Eastern Nebraska Water Resources Assessment (ENWRA)

INTRODUCTION TO A HYDROGEOLOGICAL STUDY

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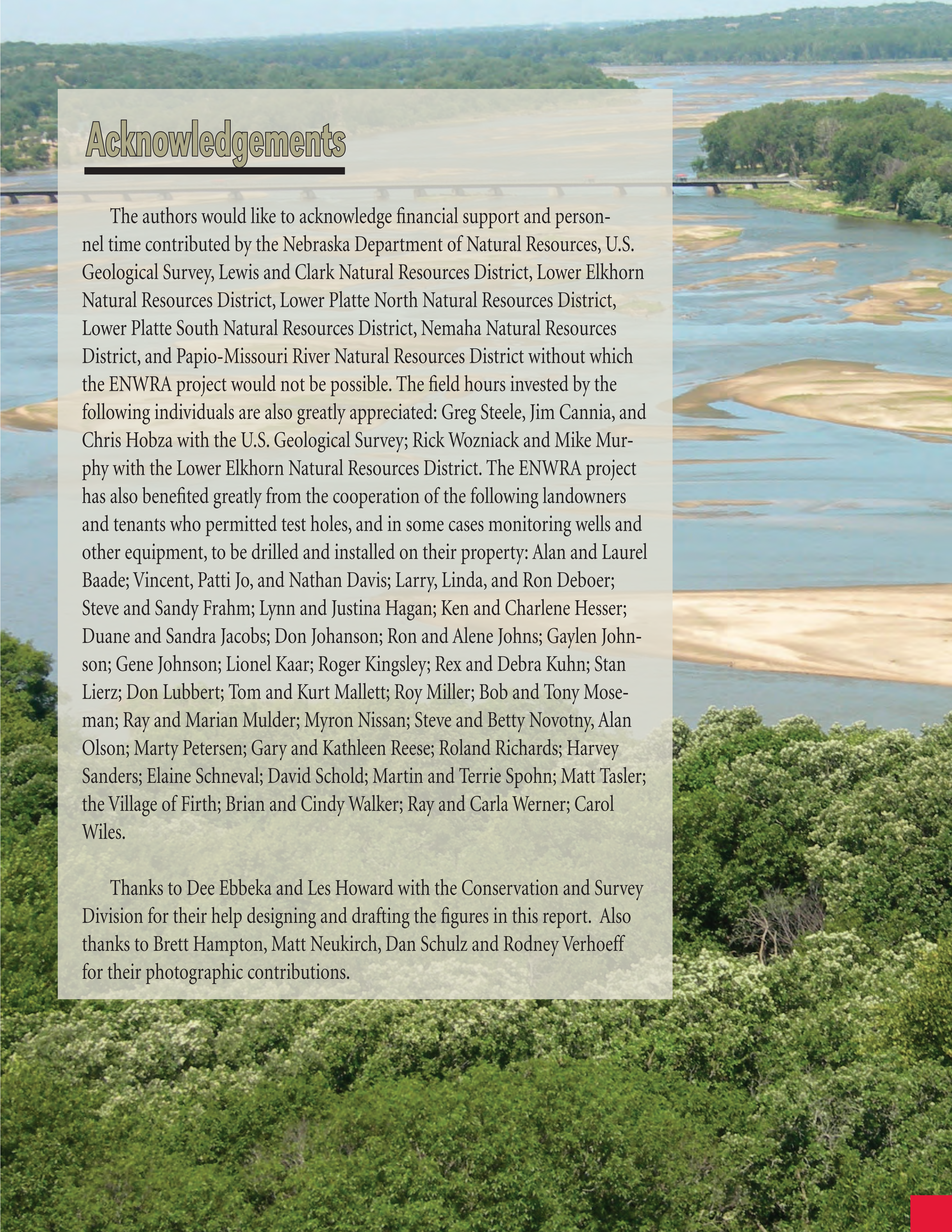
Geologic Time Scale for Nebraska

Era	Period	Epoch	Age, Ma	Group or Formation	Lithology	Water-Bearing Properties
Cenozoic	Quaternary	Holocene	present to 0.01	Recent alluvium	sand, silt, gravel and clay	Principal aquifers for municipal and irrigation
		Pleistocene	0.01-0.06	Peoria	loess	Not an aquifer
				Gilman Canyon		
				Loveland		
			0.06 to ~2.0		glacial till	Not an aquifer
					sand, gravel, silt, clay associated with glaciers	Aquifers for irrigation, small municipalities, domestic. Sometimes paleovalley aquifers.
	Tertiary	Pliocene	~2.0 to 5			
		Miocene	5 to 24	Ogallala	sand, sandstone, siltstone, and some gravel	Principal aquifer in most of western Nebraska, not present in eastern Nebraska
		Oligocene	24 to 37	Arikaree	sandstone and siltstone	
				White River	siltstone, sandstone, and clay in lower portion	Secondary aquifer in west; water may be highly mineralized
		Eocene	37 to 58	Rocks of this age are not identified in Nebraska		
		Paleocene	58 to 67			
Mesozoic	Cretaceous	Late Cretaceous	67 to 98	Lance	sandstone and siltstone	Generally not an aquifer
				Fox Hills		
				Pierre	shale	Not an aquifer
				Niobrara	shaly chalk and limestone	Secondary aquifer where fractured and at shallow depths, primarily in northeast
				Carlile	shale; in some areas contains sandstones in upper part	Generally not an aquifer; sandstones yield water to few wells in the northeast
				Greenhorn-Graneros	limestone and shale	
		Early Cretaceous	98 to 144	Dakota	sandstone and shale	Secondary aquifer in the east
	Jurassic		144 to 208		siltstone, some sandstone	Not an aquifer
	Triassic		208 to 245		siltstone	Not an aquifer
Paleozoic	Permian		245 to 286		Limestones, dolomites, shales, and sandstones	Some sandstone, limestone, and dolomites are secondary aquifers in the east. Water may be highly mineralized.
	Pennsylvanian		286 to 320	Lansing, Kansas City, Douglas		
	Mississippian		320 to 360			
	Devonian		360 to 408			
	Silurian		408 to 438			
	Ordovician		438 to 505			
	Cambrian		505 to 570			
Precambrian						

Adapted from: The Groundwater Atlas of Nebraska, Anonymous, 1998



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1. The Challenge of Water Supply in Nebraska

1.1. Groundwater: A Critical Resource

Supplying adequate water for drinking, household use, and irrigation presents a considerable challenge for many places on Earth (World Water Assessment Program, 2006a). Water supply is emerging as a global crisis to which even the USA is not immune. Parts of the southern Great Plains, for example, have experienced groundwater-level declines of as much as 277 ft (84 m) since irrigation development began, presenting a definite limit on production agriculture (McGuire, 2007).

From a Nebraska standpoint, the link between groundwater and civilization across the Great Plains and adjoining regions is fundamental (e.g., White, 1994; Burbach and Joeckel, 2006). Groundwater supplies in most of the state are abundant because it encompasses a major part of the High Plains Aquifer, one of the largest groundwater reservoirs in the world (Gutentag et al., 1984). In eastern Nebraska, where 70% of the state's population lives at or beyond the easternmost limit of the High Plains Aquifer, the use of surface water supplements the pumping of less abundant groundwater reserves. Therefore, understanding the intimate connection between surface water and groundwater is particularly necessary in the eastern part of the state. As water-use and population pressures increase, and as projected changes in global climate loom, it has become clear that Nebraskans can no longer take their water supply for granted.

In 1999, Nebraska entered into what would become an eight-year drought. Although this drought was not the first one Nebraskans had faced, it attained special significance because it followed a 30-year period of unprecedented development of groundwater irrigation. Burgeoning groundwater use since 1950 has been a trend not only in Nebraska but also across much of the western half of the United States following the development of new technologies such as center-pivot irrigation (Sheffield, 1993; Glennon, 2002). Only two years into the 1999-2006 drought local groundwater levels in Nebraska had dropped, some streams always known to have flowed were going dry, and the discharges of streams that were still flowing were noticeably diminished. The linkages between surface water and groundwater in Nebraska, as well as the need to develop a better understanding of both, were more apparent than ever.

The existence of interstate legal battles over water further underscores the need to know more about groundwater and groundwater-surface water interactions. The State of Kansas sued Nebraska in 1998 over flows in the Republican River, exacerbating issues that would be raised by the drought that began the next year. Negotiations between the two states continued until 2003. In Nebraska, the subsequent legal settlement spurred: (1) new groundwater-use allocations, (2) incentive programs to temporarily or permanently retire irrigated acres, and (3) the purchase of surface water leases. Many eastern Nebraskans began to consider a proactive assessment of water resources in hopes of circumventing similar water-resources problems in the future.

1.2. Governance of Water in Nebraska

As water became scarcer in Nebraska during the 1999-2006 drought, rights to the remaining water became an issue of great contention. The laws regulating groundwater use in Nebraska are separate from those that address surface water use. The Nebraska Department of Natural Resources (DNR), a state agency, regulates the use of surface water statewide, while 23 separate Natural Resources Districts (NRDs) manage groundwater use locally.

Platte River near Grand Island, Nebraska.

In hopes of diffusing conflicts resulting from disparate water laws, and to anticipate and prevent conflicts between groundwater and surface-water users, the Nebraska State Legislature passed bill LB962 in 2004. This bill gave the Nebraska DNR new authority to regulate groundwater in areas classified as having groundwater-surface water connections. Therefore, identifying areas in which groundwater and surface water are interconnected is of paramount importance.

1.2.1 Surface Water Law

According to Section 46-202 of the Nebraska Reissue Revised Statutes, surface water is the property of the public (Nebraska State Legislature, undated). A prospective user of surface water must file an application with the DNR in order to appropriate a specific amount of water. Surface water resources are regulated by the "first in time is first in right" priority system (Chapter 46-203). Therefore, if there is not enough surface water available to a senior appropriator, junior water users are not allowed to withdraw any water until the senior user is able to pump all of the water that is his/her right to use.

1.2.2 Groundwater Law

Groundwater is shared by everyone and can be withdrawn for reasonable and beneficial uses on the overlying land, according to the American or Reasonable Use Doctrine (Anonymous, 2008). In times of water shortage, all groundwater users get less water in keeping with the correlative rights of others and the provisions of the Nebraska Ground Water Management and Protection Act, Chapter 46, Article 6 (Nebraska State Legislature, undated). Prior to the formation of groundwater management areas, no permits were required to develop and use groundwater resources. The majority of the state is now controlled by management areas that require permits be obtained from the local NRD for all wells that are designed to pump more than 50 gallons per minute.

The only Nebraska law that pertains to both kinds of water resources is the preference system, as outlined in sections 46-613 and 46-204 of the Nebraska Reissue Revised Statutes (Nebraska State Legislature, undated). This system gives highest preference to domestic water use, then agricultural uses, and finally manufacturing or industrial purposes. The chief basis of groundwater use laws is court decisions (Ginsberg, 1981).

2. Recent History of Hydrogeologic Studies in Nebraska

2.1. High Plains Aquifer Modeling Studies

Although the geology of the High Plains Aquifer is partially characterized and groundwater levels are monitored across the plains, the relationships between the aquifer and the streams that flow across the superjacent landscape are understood only at a rudimentary level. Several hydrogeologic modeling studies are beginning to improve the understanding of this issue. Two studies in Nebraska, the Cooperative Hydrology Study (COHYST) and the Elkhorn-Loup Model (ELM), have been underway for several years (*Figure 1*).

COHYST is centered on the Platte River Valley and was initiated in the late 1990s to collect hydrogeologic data and build a computer model of local hydrology. The impetus for COHYST was an agreement between Colorado, Wyoming and Nebraska to preserve flows in the Platte River for endangered species. As a result of COHYST, connections between the Platte River, its alluvial fill, and the High Plains Aquifer were already being quantified by the time LB962 was passed.

The ELM focuses on building a computer model that encompasses almost 31,000 square miles (80,300 km^2) around the Elkhorn and Loup rivers. The purpose of the ELM is to characterize the groundwater system and to evaluate groundwater-surface water interactions. The first phase of the model was completed in 2007.

Geologists were able to build the COHYST and ELM models because the geographic extent of the High Plains aquifer had already been established, and because its geology was understood at a coarse scale of resolution. In eastern Nebraska, similar modeling efforts would require finer-scale investigations, presently lacking, because of the more complex local hydrogeologic conditions.

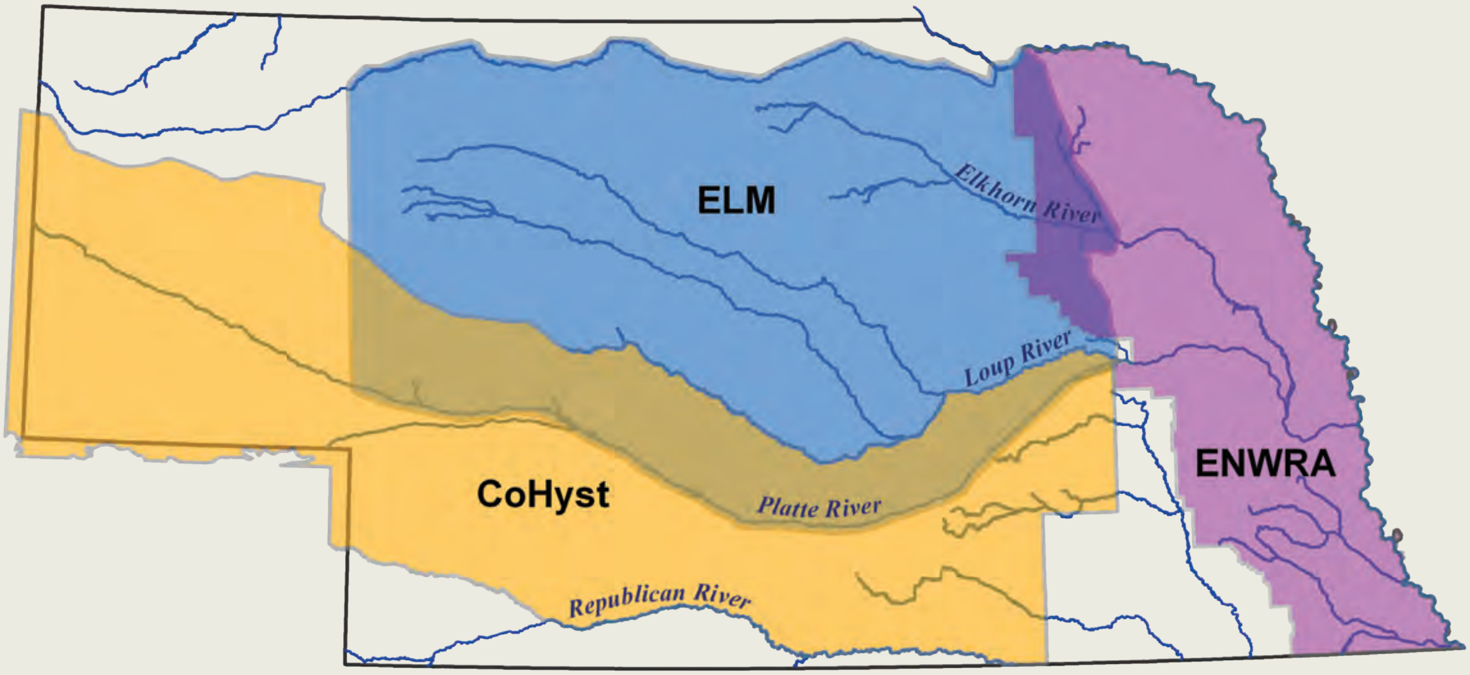

Figure 1. *Geographical boundaries of the COHYST, ELM, and ENWRA hydrogeological studies. COHYST concentrates on Platte River, ELM on Loup and Elkhorn Rivers.*

Groundwater discharging from an artesian well in eastern Nebraska.

2.2. Eastern Nebraska Water Resources Assessment (ENWRA)

In 2006, representatives of six NRDs and other organizations began discussing the assessment of groundwater-surface water relationships in eastern Nebraska. It became clear during these discussions that the careful management of all aquifers, even those not directly connected to surface water, are also important because the localized and hydrogeologically-complex nature of many aquifers in eastern Nebraska makes them susceptible to overdevelopment and depletion.

As a result of these discussions, the Lewis and Clark, Lower Elkhorn, Lower Platte North, Lower Platte South, Nemaha, and Papio-Missouri River NRDs agreed to form a coalition to study the water resources of eastern Nebraska, thereby initiating the Eastern Nebraska Water Resources Assessment (ENWRA). The Nebraska Water Science Center (an office of the U.S. Geological Survey), the Conservation and Survey Division (CSD) of the School of Natural Resources at the University of Nebraska, and staff from the Nebraska Department of Natural Resources (NDNR) also joined the project as technical advisors. ENWRA established contracts with the USGS and CSD to perform much of the research work.

The ultimate goal of ENWRA is to develop a three-dimensional geologic framework and water budget for all of eastern Nebraska. Current geologic knowledge of the area is insufficient to support the NRDs in their goals of achieving sustainability and managing interconnected surface-water and groundwater supplies.

The ENWRA partners decided that the complexities of local hydrogeology made the characterization of the entire study region at once practically impossible. Even the technology needed to map aquifers remained unproven in eastern Nebraska. Therefore, pilot studies, designed to investigate these complex systems on a limited scale, were deemed necessary in order to both predict the level of success achieved by methods employed and to identify any potential procedural and interpretational challenges at an early stage. It was decided that three years would be spent characterizing three pilot-study sites in eastern Nebraska. In the process of those studies, a "toolbox" of investigative methods and procedures was to be identified, developed, and tested. Upon successful completion of the pilot studies the characterization of larger areas of eastern Nebraska would be practicable.

3. Nebraska's Groundwater in the Hydrologic Cycle

3.1. Origin and Occurrence of Groundwater

In the hydrologic cycle, Earth's water is constantly moving between different reservoirs such as the atmosphere, oceans, glaciers, streams, and groundwater, but at highly variable rates and over a wide range of spatial scales. Water remains in the atmosphere for mere days, perhaps traveling hundreds of miles during that time, but groundwater may remain in an aquifer for thousands of years, traveling only a matter of inches per day (Berner and Berner, 1987; Allen, 1997; Winter et al., 1998).

Groundwater and surface water are the most important reservoirs in the hydrologic cycle in terms of human use (Winter et al., 1998). Water enters, or *recharges*, the groundwater system as precipitation that percolates through the soil and other unsaturated materials in the *vadose zone* and eventually recharges an aquifer. Groundwater may also be recharged from streams and lakes that "lose" water to the ground. Vice versa, groundwater may discharge into streams, in which case the stream is referred to as a *gaining stream*. Many streams in Nebraska are gaining streams.

Once it is below ground, water resides in and moves through tiny pores between grains or in larger openings such as fractures in solid bedrock. The amount of open space within a given volume of material is its *porosity*. Generally, the more interconnected pores and cracks are, the higher the material's *hydraulic conductivity*, or ability to transmit water. Porosity and hydraulic conductivity vary considerably in soils and geologic materials (Domenico and Schwartz, 1998) (*Table 1*).

Table 1. Ranges of porosity and hydraulic conductivity

	Material porosity (%)	Hydraulic conductivity (ft/day)	Hydraulic conductivity (m/s)
Gravel	25 to 40	85 to 8,500	$3x10^{-4}$ to 0.03
Coarse sand	30 to 45	0.2 to 1,700	$9x10^{-7}$ to $6x10^{-3}$
Fine sand	25 to 50	0.06 to 60	$2x10^{-7}$ to $2x10^{-4}$
Sandstone	5 to 30	$9x10^{-5}$ to 1.7	$3x10^{-10}$ to $6x10^{-6}$
Silt, loess	35 to 60	$3x10^{-4}$ to 6	$1x10^{-9}$ to $2x10^{-5}$
Till	25 to 40	$3x10^{-7}$ to 0.6	$1x10^{-12}$ to $2x10^{-6}$
Clay	35 to 60	$3x10^{-6}$ to $1x10^{-3}$	$1x10^{-11}$ to $5x10^{-9}$
Shale	0 to 10	$3x10^{-8}$ to $6x10^{-4}$	$1x10^{-13}$ to $2x10^{-9}$

Adapted from: Physical and Chemical Hydrogeology, 2nd ed., Domenico and Schwartz, 1998

3.2. Management of Groundwater in the Hydrologic Cycle

In the aftermath of the drought of 1999-2006 and interstate legal battles over water, many Nebraskans have realized the connection between Nebraska's water and the global hydrologic cycle. Nonetheless, there is a prevailing misperception that as long as groundwater pumping does not exceed recharge by precipitation, "safe yield" will be achieved (Bredehoeft, 1997; Sophocleous, 1997). The doctrine of "safe yield," however, is scientifically untenable because it fails to take into account the connection between groundwater and the rest of the hydrologic cycle. Pumping groundwater at rates equaling or exceeding the natural recharge rate can lead to dramatic water table declines and reduced flows in streams, springs, and marshes, as is the case in some areas overlying the high Plains Aquifer (Angelo, 1994; Sophocleous, 2000; McGuire, 2007).

In order to adequately assess the effects of groundwater pumping, all the inflows, storages, and outflows, in total the *water budget*, (*Fig. 2*) must be understood prior to establishing an effective doctrine of use (Alley et al., 1999; Johnston, 1989). Under natural conditions, the amount of water stored in the aquifer is essentially constant, and recharge is generally equal to discharge. If the transfers of water within a system are averaged over sufficiently long periods of time to account for variable climatic conditions, then changes in groundwater storage are negligible and the system is in a state of *dynamic equilibrium* (Theis, 1940). Dynamic equilibrium can be expressed by a simple equation:

Recharge (water entering) = Discharge (water leaving)

When groundwater is pumped, the amount of water in storage changes and the aquifer is no longer in dynamic equilibrium. The water table in the vicinity of pumping wells is depressed, causing groundwater to flow toward them. This water must be supplied by removal from storage, increased recharge, decreased discharge, or some combination of these three, as shown in the equation:

Pumping =
Change in Recharge + Change in Storage + Change in Discharge

If pumping is limited so that the water table decline is stabilized, that is, change in storage is zero, a new dynamic equilibrium will be achieved. It can be expressed by a modified equation:

Pumping = Change in Recharge + Change in Discharge

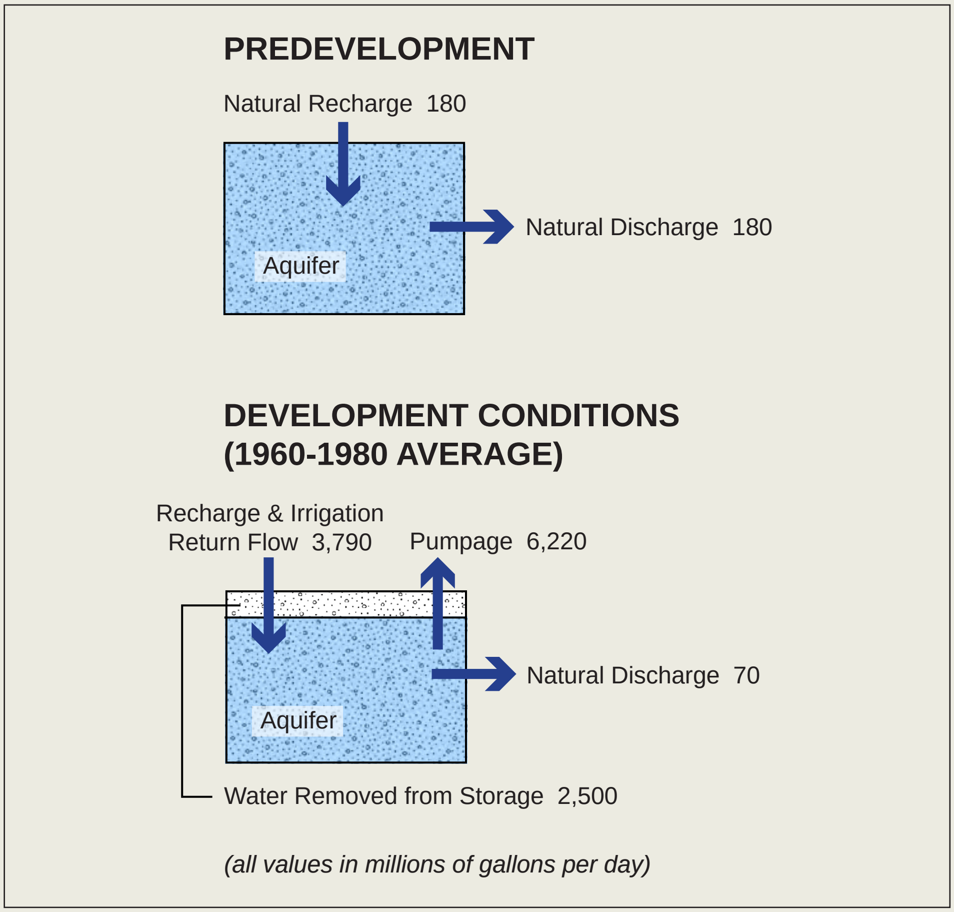

Figure 2. *Generalized schematic relating key inputs and outputs of water budgets. Example is based on the southern High Plains Aquifer, after Johnston (1989).*

The change in recharge will typically not be greater than the rate of pumping. Therefore, some reduction in discharge to surface water bodies is inevitable in most groundwater developments.

Practical application of the water budget equation requires large volumes of hydrologic and geologic data and sound scientific analyses. Factors such as porosity, permeability, storage characteristics, size and shape of the groundwater reservoir, and its degree of connection to surface water sources must be characterized. In eastern Nebraska, these variables have only been characterized at a coarse scale of resolution, one that is entirely insufficient for developing accurate water budgets.

As an alternative to the concept of "safe yield," a groundwater-use policy emphasizing *sustainability* would evaluate the water budget: (1) in the contexts of social, environmental, and economic needs; (2) as a compromise between potential impacts; and (3) using the best scientific information available (Maimone, 2004). Characterizing the complex variables relating to groundwater pumping and the geographic extent of the interconnected ground and surface water supplies are essential components in managing sustainable water-resources development.

4. Geologic Setting of Groundwater in Eastern Nebraska

4.1. Types of Aquifers

The geology of eastern Nebraska is diverse. Local complexities in near-surface geology are difficult to map using currently available data and traditional research methods. Therefore, uncertainty always arises in the assessment of groundwater resources. An accurate general framework for the geology and hydrogeology of eastern Nebraska exists, but it is inadequate for constructing detailed local models.

Eastern Nebraska's aquifers can be divided into two general categories: bedrock aquifers and aquifers in unconsolidated (soft, loose, and uncemented) sediments above bedrock. The latter group includes: (1) aquifers in buried ancient stream valleys (paleovalleys), (2) aquifers in the alluvium of modern and abandoned stream valleys, and (3) smaller-scale aquifers of multiple origins. Modern stream-valley and paleovalley aquifers are the most important water sources for municipal and irrigation uses. All three of these unconsolidated sediment aquifers are included by the U.S. Geological Survey in the *surficial aquifer system* (Miller and Appel, 1997).

4.2. Bedrock and Bedrock Aquifers

In Nebraska east of 97° W longitude, the Ogallala Group, the Arikaree Formation and other geologic units that comprise the High Plains Aquifer or *High Plains aquifer system* are generally absent (Gutentag et al., 1984; Miller and Appel, 1997). Some or all of these

The Platte River in eastern Nebraska.

strata, in particular the Ogallala Group, probably extended east of 97° W prior to the glaciation of eastern Nebraska 2.5 million years ago. If these strata were indeed present in preglacial times, they would have been eroded by the time the last of at least seven glacial advances into the Midcontinent had ended, around 600,000 years ago (Reed et al., 1966; Boellstorff, 1978a, b; Roy et al., 2004).

Of the bedrock strata that remain in eastern Nebraska, the Cretaceous Dakota Formation, dating to about 95-100 million years ago (Brenner et al., 2000; Joeckel et al., 2004), is particularly important because it serves as a secondary aquifer in eastern Nebraska and parts of the adjacent states of South Dakota, Iowa, and Kansas. Water quality within the Dakota Formation in eastern Nebraska varies considerably (Lawton et al., 1984; Gosselin et al., 2001). The Dakota Formation in eastern Nebraska is included by the U.S. Geological Survey in the *Maha aquifer* of the *Great Plains aquifer system* (Miller and Appel, 1997).

Other Cretaceous bedrock units in eastern Nebraska are, in order of decreasing geologic age, the Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation, and Pierre Shale. Unlike the Dakota Formation, none of these units except for the Niobrara Formation are classified as secondary aquifers. Rather, these units function as lower confining units to overlying aquifers. The Niobrara Formation is a secondary aquifer in parts of northeastern Nebraska.

In the southeastern corner of Nebraska all Cretaceous bedrock units have been completely eroded and older Upper Pennsylvanian and Lower Permian strata are the regional bedrock. These older rocks can generally be considered to be confining units.

Dan Schulz and Arianna Kennedy of the Lower Platte South Natural Resources District investigate flows between surface water and groundwater.

4.3. Aquifers in Unconsolidated Sediments

Except along major stream valleys, bedrock in eastern Nebraska is buried at shallow depths (usually less than 300 ft or 90 m) by much younger unconsolidated sediments (Reed and Dreeszen, 1965). Unconsolidated sediments overlying bedrock in eastern Nebraska include glacial till and outwash, fluvial and lacustrine sediments, and loess. Most groundwater currently being used in eastern Nebraska occurs in these unconsolidated sediments, all of which are less than 2.5 million years old (Boellstorff, 1978a, b; Balco, 2005).

4.3.1. Paleovalley Aquifers

A significant part of eastern Nebraska's groundwater is concentrated in the unconsolidated sediments of ancient valleys (paleovalleys), the origin of which can be related directly to the long-term evolution of the regional

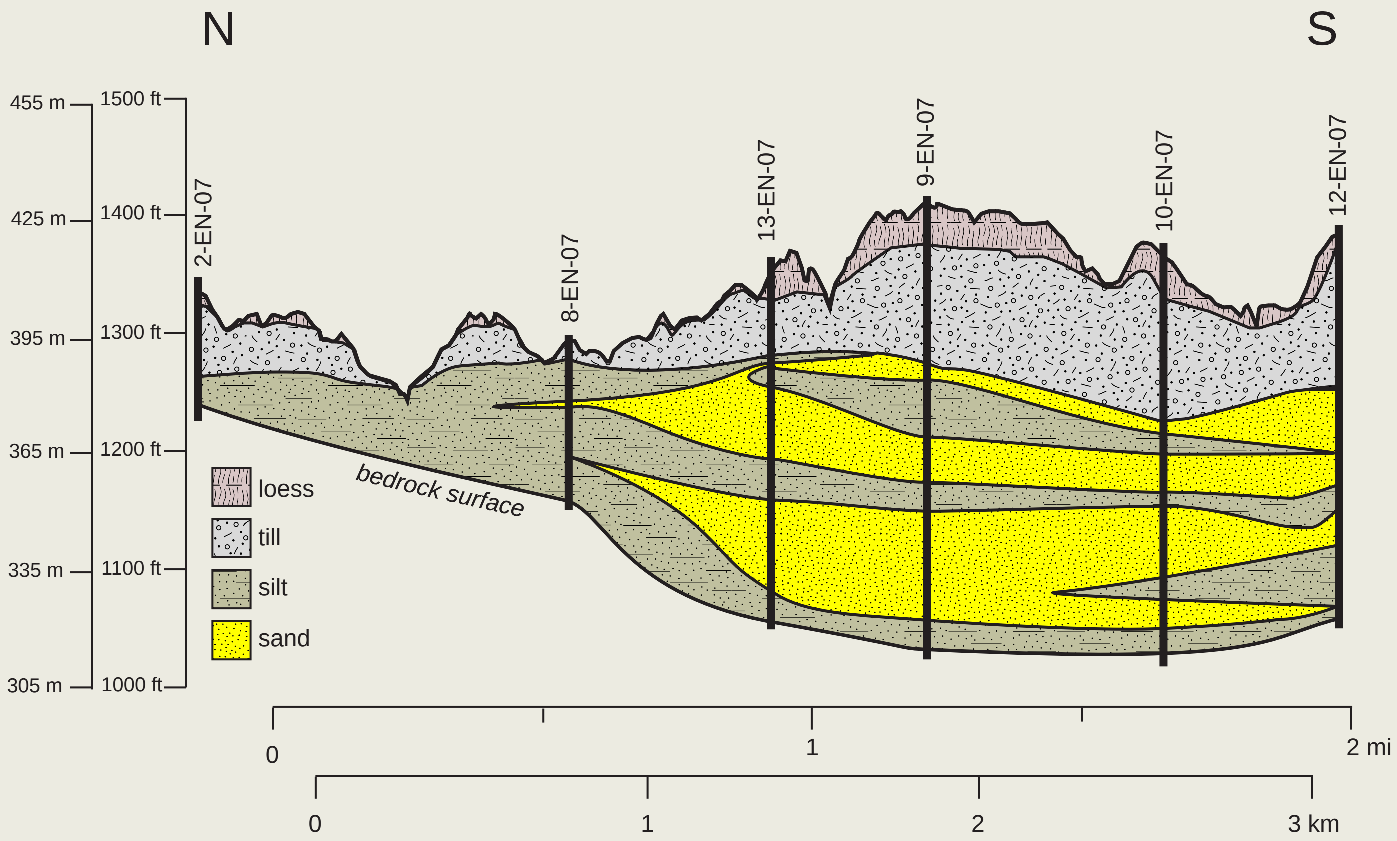

Figure 3. *Geologic cross-section through a paleovalley aquifer near Firth, Nebraska produced on the basis of ENWRA test-hole logs.*

landscape. During the Late Pliocene and Pleistocene, eastward-draining streams incised valleys into bedrock across eastern Nebraska. The orientation of the ancient stream valleys is only locally coincident with the orientation of modern streams (Johnson and Keech, 1959; Keech, 1962; Emery, 1964; Reed and Dreeszen, 1965; Keech and Engberg, 1978; Ginsberg, 1983). This different orientation is illustrated by the occurrence of certain paleovalleys in eastern Nebraska that appear to extend eastward across the drainage line of the modern Missouri River into Iowa and Missouri (Todd, 1915; Greene and Trowbridge, 1935; Heim and Howe, 1963; Burchett, 1970; Aber, 1999). Some of these paleovalleys are clearly delineated on maps depicting aquifer characteristics in eastern Nebraska (e.g., Summerside et al., 2005). The incision of paleovalleys in eastern Nebraska occurred both before the first glaciation of the region and in between at least some of the subsequent glacial advances. During the Late Pliocene and Pleistocene, paleovalleys were gradually filled with sediments, including comparatively thick gravels and sands that generally have excellent aquifer properties. Some authors have suggested that the filling of paleovalleys with sediments resulted in part from the damming of streams by glacial ice (e.g., Johnson and Keech, 1959).

Glacial advances over sediment-filled paleovalleys deposited low-permeability tills over the paleovalley sediments. Even later, loess was deposited on top of the glacial sediments. Although in some places paleovalley fills are shallowly buried or in direct contact with modern streams (e.g., Emery, 1964), across much of eastern Nebraska paleovalley aquifers are buried by as much as 300 ft (91 m) of unconsolidated sediments. Paleovalley sediments can be high-quality aquifers because of their generally high porosity and permeability. A prominent paleovalley is present under glacial till near Firth, Nebraska (*Fig. 3*).

The geographic distribution of paleovalley aquifers is known at a coarse scale of resolution, but overall our knowledge about their extents, geometries, and geologic relationships is rudimentary. Prior experience indicates that paleovalley aquifers can end abruptly, and that their groundwater yields can vary considerably from place to place. Thus, understanding the dynamics of paleovalley aquifers is made more difficult by the lack of detailed geologic information. Furthermore, the connections between local paleovalley aquifers and surface water have not been adequately documented. Therefore, extensive new subsurface investigation and geologic mapping must be completed prior to the construction of detailed models for paleovalley aquifers.

4.3.2. Aquifers in Alluvium of Modern and Abandoned Stream Valleys

Alluvium within the valleys of modern streams (e.g., the Big Nemaha, Elkhorn, and Platte rivers and Logan Creek) typically contain sands and gravels and therefore can have excellent aquifer properties. The primary well fields for both Lincoln and Omaha are located in the Platte River Valley and concentrations of center-pivot irrigation systems in the region lie either within or near that same valley. The Todd Valley between North Bend and Ashland is a conspicuous example of an abandoned stream valley that yields considerable groundwater.

4.3.3. Smaller-Scale Aquifers of Multiple Origins

Discontinuous alluvial deposits include the sediments from streams that flowed atop, within, or under glaciers. Deposits of ancient lakes that existed in front of glaciers are probably associated with these alluvial sediments in the subsurface. These sediments generally produce relatively small quantities of water and then only locally. Typically domestic wells, rather than municipal or irrigation wells, withdraw water from these aquifers.

Some domestic wells in eastern Nebraska also tap "perched" aquifers in non-alluvial sediments atop aquitards, where water accumulates because of the difference in hydraulic properties between the overlying and underlying geologic units. Near Oakland and elsewhere in eastern Nebraska, perched aquifers exist at the contact between the Peoria Loess and underlying loess units (i.e., the Gilman Canyon Formation or Loveland Loess) or between loess and an underlying till (Gosselin et al., 1996).

Unsaturated zone equipment and weather station used to study groundwater recharge near Firth, Nebraska.

5. Pilot Study Sites

5.1. Selection Criteria

The general locations of the pilot study sites were chosen to encompass the wide range of hydrogeologic settings in eastern Nebraska. The ENWRA partners determined that pilot study sites would be representative of one or more of these settings and would have the following characteristics:

- Presence of a primary aquifer.
- Proximity to a stream, so that the groundwater-surface water interactions could be assessed.
- Existing geologic data sets sufficient to support the formulation of working hypotheses.
- Local water quality or quantity problems that would benefit from intensified study.

On the basis of these criteria, sites were selected near the towns of Oakland, Ashland, and Firth, Nebraska (*Figure 4*).

5.2. Oakland Pilot Study Site

The Oakland Pilot Study Site is oriented northwest-southeast between the towns of Oakland and West Point in Burt and Cuming

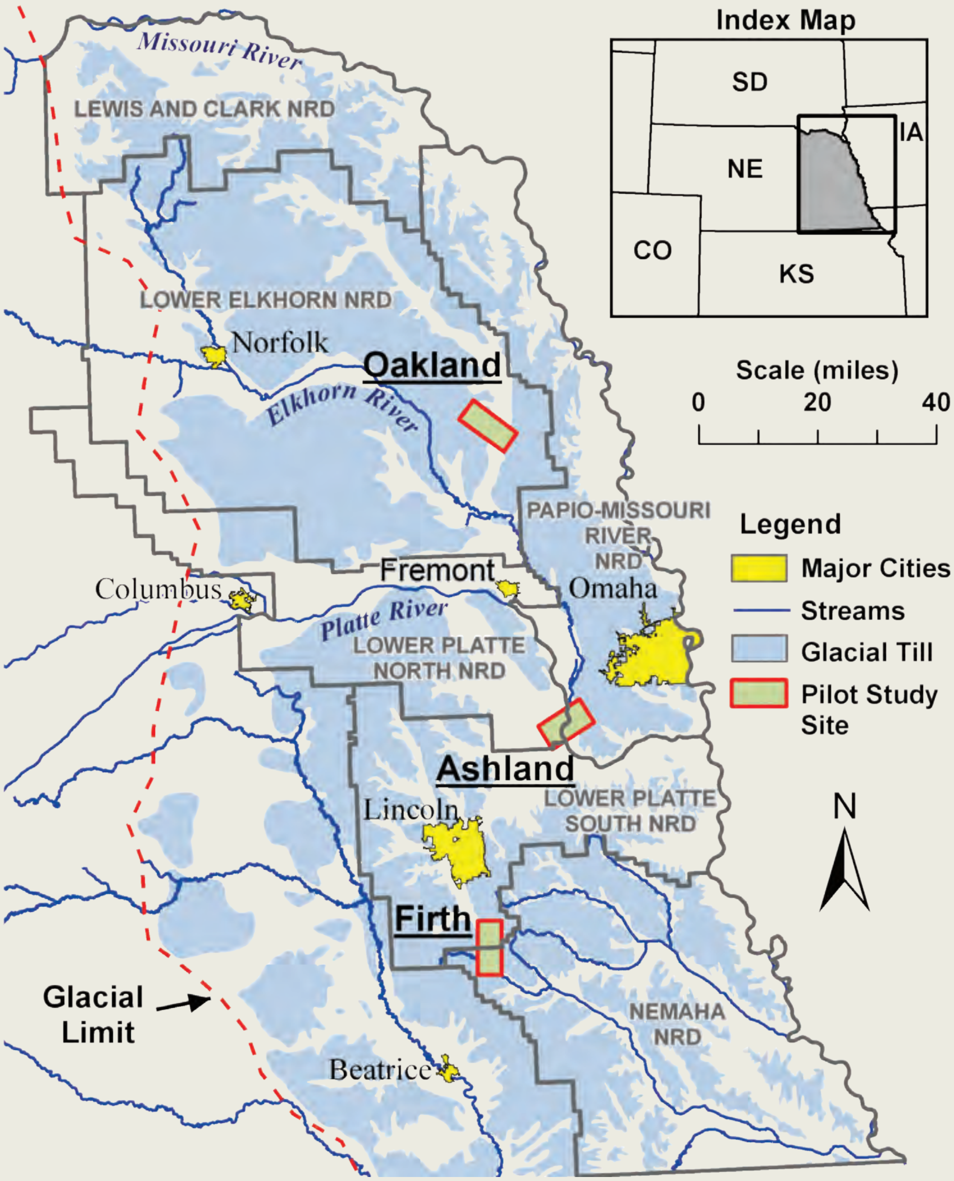

Figure 4. Location of ENWRA pilot study sites. Note extent of glacial till in eastern Nebraska.

counties (*Figure* 5). The site lies in the topographic region of Nebraska called the “Rolling Hills” in *The Groundwater Atlas of Nebraska* (Anonymous, 1998), and within the Northeast Nebraska Glacial Drift Area, Groundwater Region 10, identified by Gosselin et al. (1996). This part of Nebraska is characterized by rolling, stream-dissected terrain eroded out of thick glacial deposits overlain by multiple loess units. The depth to the regional water table ranges from 50 to 200 ft (15-60 m), but perched groundwater exists locally (Gosselin et al., 1996).

The bedrock beneath this site is the Cretaceous Dakota Formation. In this area it consists of complex sequences of shale, siltstone, and sandstone layers with varying degrees of cementation. In upland areas, historical test-hole and registered well data indicate a paleovalley trending northwest to southeast. This valley was formed by the erosion of the Dakota Formation, either prior to the first glaciation or during a time between glacial advances, and it was subsequently filled with sand and gravel deposits that are mapped at a coarse scale of resolution. Glacial till and multiple loess units including the Peoria, Gilman Canyon, Loveland, and possibly older loess units (Mason et al., 2007) overlie these sand and gravel units.

Multiple episodes of erosion and deposition have occurred in the Logan Creek Valley in recent history. The earliest erosional episode cut a deep channel along the east edge of the uplands. Existing test-hole data indicate that this channel did not erode the Dakota Formation between the uplands and the present Logan Creek channel, leaving a remnant bedrock high. Existing subsurface data indicate that fine-grained sediments filled much of this channel. Shallower channels were later eroded into these sediments.

Most large-capacity wells withdraw water from the paleovalley aquifer beneath the uplands and the younger sands and gravels present locally beneath the terrace and Logan Creek Valley. Adequate supplies of good-quality groundwater are difficult to find in areas that are not underlain by these aquifers. Some domestic and stock water supplies are provided by the Cuming County Rural Water System. The Logan East Rural Water System operates three production wells that withdraw water from the paleovalley aquifer, supplying about 4,000 domestic customers east of Logan Creek.

The Dakota Formation presents an additional challenge in this area because groundwater derived from it can have high total dissolved solids (TDS) and iron contents. When high-capacity wells penetrating sands and gravels on top of the Dakota Formation are heavily pumped, poorer-quality water from the Dakota Formation may be drawn upward.

Future investigations at the Oakland site will focus on accurately delineating aquifer boundaries, recharge sources, and movement of water between aquifers and the surface water system.

5.3. Ashland Pilot Study Site

The Ashland Pilot Study site is oriented southwest-northeast, with its southern boundary extending along the north side of

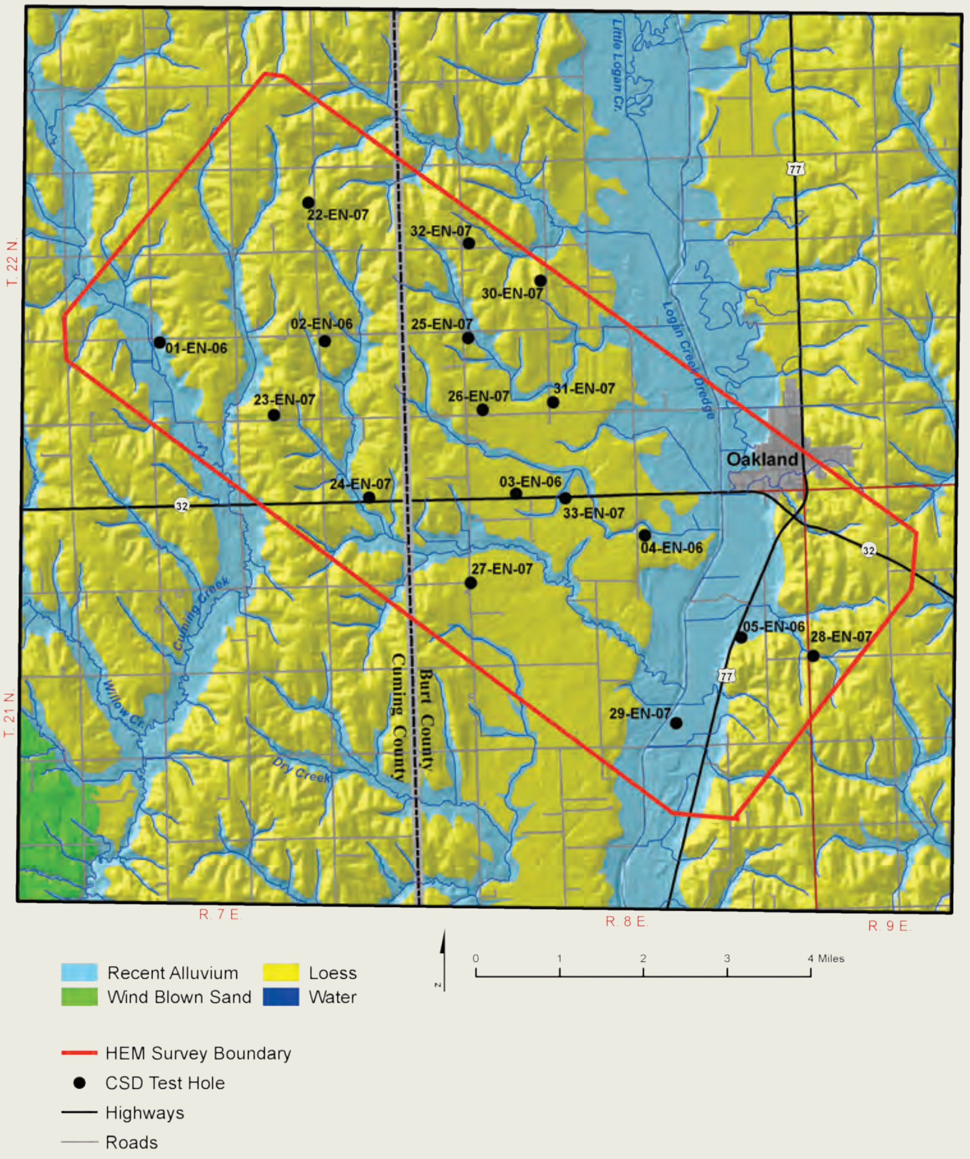

Figure 5. Surficial geologic and shaded relief map for the Oakland study area. Also shown are the HEM survey boundary and CSD test hole locations.

I-80 between Ashland and Gretna, Nebraska (*Figure* 6). The Ashland site lies mostly within Groundwater Region 2 (Platte River Valley) of Gosselin et al. (1996) which is characterized by shallow regional water tables (<50 ft or <15 m) and comparatively large groundwater yields.

The study area's geology includes loess covered glacial deposits in the uplands, and a bedrock-incised trench under the Platte River valley filled with sandy alluvium that locally approaches 90 ft (27 m) in thickness. In the general area of the study site, the pattern of bedrock geology is complex. The Platte River Valley is underlain by limestones and shales of the Pennsylvanian Lansing and Kansas City groups (Burchett et al., 1975). To the east and northeast, the uplands are underlain by the Lansing Group and to the west to southwest by the Pennsylvanian Douglas Group (Burchett et al., 1975). Sandstones of the Cretaceous Dakota Formation are found throughout the area and some clearly occur in paleovalleys eroded during the Early Cretaceous (Joeckel et al., 2004). The age, origin, and orientation of these Early Cretaceous paleovalleys are entirely separate from those of the more recent Late Pliocene-Pleistocene paleovalleys in eastern Nebraska.

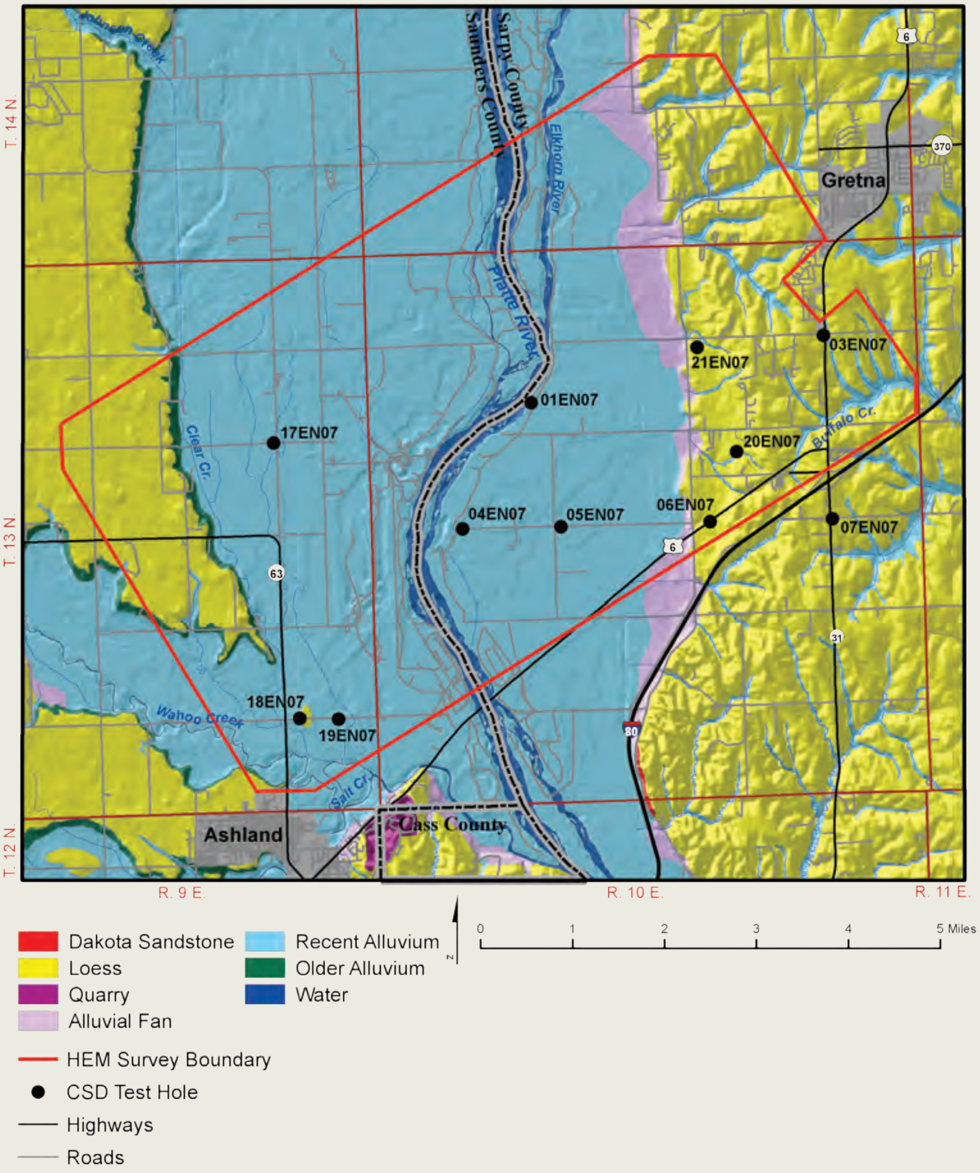

Figure 6. Surficial geologic and shaded relief map for the Ashland study area. Also shown are the HEM survey boundary and CSD test hole locations. Surficial geologic map was adapted from the Ashland East (Mason and Joeckel, 2001), Ashland West (Joeckel and Mason, 2001), and Wann (Mason and Joeckel, 2000) 7.5' Surficial Geologic Quadrangle maps.

Unconsolidated aquifers found in the study area's river valleys include the alluvial fills of the Wahoo Creek and Platte River valleys, plus their alluvial terraces, the Todd Valley alluvial fill, and possibly sediments found within a Pliocene or Pleistocene paleovalley in the southern half of the site that trends approximately east to west. The westernmost edge of the study area overlaps the Todd Valley, an abandoned part of the Late Pleistocene Platte River. The Todd Valley now functions as a terrace, and appears as a low, broad plateau between the Wahoo Creek Valley and the extant Platte River Valley. Being a former course of the Platte River, the Todd Valley is underlain by sandy to gravelly alluvium that serves as an aquifer supporting irrigated agriculture.

In the region's uplands, locally important aquifers are found in alluvial and lacustrine sediments that lie within or below glacial till. The purported paleovalley that underlies the Platte River valley may also extend into the uplands lying below these glacial sediments.

The practical justification for the Ashland site is abundant and manifold. The municipal well fields for the cities of Omaha and Lincoln, both of which lie outside of the study area and encompass an aggregate population exceeding 650,000, pump water from this complex hydrogeologic environment. Furthermore, a Department of Defense Superfund site nearby has produced Royal Demolition eXplosive (RDX), known also by the chemical name cyclotrimethylenetrinitramine, and trichloroethylene (TCE) contaminant plumes that migrated in the general direction of these well fields. Nitrate contamination also exists in the area. Finally, the degree of hydrogeologic connection between these aquifers is unknown.

5.4. Firth Pilot Study Site

The Firth Pilot Study site lies in the topographic region of Nebraska called the "Rolling Hills" in *The Groundwater Atlas of Nebraska* (Anonymous, 1998). It lies within Groundwater Region 11 (Southeastern Glacial Drift Area) identified by Gosselin et al. (1996), which is characterized by rolling, stream-

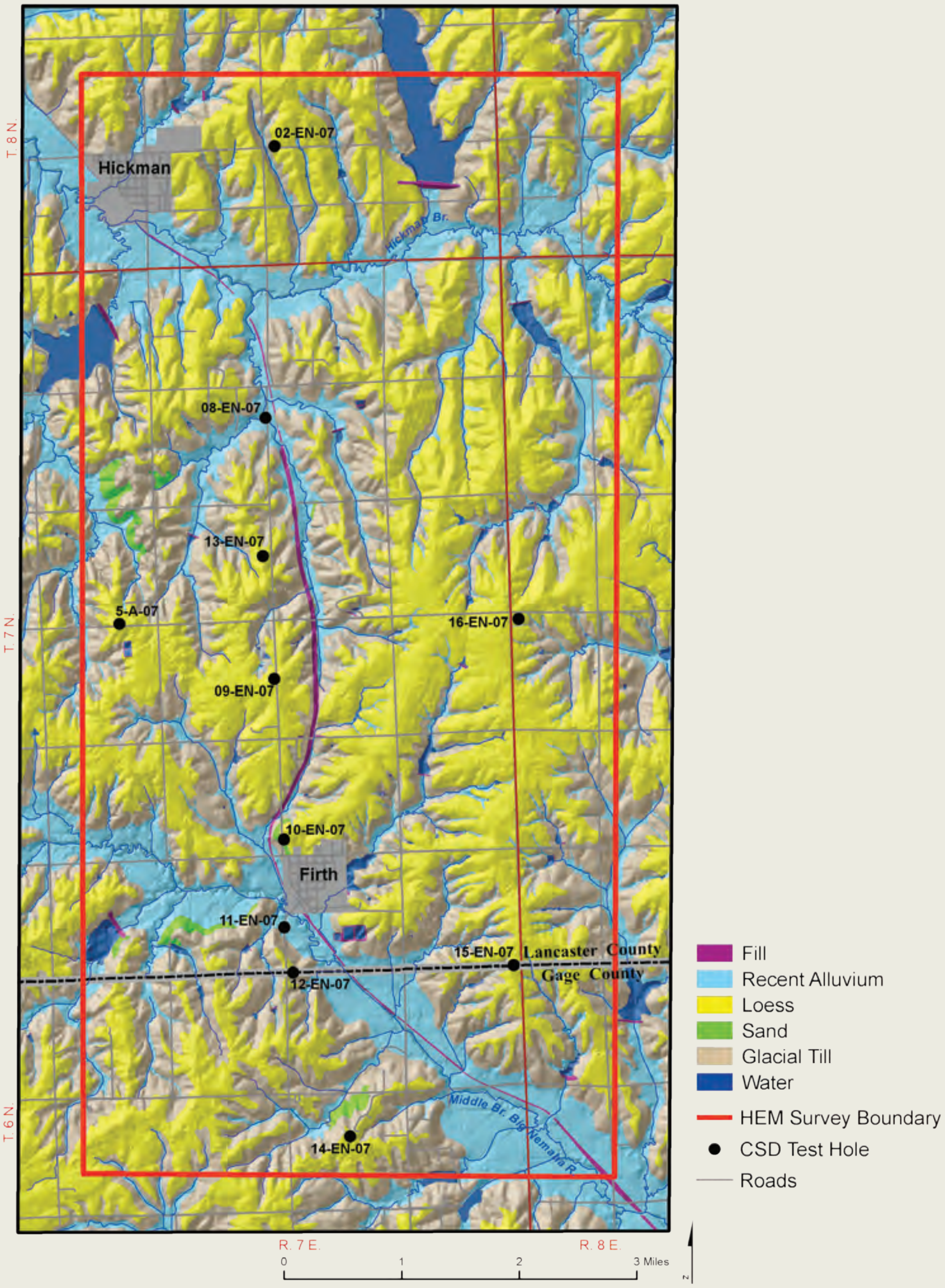

Figure 7. Surficial geologic and shaded relief map for the Firth study area. Also shown are the HEM survey boundary and CSD test hole locations. Surficial geologic map was adapted from the Bennet (Joeckel and Dillon, 2006), Cortland (Joeckel and Dillon, 2007), Firth (Joeckel and Dillon, 2007), and Roca (Joeckel and Dillon, 2006) 7.5' Surficial Geologic Quadrangle maps.

dissected terrain eroded out of thick glacial tills and overlain by thin loess. Regional water tables are usually about 50 to 200 ft (15-60 m) below the ground surface, although shallower, perched groundwater exists locally (Gosselin et al., 1996).

The Firth Pilot Study site is oriented north-south between the towns of Hickman and Firth in Lancaster and Gage counties (*Figure 7*). Glacial till covers the entire site, except for the valley of the Middle Branch of the Big Nemaha River in the southern portion of the study area. The southern half of the pilot study site intersects a deep, linear paleovalley aquifer, oriented roughly east-west from around the town of Crete, eastward through Princeton and Sterling, and then branching eastward toward the Missouri River and southeastward toward Tecumseh. This aquifer is an important local source of water for municipalities, industries, and irrigation wells. The paleovalley is incised into Upper Pennsylvanian and Lower Permian limestone and shale bedrock units of the Admire Group and the overlying Council Grove Group (Condra and Reed, 1959; Burchett et al., 1972; Sawin et al., 2006). The degree of connection between this paleovalley, localized sand bodies nearby, and the Nemaha River is generally unknown.

The Hickman-Firth area is one of the most rapidly growing rural areas in Nebraska. Hickman's population increased by a full 25% from 2000 to 2005, and Firth's by 21%, in comparison with an overall population increase of 5% for the entire county during the same period. This population increase has resulted in a rapid rise in domestic well development. Irrigation well development has also risen during that same time period, increasing the potential for interference with domestic wells. The municipal water supply wells for Hickman and Firth are present in the study area. Some of the Hickman water supply wells have yielded high test values for nitrates, and the community has had to drill new wells to replace them. The source(s) of these nitrates are not fully known. Maintaining an adequate supply of good quality water for these uses will be a great challenge for this area as it continues to grow.

6. Investigative Tools and Techniques

6.1. Construction of a Geologic Framework

The pilot studies were intended to: (1) investigate, on a limited scale, the three-dimensional geologic framework and water budget of each site; (2) evaluate different investigative methods in terms of their practicability and cost-effectiveness; and (3) develop a "toolbox" of techniques for use in future efforts. The "tools" within this "toolbox" allow scientists to determine the regional geologic framework and define local water budgets.

Constructing an accurate regional geologic framework requires considerable subsurface data. Test-hole drilling, employed by CSD to investigate the geology of Nebraska since the 1930s, remains the essential method of obtaining subsurface geologic data. Drilling is the fundamental method by which buried geologic materials are sampled and characterized. Extrapolating between test holes, however, remains a challenge. This challenge is especially evident in eastern Nebraska where existing data do not allow geologists to fully delineate aquifers, calculate their volumes, or determine their spatial and hydrologic relationships.

6.1.1. Helicopter Electromagnetic (HEM) Surveys

The Helicopter Electromagnetic (HEM) survey is a very rapid and efficient way of remotely sensing geology across an entire site without engaging in extensive drilling or trenching. More importantly, HEM results can be tested, interpreted, and refined by a supportive program of selective test-hole drilling, contributing to a comprehensive analysis of site geology.

In HEM surveys, a geophysical device containing sensors is suspended beneath a helicopter. An electromagnetic field is continuously transmitted to the land surface (and subsurface) while the helicopter is in flight, and the sensors carried under the helicopter receive the subsequent return of electromagnetic energy from the land surface. This return can be interpreted as a representation of surface and subsurface geologic characteristics, specifically their electrical resistivity values and magnetic properties. The amount of the electromagnetic energy returned from the land surface to the sensor indicates the differential behavior of various kinds of geologic materials. HEM surveys have been used in several parts of the United States to map and locate various types of natural resources, including groundwater (Smith, et al., 2003, 2006).

Helicopters are particularly good vehicles for airborne electromagnetic surveys because they can fly at low airspeeds and low altitudes. In an HEM survey, the helicopter flies along regularly spaced flight lines over a large geographic area, continuously recording data. The system is sensitive to subtle differences in resistivity and has the ability to resolve differences in geologic materials. High resistivity values typically indicate the presence of sand and gravel, sandstone and limestone bedrock, and/or fresh groundwater. Low resistivity values typically indicate silt and clay, shale bedrock, and/or saline groundwater. In eastern Nebraska, aquifers typically have high resistivity values and aquitards typically have low values. HEM survey results can be compiled as computerized three-dimensional maps depicting the resistivity of geologic materials.

HEM survey analyses produce high-resolution "slices" (vertical cross-sections) of geologic information from the subsurface. At each of the ENWRA Pilot study sites, these slices were generally about six miles (10 km) in length, were spaced 0.17 miles (0.27 km) apart, and described a 36 square mile (93 km^2) area. The raw HEM data for the ENWRA project were interpreted by the USGS. A more

Helicopter electromagnetic survey being conducted in eastern Nebraska.

Test well pumps water from Dakota Formation, a secondary aquifer in eastern Nebraska.

detailed description of HEM technology and its application to the ENWRA project can be found in Smith et al. (2007) or at *http://pubs.usgs.gov/of/2008/1018/*.

6.1.2. Test Holes and Downhole Geophysics

A test-hole drilling program is required in order to make a direct association between HEM survey results and subsurface geology, particularly because the depth of penetration of the HEM survey varies, depending on the geologic materials encountered. The number of test holes necessary to adequately assess HEM results depends on the land area and geologic complexity of the site. ENWRA drilled 17 test holes at the Oakland site, 11 test holes at the Ashland site, and 11 test holes at the Firth site. Conservation and Survey Division's test-hole drilling practices have been developed over a period of more than 70 years. Geologic samples are collected continuously by a trained geologist during drilling. The geologist notes changes in *lithology* or sediment/rock type, recording such characteristics as material type/texture, color, reaction to 10% hydrochloric acid (a test for calcium carbonate), and other features visible in the field. Geologic descriptions are logged on the Nebraska Water Survey-Field Log and the samples bagged and archived on a minimum of five-foot intervals. Detailed descriptions of the archived samples are made in the laboratory using a microscope. Strata encountered in drilling are eventually assigned formal stratigraphic names that relate to a specific interval of geologic time, such as the Peoria Loess (Pleistocene) and the Dakota Formation (Cretaceous). Lithologic information and other data from the CSD test hole drilling program is available at the School of Natural Resources Web site (*http://snr.unl.edu/, keyword "Nebraska test holes"*).

Downhole geophysical tools are used to log both electrical resistivity and gamma-ray emissions of the geologic materials encountered in the test holes. The electrical resistivity values measured downhole are compared to retrieved geologic samples, which can then be used to calibrate HEM results. Downhole electrical logs can also be used to differentiate between fresh and salty groundwater, and between coarse- and fine-grained sediments. Gamma logs record the natural radiation emitted by the radioactive decay of particular isotopes of elements (e.g., potassium, thorium, and radium) within certain minerals. Clay-rich sediments or shale will tend to exhibit increases in natural gamma-ray emissions relative to other materials, as will volcanic ashes. Overall, downhole geophysical results are used to enhance the accuracy of the geologic logs produced by the geologists and to compliment the HEM and Time Domain Electromagnetic (TDEM) surveys.

6.1.3. Time Domain Electromagnetic (TDEM) Surveys

In addition to HEM and downhole geophysical logs, Time Domain Electromagnetic (TDEM) surveys are a third geophysical technique that is applied to the ENWRA Pilot Study sites. TDEM surveys are conducted on the ground surface. An electromagnetic wave signal is transmitted from the surface through the ground, and its rate of decay measured by a separate receiver. The rate at which the signal decays relates to resistivity values that can be compared to the resistivity values measured independently by HEM. USGS personnel performed TDEM surveys at 38 ENWRA test hole locations.

6.1.4. Passive Seismic

A fourth geophysical technique tested at the pilot study sites was the horizontal-to-vertical (H/V) ambient-noise seismic method, also known as the passive seismic method. The technique was applied to the ENWRA study by the USGS. Typical geological seismic investigations generate seismic waves either by a heavy hammer blow to the ground surface or by detonating explosives. A passive seismic investigation does not artificially generate seismic waves. Instead, it monitors ambient vibrations that are produced by such sources as automobile traffic. The goal of performing a passive seismic investigation is to estimate the thickness of sediment overlying bedrock. This information is applicable to the study of hydrogeology in eastern Nebraska because much of the water here occurs in unconsolidated sediments above bedrock. Determination of the depth to bedrock provides the potential thicknesses of an aquifer and the maximum depth to water from the land surface.

Dan Schulz and Jesse Korus examine groundwater discharging at a spring along the bank of a stream.

The passive seismic analysis at the pilot study sites was performed near test holes so that the known actual depth to bedrock could be compared to the depth indicated by the passive seismic data. The passive seismic data did not accurately indicate the depth to bedrock at most of the locations tested in the pilot study sites. Possible reasons for the differences between known bedrock depth determined from test holes and the interpreted depth from the passive seismic data include: (1) the acoustic impedance contrast between the sediment and the bedrock was not large enough to identify the geologic contact (i.e., the sediment and the bedrock transmitted the seismic waves at roughly the same velocity and therefore appear to be the same seismically), or (2) wind noise drowned out the ambient seismic waves and prevented clear recording of the data (Lane, et al., 2008). Conclusions from this study indicate that the passive seismic technique works better in areas where the bedrock is crystalline (i.e., igneous or metamorphic rocks), which is not the case across Nebraska, where the bedrock is sedimentary rock.

6.2. Defining Water Budgets

Scientists define water budgets by collecting hydrological data to determine the movement of water though the subsurface. Recharge, the amount of water entering an aquifer during a given time period, is determined by precipitation, evapotranspiration, and infiltration rates. The values of storativity and transmissivity determine the volume and rates of groundwater movement within an aquifer. Discharge, the amount of water leaving an aquifer, includes removals from an aquifer by pumping and natural discharge to the surface. Altogether, this information constitutes a water budget, which is fundamentally important in assessing whether water use is sustainable in a given area.

6.2.1. Estimating Recharge

Aquifers are open systems: water can be added to them as recharge or removed from them by discharge. Recharge includes any water entering an aquifer, particularly infiltrated precipitation. Recharge rates vary considerably from site to site, depending on local soils, geology, and precipitation patterns.

Measuring the amount of precipitation that falls at a given station is relatively easy, but only some of it percolates deep enough to recharge a local aquifer. The remainder of the rain runs off the land surface, remains as soil moisture, evaporates, or is used by plants. Together, the latter two processes are called *evapotranspiraton* (ET). The portion of precipitation that penetrates beyond the root zone percolates down through the soil column as soil moisture. Some types of soil hold moisture tightly and, therefore, percolation down to the aquifer is slow. Other types of soil do not hold water as tightly and percolation is much faster. If very little rain falls on the ground surface, it is possible that all of it will be lost to ET or held by the soil very tightly, and as a consequence, none of it will reach the aquifer as recharge. Using numerical models, scientists estimate that only 7% to 13% of the total precipitation that falls over eastern Nebraska eventually recharges regional aquifers (Szilagyi et al., 2003).

Estimating groundwater recharge can be difficult because it depends not only on the amount of rainfall received in a given area, but also on wind speed, humidity, solar radiation, soil characteristics, local geology, and vegetation. ENWRA measures these parameters using soil moisture probes, heat dissipation probes, and weather stations. Soil moisture probes measure the amount of soil moisture at various depths. The heat dissipation probes measure how tightly the percolating water is held by the soil at various depths. The weather stations, installed as part of the Automated Weather Data Network, are maintained by the High Plains Regional Climate Center (HPRCC) and the data is available to the public on the internet at *http://www.hprcc.unl.edu/*.


Samples being collected to investigate soil nitrate levels.

Other tools ENWRA uses to measure recharge include tritium profiles and bromide tracer tests. The concentrations of these compounds at various depths below the ground surface can be used to estimate infiltration rates.

6.2.2. Well Installations and Groundwater Monitoring

Monitoring wells are access points to aquifers from which water quantity and quality data can be collected. ENWRA installed monitoring wells at selected test hole locations. At each location, multiple wells are installed at different depths, enabling geologists to: (1) compare vertical differences in water levels and chemistry, (2) evaluate potential groundwater flow paths, and (3) assess the connections between surface water and different aquifers. Differences in chemical composition and/or hydraulic heads can be used to identify distinct aquifers and their potential connections. For instance, groundwater that is in connection with surface water typically has higher oxygen content, and hydraulic heads may be distinct because water in separate aquifers may be under different pressures.

ENWRA monitoring wells are sampled for the following chemical parameters: calcium, magnesium, sodium, potassium, bicarbonate/alkalinity, chloride, nitrate as nitrogen, sulfate, total dissolved solids, iron, and manganese. These parameters can be used to determine a chemical “fingerprint” of the groundwater’s history, source, and connections within individual aquifers.

In cases where general water chemistry or water levels do not provide a clear answer regarding connections, groundwater samples can be age-dated. The groundwater age indicates how long it has resided in an aquifer. Water in deep aquifers is generally older, and has resided in the ground longer than water in shallower aquifers. Age-dating of the ENWRA monitoring well water will be accomplished by collecting groundwater samples for analyses of environment tracers, such as chlorofluorocarbons, sulfur hexafluoride, and tritium.

6.2.3. Aquifer Tests

Aquifer tests are performed to determine aquifer extent, the amount of water in storage, the rate of water movement, and its potential hydraulic connection to surface water and other aquifers. To perform an aquifer test, hydrogeologists install a high-capacity production well in the aquifer they are studying. Observation wells are then installed at selected distances and in different directions outward from this pumping well. These observation wells are designed to monitor water levels within, above, or below the pumped aquifer.

Water is pumped from the production well at a constant rate over a period of multiple days. The amount of water level decline in each observation well (drawdown) provides hydrogeologists with the information they need to estimate the transmissivity and storativity of the aquifer. Changes in the rate of water-level decline allow hydrogeologists to assess flow boundaries and the potential connections between aquifers.

6.2.4. Water Usage

In eastern Nebraska, groundwater leaves an aquifer by two main paths: (1) natural discharge to surface water, and (2) pumping. Geologists can estimate the amount of groundwater discharged to streams (baseflow) by measuring surface water flow rate during the dry season at various locations along the stream. If the stream flow increases from the first measuring site to the second, the additional amount of water gained in the stream is from groundwater discharge between these stations.

Summing the total withdrawal from an aquifer by pumping is difficult. Usage can be estimated directly by water meters, or indirectly by the analyses of satellite or aerial images of agricultural areas (remote sensing) or through electrical consumption, although not all wells are powered by electricity. Remotely sensed infrared images differentiate irrigated plots, but the volume of water being applied depends on the crop being produced. Volumes can be estimated on the basis of the type of crop being irrigated.

The convergence of two small streams in eastern Nebraska.

7. Preliminary Results

7.1. Oakland Pilot Study Site

The preliminary results of the test-hole drilling program confirmed the complex nature of the sediments beneath the Oakland Pilot Study Site. A total of 17 test holes were drilled in 2006 and 2007 (*Table 2*). The five test holes drilled in 2006 were located to target the broadest range of geologic units in order to provide variable control points for the HEM survey. The HEM survey did not penetrate finer-grained materials on terraces and uplands. Therefore, the 2007 test holes were concentrated in those areas in order to provide additional subsurface information.

The Logan Creek Valley sediments are characterized by silt and clay units that overlie sand and gravel materials (*Figure* 5, page 14). Test hole 29-EN-07 was drilled in an area where the HEM survey indicated highly resistive material at about 20 to 90 ft (6 to 27) in depth. The test hole samples and downhole geophysical logs confirmed the presence of 18 ft (6 meters) of silt overlying sand and gravel material to about 90 ft where shale bedrock was encountered. Resistive units identified in the HEM survey to the north are confirmed by the results of a CSD test hole drilled in 1950.

The sediments beneath the terrace are very complex and more analysis will be necessary in order to reconstruct past erosion and deposition. Preliminary results confirmed the presence of a bedrock high around test hole 04-EN-06. New test hole data indicate a relatively steep-sided incision into this bedrock high between test holes 33-EN-07 and 03-EN-06. The bedrock surface is 50 ft lower in test hole 03-EN-06, 3500 ft to the west of

Table 2. Oakland pilot study site test hole data

Test Hole #	Longitude[1]	Latitude[1]	Legal	Elevation (ft)[2]	Cored Depth (ft)	Rotary Depth (ft)
01-EN-06	-96.611	41.858	T22N R7E 27NW	1348	55	156.5
02-EN-06	-96.573	41.857	T22N R7E 25NW	1400	80	256.5
03-EN-06	-96.530	41.830	T22N R8E 33SE	1293	60	237
04-EN-06	-96.500	41.822	T21N R8E 2NW	1276	55	178
05-EN-06	-96.479	41.804	T21N R8E 12SW	1245	40	158
22-EN-07	-96.576	41.881	T22N R7E 14SE	1454	—	238
23-EN-07	-96.586	41.844	T22N R7E 26SW	1405	—	258
24-EN-07	-96.564	41.830	T22N R7E 36SE	1309	—	217
25-EN-07	-96.540	41.857	T22N R8E 28NW	1325	—	217.5
26-EN-07	-96.537	41.844	T22N R8E 28SW	1328	—	237.5
27-EN-07	-96.541	41.815	T21N R8E 9NW	1299	—	198
28-EN-07	-96.462	41.800	T21N R9E 7SW	1300	—	178
29-EN-07	-96.494	41.789	T21N R8E 14SW	1238	—	118
30-EN-07	-96.523	41.866	T22N R8E 21NE	1355	—	277.5
31-EN-07	-96.521	41.845	T22N R8E 27SW	1295	—	177.5
32-EN-07	-96.539	41.873	T22N R8E 16SW	1408	—	237.5
33-EN-07	-96.519	41.829	T21N R8E 3NW	1282	—	154.5

Note: All Oakland test holes penetrated bedrock. Cores were collected using split spoons.

[1] Horizontal Datum NAD 83
[2] Vertical Datum NAVD 88

test hole 33-EN-07, a feature also noted by local landowners to the south. Test holes and registered well logs indicate that the terrace fill consists mainly of silt and clay with variable amounts of sand and gravel.

The sediments beneath the uplands consist of loess units including the Peoria, Gilman Canyon and Loveland loesses that were deposited on glacial till. These glacial sediments locally overlie sand and gravel units of variable thicknesses. Prior to conducting this test-hole drilling program, it was thought that an erosional channel on top of the Dakota Formation created a northwest-southeast trending paleovalley that was in-filled with sand and gravel. New test hole data reveal a more complex geologic relationship that includes an additional, deeper paleovalley trending east-northeastward. The physical relationship between these paleovalleys will be further investigated.

In some test holes, multiple aquifer units can be identified based on the sediment's mineral compositions. Groundwater obtained from each aquifer may have a distinct water chemistry based on these mineral compositions. If unique chemical signatures are identified, water chemistry will be important for defining the movement of water between aquifers and between these aquifers and Logan Creek.

7.2. Ashland Pilot Study Site

A total of eleven test holes were drilled in the Ashland Pilot Study Site in 2007 (*Table 3*). Test hole locations were chosen in order to fully characterize the area's different geologic and hydrogeologic environments, and to identify the distribution of bedrock strata in the Ashland study area. The majority of the holes drilled in the Ashland area were concentrated in the Platte River Valley and on associated terraces, but others were located in the adjacent glaciated uplands, on alluvial fans, and in the Todd Valley. Test hole investigations included a combination of both coring and mud-rotary drilling. Coring depths (44-88 ft or 13.4-26.8 m) were limited by the nature of the subsurface materials, and as a result bedrock was not encountered in a number of the cored test holes (*Table 3*). Mud-rotary drilling was conducted at most sites to acquire cuttings and geophysical logs through the extent of the potential aquifer units, including the upper portions of bedrock.

The test holes provided new information about regional stratigraphy and provided geophysical data with which the effectiveness of HEM surveys can be evaluated. The bedrock under the Platte River alluvial fill is Upper Pennsylvanian limestones and shales and sandstones of the Cretaceous Dakota Formation. New test-hole drilling provided data with which to refine the mapping of bedrock in the area.

Preliminary HEM results show good correspondence with surficial geologic mapping units shown in the Ashland East (Mason and Joeckel, 2001) and Wann (Mason and Joeckel, 2000) 7.5 minute quadrangles. The HEM survey indicates zones of low resistivity that generally correspond to mapped silty and clayey sediments and zones of high resistivity materials that roughly correspond to sandy surficial materials. The configuration of the bedrock surface determined by HEM is comparable to results derived from earlier seismic

Table 3. Ashland pilot study site test hole data

Test Hole #	Longitude[1]	Latitude[1]	Legal	Elevation (ft)[2]	Cored Depth (ft)	Rotary Depth (ft)
01EN07-	96.315	41.108	T13N R10E 8SE	1078.5	65	143
03EN07	-96.254	41.118	T13N R10E 11NE	1213.1	70	273
04EN07	-96.330	41.089	T13N R10E 20NW	1068.5	49	50
05EN07	-96.309	41.089	T13N R10E 21NW	1066.1	44	46
06EN07	-96.278	41.089	T13N R10E 15SE	1117.4	55	99
07EN07	-96.253	41.089	T13N R10E 24NW	1258.9	70	198
17EN07	-96.369	41.103	T13N R9E 11SE	1072.9	88	—
18EN07	-96.365	41.060	T13N R9E 25SW	1070.7	45	—
19EN07	-96.357	41.060	T13N R9E 36NE	1063.2	80	—
20EN07	-96.272	41.100	T13N R10E 14NW	1165.8	—	197
21EN07	-96.280	41.116	T13N R10E 10NE	1136.0	—	186

Note: All cores were Geoprobe cores except for 03-EN-07 and 07-EN-07, which were split spoon.

[1] Horizontal Datum NAD 83

[2] Vertical Datum NAVD 88

surveys (Ayers, 1987). The HEM results, however, resolve previously unknown details of the Platte Valley's alluvial fill. Moreover, preliminary results from the HEM survey also strongly suggest a physical, and therefore hydrologic, connection between the alluvial aquifer underlying the Todd Valley, the loess-mantled alluvial deposits that flank the Platte River Valley, and the alluvial sediments under the Platte River itself.

7.3. Firth Pilot Study Site

A total of 11 test holes (*Table 4*) were drilled at the Firth site in 2007. Test holes were located at a variety of landscape positions, from the valley wall of the Middle Branch of the Big Nemaha River to the loess-mantled till uplands to the north. Each test hole was drilled with the intent of fully penetrating the Peoria and Loveland loesses, thick glacial tills, and west to east trending paleovalley aquifer sediments that overlie the Upper Pennsylvanian-Lower Permian bedrock. Results from new test-hole drilling helped delineate the Crete-Princeton-Sterling paleovalley and determine the nature of its sedimentary fill (*Fig. 3,* page 11).

Results from the Firth site suggest that HEM surveys are an important tool for delineating aquifers when used in conjunction with test hole drilling. Test hole results indicate that the thicknesses of unconsolidated sediment are highly variable. Glacial tills range from less than 10 ft (3 m) to more than 150 ft (46 m) in thickness across the study area. The thicknesses of loess and glacial till, both being materials that exhibit low resistivity, limited the depth of HEM penetration. Test holes drilled immediately to the south and approximately 3 miles (5 km) north of the town of Firth indicate that both loess and till units are thin or absent. The limited thicknesses of these overlying units allowed the HEM surveys to penetrate into the underlying aquifer, showing their complex geometries and interconnections. In addition, the shallow depths and thicknesses of these units are confirmed by borehole information. Test holes drilled immediately north of Firth, however, indicate aggregate loess-till thicknesses exceeding 150 ft (46 m). The HEM surveys did not effectively penetrate these resistive sediments.

Overall, the HEM results from the Firth site will aid geologists in identifying aquifer boundaries and their connections. For example, the shallow aquifer identified in HEM data three miles north of Firth correlates with wells containing elevated nitrate levels. This is evidence that these shallow aquifers are potentially important recharge areas, and could be susceptible to groundwater contamination. The connectivity between these shallow aquifers and the more deeply buried aquifers, however, cannot presently be deciphered with HEM, but will be investigated in future work through additional test hole drilling and other methods.

Table 4. Firth pilot study site test hole data

Test Hole #	Longitude[1]	Latitude[1]	Legal	Elevation (ft)[2]	Cored Depth (ft)	Rotary Depth (ft)
02-EN-07	-96.608	40.626	T8N R7E 26SW	1338.3	86	88
08-EN-07	-96.611	40.592	T7N R7E 10NE	1270.6	70	119
09-EN-07	-96.611	40.560	T7N R7E 22NE	1411.7	95	376
10-EN-07	-96.610	40.540	T7N R7E 26SW	1360.9	75	318
11-EN-07	-96.610	40.529	T7N R7E 35SW	1315.8	50	185
12-EN-07	-96.609	40.524	T7N R7E 35SW	1374.8	60	285
13-EN-07	-96.612	40.575	T7N R7E 15NE	1379.8	—	328
14-EN-07	-96.601	40.503	T6N R7E 11NE	1397.4	—	138
15-EN-07	-96.573	40.524	T7N R7E 36SE	1405.6	—	251
16-EN-07	-96.571	40.566	T7N R8E 19NW	1411.0	—	378
5-A-07	-96.636	40.567	R7N R7E 16SE	1408.1	120	378

Notes: Test holes 10-EN-07 and 14-EN-07 did not penetrate bedrock. Cores were collected using split spoons.

[1] Horizontal Datum is NAD 83

[2] Vertical Datum is NAVD 88

8. The Road Forward

Ensuring a sustainable supply of water in eastern Nebraska is essential to the region's economic, environmental, and social well-being. Managing groundwater at sustainable levels requires a detailed understanding of the geologic framework and water budget for a given region. As ENWRA moves forward, these details will be resolved using tools tested at the pilot study sites and deemed to be appropriate for application to other areas in eastern Nebraska. Results, including the details regarding the connection of surface and groundwater, the extents and characteristics of aquifers, and the groundwater flow system, will allow local resource managers to employ conservation and development strategies based on modern scientific techniques.

Some of the data already generated at the pilot study sites will be immediately useful for resource managers. At the Firth study site, nitrates in the local water supply are sufficiently elevated to trigger a higher phase of groundwater management, which will require an accurate delineation of the groundwater flow system. The Lower Platte South NRD and the city of Hickman are using data generated by ENWRA to understand the source of nitrates, characterize the hydrogeology, and develop a more accurate protection plan than would have been possible without this data. At the Oakland study site, ENWRA efforts have generated data that will be useful to the Logan East Rural Water System. The current well-head protection area is highly generalized and may not fully protect the paleovalley aquifer. New ENWRA data will be used to more accurately determine recharge areas and groundwater flow, thereby ensuring a sustainable water supply for 4,000 customers.

Although the benefits from the Firth and Oakland pilot study sites are clearly evident, providing similar useful information to other parts of eastern Nebraska will be a long-term effort. Long-term data sets are needed to understand natural trends, human influences on the water budget, and the impacts of these influences on the interconnected ground and surface water resource. It will also take time to utilize the tools and methods identified in the pilot study sites to help address specific water resource issues throughout eastern Nebraska. New tools will become available in the future and will require further testing.

ENWRA and successor studies will provide solutions to critical water resource issues and ensure that these resources are sustainable for future generations of Nebraskans.

A lake alongside the Platte River.

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Appendix 1. Abbreviations and Acronyms

CSD: Conservation and Survey Division

CWSPA: Community Water System Protection Area

DNR: Department of Natural Resources

ENWRA: Eastern Nebraska Water Resources Assessment

ET: evapotranspiration

ft: feet

HEM: Helicopter Electromagnetic

IWMPP: Interrelated Water Management Plan Program

ka: *kiloannum* or thousand years, referring to geologic age; e.g., 100 ka means one-hundred thousand years ago

m: meters

Ma: *megaannum* or million years, referring to geologic age; e.g., 100 Ma means one-hundred million years ago

NRD: Natural Resources District

RDX: Royal Demolition Explosive

TCE: Trichloroethylene

USGS: United States Geological Survey

Irrigation well.

Appendix 2. Glossary

alluvial: sediment deposited by a river or other running water. Alluvial sediment (alluvium) typically consists of fine particles (silt and clay) along with sand and gravel. Sand and gravel are transported and deposited at higher flow velocities.

aquifer: saturated permeable geologic unit that can transmit enough water to make pumping from the unit economically viable.

aquitard: a geologic unit that does not transmit water easily; an aquitard may or may not be saturated with water.

artificial recharge: the process of artificially increasing the volume of water in the saturated zone by means of spreading water on the surface, injection wells, or inducing infiltration from streams or lakes.

base flow: the amount of water in a stream that results from groundwater discharge.

conceptual model: a model that describes the general functional relationship among components of a system.

estuarine: refers to conditions or sediments deposited where the broad mouth of a river opens into a sea.

evapotranspiration: the process by which water is transmitted as a vapor to the atmosphere as the result of evaporation from any surface and transpiration from plants.

fluvial: refers to streams and the sediments transported and deposited by them.

geophysics: the branch of geology that studies the physics of Earth, using the physical principles underlying such phenomena as seismic waves, heat flow, gravity, and magnetism.

hydraulic head: water-level elevation in a well, or elevation to which the water of a flowing artesian well will rise in a pipe extended high enough to stop the flow.

loess: windblown silt-dominated deposit; many soils in the uplands of eastern Nebraska are developed in Peoria Loess which was deposited during the last ice age.

natural recharge: naturally occurring water added to an aquifer. Natural recharge generally comes from snowmelt and precipitation or storm runoff.

paleovalley: an ancient stream valley filled with sediment and usually not recognizable at the land surface because it is so deeply buried; paleovalley aquifers, or aquifers in sediments (sand, gravel) that fill a paleovalley, are common in eastern Nebraska.

permeability: the ability of a material to transmit fluid through its pores.

safe yield: the balance between the amount of water withdrawn and that recharged to a given aquifer.

specific yield: the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table.

storativity: the amount of water released from storage in a confined aquifer per unit surface area of aquifer per unit decline in the hydraulic head.

sustainability: the concept of meeting the present needs without compromising the ability of future generations to meet their needs.

till: poorly sorted sediment deposited by a glacier. Tills usually contain abundant clay, but also contain boulders, cobbles, and pebbles. In eastern Nebraska, glaciers moving southward from the Canadian Shield deposited multiple tills between 2.5 Ma and 600 ka.

transmissivity: the rate at which water is transmitted through a unit width of an aquifer under a unit head.

water banking: a water management strategy that transfers water from those who are willing to cease using it to those who are willing to pay to use it.

water budget: a summation of inputs, outputs, and net changes to a particular water resource system over a fixed period of time.

ENWRA
EASTERN NEBRASKA WATER
RESOURCES ASSESSMENT

ENWRA COOPERATING AGENCIES

Conservation and Survey Division
School of Natural Resources
University of Nebraska–Lincoln
http://snr.unl.edu/csd/

Lewis and Clark Natural Resources District
www.lcnrd.org/

Lower Elkhorn Natural Resources District
www.lenrd.org/

Lower Platte North Natural Resources District
www.lpnnrd.org/

Lower Platte South Natural Resources District
www.lpsnrd.org/

Nebraska Department of Natural Resources
www.dnr.state.ne.us/

Nemaha Natural Resources District
http://nemahanrd.org/

Papio-Missouri River Natural Resources District
www.papionrd.org/

United States Geological Survey
www.usgs.gov

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