silt lenses from 240 to 242 ft and 248 to 250 ft
Sand: very fine to fine with some medium and trace of coarse
Sand: and gravel, fine sand to medium gravel
Silt: sandy, clayey, pale brown; sand is very fine to fine
Gravel: sandy; medium sand to coarse gravel; lithic clasts common
Silt: slightly clayey, mostly pink
Silt: probably sandy, mostly light yellow brown
Sand: very silty, light gray to brown; sand is very fine
Silt: slightly to very sandy, slightly clayey in parts, mostly light yellow brown, sand is very fine, grades to very silty sand in parts
Ash: impure, light gray (nonpareil ash zones)
Silt: slightly sandy, slightly clayey, probably very ashy, pale to very pale brown
Silt: light yellow brown

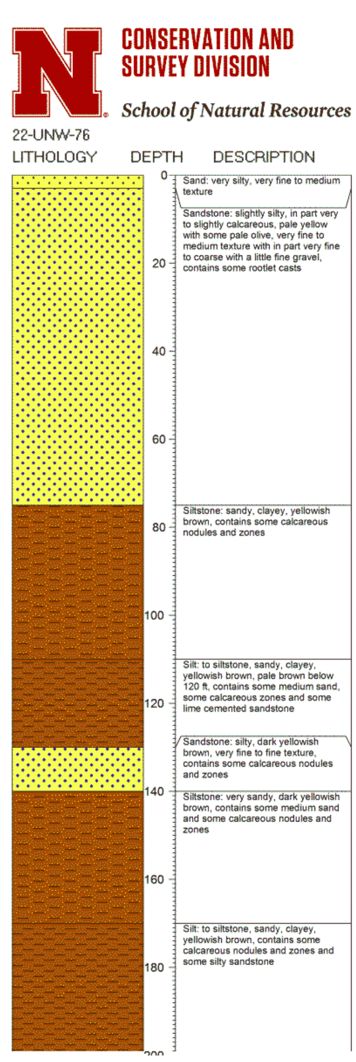

CONSERVATION AND SURVEY DIVISION
School of Natural Resources
7-UNW-75
LITHOLOGY DEPTH DESCRIPTION
Sand: very silty, very fine to medium texture with a trace of coarse to fine gravel
Sand: very fine to coarse texture with a trace of very coarse to fine gravel
Silt: moderately sandy, slightly clayey, slightly calcareous, dark brown, contains little medium sand
Sand: gravelly, texture grades from very fine sand to very coarse gravel
Limestone: sandy, silty, light brown, texture of sand is very fine
Siltstone: slightly clayey, slightly sandy, brown to yellowish brown, contains few calcareous and siliceous fragments
Limestone: sandy, light gray
Silt: moderately sandy, slightly clayey, moderately calcareous, brown to yellowish brown, brown below 80 ft, contains calcareous nodules and some silty sandstone
Sandstone: yellowish brown, very fine texture, contains some calcareous material
Silt: slightly clayey, slightly sandy, in part moderately calcareous, yellowish brown
Silt: to siltstone, slightly clayey, slightly sandy, in part very calcareous, brown, contains some calcareous material, with some sandstone lenses from 206 to 214 ft

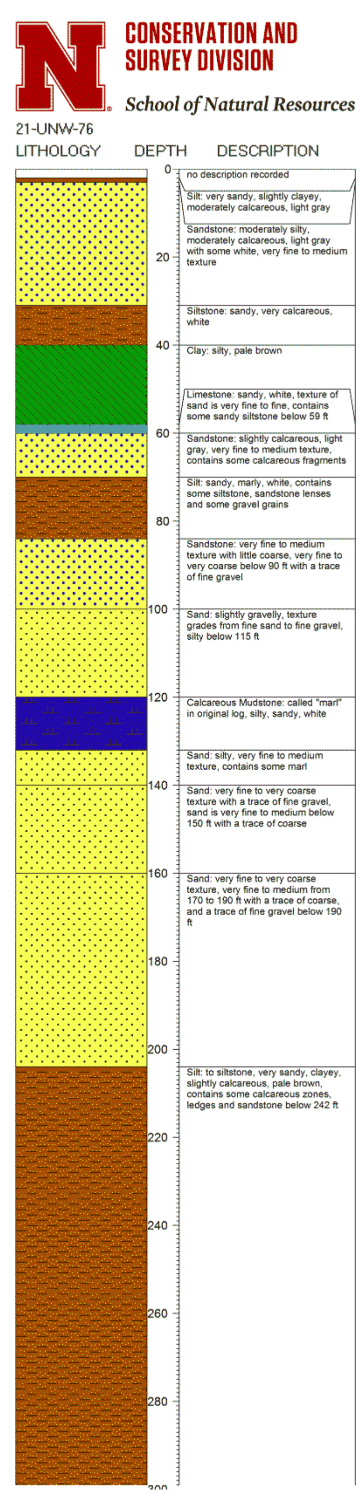

CONSERVATION AND SURVEY DIVISION
School of Natural Resources
8-UNW-75
LITHOLOGY DEPTH DESCRIPTION
Silt: very sandy, slightly clayey, very dark gray
Sandstone: very silty, slightly calcareous, pale brown, very fine to fine texture with some medium
Clay: silty, moderately sandy, pale brown with some light gray
Silt: very sandy, moderately to very clayey, light brown, contains some calcareous zones below 32 ft
Clay: moderately sandy, pink, contains some sandstone beds
Silt: very sandy, moderately to very clayey, in part very calcareous
Sand: very silty, very fine to fine texture with a trace of medium
Silt: very sandy, moderately clayey, pale yellow
Sand: slightly silty, very fine to coarse texture with some very coarse and a trace of fine gravel
Sand: slightly gravelly, texture grades from very fine sand to fine gravel, most gravel is composed of lithic material
Sand: very fine to medium texture with some coarse, contains some silt beds
Clay: silty, sandy, pale yellow
Sand: very fine to medium texture with some coarse, contains some lithic material
Silt: very clayey, moderately sandy, pale yellow, contains sand from 165 to 168 ft
Sand: very fine to medium texture with in part some coarse sand to fine gravel
Silt: very sandy, slightly clayey, pale yellow to pale olive
Sand: very fine to medium texture with some coarse, very fine to fine below 220 ft, contains a trace of lithic material, with some calcareous sandstone below 220 ft
Sandstone: silty, light gray, very fine texture, contains some calcareous sandstone
Silt: very sandy, slightly clayey, very calcareous, light yellowish brown
Silt: very sandy, slightly clayey, very calcareous, pale brown, contains some calcareous sandstone
Silt: very sandy, slightly clayey, very calcareous, yellowish brown, in part slightly to noncalcareous

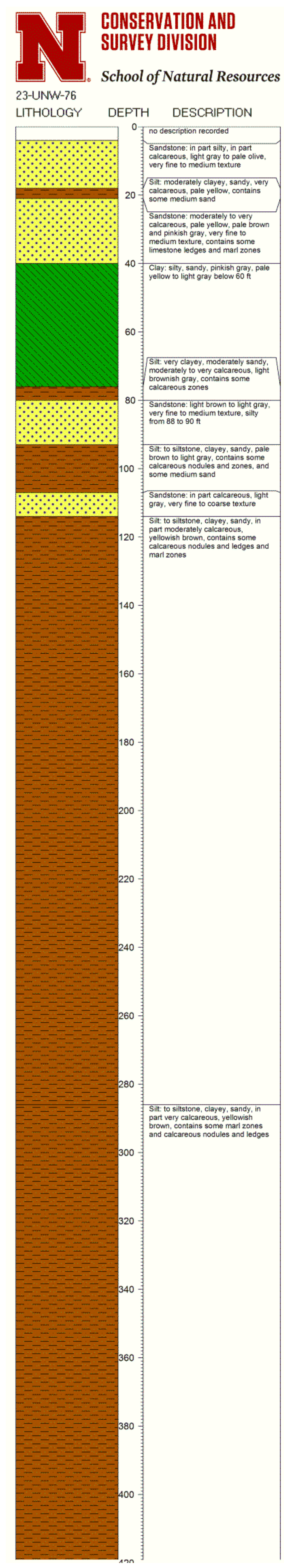

CONSERVATION AND SURVEY DIVISION
School of Natural Resources
6-UNW-75
LITHOLOGY DEPTH DESCRIPTION
Silt: very sandy, slightly clayey, dark grayish brown, moderately calcareous below 2 ft
Sandstone: pale olive, very fine to fine texture
Silt: sandy, calcareous, pale yellow
Sandstone: very calcareous, light gray, very fine to fine texture
Silt: very sandy, slightly clayey, very calcareous, light gray
Clay: silty, in part calcareous, light brown to light gray and pale yellow
Sandstone: moderately silty, in part calcareous, white to pale brown, very fine to fine texture
Silt: to siltstone, moderately sandy, slightly clayey, in part slightly to very calcareous, yellowish brown to brownish yellow
Sandstone: very silty, moderately calcareous, yellowish brown, very fine to fine texture
Silt: to siltstone, very sandy, slightly clayey, very calcareous, yellowish brown with some brownish yellow, in part slightly to moderately calcareous
Sandstone: moderately silty, very calcareous, light gray, very fine to fine texture
Silt: very sandy, slightly clayey, very calcareous, light gray
Sandstone: very silty, moderately calcareous, pale yellow, very fine to fine texture, contains some lithic fragments
Sand: slightly gravelly, texture grades from very fine sand to fine gravel, contains some lithic fragments
Silt: very sandy, slightly clayey, slightly calcareous, brownish yellow to yellowish brown, contains some calcareous nodules


CONSERVATION AND SURVEY DIVISION
School of Natural Resources
11-B-78
LITHOLOGY
DEPTH
DESCRIPTION
Topsoil: called "soil" in original log, no detailed description recorded
Silt: sandy, brown and gray brown, sand is very fine to very coarse with some fine gravel, contains lithic clasts
Silt: slightly sandy, dark brown; sand is very fine
Gravel: and sand, silty, brown; very fine sand to very coarse gravel
Sand: fine to medium with some very fine and coarse to very coarse sand and fine gravel
Sand: very fine to medium with some coarse, some very coarse sand and trace of fine to medium gravel from 60 to 70 ft, 75 to 80 ft, and 85 to 97 ft, silt beds or silty zones from 50 to 52 ft, 65 to 66 ft, 70 to 71 ft, and 82 to 84 ft
Silt: sandy, gray
Sand: very fine to medium, trace of coarse
Sand: fine to medium with some very fine and very coarse sand, silt bed from 110 to 112 ft
Sand: fine to very coarse with trace of fine to medium gravel
Sand: gravelly, fine sand to fine gravel; much very coarse sand to fine gravel
Sand: fine to medium with some very fine, coarse and very coarse sand, trace of fine gravel; silty in lower part
Sand: very fine to medium, trace of coarse and very coarse
Sand: fine to medium, some very fine, coarse and very coarse
Sand: fine to coarse, some very fine sand and trace of fine gravel
Sand: sandstone, and gravel, fine sand to fine gravel with much very coarse sand to fine gravel
Sand: very fine to medium with some coarse sand to fine gravel
Sand: medium to very coarse with some very fine to fine sand and fine gravel
Sand: medium to coarse with some very fine, fine, and very coarse sand, trace of fine gravel
Sand: and gravel, fine sand to medium gravel; much coarse sand to fine gravel
Sandstone: very silty, mostly brown; sand is very fine; grades to very sandy in parts; contains some thin limy zones
Silt: sandy, brown; sand is mostly very fine; grades to very sandy silt in parts in is slightly clayey in parts; contains some limy zones
Sand: very silty, brown; sand is very fine to fine except below 550 where there is also some medium to coarse; lithic clasts common to abundant
Silt: very sandy, light brown
Sand: very silty, light brown and brown; sand is very fine to fine with some medium to very coarse; lithic clasts common to abundant
Silt: slightly sandy, slightly clayey, brown


CONSERVATION AND SURVEY DIVISION
School of Natural Resources
10-B-78
LITHOLOGY
DEPTH
DESCRIPTION
Topsoil: called "soil" in the original log, no detailed description recorded
Sand: very silty, dark brown; sand is very fine to fine
Sand: fine to medium with some coarse sand to coarse gravel
Silt: and siltstone, sandy, pale yellow; sand is very fine to medium
Silt: very sandy, mostly pale olive and brown, with interbedded silty sand; sand is mostly very fine to medium but has some coarse in parts and contains a gravelly zone somewhere between 30 and 35 ft
Sand: and sandstone, very fine to medium with some coarse to very coarse, yellow brown
Sand: and sandstone, very fine to fine, brown
Silt: slightly sandy, pale olive and light yellow brown, with a few interbedded silty sand zones. Sand is very fine
Sandstone: gravelly, silty, pale olive, very fine sand to fine gravel, bed is lime cemented
Sand: very fine to fine with some medium, pale olive and light yellow brown, sandy silt zones from 131 to 132 ft, 135 to 137 ft, 146 to 147 ft, contains some limy zones in lower part
Sandstone: silty, brown; sand is very fine to fine; contains some thin limy zones
Silt: very sandy, brown and yellow brown, grades to very silty sand in parts, sand is very fine to fine, contains a few, thin limy zones
Silt: very sandy, yellow brown, sand is very fine with some fine, less sandy and slightly clayey in parts below 370 ft
Silt: very sandy, yellow brown, probably grades to silty sand in parts, sand is very fine to fine, interval contains lithic clasts
Silt: sandy, yellow brown, sand is very fine
Sand: very silty, and silt, very sandy, yellow brown and brown, sand is very fine, contains lithic clasts, Aborted hole at 560 ft. because of drilling problems


CONSERVATION AND SURVEY DIVISION
School of Natural Resources
22-UNW-76
LITHOLOGY
DEPTH
DESCRIPTION
Sand: very silty, very fine to medium texture
Sandstone: slightly silty, in part very to slightly calcareous, pale yellow with some pale olive, very fine to medium texture with in part very fine to coarse with a little fine gravel, contains some rootlet casts
Siltstone: sandy, clayey, yellowish brown, contains some calcareous nodules and zones
Silt: to siltstone, sandy, clayey, yellowish brown, pale brown below 120 ft, contains some medium sand, some calcareous zones and some lime cemented sandstone
Sandstone: silty, dark yellowish brown, very fine to fine texture, contains some calcareous nodules and zones
Siltstone: very sandy, dark yellowish brown, contains some medium sand and some calcareous nodules and zones
Silt: to siltstone, sandy, clayey, yellowish brown, contains some calcareous nodules and zones and some silty sandstone


CONSERVATION AND SURVEY DIVISION
School of Natural Resources
21-UNW-76
LITHOLOGY
DEPTH
DESCRIPTION
no description recorded
Silt: very sandy, slightly clayey, moderately calcareous, light gray
Sandstone: moderately silty, moderately calcareous, light gray with some white, very fine to medium texture
Siltstone: sandy, very calcareous, white
Clay: silty, pale brown
Limestone: sandy, white, texture of sand is very fine to fine, contains some sandy siltstone below 59 ft
Sandstone: slightly calcareous, light gray, very fine to medium texture, contains some calcareous fragments
Silt: sandy, marly, white, contains some siltstone, sandstone lenses and some gravel grains
Sandstone: very fine to medium texture with little coarse, very fine to very coarse below 90 ft with a trace of fine gravel
Sand: slightly gravelly, texture grades from fine sand to fine gravel, silty below 115 ft
Calcareous Mudstone: called "marl" in original log, silty, sandy, white
Sand: silty, very fine to medium texture, contains some marl
Sand: very fine to very coarse texture with a trace of fine gravel, sand is very fine to medium below 150 ft with a trace of coarse
Sand: very fine to very coarse texture, very fine to medium from 170 to 190 ft with a trace of coarse, and a trace of fine gravel below 190 ft
Silt: to siltstone, very sandy, clayey, slightly calcareous, pale brown, contains some calcareous zones, ledges and sandstone below 242 ft


CONSERVATION AND SURVEY DIVISION
School of Natural Resources
23-UNW-76
LITHOLOGY
DEPTH
DESCRIPTION
no description recorded
Sandstone: in part silty, in part calcareous, light gray to pale olive, very fine to medium texture
Silt: moderately clayey, sandy, very calcareous, pale yellow, contains some medium sand
Sandstone: moderately to very calcareous, pale yellow, pale brown and pinkish gray, very fine to medium texture, contains some limestone ledges and marl zones
Clay: silty, sandy, pinkish gray, pale yellow to light gray below 60 ft
Silt: very clayey, moderately sandy, moderately to very calcareous, light brownish gray, contains some calcareous zones
Sandstone: light brown to light gray, very fine to medium texture, silty from 88 to 90 ft
Silt: to siltstone, clayey, sandy, pale brown to light gray, contains some calcareous nodules and zones, and some medium sand
Sandstone: in part calcareous, light gray, very fine to coarse texture
Silt: to siltstone, clayey, sandy, in part moderately calcareous, yellowish brown, contains some calcareous nodules and ledges and marl zones
Silt: to siltstone, clayey, sandy, in part very calcareous, yellowish brown, contains some marl zones and calcareous nodules and ledges