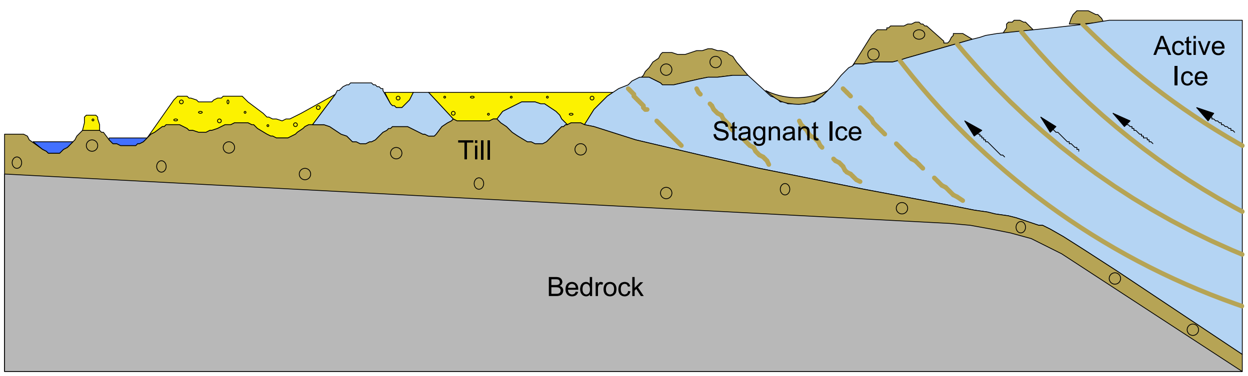
Wastin' Away in Central North Dakota: Glacial Ice Stagnation and the Central Dakota Aquifer System



By
Gordon M. Sturgeon

Water Resource Investigation No. 57
North Dakota State Water Commission

2014

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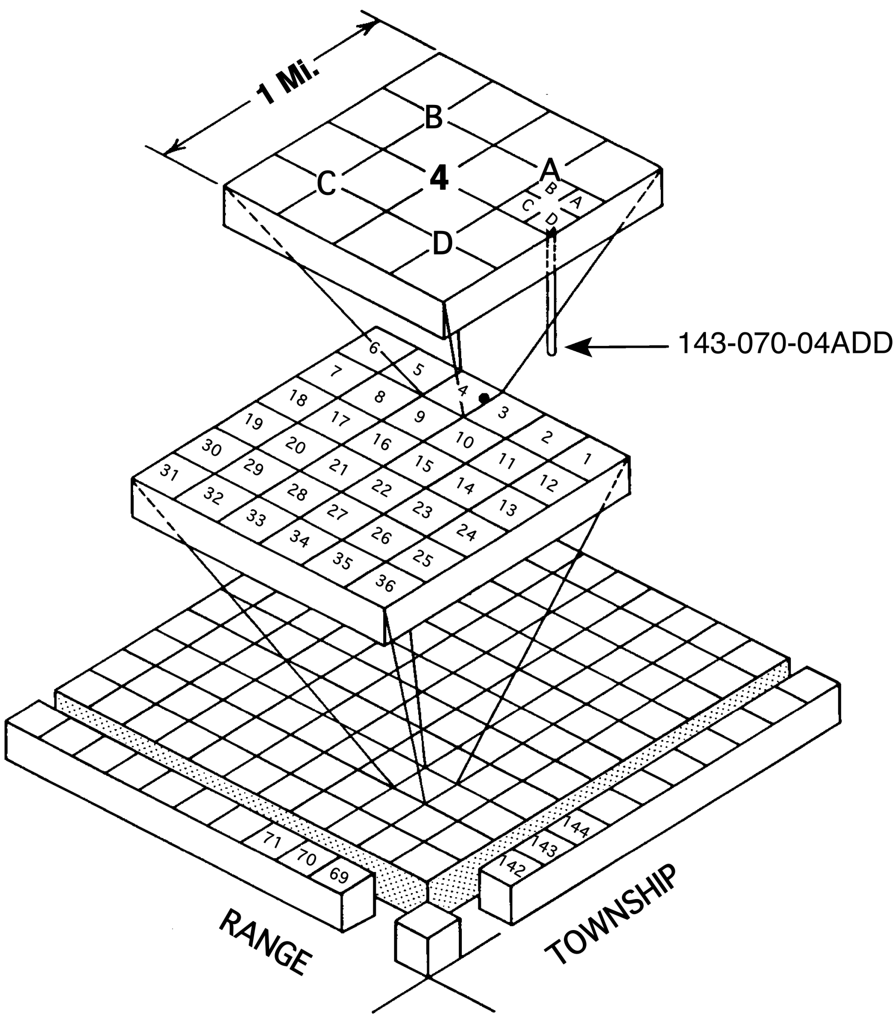
LOCATION-NUMBERING SYSTEM FOR TEST HOLES AND WELLS

The location-numbering system is based on the public land survey system (PLSS) of the U.S. Government. The PLSS typically divides the land into 6-mile by 6-mile townships that are subdivided into 36 1-mile by 1-mile sections, each containing 640 acres. The location of each township is identified by a township and range designation. The township designation indicates its location north or south of an east-west trending base line. The range designation indicates its location east or west of a north-south line called a Principal Meridian. For example, T143N R70W refers to the township that is in the 143rd row of townships north of a base line and the 70th column of townships west of a Principal Meridian.

The test hole and well location-numbering system used in this report is illustrated below. The first six numbers identify the township in terms of its township and range designation. The seventh and eighth numbers denote the section in the township, and the first letter A, B, C, or D indicates the northeast, northwest, southwest, or southeast quarter of the section, respectively. The second letter denotes the quarter of the quarter, and the third letter identifies the ten-acre tract within the quarter-quarter. Consecutive numbers follow the letters if more than one test hole or well is located within a ten-acre tract (e.g. 14307004ADD1 and 14307004ADD2).



Wastin' Away in Central North Dakota: Glacial Ice Stagnation and the Central Dakota Aquifer System

INTRODUCTION

The purpose of this study was to advance our understanding of the Central Dakota Aquifer System (CDAS) in general and its northern half in particular. The thick and laterally extensive sand and gravel deposits that constitute the CDAS were laid down by rivers that flowed during the last ice age across what is now Kidder and Stutsman Counties. The rivers flowed across a highly irregular and shifting landscape of glacial debris and melting blocks of ice. The consequences of this interplay between rivers, drift, and stagnant ice include a relatively high relief landscape comprised of collapsed till and outwash, numerous pothole lakes, and occasional topographic inversion features, all of which exert a strong influence on the hydrogeologic character of the aquifer system. The high relief landscape creates nested flow systems in the upper aquifer and causes recharge to be unevenly distributed and depression focused. The large number of pothole lakes generates complex patterns of recharge and discharge that affect groundwater chemistry. Topographic inversion placed unsaturated sand and gravel high on the landscape, and sediment collapse produced complex aquifer geometries, locally confined conditions, sporadic zones of inter-aquifer connectivity, and spatially variable transmissivities.

The CDAS is an important groundwater resource that sustains innumerable lakes, ponds, and sloughs in central North Dakota that are essential for migrating waterfowl and other wildlife. The CDAS also supports irrigated agriculture, which is vitally important to the regional economy (Coon and Leistritz, 2001). Balancing these interests in the face of burgeoning agricultural production calls for a continued study of water quality and quantity and an ever-improving knowledge of the system's response to natural and anthropogenic stresses.

The first comprehensive evaluations of the geology and hydrology of the counties that contain the CDAS were published in the early 1960s (Rau et al., 1962; Winters, 1963). Sturgeon (2011) published an update for the northern portions of these counties that incorporated findings from hundreds of well borings and thousands of water level and chemistry measurements that were not available to Rau et al. and Winters. The current investigation differs from the broad geologic overview and emphasis on water management presented in Sturgeon (2011) by its focus on the CDAS and emphasis on hydrogeologic interpretation. It also complements the aforementioned investigation by answering questions raised in that work, improving aquifer characterization in areas with low data density, and shedding additional light on groundwater-lake interactions. For information on the local climate, water quality, bedrock topography, and bedrock geology, see Rau et al. (1962), Winters (1963), and Sturgeon (2011).

AQUIFER GENESIS AND MORPHOLOGY

The CDAS lies within the Missouri Coteau physiographic province – an upland area of hummocky, glaciated plains with isolated drainages (Figure 1). The thick glacial deposits of the Coteau resulted from the large-scale stagnation and gradual wasting away of glacial ice, accompanied by the collapse of the glacial sediment that was carried by the ice. Areas in North Dakota that are characterized by collapsed glacial topography include the Missouri Coteau, the Turtle Mountains, and the Prairie Coteau. Hummocky collapsed topography formed in these three areas, because the glaciers were forced to advance up steep escarpments before they flowed onto the uplands.

When the glaciers advanced over these escarpments, the resulting internal stress in the ice caused shearing (Figure 2). Large amounts of sediment originally beneath the ice were forced upward into the glacier and onto its surface along shear planes. As the climate warmed, the glaciers stopped advancing and large masses of ice stagnated over the uplands. The ice became isolated and detached from the main body of the retreating glacier, because it was relatively thin and often covered by a thick blanket of rock debris. East of the escarpments the ice was more thick and less debris-rich, so the glaciers did not stagnate.

As the stagnant ice slowly wasted away, the ice surface topography became progressively more irregular. Ice covered with a lot of debris was well insulated and melted very slowly; ice with little debris melted more rapidly. The debris on top of the ice was unstable and prone to slumping and flowing into low areas.

Rivers were common features on the irregular surface of the wasting ice. Consequently, test borings in ice-wasting depositional environments often encounter multiple layers of till, separated by layers of fluvial sand and gravel. This stratigraphic sequence is often misinterpreted to be the product of multiple glaciations, when in many cases, it is the manifestation of a single episode of ice advance and retreat (Figure 3).

Rivers also extended beyond the margins of the melting ice. Most of the southern halves of northern Kidder and northwestern Stutsman Counties are covered by stratified sand and gravel that was “washed out” of the ice by meltwater streams (Figure 4). If the outwash was deposited on buried ice, melt out of the underlying ice caused the outwash to have a hummocky topography like the collapsed glacial till. Collapsed outwash has the same composition as uncollapsed river sediment, but its bedding is usually faulted and folded.

There is evidence of two cycles of ice advance, stagnation, and wasting in the study area. Most of the land in the north half of Figure 4 is covered by hummocky stagnation moraine and tall, arc-shaped end moraines from the younger Streeter advance. The stagnation moraine, end moraines, and outwash associated with the Streeter advance partially bury the ground moraine and end moraines from the older Long Lake advance.

The Streeter outwash is the most abundant surficial deposit south of Highway 36 (Figure 4). The meltwater streams that formed this outwash plain generally flowed from the north, so the plain slopes to the south, and grain size decreases to the south. The outwash contains several closed depressions that were produced by the melting of isolated blocks of stagnant ice.

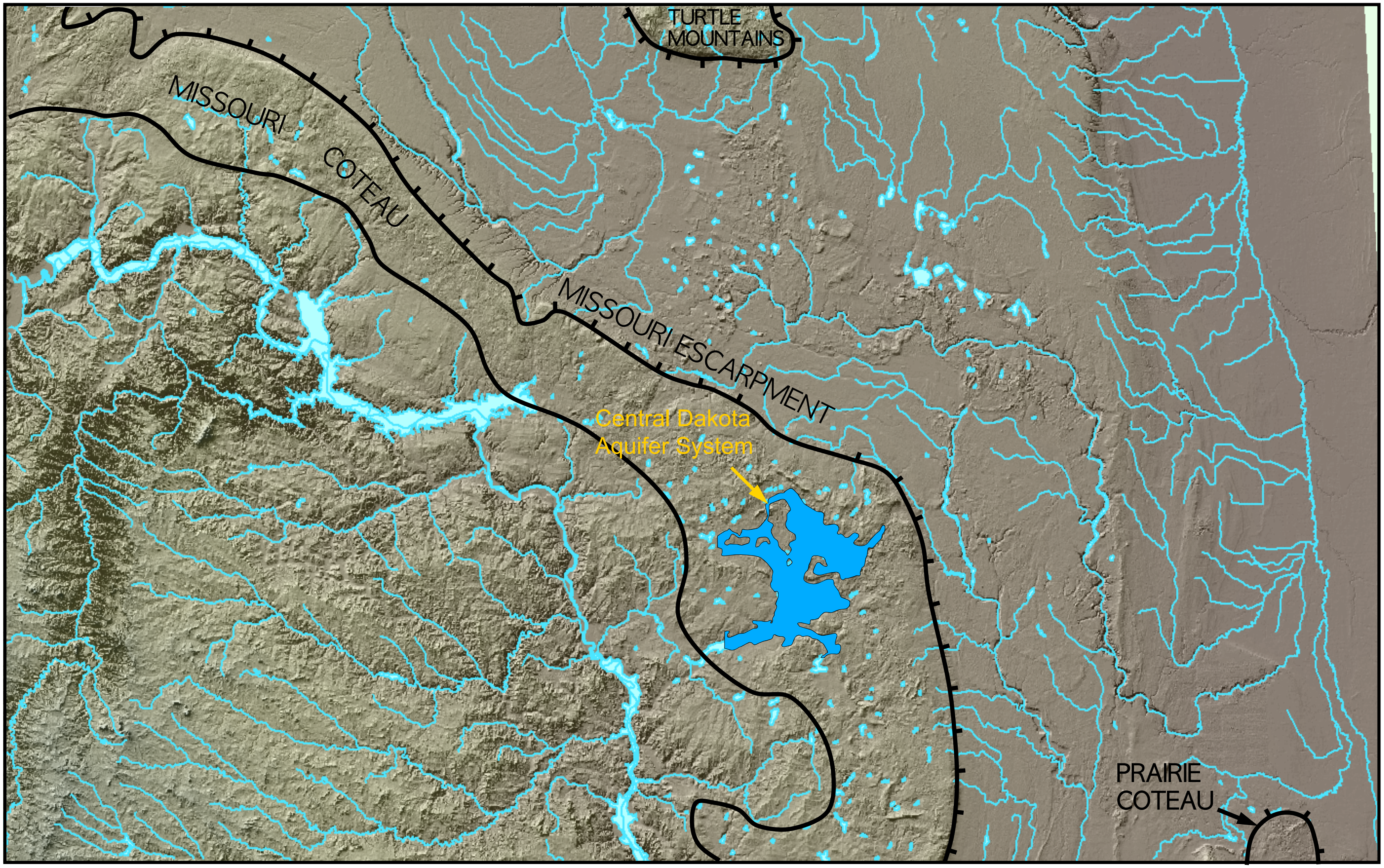


Figure 1. Physiography of North Dakota showing the three provinces that are characterized by collapsed glacial topography as well as the escarpments that bound these areas. The Central Dakota Aquifer System is located within the Missouri Coteau province. The lack of an integrated drainage network in the coteau indicates that there has been little postglacial erosion of the landscape. Consequently, the land surface in the coteau looks essentially the same as it did at the end of the ice age.

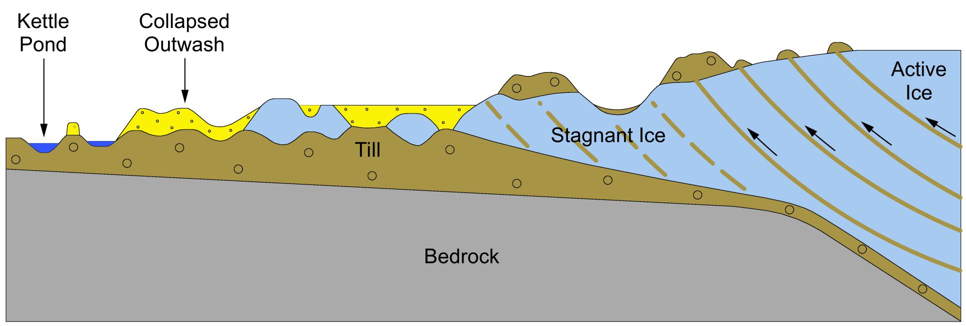


Figure 2. Cross section showing the collapsed glacial topography that arises from ice-sheet stagnation and wasting.

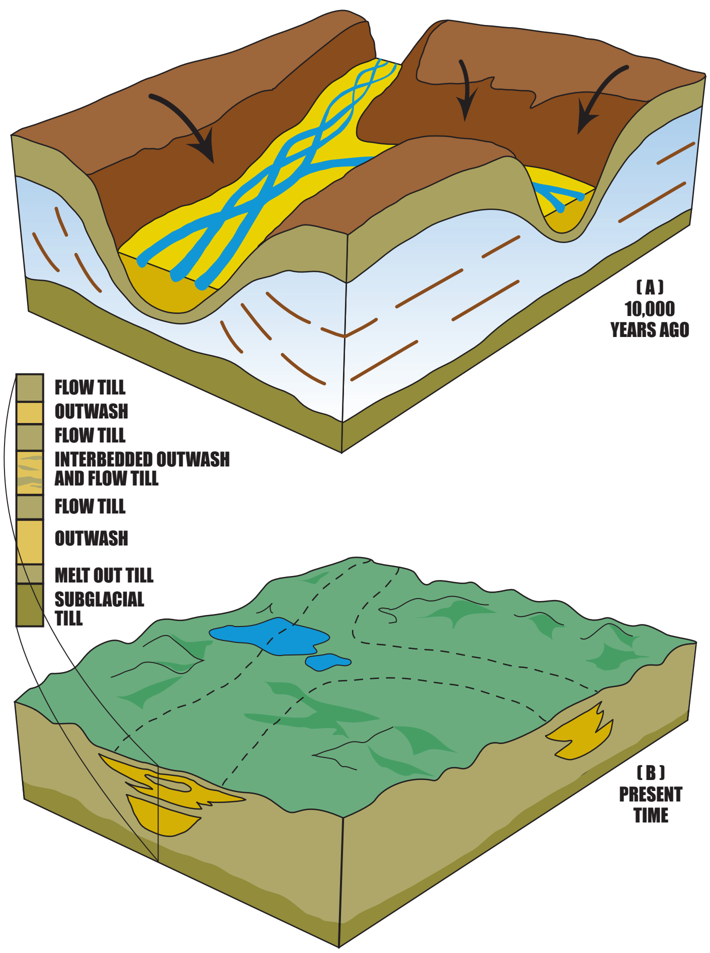


Figure 3. Formation of interbedded outwash and till from a single episode of glacial advance and retreat in an ice-wasting depositional environment. First, glacial ice advances over an area, depositing subglacial till. Later, as the ice retreats and stagnates, a series of ice-cored ridges develops (A). Glaciofluvial sands and gravels are deposited in the intervening valleys by meltwater streams. Till slumping and flowing off the adjacent ice-cored highlands occasionally buries the outwash. Eventually, the meltwater streams become abandoned and buried once and for all by till from the highlands (B).

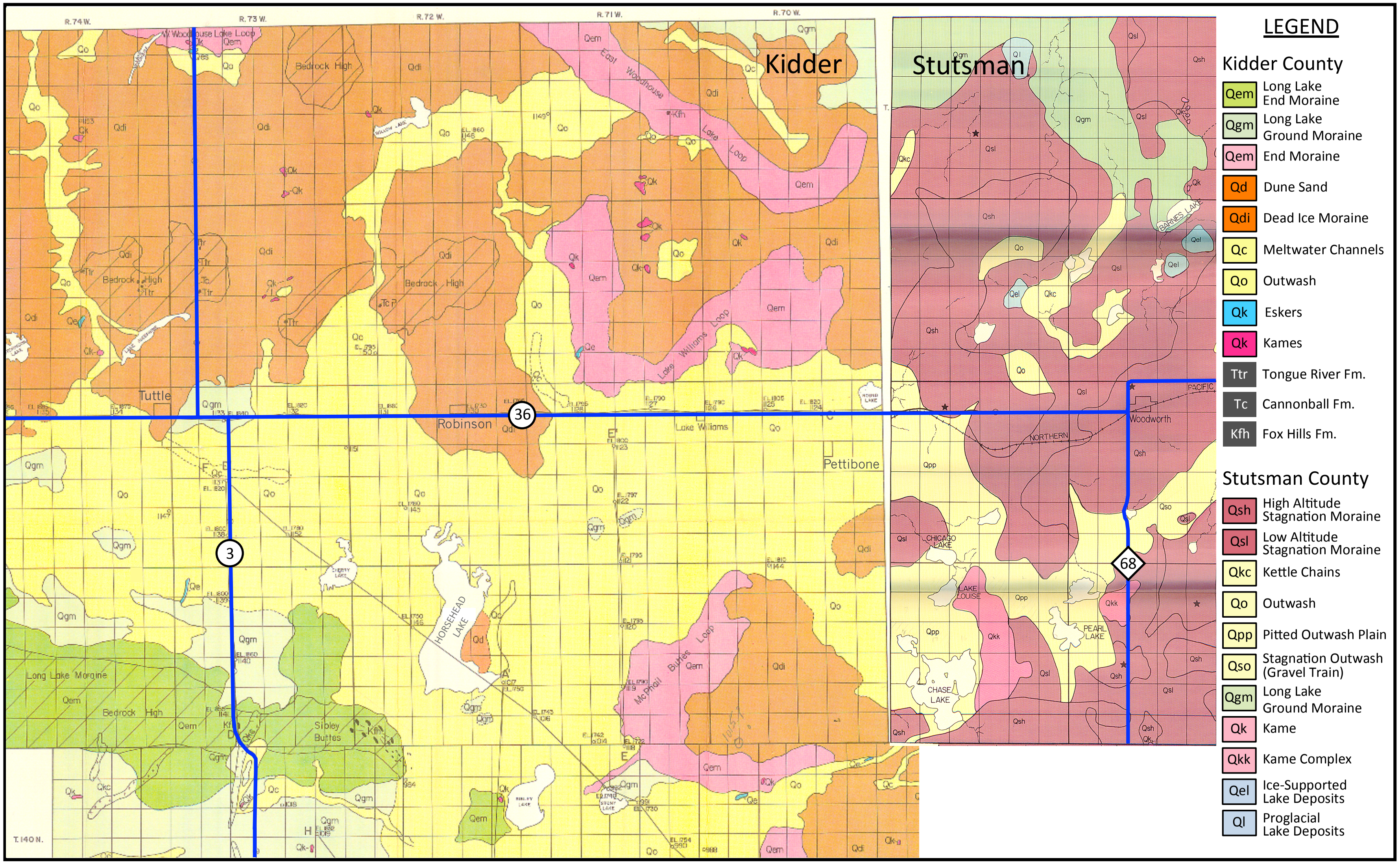


Figure 4. Surficial geology of northern Kidder and northwestern Stutsman Counties. Yellow is outwash. Orange and maroon are hummocky stagnation moraine. Pink and dark green in Kidder County are end moraine. Pink areas in Stutsman County are kames. Light green is low relief ground moraine. Pale blue is lake sediment. Sources: Rau et al. (1962) and Winters (1963).

Figure 5 is a conceptual model of the hydrogeology in northeastern Kidder County and parts of northwestern Stutsman County. It shows the large, collapsed outwash plain that constitutes the upper member of the CDAS. This upper aquifer occurs at elevations between 1700 and 1900 feet. Saturated thickness can exceed 100 feet, and the aquifer may be buried beneath more than 50 feet of silt- and clay-rich till in the highlands north of Highway 36 and east of Pettibone.

A discontinuous layer of clay-rich till and lake sediment separates the upper aquifer from a second, narrower body of collapsed outwash that constitutes the lower member of the CDAS. This lower aquifer generally lies at elevations between 1580-1650 feet. The strongly heterogeneous lithology and collapsed nature of the aquifer produce a spatially variable transmissivity. Underlying the lower aquifer are smaller sand and gravel bodies that lie in ancestral river channels – their small size, presumably poor water quality, and great depth below the land surface render them poor appropriation targets. Consequently, they are not considered part of the CDAS.

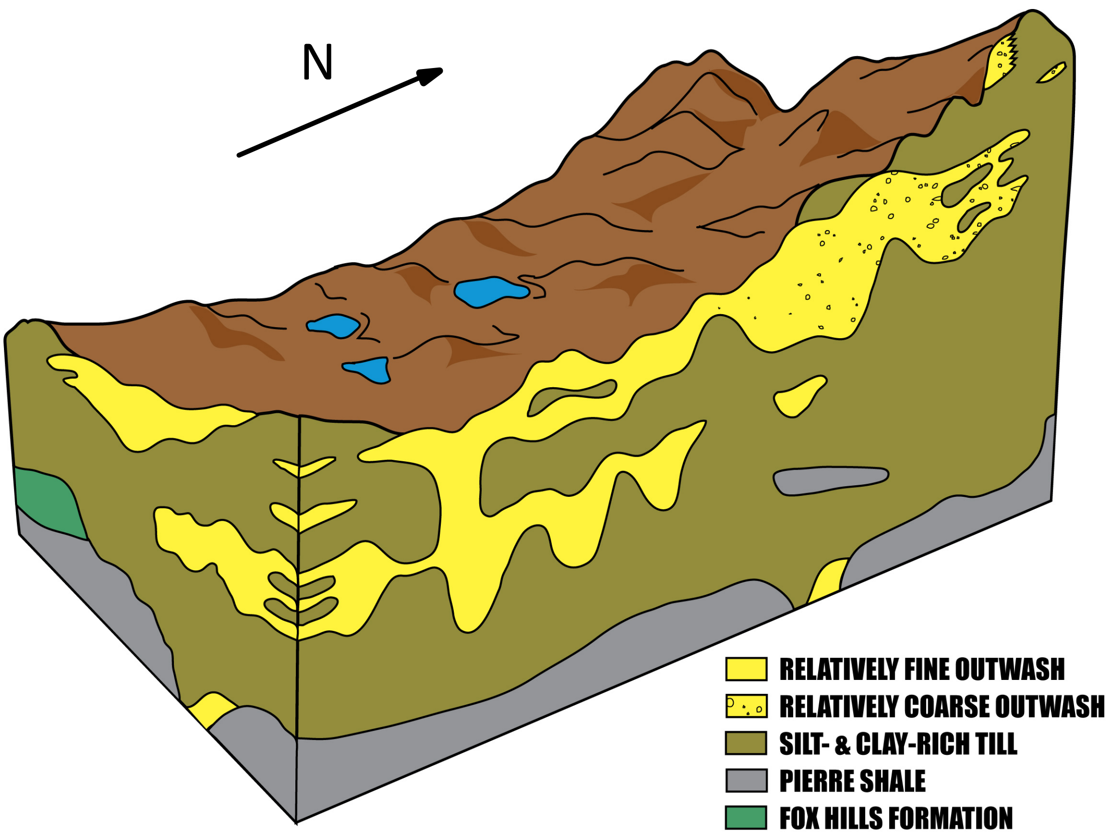


Figure 5. Conceptual block diagram of the hydrogeology of northeastern Kidder and northwestern Stutsman Counties showing: upper and lower aquifers composed of collapsed outwash, isolated sand and gravel deposits in deep bedrock valleys, and ice-shove blocks of bedrock that occasionally conceal lower-lying sands and gravels. Notice that the northern boundary of the upper aquifer is buried beneath the till highlands, and the aquifer fines and thins to the south. The block diagram also shows the presence of isolated recharge areas in the till highlands, direct connections between the upper and lower aquifers, and discontinuous layers of till within the aquifers. These discontinuous till layers often create locally confined conditions within the upper aquifer.

Deviations from the archetype shown on Figure 5 occur primarily near the perimeter of the study area. In Strong Township (T142N R68W) at the eastern end of the project area, the upper aquifer is generally absent (Figure 6). There is a long and narrow band of gravelly outwash east of Highway 68 (Qso in Figure 4); however, this outwash was deposited near the end of the ice age by rivers that flowed through a valley flanked by till-covered, ice-cored ridges, and over time, the ice beneath the ridges melted away, leaving the gravel train at a higher elevation than the surrounding till. Because of its ridge top location, this topographic inversion feature is believed to be mostly, if not completely unsaturated, and the fact that there are no wells in the gravel supports this interpretation. The lower aquifer is also absent beneath most of Strong Township (Figure 7). It was only encountered in 14206829CCD and perhaps in two borings advanced through the gravel train (14206812CDD and 14206814CCD). Since the deep sands and gravels in these latter two borings lie at slightly lower elevations than, and are far removed from, the nearest confirmed occurrences of the lower aquifer, it is not clear if they are connected to it.

In neighboring Marstonmoor Township (T142N R69W) the hydrostratigraphy closely resembles Figure 5 with the exception of the lower aquifer, which is absent. Immediately to the south in Iosco (T141N R68W) and eastern Chase Lake (T141N R69W) Townships, the CDAS consists of three aquifers (Figure 8).

There are also three aquifers near the western edge of the study area in Robinson (T142N R72W) and Quinby (T141N R72W) Townships, where a middle aquifer comprised of meandering stream deposits is sandwiched between the upper and lower aquifers (Figures 9 through 11). One branch of the middle aquifer trends west to east and may follow the course of the ancestral Wing River; the other branch trends north to south. The two branches coalesce beneath Horsehead Lake. South of the lake, the sands and gravels of the middle and upper aquifers are frequently interconnected.

A western offshoot of the lower aquifer may also follow the course of the ancestral Wing River before it merges with the main body of the lower aquifer near the southeast terminus of Horsehead Lake (Figures 7 and 9). The upper, middle, and lower aquifers extend into the southern half of Kidder County where they are often referred to as the surficial, shallow semi-confined, and deep confined aquifers.

At the northern end of the study area, most of the land is covered by a thick layer of collapsed till. The aquifer sediments beneath this till vary greatly in thickness and may be concentrated in discrete channels. The channel fill tends to be gravelly with till interbeds, as expected for glaciofluvial deposits near their source area. Boring logs indicate there are at least two, and perhaps as many as five layers of channel sands and gravels between the elevations of 1600 feet and 1900 feet. The shallowest channel deposits coalesce toward the south to form the Streeter outwash plain (Figures 4, 6, and 12). However, given the collapsed nature of the outwash and the lack of any pumping test data, there is not enough information at some sites to verify whether the deeper sand and gravel layers are connected to the upper aquifer, the lower aquifer, or neither aquifer.

For a more detailed view of the subsurface, Appendix A in Sturgeon (2011) has 50 geologic cross sections that crisscross the entire study area.

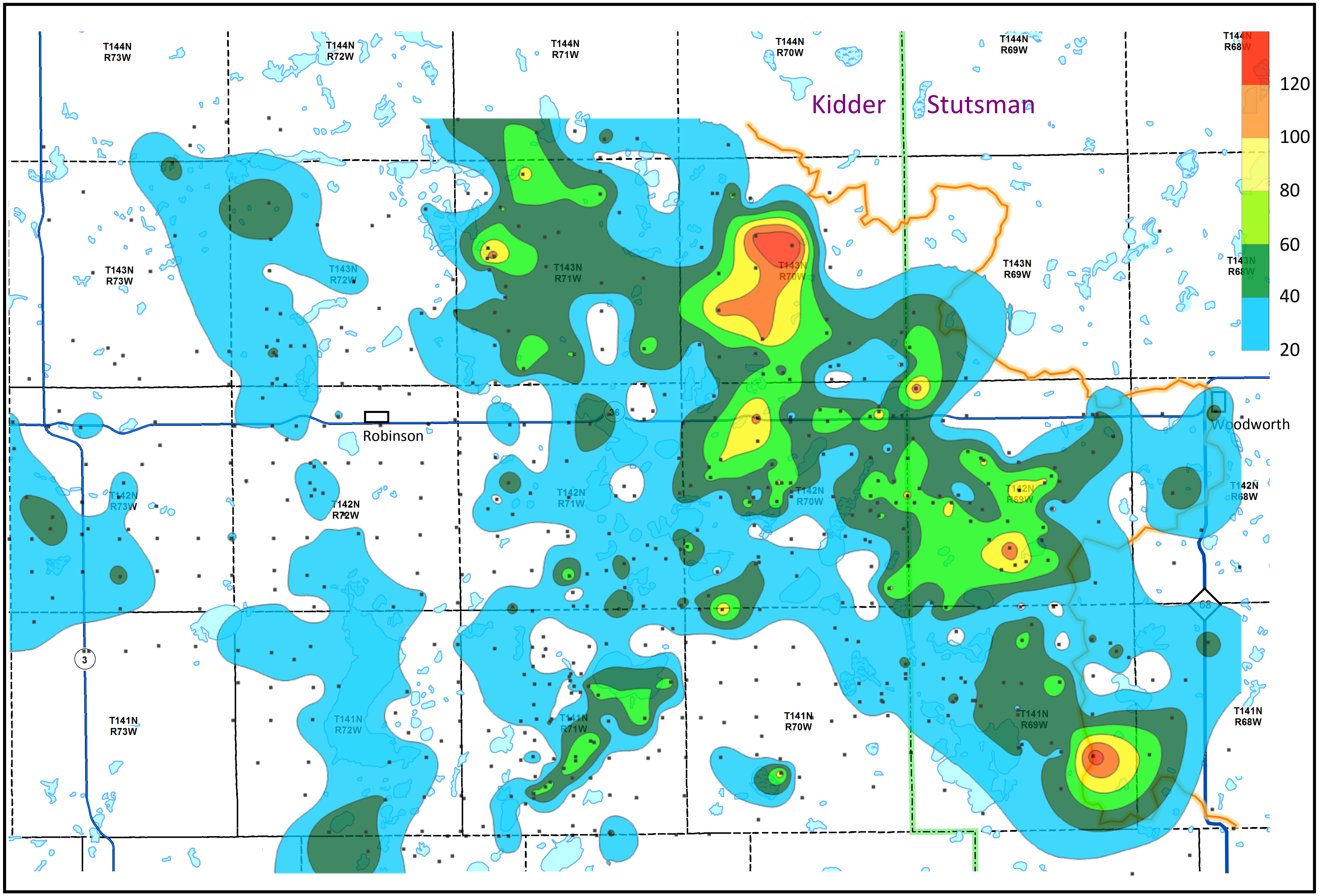


Figure 6. Saturated thickness of sand and gravel (feet) in the upper aquifer. The map includes sand and gravel deposits that lie between the upper and lower aquifers. Black dots represent data locations. Orange line is the Apple Creek / Pipestem River sub-basin divide.

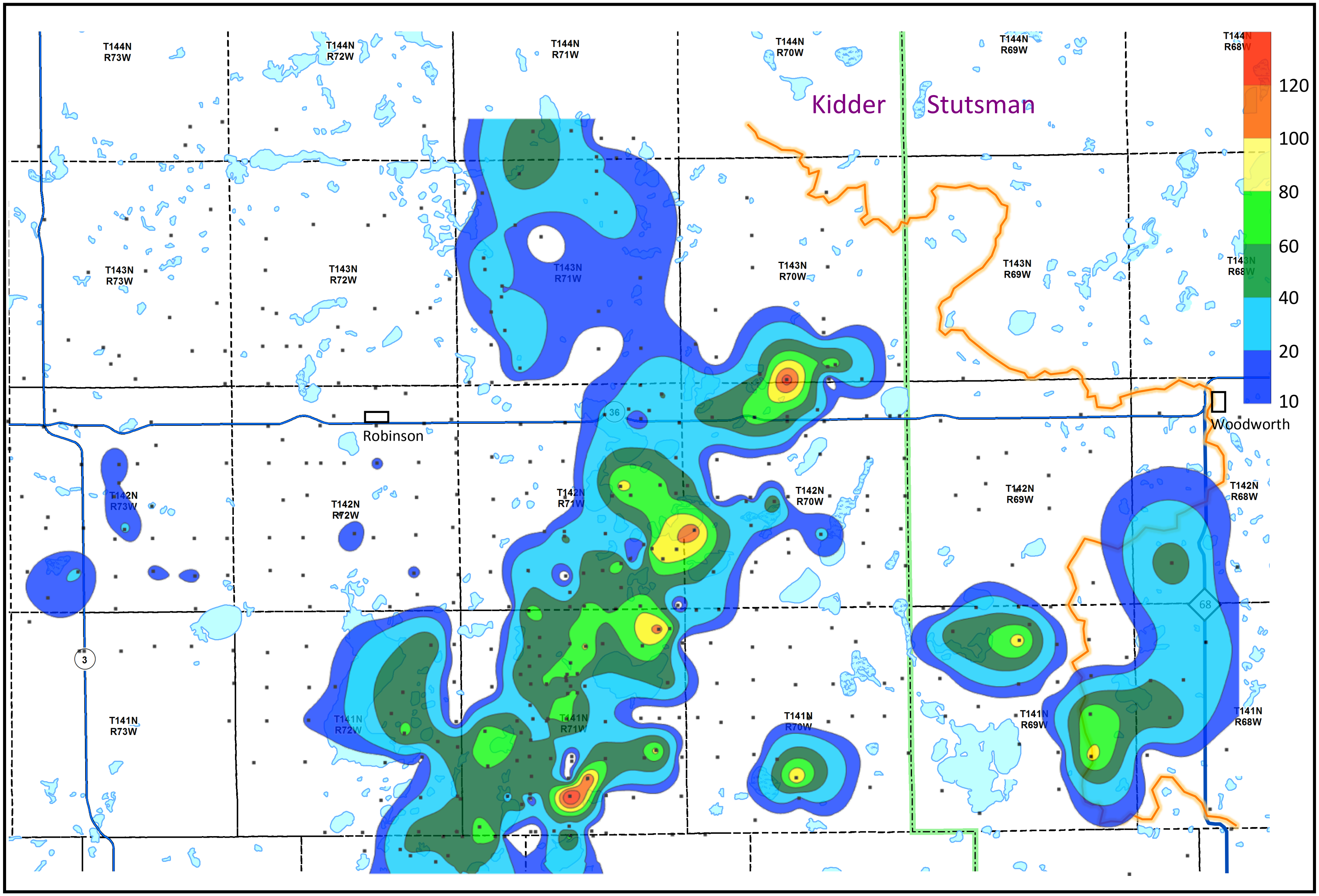


Figure 7. Thickness of sand and gravel (feet) in the lower aquifer. Orange line is the eastern boundary of the Apple Creek sub-basin. The lower aquifer in T141N R70W may be connected to the main body of the lower aquifer in T141N R71W.

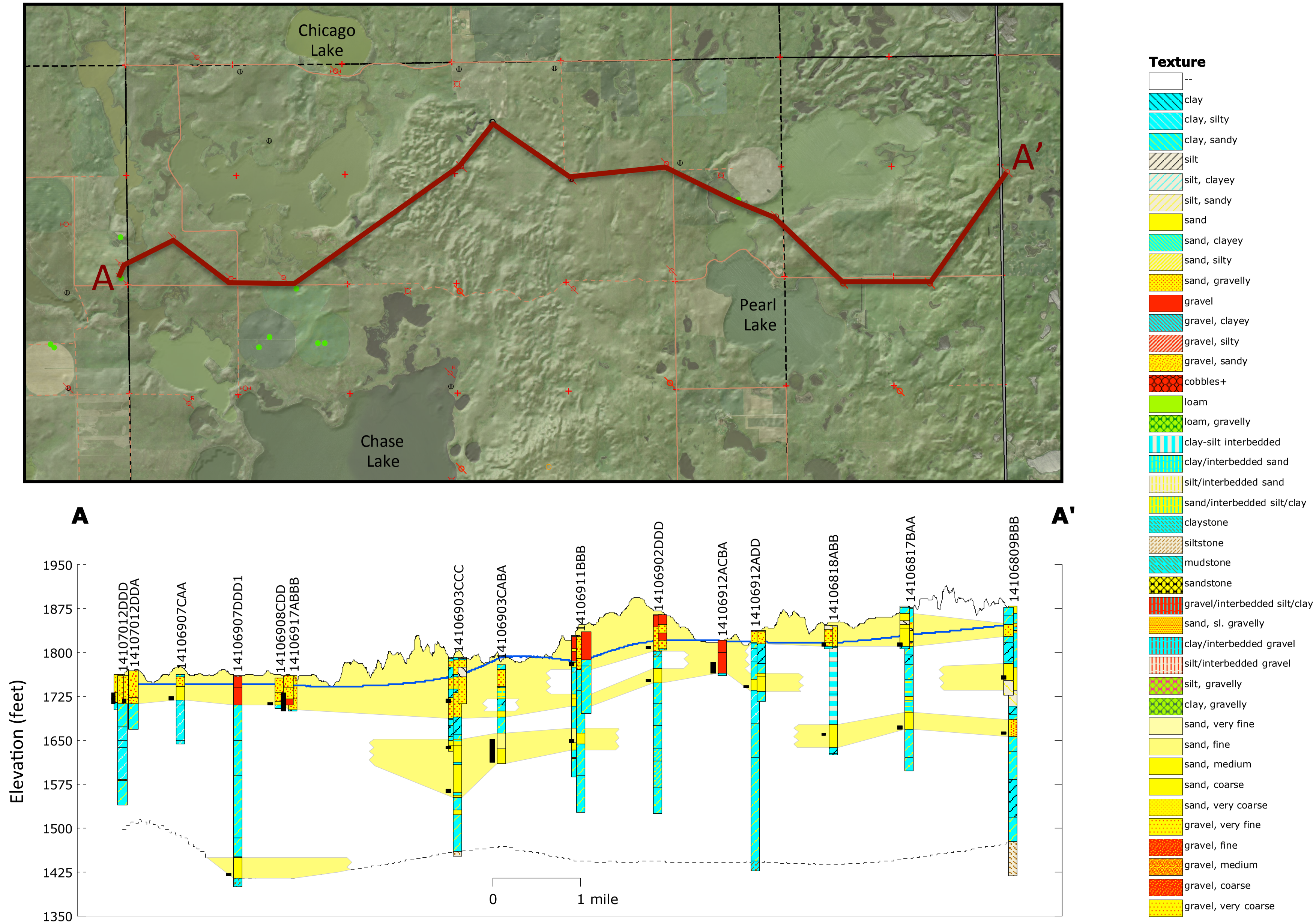


Figure 8. Vertical distribution of geologic materials north of Chase and Pearl Lakes. Yellow fill indicates aquifer. (The deep sand unit at 14106907DDD1 lies below the CDAS.) Dashed line is the bedrock surface. Blue line is the water table. Note the three aquifers in the eastern half of the cross section. The intermediate, or upper confined aquifer appears to merge with the surficial aquifer near Pearl Lake and 14106912ACBA.

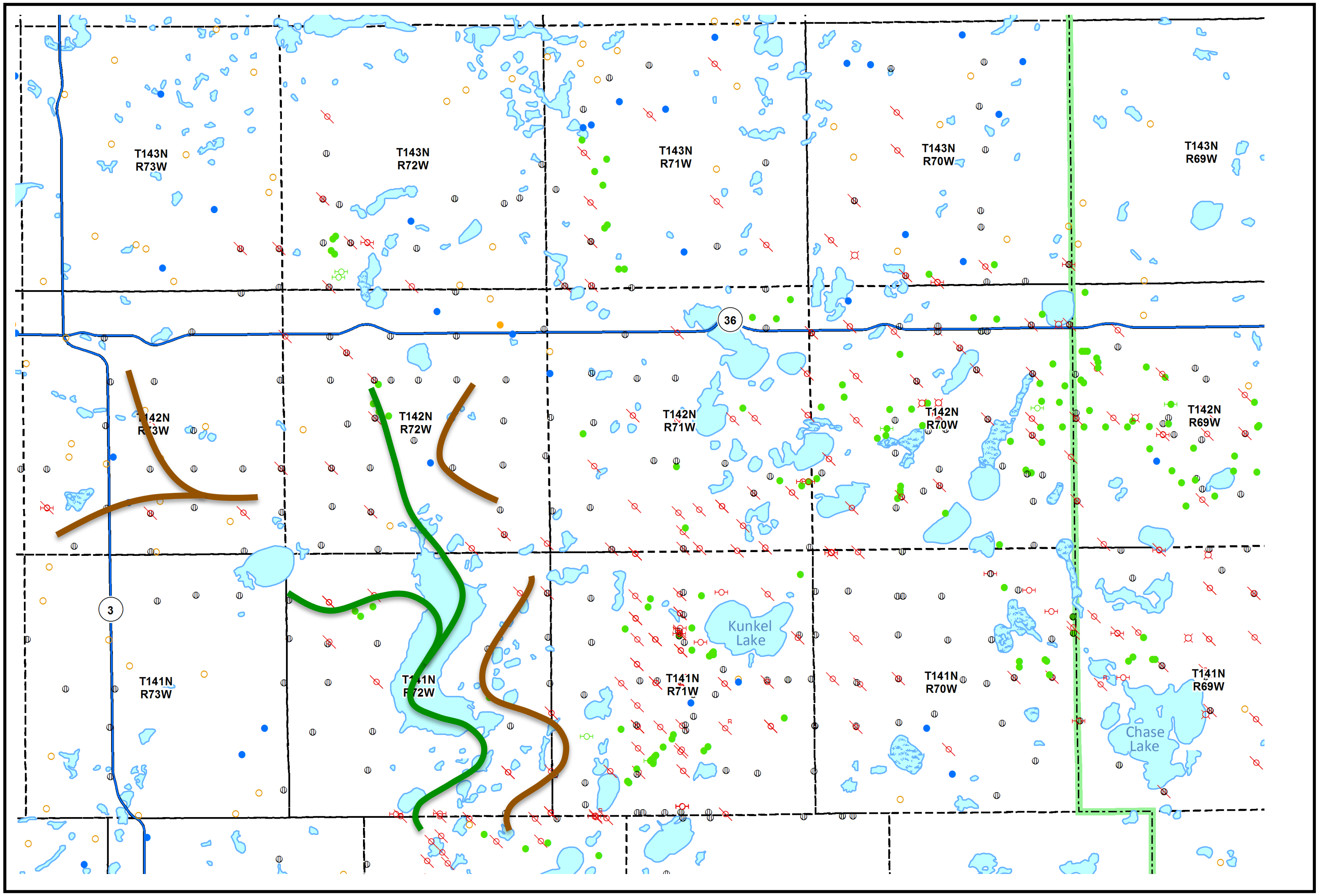


Figure 9. Approximate longitudinal axes of buried meandering stream deposits in the Horsehead Lake area. The middle aquifer (axes shown in green) lies at an elevation of approximately 1650-1710 ft. The western branch of the lower aquifer (axes shown in brown) is found at 1560-1650 ft. Notice that Horsehead Lake follows the meanders in these buried channel deposits.

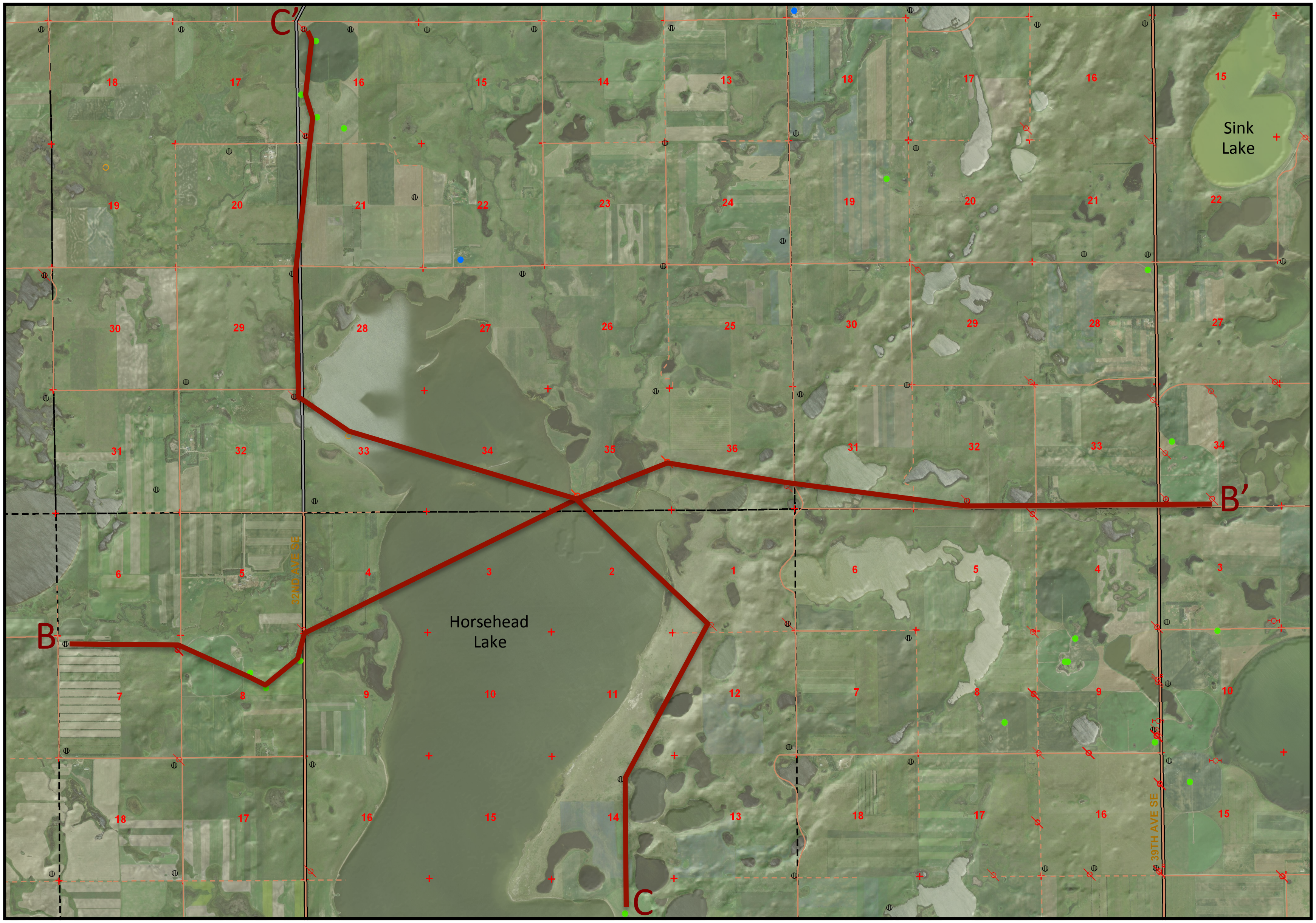


Figure 10. Locations of geologic cross sections shown on Figure 11.

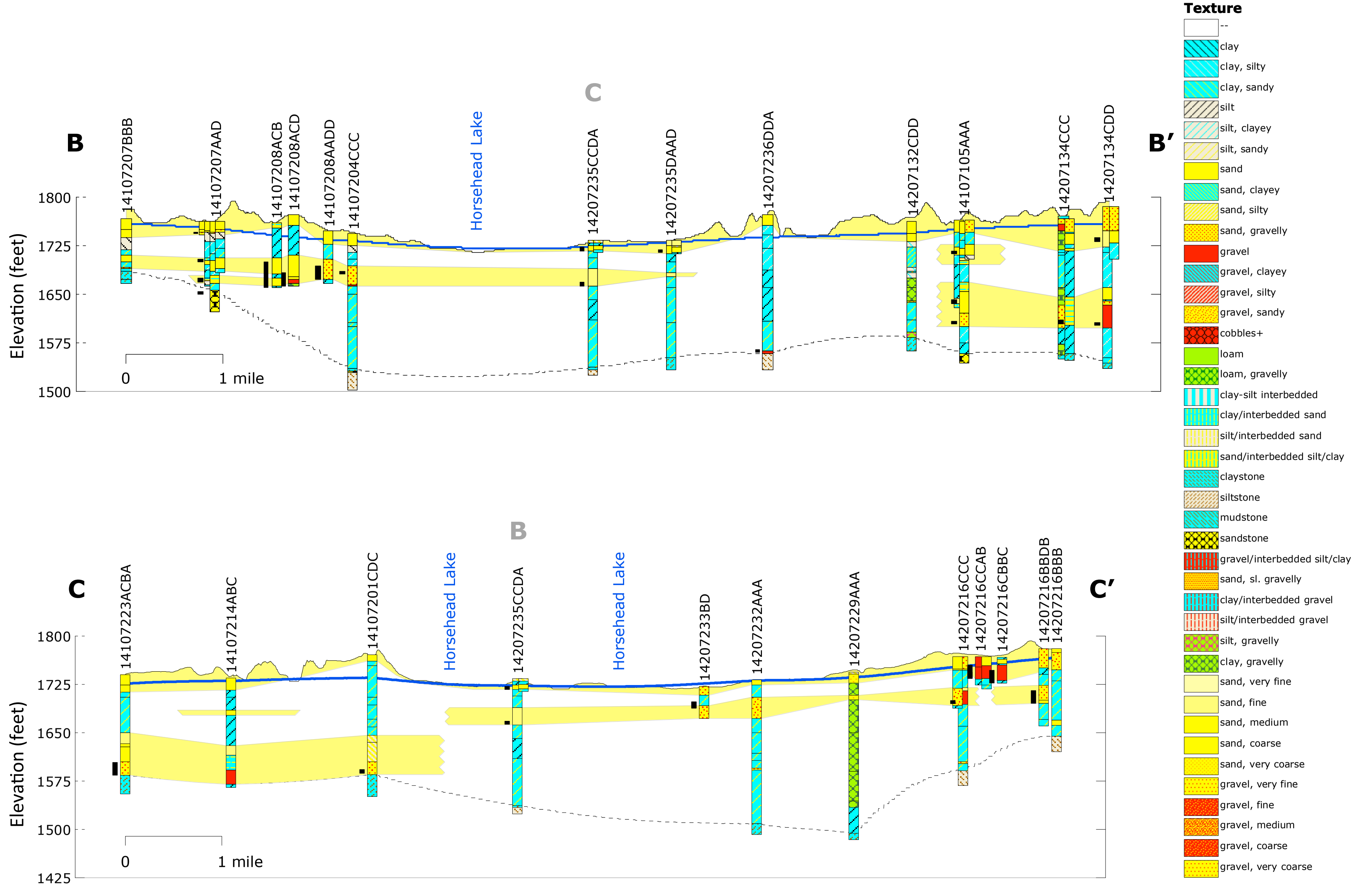


Figure 11. Cross sections showing the vertical distribution of geologic materials in the Horsehead Lake area. BB′ extends west (B) to east (B′). CC′ extends south (C) to north (C′). Yellow fill represents aquifer. Dashed line is the bedrock surface. Blue line is the water table. Gray labels B and C indicate cross-section intersection.

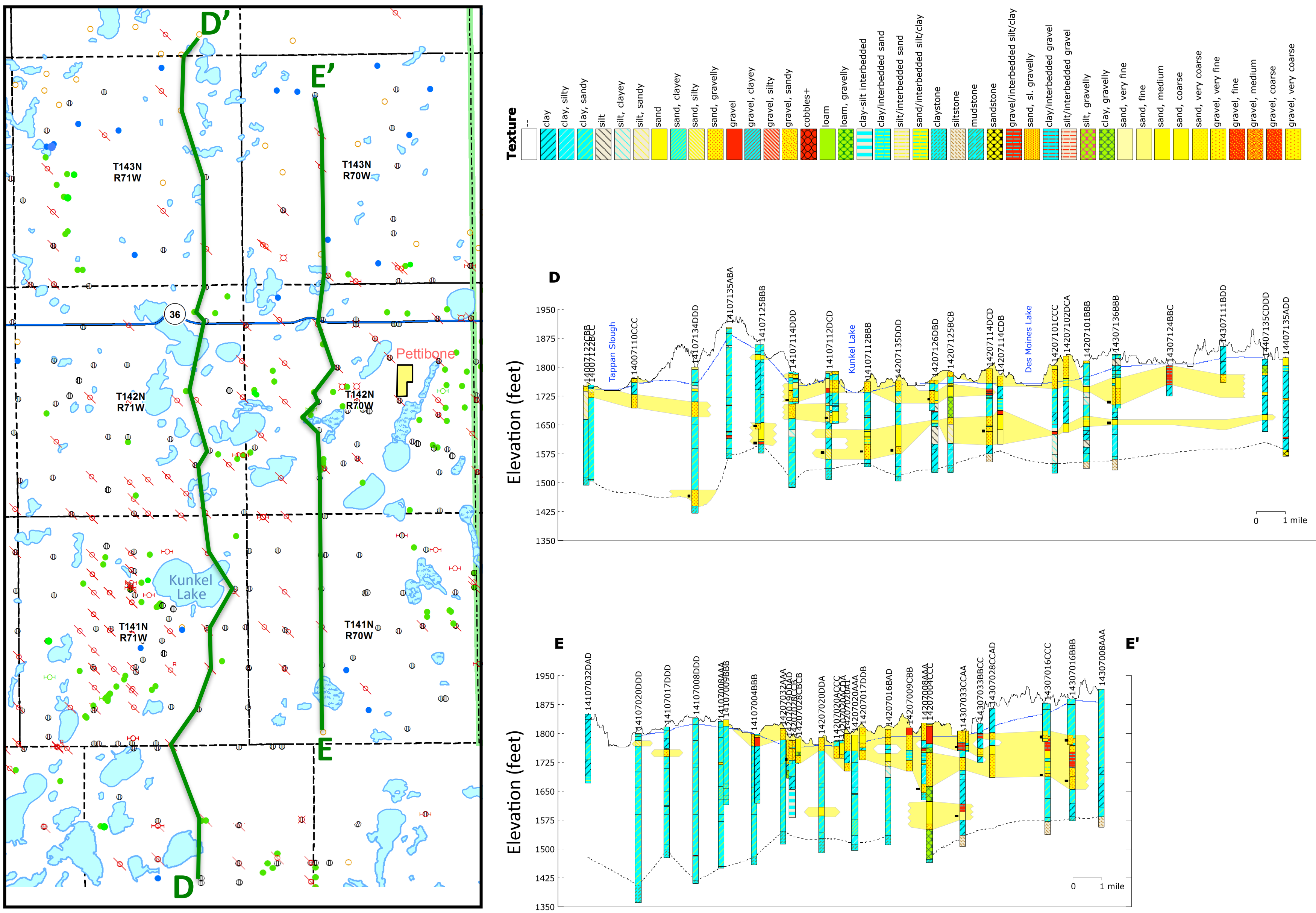


Figure 12. Cross sections trending south to north across north central Kidder County. Yellow fill indicates aquifer. Dashed line is the bedrock surface. Blue line is the water table. Note that the upper aquifer sediments are often buried beneath collapsed till in the northernmost reaches of the study area.

AQUITARD MORPHOLOGY

The low permeability, silt- and clay-rich aquitard that separates the upper and lower aquifers varies greatly in thickness, ranging from 0 feet to 160 feet. Figure 13 shows that it is absent in at least four locations (14106820BBB, 14107028ACC, 14107115BAA, and 14307105AD), providing conduits for interaquifer groundwater exchange. Moreover, Figures A3, A4, A5, A8, A14, A15, and A21 in Sturgeon (2011) suggest that the two aquifers may be united near several other sites where the aquitard is quite thin or contains sand and gravel interbeds, or where the sand and gravel units in adjacent borings are staggered and provide a vertically zigzagging connection. In addition, water chemistry data imply one or more connections near 14107122AAA where the deep groundwater has extremely low concentrations of sodium, sulfate, and dissolved solids. And, water level responses to the capping and uncapping of a flowing well at 14106903CABA indicate a connection near 14106914BBB. Indeed, direct connections may be commonplace given the rapid, post-irrigation recovery of water levels in lower aquifer wells.

One final observation from the aforementioned map and cross sections is that the aquitard is often thin, interbedded, or absent in the vicinity of large lakes and sloughs, perhaps allowing for the discharge of lower aquifer groundwater to some of these surface water bodies. Potential connections between the lower aquifer and specific lakes are discussed in the next section.

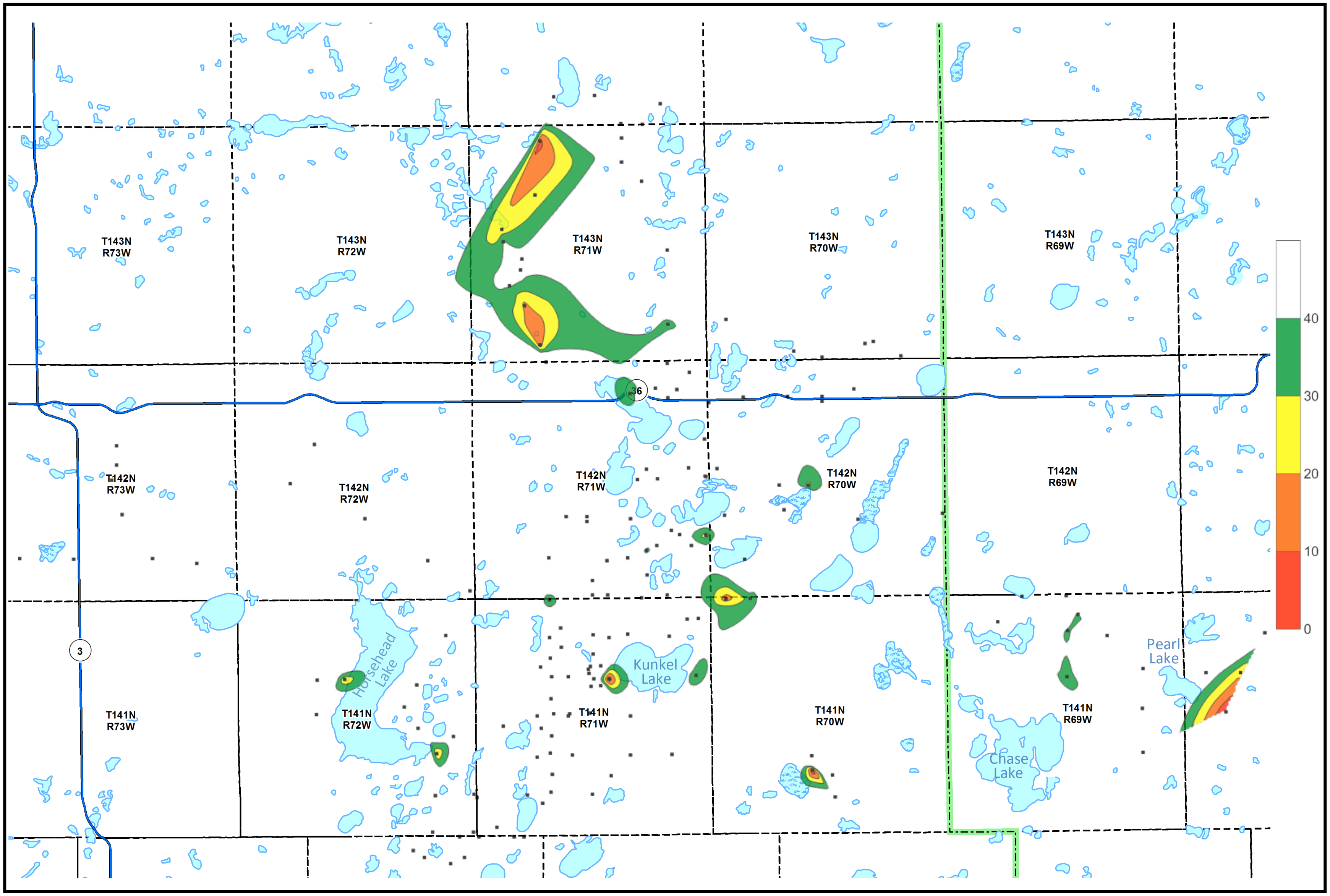


Figure 13. Aquitard thickness. Black dots are test hole or well locations where both the upper and lower aquifers are present. Colored contours delineate areas where the total thickness of silt and clay between the aquifers is less than 40 feet. These areas contain several of the known and probable points of groundwater exchange between the two aquifers.

GROUNDWATER DYNAMICS

The Upper Aquifer and Chase Lake
Groundwater in the upper aquifer moves from the highlands around the perimeter of the study area to five terminal lakes: Horsehead, Sink, Kunkel, Chase, and Pearl (Figure 14). Groundwater flow is fastest on the flanks of the highlands where the land surface elevation changes rapidly, and it slows considerably as the topography flattens near the terminal lakes. In all probability, the pitted outwash also contains smaller-scale groundwater flow systems (Toth, 1963; Freeze and Witherspoon, 1967) that cannot be detected with our regional scale observation well network.

In the area north of Chase Lake, the average groundwater velocity is roughly 1000 feet per year (assuming the hydraulic conductivity of the aquifer is 200 feet per day, the horizontal hydraulic gradient is -0.00357, and the effective porosity is 0.25). The slow rate of groundwater movement, relatively large drainage basin, and lack of an integrated drainage network help explain why water levels have been rising steadily in Chase Lake despite several recent years with little fall or winter precipitation. [According to Sloan (1972) and Winter and Rosenberry (1995) the upper aquifer is recharged primarily by precipitation that falls in late autumn through early spring.]

Water levels continue to rise in Chase Lake, because much of the large volume of water that fell on the basin in the mid- to late-1990s has not yet reached the lake. Precipitation that fell near the lake in the late nineties has already entered the lake and evaporated. Water that infiltrated and recharged the aquifer a little further from the lake is currently discharging to the lake, and precipitation that fell several miles from the lake is still on its way. It may take more than 40 years for most of the precipitation and snowmelt that entered the aquifer system near Highway 36 to reach Chase Lake.

Figure 14 not only reveals the pattern and rate of flow in the upper aquifer, it also reveals two major groundwater divides. One coincides with the surface water divide that separates the Apple Creek and Pipestem River sub-basins. The other extends from Round Lake, down the longitudinal axis of Brock Slough, and along the crest of the recessional moraine west of Chase Lake.

All of the shallow groundwater between these two divides passes beneath any intervening sub-watershed divides (Figure 15) and ends up in Chase Lake. The low concentrations of dissolved solids in Brock Slough, Chicago Lake, and Lake Louise (420, 690, and 770 milligrams per liter, respectively, in 2001) support this interpretation, because they show that these water bodies are not terminal lakes. In addition, the large size and high salinity in Chase Lake (47,300 mg/l in 1984 and 13,500 mg/l in 2001) strongly suggest it is the terminal lake for groundwater from more than one sub-watershed.

Since the shallow groundwater between these two divides ultimately discharges to Chase Lake, and pumping from this area may remove water that would otherwise enter the lake, the US Fish and Wildlife Service (USFWS) is concerned about the impact of agricultural development on the lake. The Chase Lake National Wildlife Refuge was established in 1908 by President Theodore Roosevelt to protect the American White Pelican. The birds nest on islands in the large saline lake, and changes in the lake level impact the area available for nesting and the ability of predators to access the islands.

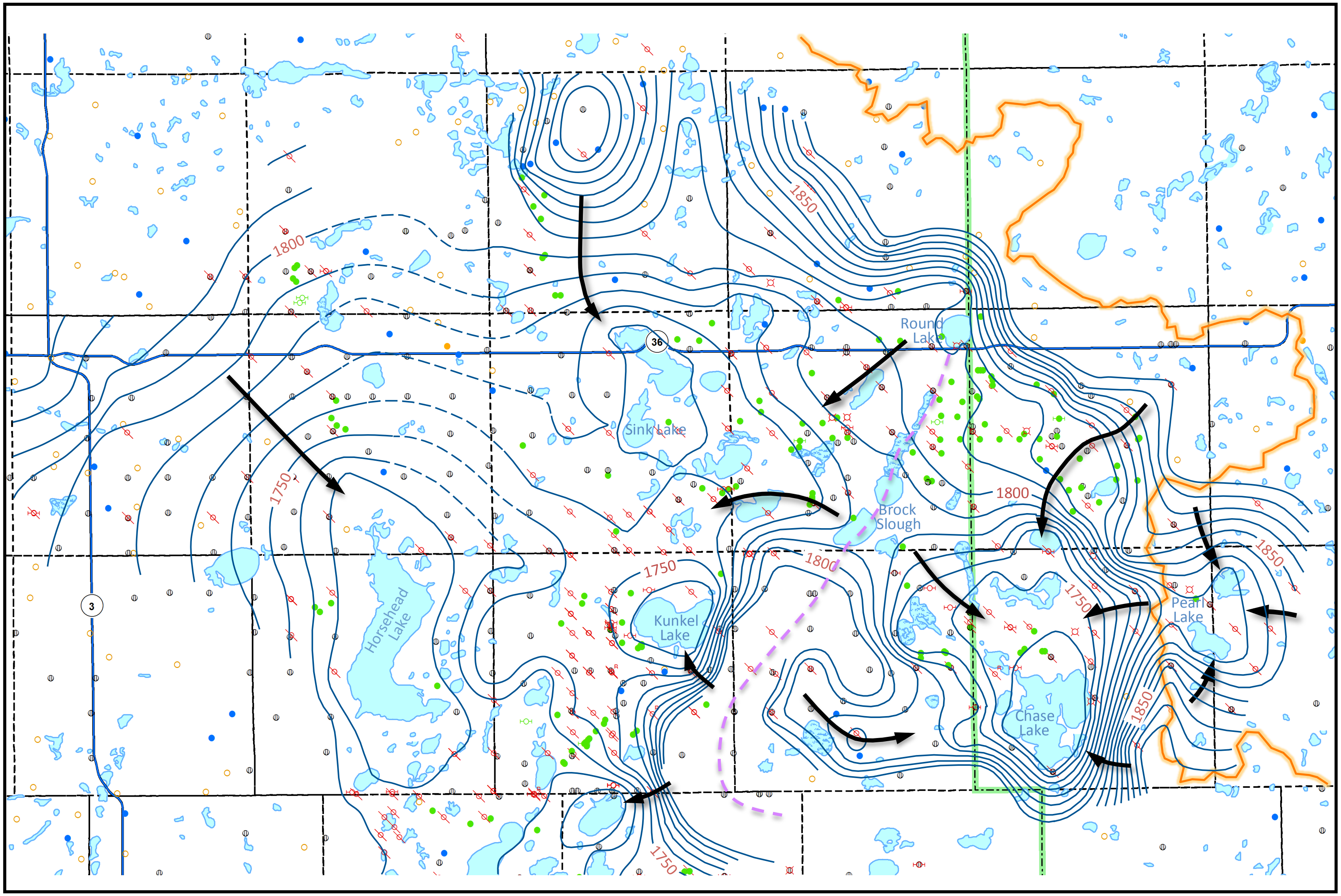


Figure 14. Potentiometric surface for the upper aquifer (April 2010). Black arrows indicate the direction of groundwater flow. Note the presence of two major groundwater divides: the Apple Creek / Pipestem River sub-basin divide shown in orange, and a northeast-southwest trending divide shown in purple. The latter divide is caused in part by the arcuate recessional moraine west of Chase Lake (Figure 4).

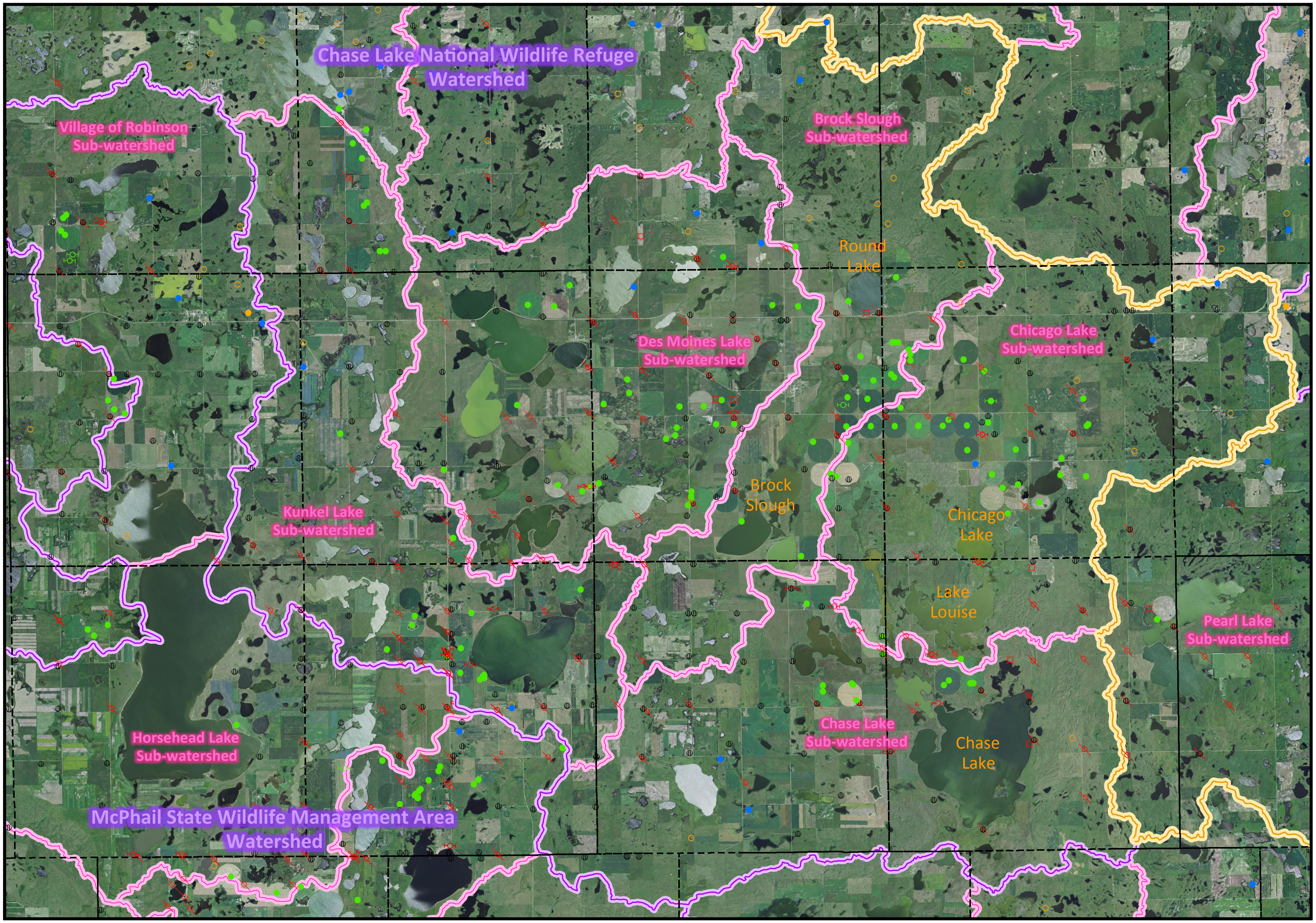


Figure 15. Basin and watershed boundaries. The yellow line separates the HUC8 Apple Creek and Pipestem River sub-basins. The purple lines delineate HUC10 watersheds, and the pink lines separate HUC12 sub-watersheds. According to the water level data summarized on Figure 14, groundwater east of Round Lake and Brock Slough and west of the Apple / Pipestem sub-basin divide eventually discharges to Chase Lake.

At present, total permitted water use from the area between the two divides is about 9500 acre-feet. The cumulative effect of this irrigation is being measured and monitored by an extensive observation well and staff gauge network that encircles the refuge and extends outward for several miles in all directions. The measurements show that water levels in the upper aquifer are higher today than they were in the 1980s when there was very little irrigation in the county (Figure 16).

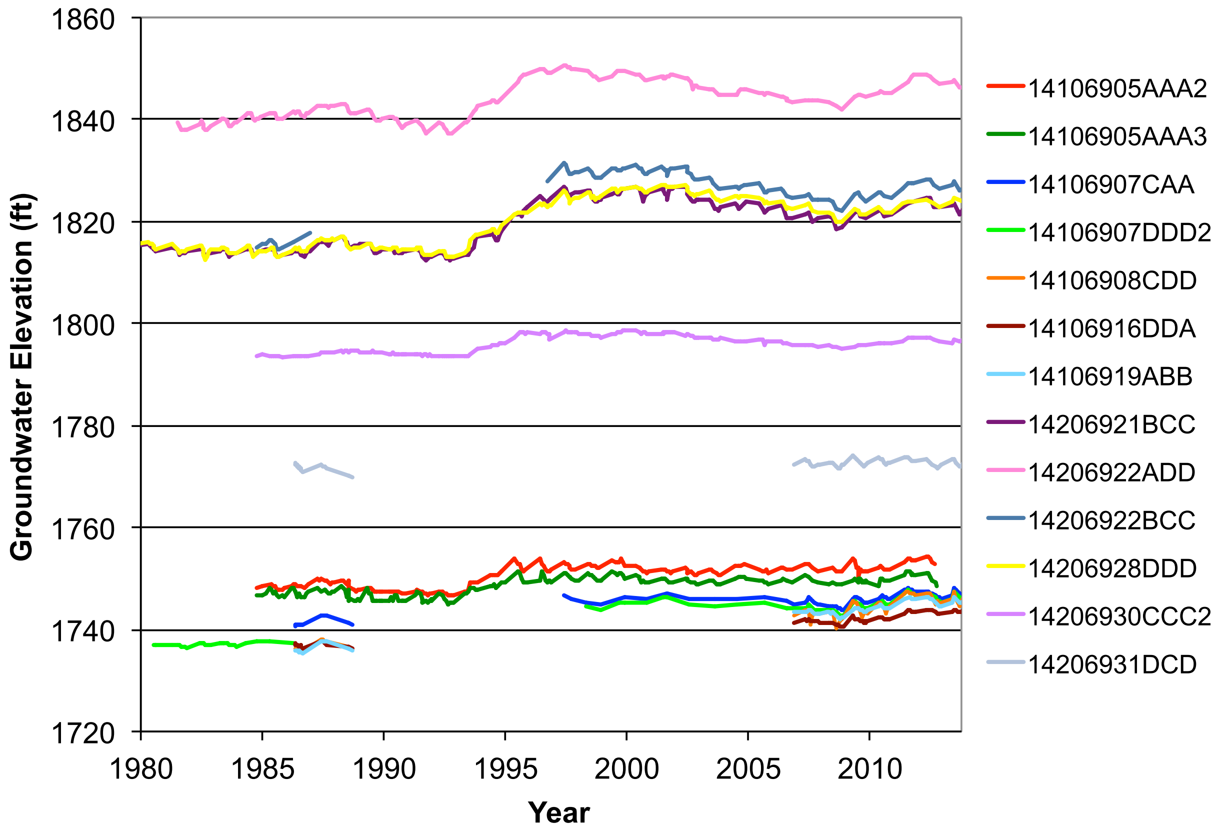


Figure 16. Hydrographs for the 13 upper aquifer wells in Chase Lake (T141N R69W) and Marstonmoor (T142N R69W) Townships that have water level records in the 1980s. The chart shows that water levels increased significantly in the mid- to late-1990s, and they are not significantly affected by irrigation.

Two US Geological Survey maps (1985, 1986) show that the water level in Chase Lake is 15 feet higher today than it was in 1985 and 1986, and the staff gauge installed in the lake in 2007 reveals that the lake level dropped no more than one foot during each of the past eight years due to the combined effects of irrigation and evaporation (Figure 17). The readings also show that any seasonal decline was offset by irrigation return flow and natural recharge during the off-season, because each year the early springtime lake level was as high or higher than it had been in the previous spring.

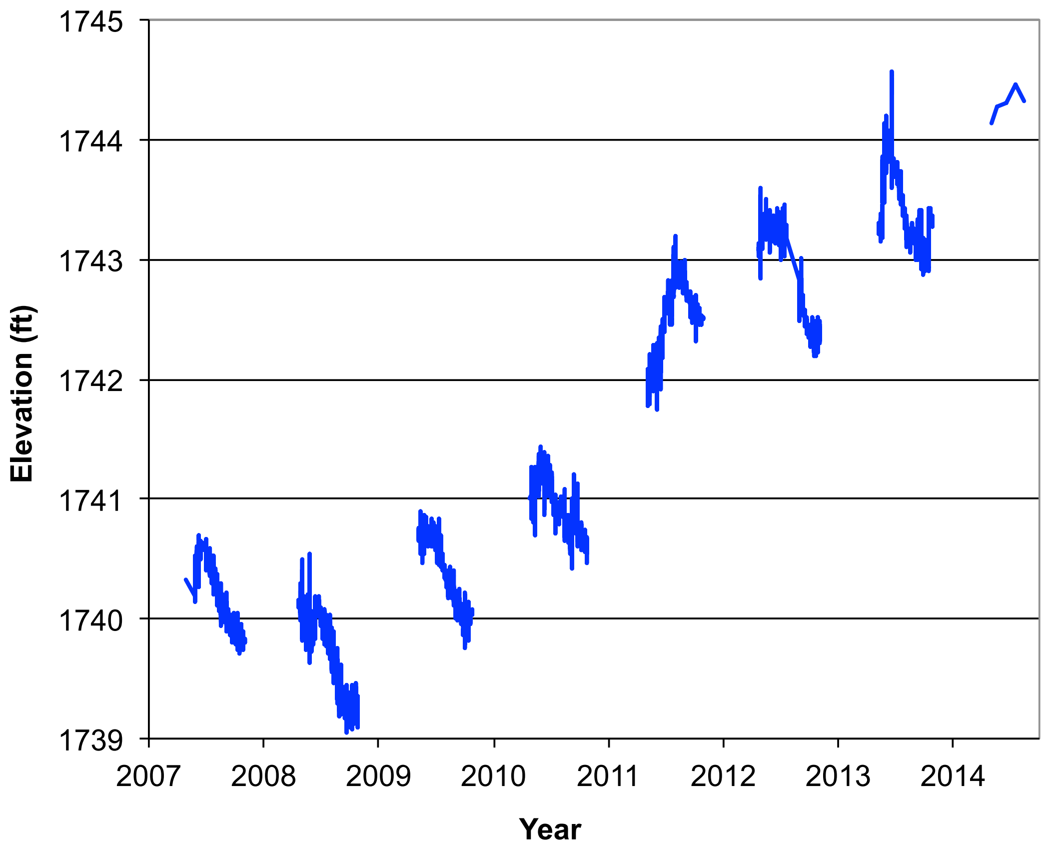


Figure 17. Hydrograph for the staff gauge in Chase Lake. The period of record includes the last two years of a nine-year stretch (2000 to 2008) with little fall and winter precipitation. Note that the combined effects of irrigation and evaporation cause the lake level to drop less than one foot each year. Also note that in every year, early springtime lake levels were as high or higher than they had been in the previous year. At the time of publication, the only lake level data available for 2014 were the five manual measurements taken between May 1 and August 13.

In short, the available information suggests that the current amount of irrigation has a very small, if perceptible, impact on the lake. Nevertheless, even a very small impact could be considered unacceptable when the lake level is low. Therefore, in order to balance the interests of refuge protection and irrigation development, any future water permits issued near the lake will include a condition that prohibits irrigation during any year in which the previous November water level in Chase Lake is below the spillway at the Chase Lake dam.

In a letter to the North Dakota State Engineer dated May 13, 1938, the USDA Bureau of Biological Survey included plans for the construction of a dam to keep water out of the lake, presumably to maintain what they believed to be the optimum water level for nesting. This dam has been completely submerged for the past 15 years based on available aerial photographs. According to the original blueprints for the dam, the spillway is exactly four feet below the crest of the dam. However, the elevations posted on the blueprints are relative to an arbitrary benchmark, and the USFWS has been unable to provide an elevation relative to sea level. A few online sites claim that the elevation of the top of the dam is 529 meters, or 1735.6 feet, but they do not cite their sources. Until a more accurate elevation relative to sea level can be obtained for the spillway, the action level will be 1731.6 feet.

The Upper Aquifer and Pearl Lake

There appear to be three aquifers east of Chase Lake: a surficial (unconfined) aquifer and two confined aquifers. The lower confined aquifer occurs at roughly the same elevation as the lower aquifer in Kidder County and will be discussed separately in the next subsection. The upper confined aquifer occurs at the same elevation as the upper aquifer north and west of Chase Lake, and the surficial aquifer lies at a higher elevation (Figure 8). Although the surficial aquifer is set higher on the landscape, its sands and gravels are physically continuous with the upper aquifer sands and gravels elsewhere in Stutsman and Kidder Counties (Figures 4 and 8).

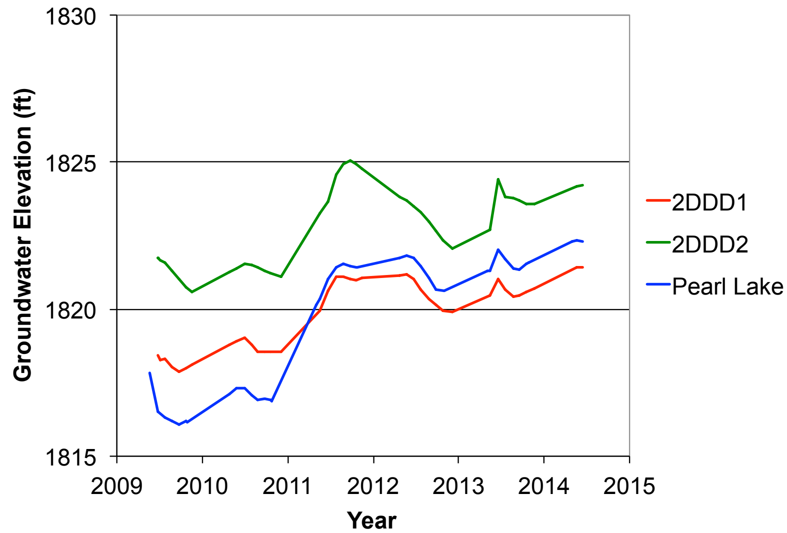
The relationship between the unconfined and upper confined aquifers is not clear. They may be so frequently interconnected that they can be considered a single aquifer with a discontinuous, intervening clay layer, or they may be unconnected or rarely connected and better conceptualized as separate aquifers. Figure 8 in this report and Figures A3 and A4 in Sturgeon (2011) suggest that the two aquifers are generally unconnected apart from a likely connection near Pearl Lake and their eventual merger near the western shore of Chase Lake.

Although both aquifers cross the topographic divide that separates the Apple Creek and Pipestem River sub-basins, Figure 13 in this report and Figure 19 in Sturgeon (2011) show that the water levels along the divide north and south of 14106902DDD are so much higher than the water levels on either side of the divide that, north and south of 2DDD, the divide acts as a permanent barrier to flow in both aquifers. In other words, the aquifer sands and gravels cross the divide, but the groundwater does not. Groundwater west of the divide flows toward Chase Lake, and groundwater east of the divide flows toward Pearl Lake.

The situation at 2DDD, which occupies a low point on the divide, is more complicated. Water levels in the unconfined well (2DDD2) have remained higher than water levels on either side of the divide since monitoring began. Therefore, the entire length of the divide appears to be a permanent barrier to flow in the unconfined aquifer.

When monitoring began in 2009, water levels in the upper confined well (2DDD1) were also higher than water levels on either side of the divide, so the upper confined groundwater did not cross the divide. However, as water levels in the area continued to rise, the relationship between the water levels in 2DDD1 and Pearl Lake reversed (Figure 18). If the upper confined aquifer and Pearl Lake are connected, water in the upper confined aquifer east of the divide may now be passing beneath the divide at 2DDD en route to Chase Lake. Consequently, the topographic divide at 2DDD may only be a transitory barrier to flow in the upper confined aquifer, and Pearl Lake may only be a terminal lake during extended periods of relatively dry weather.

Figure 18. Hydrographs for Pearl Lake and two wells on the Apple Creek / Pipestem River sub-basin divide at 14106902DDD. Water levels in the unconfined well (2DDD2) have been higher than Pearl Lake throughout the period of record. Water levels in the upper confined well (2DDD1) were higher than the lake in 2009 and 2010 and lower than the lake since 2011.



The Lower Aquifer and Chase Lake

The pattern of groundwater flow is simpler in the lower aquifer compared to the upper aquifer (Figure 19). In northern Kidder County, the lower aquifer groundwater generally flows from north to south. In northwestern Stutsman County, the flow appears to be to the west and southwest, and it is not affected by the Apple Creek / Pipestem River divide.

There are relatively few lower aquifer wells in northwestern Stutsman County, so additional test drilling is needed to improve our understanding of the nature and extent of the aquifer in this part of the study area. Based on our available information, it appears that the lower aquifer in Stutsman County is not connected to the lower aquifer in Kidder County (Figure 7). Instead, it unites with the upper aquifer north and east of Chase Lake. This interpretation is based in part on the response of the upper aquifer to the pressurizing and depressurizing of an artesian, lower aquifer well at 14106903CABA.

From July to October 2009, the well at 3CABA was periodically capped and uncapped, while water levels were monitored in five upper and three lower aquifer wells. The upper aquifer at 1410693CCC, 5AAA, 11BBB, and 16DDA was not affected by the actions at the test well (Figures 20 and 21). The response in the upper aquifer at 14BBB, which is situated southeast of the test well and northeast of the lake, along with the strong upward hydraulic gradient at the two nested well sites that lie between the test well and the lake (14106903CCC and 14106915BBBC), suggest that the groundwater in the lower aquifer merges with the upper aquifer north and east of Chase Lake and ultimately enters the lake. Additional evidence for the convergence of upper and lower aquifer groundwater en route to Chase Lake includes the observation that the lower aquifer groundwater flows toward the lake, and yet the lower aquifer appears to terminate a short distance north and east of the lake (Figure 7).

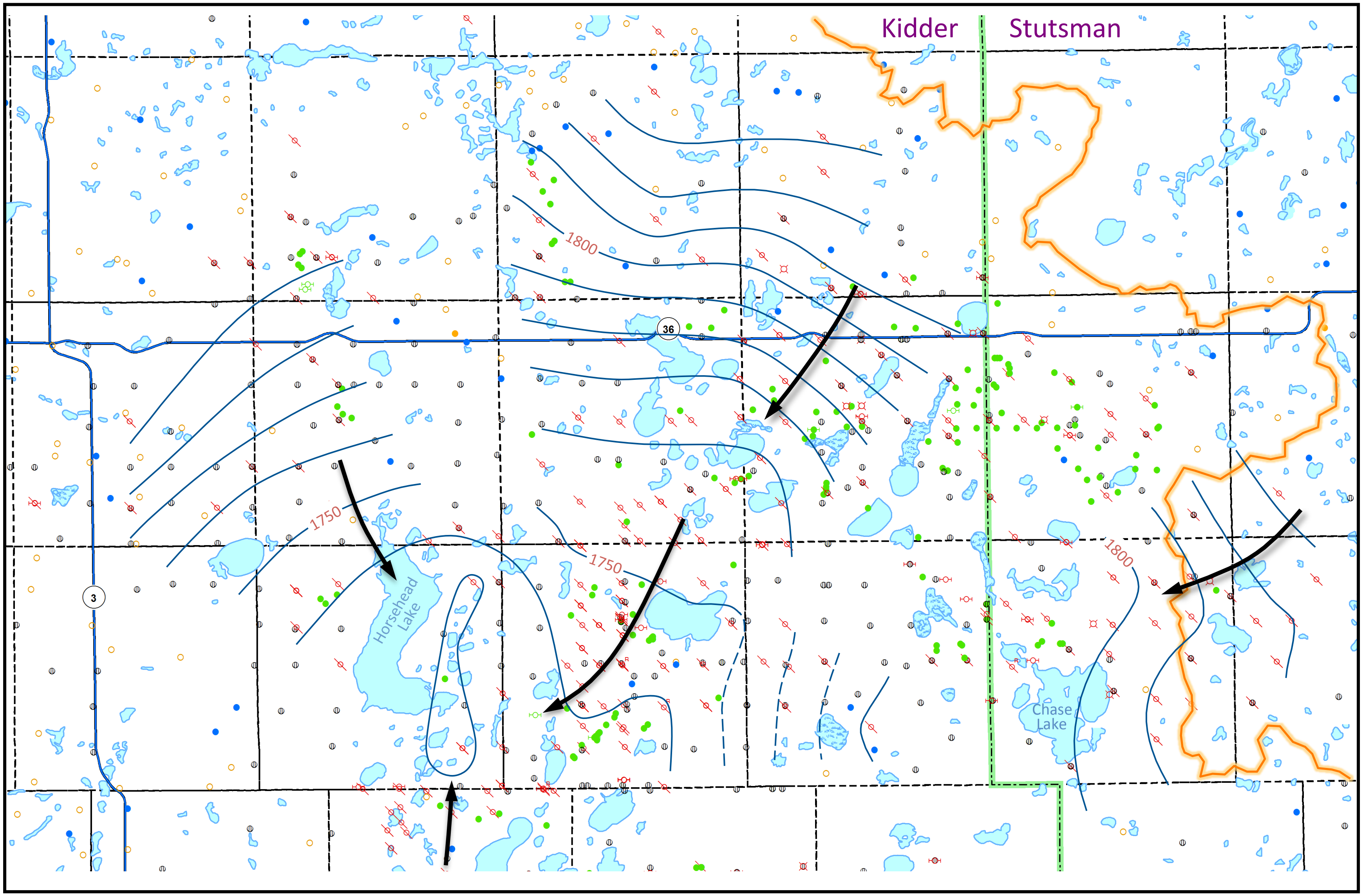


Figure 19. Potentiometric surface for the lower aquifer (April 2010). In Stutsman County, the lower aquifer groundwater ultimately discharges to Chase Lake. In Kidder County, the lower aquifer groundwater discharges to the middle aquifer that lies roughly 22 feet below Horsehead Lake (Figures 9 and 11). If the middle and upper aquifers are connected beneath the lake, the lower aquifer groundwater subsequently discharges to the lake.

Figure 20. Hydrographs for quasi aquifer test observation wells with water levels between 1740 and 1765 feet. The background well at 19ABB was included to show the trend in the upper aquifer outside the test area. There was no response to the capping and uncapping of the artesian test well in these upper aquifer wells.

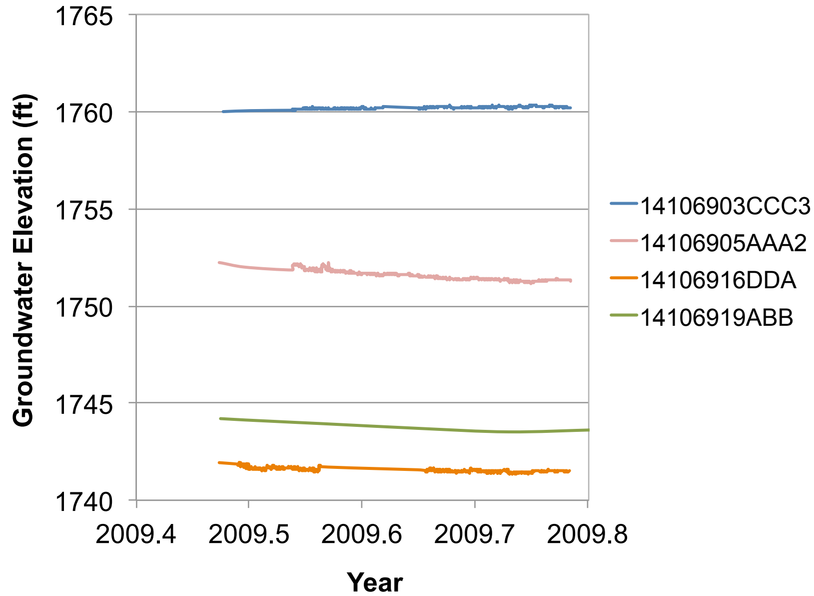
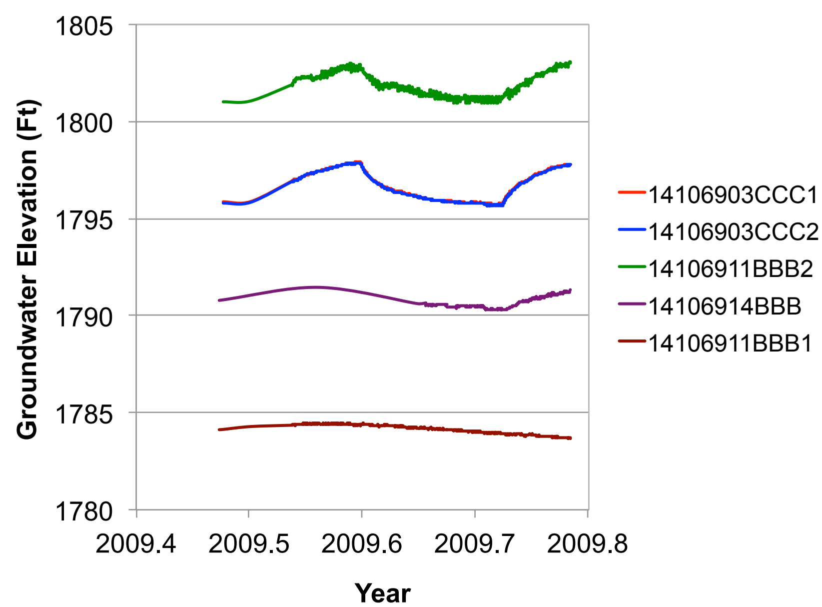


Figure 21. Hydrographs for quasi aquifer test observation wells with water levels between 1780 and 1805 feet. The upper aquifer at 11BBB was unaffected by the pressurizing and depressurizing of the test well. On the other hand, water levels in the lower aquifer at 3CCC and 11BBB responded almost immediately, and water levels in the upper aquifer at 14BBB showed a clear, albeit subdued response.



The Lower Aquifer and Horsehead Lake

There is a groundwater divide in the lower aquifer south of the study area that trends east to west across the middle of T139N R72W. Groundwater south of the divide flows to the south. Groundwater north of the divide flows north toward Horsehead Lake, where it meets with the southerly flowing lower aquifer groundwater from northern Kidder County (Figure 19). The large volume of deep groundwater converging near the lake does not flow downward into the underlying bedrock, because the Pierre Formation is essentially impermeable, and the heads in the Fox Hills Formation are higher than those in the lower aquifer. Instead, it appears that the deep groundwater discharges to the overlying intermediate aquifer, as the groundwater has to go somewhere, and there is an upward hydraulic gradient between the two aquifers at 14107216CCC. There is also an upward gradient between the intermediate and upper aquifers at the only other nested well site near the lake (14207235CCDA). Therefore, groundwater in the intermediate aquifer may subsequently discharge to the upper aquifer and the lake, provided there is a hydraulic connection between the aquifers somewhere near the lake.

There does not appear to be a connection anywhere near 35CCDA, as the water chemistries for the intermediate and upper aquifers at 35CCDA are very dissimilar. Moreover, the volume of water in Horsehead Lake fluctuates dramatically from one year to the next, suggesting that the lake may not be fed by a steady supply of deep groundwater. Instead, there may be a more complex flow situation near the lake where the deep groundwater discharges to the intermediate aquifer and then flows to the south within the intermediate aquifer until the intermediate and upper aquifers merge south of the lake near 14107233CDD and 34CDD (Figures A2 and A12 in Sturgeon, 2011).

GROUNDWATER AVAILABILITY

At Present

Twenty-four groundwater permit applications have been processed since the publication of Sturgeon (2011), and there are now a total of 101 industrial, irrigation, and municipal groundwater permits approved in northern Kidder and northwestern Stutsman Counties. These 101 permits allow for the extraction of 25,460 acre-feet of groundwater and the irrigation of 17,260 acres of land. There is also 1 application for which a decision has been made to defer action, and 18 applications for which a decision is pending. (The oldest pending application was submitted to the State Engineer in 2012.) The requested water and land associated with these deferred and pending applications are 4751 acre-feet and 2793 acres, respectively.

The current level of appropriation from the northern half of the CDAS appears to be sustainable, assuming the climate continues to be similar to what it has been since the early 1980s (Figures 16 and 22). Nevertheless, the lower aquifer is near full appropriation in Pettibone, Lake Williams, and Buckeye Townships based on: 1) groundwater modeling forecasts, 2) complaints of poor late-season well performance by some growers, and 3) prohibitively high sodium concentrations in the groundwater where the lower aquifer abuts the underlying Fox Hills Formation. To date, there have been no legitimate reports of well interference in the upper aquifer, and poor water quality has only been a problem near the shore of Horsehead Lake, where flooding has occasionally inundated the land with saline lake water (Sturgeon, 2013).

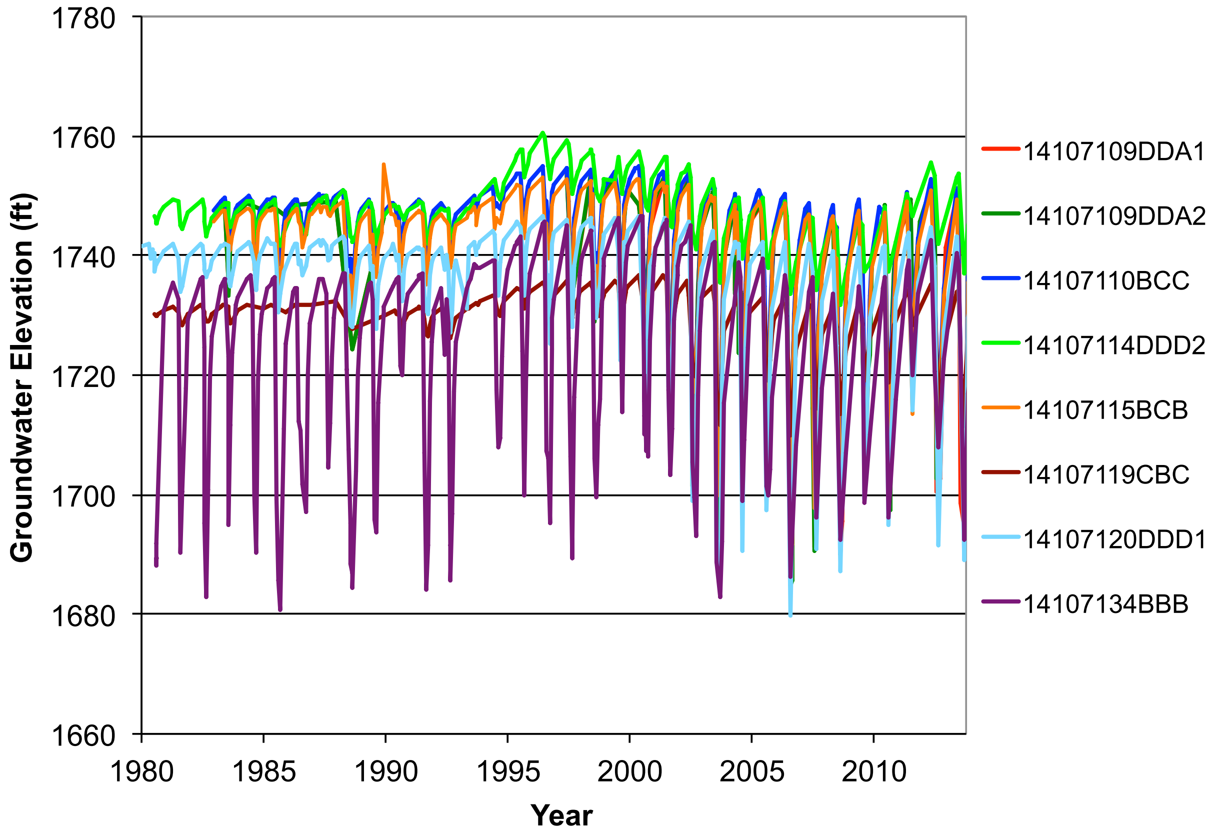


Figure 22. Hydrographs for the eight lower aquifer wells in Buckeye Township (T141N R71W) with water level records in the 1980s. Although seasonal drawdowns can exceed 60 feet, annual changes in springtime water levels are typically less than one foot per year, and springtime water levels are as high or higher today than they were 30 years ago.

In the Future

The potential for additional irrigation development is poor throughout much of the study area, because most of the land that is suited for irrigation has already been developed. In many cases, the remaining tracts of land are covered with marginally irrigable soils, or they are situated where the aquifer system is fully appropriated or its transmissivity is prohibitively low (Figure 23). For example, there is a considerable amount of water beneath the hummocky till that blankets most of Petersville (T143N R70W) and Frettim (T143N R71W) Townships, but the soils are rocky and clay-rich and the slopes are steep. The opposite problem is encountered in Lake Williams (T142N R71W), Robinson (T142N R72W), and eastern Clear Lake (T142N R73W) Townships, where there are large expanses of relatively flat, sandy soils, but transmissivity constraints and water quality issues limit their development. Three of the more promising areas for future development are: 1) the outwash covered land in Wallace (T144N R71W) and Merkel (T144N R72W) Townships, 2) the area east of the Apple Creek / Pipestem River divide and west of Highway 68, and 3) Tuttle (T142N R74W) and western Clear Lake (T142N R73W) Townships.

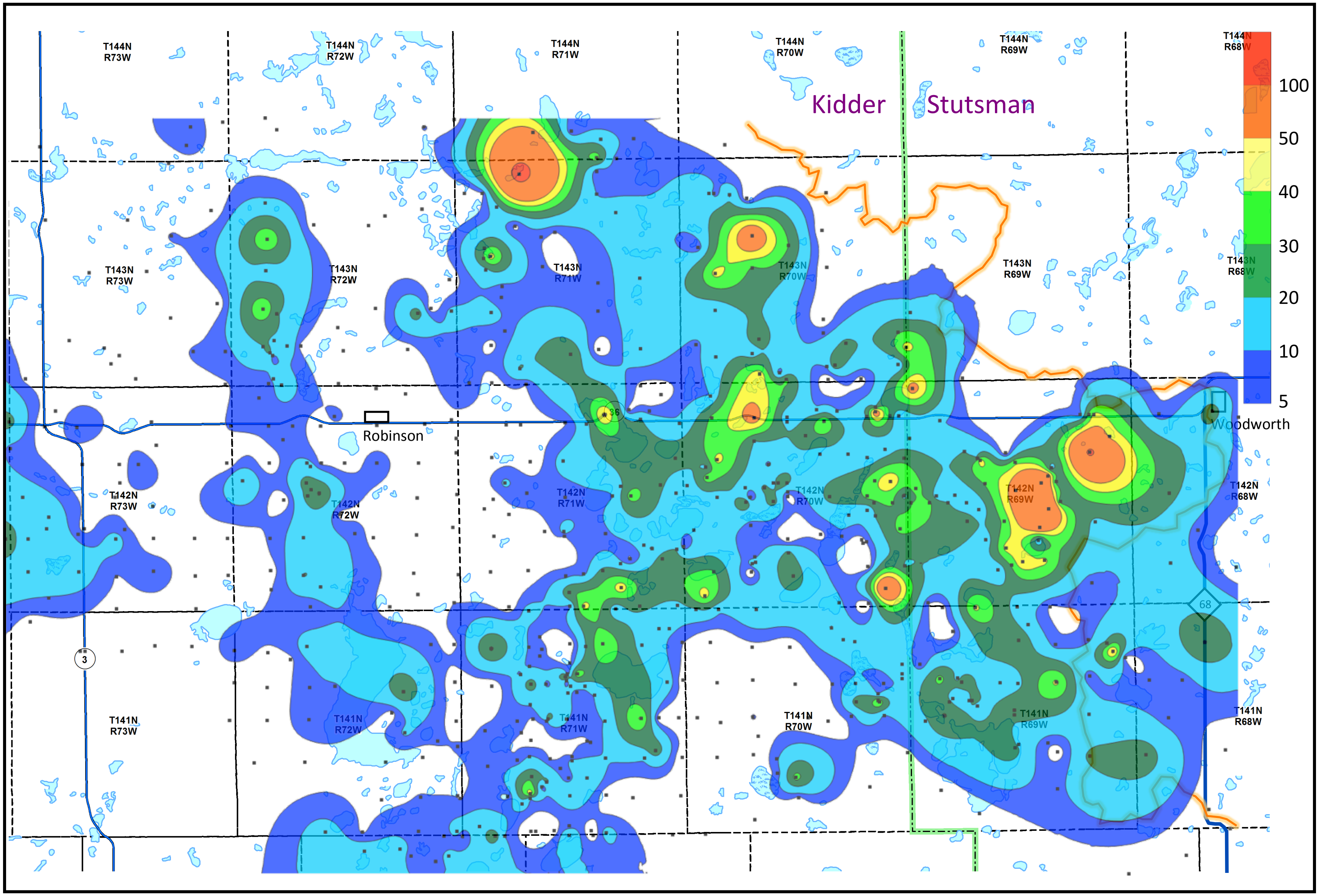


Figure 23. Estimated transmissivity (1000 ft^2/d) of the Central Dakota Aquifer System. Map includes the sand and gravel units that occasionally occur between the upper and lower aquifers, but it does not include the isolated sand and gravel deposits that lie above the upper aquifer or below the lower aquifer. See Sturgeon (2011) for a discussion of how transmissivity is calculated for each data location. Note the wide range of transmissivity values arising from the dramatic spatial variations in aquifer thickness and lithology.

Quite a few sections of land in Wallace and Merkel Townships are overlain by sandy soils derived from glacial outwash (Figure 4). However, there are very few wells in the area, so little is known about the aquifer system this far north in Kidder County.

There appears to be plenty of water east of the Apple Creek / Pipestem River divide. At present only 195 acre-feet is being diverted for irrigation, and additional withdrawals should not unduly impact the CLNWR. Years of monitoring on both sides of the Apple-Pipestem divide indicate that it is a hydrologic boundary for the unconfined and upper confined aquifers when water levels are low (page 22 and Figure 18). Since the groundwater in these aquifers only crosses the divide when water levels are high, appropriation from the unconfined and upper confined aquifers east of the divide should have no negative impact on the refuge. On the other hand, groundwater in the lower confined aquifer always crosses the divide and eventually ends up in Chase Lake. However, the large size of the aquifer, the distance from the refuge, and the current lack of any appropriation strongly suggest that with careful management, it could be exploited without harming the refuge.

Tuttle Township, at the western edge of the study area, is largely unexplored. The soils in this area are deep, coarse textured, and well drained, but the thickness and lateral extent of the aquifer system beneath the soils are not well known. It is likely that its groundwater resources are similar to those in adjacent Clear Lake Township, where recent test drilling has revealed up to 60 feet of saturated sand and gravel in the upper aquifer (Figure 6). Consequently, Tuttle and western Clear Lake Townships may contain many parcels of land with both the water and soil needed for high-value crop production.

Horizontal Irrigation Wells

Even where the saturated thickness is only 20 feet or so, horizontal wells may allow for some additional irrigation development in Tuttle, Clear Lake, and other townships where soil conditions are favorable, and the upper aquifer is too thin for conventional production wells. Numerical modeling demonstrates that a single horizontal well with an 800-foot lateral can provide enough water to irrigate 135 acres of land when conditions are ideal (a water table within 5 feet of the land surface and at least 20 feet of saturated and homogeneous sand or gravel throughout the well's capture zone). However, field trials in Kidder County are indicating that longer laterals or multiple laterals may be required in many cases, because the capture zones often contain a significant amount of clay.

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