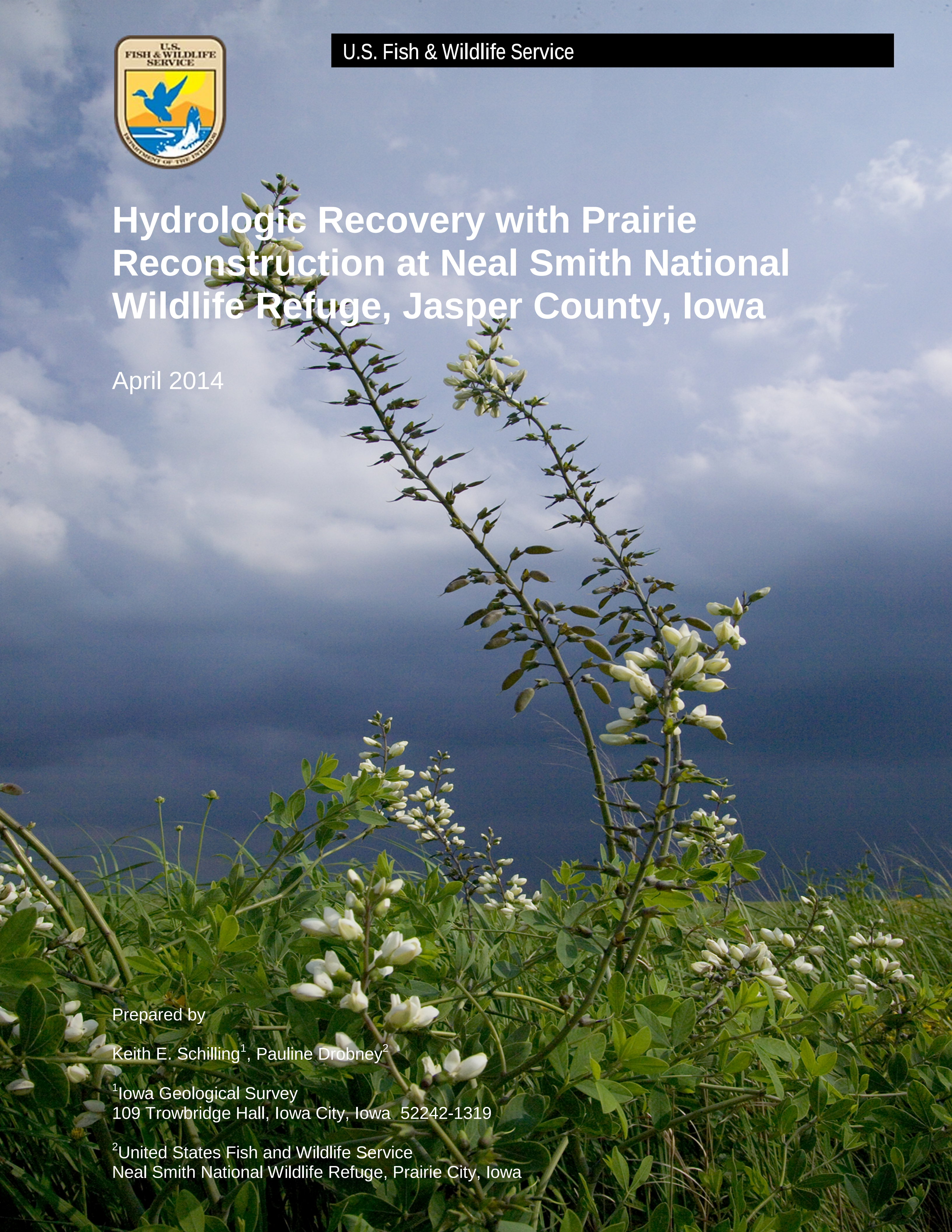

U.S. Fish & Wildlife Service

Hydrologic Recovery with Prairie Reconstruction at Neal Smith National Wildlife Refuge, Jasper County, Iowa

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Cover photograph: Bill Witt

The mission of the U.S. Fish & Wildlife Service is working with others to conserve, protect, and enhance fish and wildlife and their habitats for the continuing benefit of the American people.

The mission of the National Wildlife Refuge System is to administer a national network of lands and waters for the conservation, management and, where appropriate, restoration of the fish, wildlife and plant resources and their habitats within the United States for the benefit of present and future generations of Americans.

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Executive Summary

In this summary:

The ecological goal of Neal Smith National Wildlife Refuge (NSNWR, refuge) is to restore 11,865 acres of a former agricultural landscape as nearly as possible to the historic natural condition (USFWS, 2013). In this ambitious undertaking, the U.S. Fish and Wildlife Service (USFWS, Service) recognizes that both biotic and abiotic elements of the landscape require critical consideration. Because improving hydrologic function is key in the process of ecological restoration, hydrologic research has been a priority since refuge inception. This report synthesizes results of hydrologic research conducted at NSNWR and presents scientific conclusions and insights gained from long-term monitoring. However, the report goes one step further. Scientific conclusions are also integrated with pragmatic concerns of land management to provide new information about the process of ecological restoration. In this way, the adaptive management loop can be completed by linking the scientific research to the knowledge base needed to better manage future refuge activities.

This report is organized in seven main chapters:

> Chapter 1: Introduction and Background – Provides an overview of the report and important background information.
>
> Chapter 2: Pre-Settlement Conditions –Describes how the pre-settlement landscape may have looked and how it functioned.
>
> Chapter 3: Agriculture Intensification – Describes the settlement and land use history of the watershed. Hydrologic and land cover changes occurring over the last 150 years greatly modified the landscape, setting the stage for refuge establishment.
>
> Chapter 4: Restoration of Hydrologic Processes at NSNWR – We reconcile the restoration potential of NSNWR in light of the original landscape condition and historical impacts. Given the hydrologic changes that have occurred in the Walnut Creek watershed, what aspects of hydrology and water quality are restorable, at what location they are best addressed, and under what timeframe will improvements be seen?
>
> Chapter 5: Lessons Learned From Hydrologic Monitoring – We discuss lessons learned from the research that are important to NSNWR and also applicable to other restoration sites.
>
> Chapter 6: Land Management Implications – Discusses land management implications from hydrologic research at the NSNWR.
>
> Chapter 7: Final Thoughts – What we have learned and our hopes for future discussion and new collaboration.

In addition to the seven main chapters, a Chapter 8: References is included and is located at the end of the report.

The Walnut Creek watershed is a product of its history, containing a legacy of the geologic and native tallgrass prairie past that was greatly modified with the arrival of settlement and agricultural intensification in the 19^{th} and 20^{th} centuries. We evaluated research results to assess the progress made towards restoring five key hydrologic components at the NSNWR, namely: water balance, stream network, streamflow hydrograph, groundwater levels, and water quality.

Water Balance: From pre-settlement through agricultural intensification, the water balance of the watershed changed from an evapotranspiration (ET) and infiltration-based landscape to a water-shedding landscape involving elevated surface water runoff and baseflow. Research at NSNWR is showing that prairie reconstruction is increasing infiltration and reducing stormflow runoff at the plot scale, but at the scale of the entire watershed, significant changes in the water balance have been difficult to detect.

Stream Network: Changing the water balance early in the post-settlement history along with landscape modifications in Walnut Creek watershed had profound ramifications on the stream network. Rapid runoff from newly plowed and drained agricultural land combined with increased gradients and faster flows in channelized stream networks greatly increased stream discharge peaks, stream erosive power and sediment transport capacity, leading to extensive channel incision. The total length of the Walnut Creek stream network increased 76% after settlement. There has been little progress made in restoring the stream network as the incised channel of Walnut Creek continues to evolve over time and eventually form a new channel within a new floodplain following well documented channel evolution models. NSNWR has replaced cropland along the streambanks with perennial vegetation, which serves to strengthen streambanks by controlling soil moisture fluctuations and providing soil stability with deeper roots.

Streamflow Hydrology: The pre-settlement hydrograph likely showed a relatively slow rise and fall with a high baseflow maintained by springs and groundwater, but today, discharge in Walnut Creek is very flashy as stream stage rises and falls rapidly with every storm runoff event. Plot scale studies indicate that prairie reconstruction is helping to reduce runoff, but at a watershed scale, these small plot scale changes are lost against the backdrop of stormflow discharge derived from non-refuge lands. Water delivered to the stream network via runoff and tile drainage from cropland areas is quickly routed to the incised stream system, resulting in flashy stream discharge. Based on monitoring data collected during the prairie reconstruction process, there has been no change in the streamflow hydrograph.

Groundwater Levels: Based on well depths reported by early European settlers, good quality groundwater was recorded at depths of 30–40 feet. The range of groundwater depths reported by early geologists for upland prairie are deeper than observed today. This suggests that centuries of greater ET under tallgrass prairie lowered the water table in upland areas. Deeper water tables means a thicker unsaturated zone under prairie, greater capture of water infiltration by soils, and ultimately less water delivered to streams. Today water table depths monitored under cropland in upland areas of Walnut Creek watershed average approximately 10 feet and typically fluctuate more than 12 feet in a year (reaching within 2–3 feet of the land surface). Along the stream corridor, changes in water table depths occurred as the channel incised into its floodplain. Channel incision lowers the riparian groundwater table in the stream riparian zone and creates a large unsaturated zone in the near-stream riparian zone compared to more distant floodplain zones.

In the uplands, prairie reconstruction appears to be making progress towards restoring historic groundwater levels. In a study of a chronosequence of prairie plantings and current crop fields, groundwater depths were significantly lower in older reconstructed prairie plantings compared to younger plantings and the existing farm field. Less progress is being observed in the riparian zone as the stream channel evolves over time. In-stream obstructions such as beaver dams may provide temporary base level control and raise riparian water table levels.

Water Quality: Early reports describe surface water in streams to be “clear,” “pure,” and “excellent”; and we can be quite certain that surface water and groundwater quality conditions deteriorated under the post-settlement agriculture period. Sampling data available in Walnut Creek watershed indicate that post-settlement agricultural intensification has led to high concentrations of nutrients present in groundwater beneath cropped systems and in surface water flowing in refuge streams. High concentrations and loads of nitrate-nitrogen, phosphorus (P), and sediment are exported from agricultural regions in the watershed.

Perhaps the greatest improvement in returning to pre-settlement conditions has been restoring aspects of water quality, particularly nitrate. Beneath restored prairies, nitrate concentrations are decreasing by about 0.5–1.5 milligrams per liter per year since prairie planting. Restored prairie locations are decreasing substantially to levels approaching pre-settlement conditions. At the scale of the entire watershed, improvements have been more difficult to detect. Although sediment transport (and sediment-bound P) is being reduced in restored prairie areas, improvements in P and sediment concentrations and loads have not been observed at the watershed scale due to legacy effects and altered streamflow hydrology.

Summary of Progress Made Toward Restoring Hydrologic Processes

The impacts of prairie restoration at the NSNWR on key hydrologic processes in the Walnut Creek watershed are mixed. Research indicates that the hydrologic effects of ecological restoration are more easily observed at small spatial scales compared to larger watershed. Likewise, upland areas offer a much greater opportunity for restoring hydrologic processes than drainageways, floodplains, and the channel. The most challenging for restoration will be the Walnut Creek channel. The channel has integrated the accumulated legacy of historical changes that have occurred throughout the basin and has been completely altered from pre-settlement condition. The channel will not return to a pre-settlement equilibrium until hydrologic changes are fully implemented throughout the watershed. Observing changes in Walnut Creek water quality will probably be limited to nitrate concentrations for the foreseeable future. Streamflow discharge will continue to erode streambank and bed sediments and deliver downstream P and sediment loads until the stream hydrology becomes less flashy and the stream channel is reconnected to its floodplain.

The timeframe for restoration of key hydrologic processes in Walnut Creek watershed will vary. In a single catchment, the time may be less than a decade, but at scale of the watershed, the timeframe for restoration will be considerably longer as current prairie plantings mature and more areas are planted in the future.

Lessons Learned from Hydrologic Monitoring

The following are some lessons learned following two decades of conducting hydrological research at the NSNWR in the Walnut Creek watershed:

- It is important for ecological restorations to address hydrology.
- Monitoring hydrologic restoration is best suited at the plot or catchment scale.
- Headwater areas must be restored before hydrologic conditions in downstream areas are restorable.
- Restoring the stream channel is a long-term project.
- Hydrologic monitoring is not easy but should be conducted.
- The timeframe for hydrologic restoration should be realistic.

Management Implications

Perhaps the most profound management insight from this hydrologic synthesis has been the recognition that a synergy exists between hydrology and native plant community reconstruction/restoration. Deepening of groundwater associated with an increase in water storage potential and infiltration causes baseflow to become active in side slope and lowland seeps and springs. This provides opportunity to develop more complexity in uplands and allows a more stable hydrologic condition in some areas of the lowland.

Sedge meadow efforts along the deeply incised Walnut Creek are unlikely to be successful except in areas more distant from the stream where hydrology is more stable. Herbicide and nitrogen (N) reduction are useful to suppress reed canarygrass and establish sedge meadow flora. In the harsh conditions in the hydrologic drought zone along the stream margin we recommend constructing a community of native plants of multiple communities that can best hold the soil, survive harsh conditions, and not provide threat to the nearby sedge meadow. Sedge meadow reconstruction might be more successful in stretches of first order streams where the stream is still connected with its floodplain. We recommend lowlands and uplands associated with these areas as management priorities, because they may offer the best opportunity for ecological function in a relatively large management block.

Removal of “grassed waterways” may be best timed for three years after planting of the surrounding landscape when N has been metabolized, to achieve greatest success in suppressing N loving exotic grass and establishing N inhibited prairie species. Upland interseeding of legumes, inhibited by N loading, may be best timed at three to five years after initial planting when N levels in uplands decrease.

Additional management insights include the following:

- A greater complement of native spring flora is likely necessary for greater hydrologic function on prairie reconstructions.
- Variability in species expression after prairie planting is in part due to differences in prior farm management among fields.

- Prairie plantings could help clean water, prevent flooding, buffer drinking water reservoirs, and provide cost benefits if strategically located in large-scale landscape designs.
- Differences in locations of historic vs. current savannas may be in part due to changes in hydrology.
- Floristic diversity is important on side slopes where there is more runoff than infiltration to deter erosion and facilitate hydrologic function.
- Tile removal can allow rehydration of upland swales, repair of some erosional features, greater hydrologic function, and opportunity for development of a more nuanced natural landscape and better habitat.
- Strategically placed weirs and natural water impediments like beaver dams can help reconnect the stream to the floodplain and allow greater ecological function.
- Sufficient information now exists on stream function and hydrology to have discussion on stream restoration possibilities.

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Chapter 1: Introduction and Background

In this chapter:

Introduction

This document is the synthesis and interpretation of hydrologic research performed in the 20-year history of Neal Smith National Wildlife Refuge (NSNWR, refuge) (formerly Walnut Creek National Wildlife Refuge), and includes implications for natural land managers. Refuge staff and planners recognized hydrology as a driver of ecological function and saw the need to monitor hydrology through time to understand the role of hydrology in ecological restoration, monitor progress made toward ecological goals, and to gain information necessary to make reasonable decisions about stream restoration attempts. Hydrologists recognized a rare and important opportunity to document and understand hydrologic changes as an agricultural landscape was converted to a more natural condition as opposed to the more usual work of documenting hydrology in the unraveling of a natural system or in an agricultural or urban context.

Mutual interest between U.S. Fish and Wildlife Service (USFWS, Service) and the hydrologic research community resulted in funding the Walnut Creek Watershed Monitoring Project. This 10-year (1995–2005), multi-partner project documented changes in hydrology and water quality as cropland was converted to prairie (Schilling and Thompson, 2000). Numerous other hydrologic and water quality monitoring studies were conducted at NSNWR, and Keith Schilling, the lead author for this document, served as Principal Investigator for most of them. Integrating research results from the total body of hydrologic research provides opportunity to evaluate the potential for restoration of key hydrologic processes at various scales including the landscape scale.

Reinstating the essential condition of the native prairie landscape on a scale of more than 8,000 acres on former farmland is challenging. The starting point is to establish native flora on farmed lands and to restore quality to the small and highly degraded prairie, savanna, and sedge meadow remnants and to essentially knit these areas together with native vegetation to develop a more natural landscape. Refuge staff developed many techniques and strategies to these ends. Pauline Drobney, co-author of this document, functioned as Refuge Biologist for the first 12 years of refuge existence and continues to be involved in aspects of ecological restoration and research at NSNWR and other sites after transitioning to other positions within the Service.

Because floristic repair has been central to the work of the refuge for the last 20 years, the context of hydrologic study and analysis and development of management insights was in the realm of reconstruction of native plant communities, especially prairie. Many of the management insights and recommendations presented result directly from experiences in ecological restoration, although some are the result of scientific studies.

Hydrologic research conducted over the last two decades in the Walnut Creek watershed can be used to help inform the Service on how much progress has been made in achieving ecological restoration goals at NSNWR and in identifying additional information and management needs. An overriding question 20 years into the project is, “To what degree have ecological restoration and experimental research practices within the watershed pushed the landscape toward a more natural condition?" In addition, "Given lessons learned, what is a realistic timescale for ecological restoration progress?" Ehrenfield (2000) warns that goals should be realistic, recognizing that reconstructed systems are not a replica of the original, "natural" system. Refuge staff rejected a goal of replicating historic pre-settlement conditions in initial discussions, opting instead for a goal to ecologically restore natural conditions as nearly as possible to the historic state. In this goal, limitations were clearly recognized. Considering that a project of this scale and scope was unprecedented, there were no equivalent examples to reference as land managers proceeded in ecological restoration efforts (Drobney, 1994). The purpose of this synthesis is to: 1) integrate research results from the various hydrologic monitoring projects to address this question in the context of a very early phase of ecological restoration with only two decades of history, and 2) to distill essential management insights from hydrologic research conclusions that can help enable land managers to adjust course and do a better job of reaching management goals in the future.

This synthesis is organized in seven main chapters. Following this introduction and background, we describe in chapter 2 how the pre-settlement landscape may have looked and how it functioned. If developing a relatively close semblance of the historic natural community—including ecological function and habitat characteristics, given limitations—is the goal of NSNWR, we must understand what it is that NSNWR is striving to emulate. In chapter 3, we describe the settlement and land use history of the watershed. Hydrologic and land cover changes occurring over the last 150 years greatly modified the landscape, setting the stage for refuge establishment. In chapter 4, we reconcile the restoration potential of NSNWR in light of the original landscape condition and historical impacts. Given the hydrologic changes that have occurred in the Walnut Creek watershed, what aspects of hydrology and water quality are restorable, at what location they are best addressed, and under what timeframe will improvements be seen? How does the hydrologic condition relate to rebuilding ecologic and biotic aspects of the refuge? In chapter 5, we discuss lessons learned from the research that are important to NSNWR and also applicable to other restoration sites. In chapter 6 we discuss the land management implications from hydrologic research at the NSNWR. Some final thoughts are presented in chapter 7, and references used in this report are in chapter 8.

Background

Tallgrass prairie once occupied 67.6 million hectares in the North American Midwest, but less than 0.1% remain today (Samson and Knopf, 1994). General Land Office (GLO) surveyors reported that land cover in what is now Iowa was 81–85% prairie in 1832–1859. However, this estimate is somewhat uncertain as surveyors in various parts of the state understood and defined land cover types that we interpret as prairie, savanna, and forest somewhat differently from one another (Smith, 1998). The amount of remnant prairie left in Iowa today is less than 28,000 acres (including disturbed and degraded relict prairies), and if only remnants consisting of species composition somewhat similar to pre-settlement prairie are considered, the amount of prairie remaining in the state is likely less than 0.05% (Smith, 1998). The disappearance of American prairie has been termed one of the largest ecological and biological disturbances of modern times (Kucharik et al., 2006).

From the brink of virtual decimation, support for tallgrass prairie preservation, restoration, and reconstruction has been increasing through the late 20th and early 21st centuries. Early work by Ada Hayden [4] focused primarily on preservation of remnant prairies; whereas today, efforts are primarily addressing restoration of degraded prairie remnants and reconstruction of prairie in areas with no relict prairie species (Smith et al., 2010).

Several large-scale prairie recovery projects were implemented in the early 1990s. Walnut Creek National Wildlife Refuge, renamed Neal Smith National Wildlife Refuge, was established in 1991 by the Service in Jasper County, Iowa (figure 1-1) and was the first prairie ecological restoration project of its scale and scope to have been attempted.

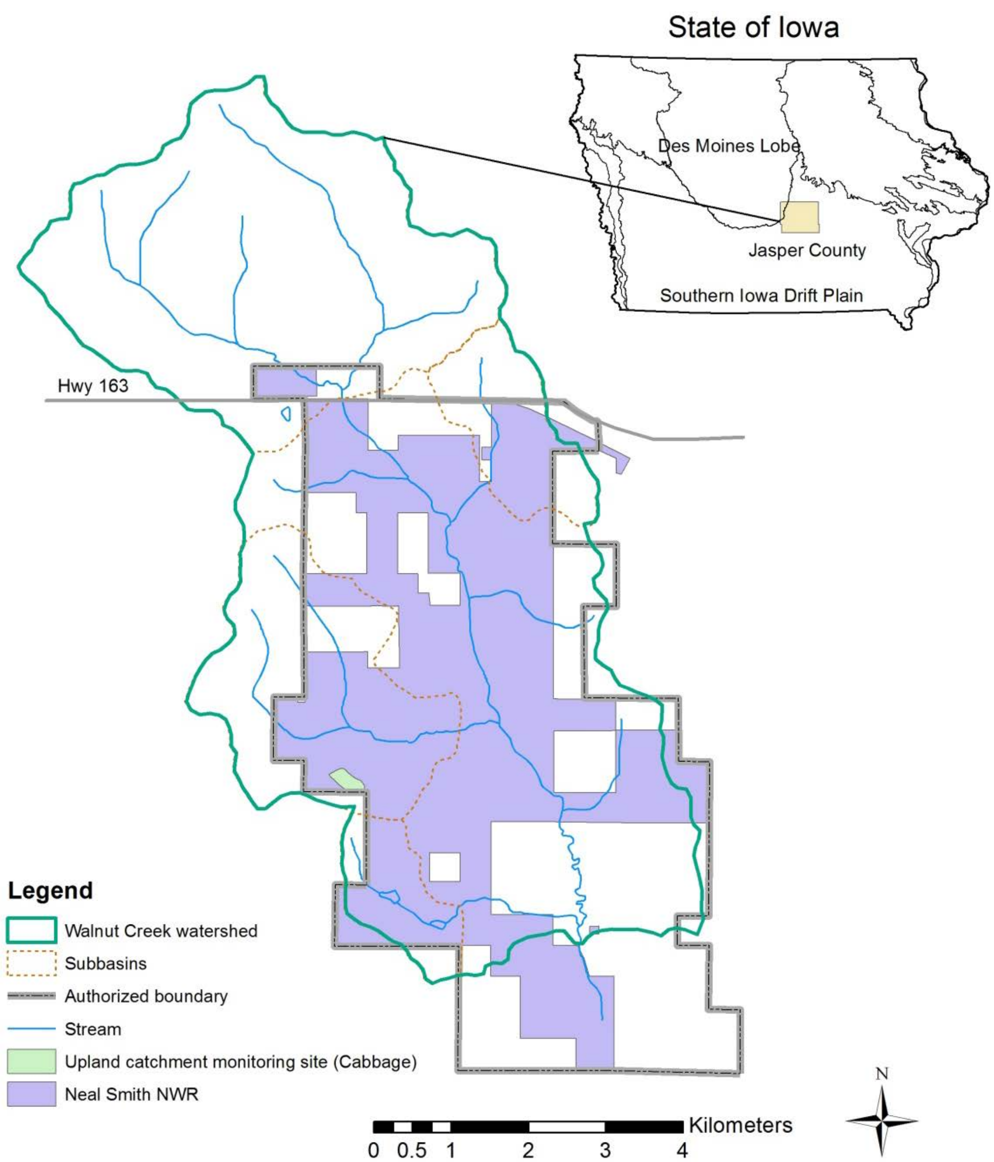


Figure 1-1: Location of Neal Smith National Wildlife Refuge and future acquisition area in the Walnut Creek watershed, Jasper County, Iowa.

The project was 8,654 acres, larger than any existing project, with a goal to emulate the historic natural landscape. Currently consisting of 5,500 acres, the future 11,810-acre (USFWS, 2013) refuge is located within the rolling hills of the12,890-acre Walnut Creek watershed. Approximately 800 acres were recorded as highly degraded remnant prairie, savanna, or sedge meadow during the establishment phase of NSNWR, and most of the remaining land was in agricultural production. Thus, large tracts of land are being converted from row crop agriculture to native prairie and savanna with the goal to restore the landscape to a semblance of the condition that existed prior to Euro-American settlement (Drobney, 1994; Smith, 1998).

The Service recognizes that duplication of the pre-European natural landscape is impossible and instead focuses on restoration as nearly as possible to the historic condition, given limitations. Limitations, for example, include the inability to reinstate extinct species such as the Passenger Pigeon (*Ectopistes migratorius*) or to reconstruct exact soil conditions of an upland, given that massive agricultural erosion has happened. It follows, then, that vegetation will not be precisely the same as existed on the historic prairie landscape, although most if not all plant species could be supported by conditions that occur or will occur somewhere on the refuge through restoration of natural processes and incremental reconstruction efforts (Roelle and Hamilton, 1993). An obvious limitation to ecological restoration is that the once contiguous tallgrass prairie and savanna ecosystems that occupied most of Iowa, and portions of at least 13 states and parts of Canada and Mexico are now relegated to appallingly small remnant and reconstructed examples. The character and effects of fires that swept over large expanses of the prairie landscape was very different from current prescribed fire on small parcels. Even on the scale of several thousand acres, it is difficult if not impossible to duplicate historic fire conditions and effects.

There are limitations in resources available to accomplish ecological restoration in terms of currently available tools, techniques and human resources. In addition, there are simply limits to knowledge. As the forester Jack Ward Thomas (1993) stated, “Ecosystems are not only more complex than you think, they are more complicated than you CAN think.” Although limited by this complexity, it is in studying carefully selected elements of the unknown and weaving together insights gained from study and experiences that will provide better tools for effective ecological restoration and long-term sustainability of natural lands.

Establishing realistic goals for any restoration project is critical for its success (Ehrenfield, 2000). Enabling legislation for NSNWR included direction by the Congress “. . . to restore native tallgrass prairie, wetland and woodland habitat for breeding and migratory waterfowl and resident wildlife . . . ” (USFWS, 1993), but clearly goals were focused on conservation of the imperiled prairie ecosystem. This intent is demonstrated by the following statement on the signature page on the Walnut Creek NWR Master Plan:

> “*The U.S. Fish and Wildlife Service proposes this Master Plan to reconstruct one of the rarest of North America’s major ecosystems, tallgrass prairie and oak savanna, at the Walnut Creek National Wildlife Refuge near Prairie City, Iowa. . . . As the largest prairie reconstruction project in the United States, establishment of the refuge provides the Service with a unique opportunity to expand its ongoing efforts to protect and enhance environmental quality and habitat diversity*.”

Thus, an ecosystem-based approach to ecological restoration within the boundaries of the refuge included both biotic and abiotic elements and was used to identify specific ecological restoration objectives (USFWS, 1993). A fundamental premise was the recognition that restoration of ecosystem processes can reinvigorate and drive the system (Roelle and Hamilton, 1993; Ehrenfield, 2000).

Palmer (2009) recommends that restoration of processes be the primary focus of all ecological restoration projects, as restoration-induced changes in key processes can have a cascading effect on natural communities and characteristics throughout the basin. For example, changes in hydrology and water quality made in upland areas are linked to conditions found downstream.

Hydrology is a defining factor in the type and function of most ecosystems, and developing a better understanding of hydrologic processes at the watershed scale has been a primary focus of research at NSNWR for nearly two decades. In 1993, during a workshop to develop monitoring and research priorities, hydrology and water quality were among the top research needs identified, noting they are “good indicators of general recovery because they are the net result of many processes occurring on multiple sites,” (Roelle and Hamilton, 1993).

Chapter 2: Pre-Settlement Conditions

In this chapter:

Although we have little first-hand knowledge of the landscape of the Walnut Creek watershed prior to settlement, we can reasonably infer what the landscape looked like and how it functioned based on an analysis of the physical characteristics of the basin, reports from early settlers, and from characteristics of extant remnant natural communities.

Pre-Settlement Landscape

Geology

The geology of the Walnut Creek watershed is unchanged from pre-settlement time, and these landform conditions transcend the time of human occupation. Based on geologic logs for wells drilled in the vicinity of the refuge, the bedrock depth ranges from about 40 feet to more than 250 feet, with greater bedrock depths located in the northern portion of the watershed (figure 2-1).

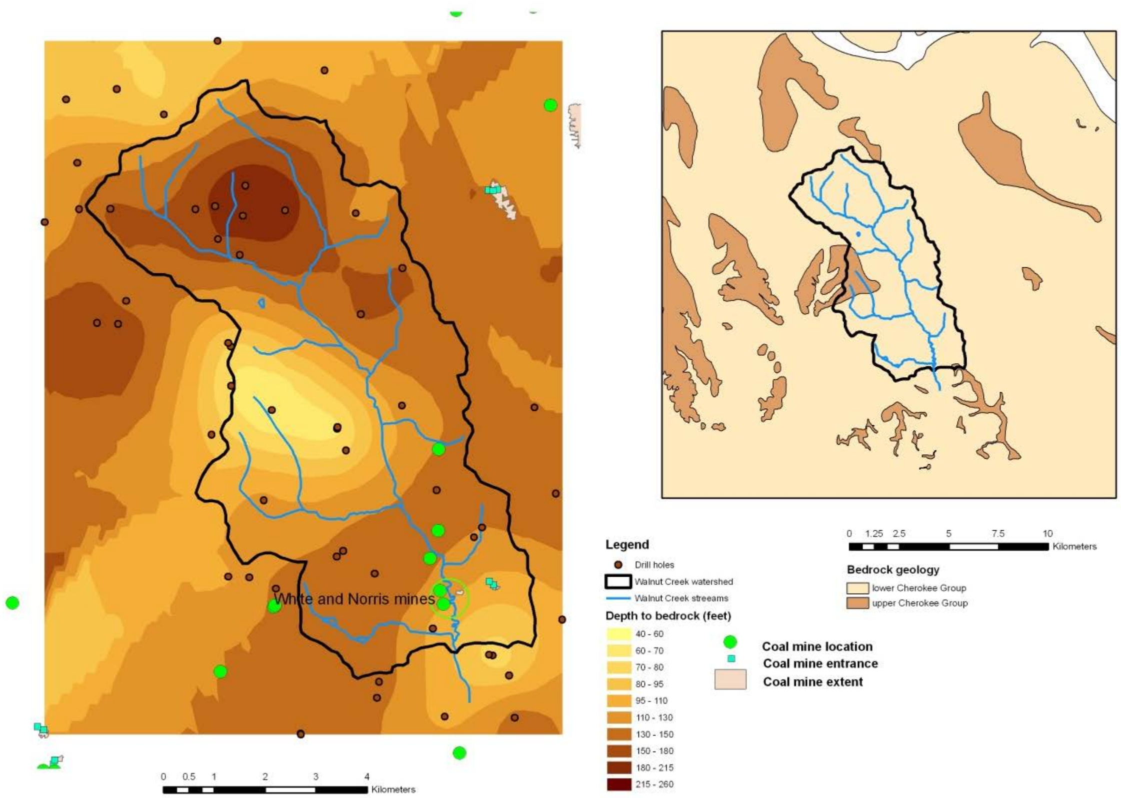


Figure 2-1: Bedrock geology and depth to bedrock surface in Walnut Creek watershed.

Bedrock is comprised of Cherokee Group rocks from the Pennsylvanian period (geologic stratigraphy formed 318–299 million years ago) (figure 2-1) that consist of a succession of shale-dominated, coal-bearing cyclothems (stratigraphy formed by geologically frequent fluctuations in marine and terrestrial deposits typically capped by a layer of coal), with locally prominent sandstones and rare, thin limestone (Pope and Goettemoeller, 2002). The thickness and depth of rock formations vary by location. Bedrock of the Cherokee Group has a widespread distribution across the central United States and can reach 400–500 feet thick at some locations. In Walnut Creek watershed, Pennsylvanian strata (including the Cherokee Group) are approximately 75 to 200 feet thick and are underlain by Mississippian-age dolomite, sandstone, and chert of the St. Louis, Warsaw, and Keokuk formations.

Topography

The topography of the Walnut Creek watershed is characterized by steeply rolling hills and well-developed drainage typical of the Southern Iowa Drift Plain landscape region of Iowa (Prior, 1991). Hillslopes dominate the landscape because the region was last glaciated more than 500,000 years ago (termed "pre-Illinoian"; Hallberg, 1980—a stage of the Quaternary Period from 2.5–0.5 million years ago typified by frequent glaciation). Unlike the recently glaciated (~10,000 years ago), flat and poorly-drained region of the Des Moines Lobe in north-central Iowa, the older pre-Illinoian landscape in southern Iowa is well dissected by a dendritic pattern of interconnected swales, drainageways, creeks, and streams. The topographic relief in the basin is 168 feet, and the average basin slope is 10.96 feet per mile (Schilling and Thompson, 1999). Early settlers remarked on the topography of the area (Whitney, 1858):

> *"The rolling prairie greatly predominates over the flat, especially in Iowa, where there are but a few tracts of any extent which are not more or less undulating. Even in the rolling prairie the irregularities of the surface are but trifling in amount, compare with the vast extent which can be taken in a one view; so that appear to be almost a deal level, is, in reality, furrowed by broad depressions, which give a wave-like character to its surface. Thus, the traveler crossing the prairie in any direction, except along its water-shed, will be surprised to find himself constantly ascending and descending, although only hills of moderate elevation*."

Hence, the pre-settlement landscape of Walnut Creek watershed was not flat, but rather consisted of hillslopes and floodplains carved over hundreds of thousands of years.

Soils

Fine-textured glacial till deposits and loess form the unconsolidated sediments found above the bedrock surface (figure 2-2). We know from studies conducted at various locations in the watershed (Schilling and Thompson, 1999; Schilling and Wolter, 2001; Schilling and Jacobson, 2008) that in the uplands, the till consists of an upper oxidized and weathered unit overlying a lower unoxidized unit. The oxidized till is typically a dark, yellowish brown silty clay loam containing abundant fractures, joints, and root casts; whereas, the unoxidized till is massive, very dark gray calcareous loam that underlies most of the refuge area to depths of more than 15 to 75 meters (m) (50 to 250 feet). Along some hillslopes, pre-Illinoian till or a relict paleosol surface (Sangamon Geosol) may form resistant outcrops and lead to side hill seeps of groundwater discharge. Loess from the Wisconsin epoch deposited across much of the midcontinent during glaciation between 25,000 and 14,000 years ago mantles the pre-Illinoian drift in upland landscape positions.

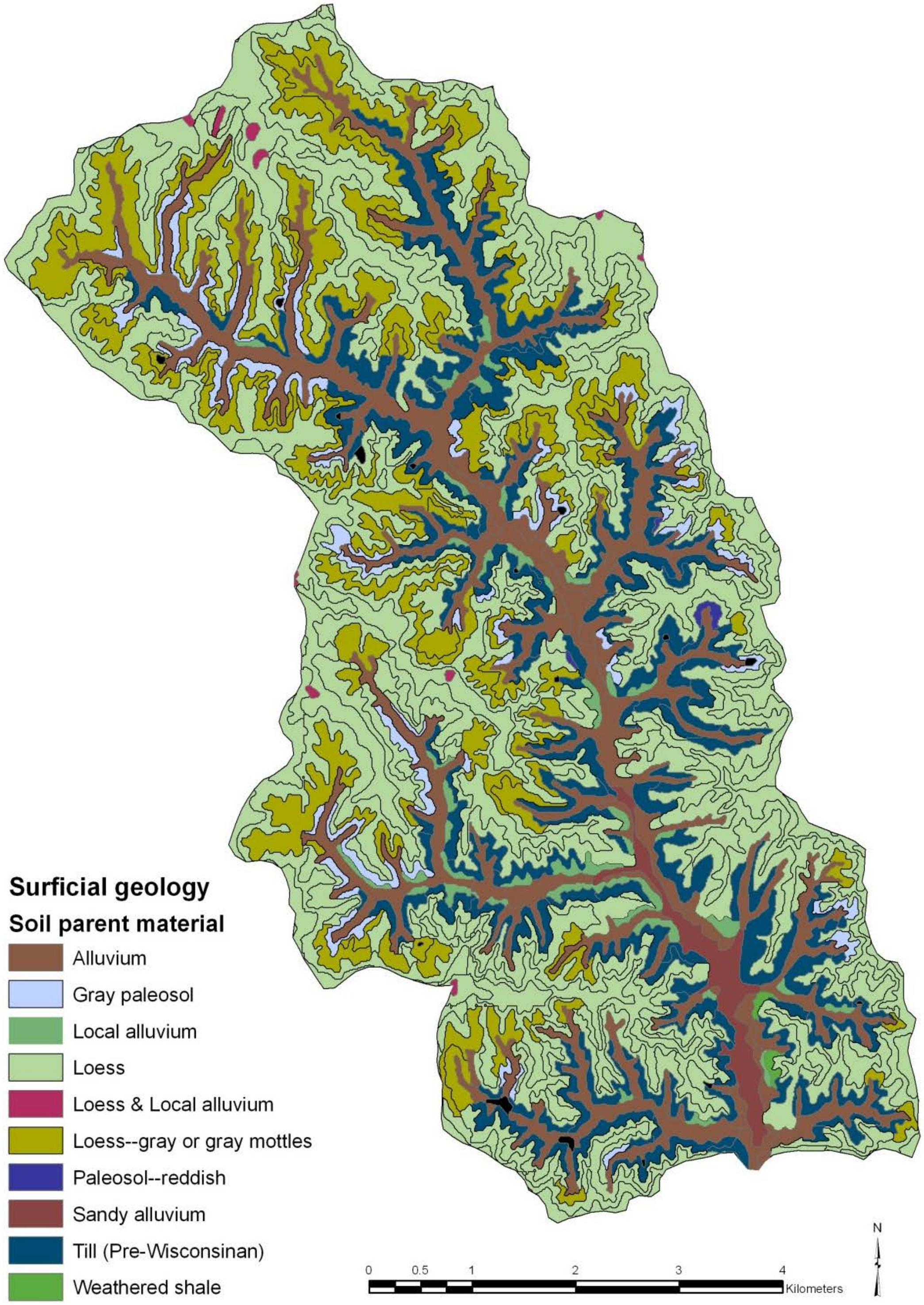


Figure 2-2: Surficial geologic map of Walnut Creek watershed based on soil parent materials.

The loess deposits are predominantly oxidized and leached silt loam to silty clay loam that range in thickness from about 2.5 meters (~8 feet) (Schilling and Thompson, 1999) to 4–6 meters (~13-20 feet) (Schilling et al., 2007) at various upland locations. Overall, loess mantles approximately two-thirds of the basin whereas outcrops of pre-Illinoian till along hillsides account for an additional 14% of the land area (Schilling and Thompson, 1999). Dominant soil taxa in the watershed reflect the parent materials of loess and till (Tama, Otley, Killduff, Ladoga-Gara series) with many soils characterized by moderate to high erosion potential.

Erosion of upland fine-textured loess and glacial till produced fine-textured alluvium deposited in the drainageways and the floodplain of Walnut Creek watershed (figure 2-3). The alluvial deposits reflect periods of erosion and deposition that have occurred since the last glaciation and thus provide a record of the post-glacial (Holocene) climate and vegetation history of the watershed. The alluvial stratigraphy in Walnut Creek watershed is characteristic of many other valleys across Iowa and in loess-mantled areas of the Midwest (Bettis, 1990; Mandel and Bettis, 1992; Bettis and Autin, 1997). The majority of alluvial fill in these valleys is dominantly silty loamy, and clayey—collectively called the DeForest Formation (Bettis, 1990; Bettis et al., 1992). The formation has been divided into members based on lithologic properties (texture, color, bedding structures and pedogenic alterations) and landscape associations and three units found in Walnut Creek watershed include the Camp Creek, Roberts Creek, and Gunder members. These units were each deposited during a restricted time range during the Holocene, with the Gunder Member deposited between about 10,500 and about 4,500 radiocarbon-years Before Present (B.P.), the Roberts Creek Member from 3,500 to about 500 B.P., and the Camp Creek Member from about 400 B.P. to present (Bettis et al., 1992). The Camp Creek member represents alluvium deposition after Euro-American settlement and would not have been present on the pre-settlement landscape. In the Walnut Creek watershed area, the Camp Creek Member would have been about 200 B.P. to present reflecting settlement in the 1800s.

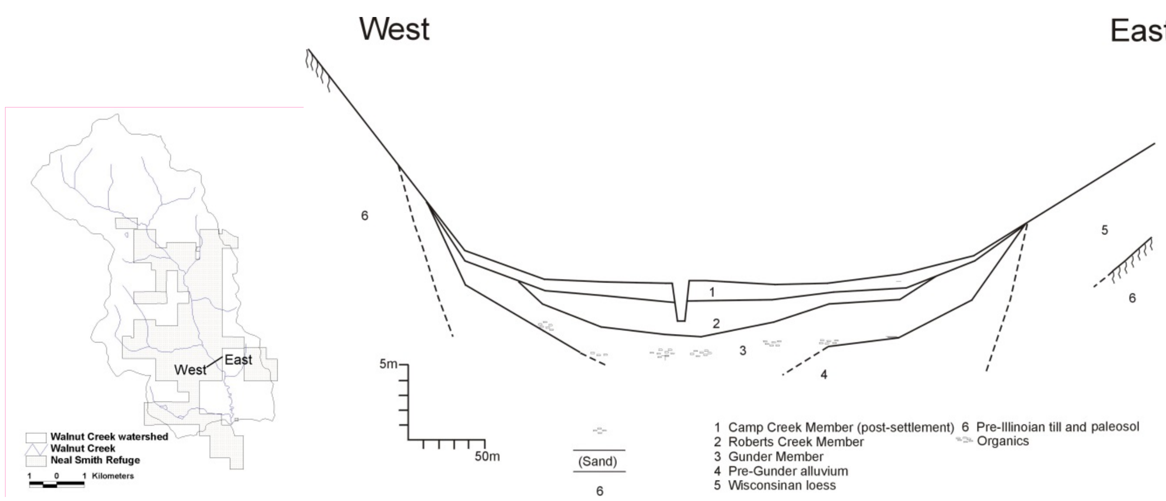


Figure 2-3: Cross section across the floodplain of Walnut Creek showing alluvial stratigraphy (modified from Schilling et al., 2004; Schilling et al., 2006).

The older alluvial member (Gunder Member and any older units termed “pre-Gunder”) is found in the drainageways and floodplains of Walnut Creek watershed at depths of approximately 1–3 meters (3.3–9.8 feet) (Schilling et al., 2007; Schilling et al., 2009; Schilling and Jacobson, 2008, 2011). Most of the Gunder Member was deposited during periods of high suspended sediment load when loess deposited during the last glacial period was eroded from slopes (Bettis and Autin, 1997). Local vegetation in central Iowa during this period was predominantly deciduous forest (Baker et al., 1993). Regionally, the Gunder Member alluvium is generally the coarsest of the Holocene alluvial fills (Bettis, 1992; Bettis and Autin, 1997;). In Walnut Creek watershed, the sand content of the Gunder Member averaged about 21%, although it was variable, ranging from 0 to 82% sand. During a period of reduced long-term precipitation in the middle Holocene (ca. 6,000–4,500 years B.P.) water tables were lower, the Gunder Member deposits were oxidized, and vegetation shifted to prairie and savanna (Bettis et al., 1992; Baker et al., 1992; 1996). The high degree of mottling we observed in the upper Gunder Member (Schilling et al., 2009) indicates long-term water table fluctuation through the zone. The nutrient content (nitrogen[N] and carbon [C]) in Gunder Member alluvium is low suggesting that labile C and N in the upper portion of the unit were oxidized and leached during the mid-Holocene period of low water tables. In some sites, we have observed larger, less labile, wood and organic fragments in the lower part of the unit (Schilling et al., 2004).

The Roberts Creek Member overlies the Gunder Member in many drainageways (Schilling et al., 2007) and in the Walnut Creek floodplain (Schilling et al., 2004; 2009). This unit accumulated between about 3,500 and 500 years B.P. during subsequent cooler and wetter conditions in the late Holocene (Bettis et al., 1992; Baker et al., 2002). Soil development in the upper part of the Roberts Creek Member represents the pre-settlement landscape surface. High water tables in the late Holocene promoted reducing conditions that preserved organic matter in the Roberts Creek Member. Unlike the Gunder Member, significant mottling was not evident in Roberts Creek sediment, which suggests that most of the unit remained saturated since deposition and labile N and C were preserved. In the Walnut Creek floodplain, the Roberts Creek Member contained more than twice as much N and C as the Gunder Member (Schilling et al., 2009). Climatic conditions during the late Holocene also favored expansion of tallgrass prairie and savanna on valley slopes and upland ridges and an increase in riparian forest (Baker et al., 1992). The open condition of prairies and savannas was ultimately maintained through frequent aboriginal fire, however, as an increasingly moist climate would have favored dominance of woody species had fire been absent. The late Holocene time period was marked by relatively small but more frequent floods compared to those characteristic of the mid-Holocene (Knox, 1993; Baker et al., 2002). This was evidenced in the Walnut Creek floodplain where the texture of the Roberts Creek Member was dominated by fines (silt and clay).

Overall, the geology of Walnut Creek watershed records the long-term evolution of the pre-settlement landscape. A flat landscape originally formed during pre-Illinoian glaciation more than 500,000 years ago was eroded into hillslopes, drainageways, and floodplains and later buried by a blanket of loess ~20,000 years ago. Erosion of upland deposits and loess deposited fine-grained silty alluvium in low areas and floodplains that records the transition of watershed vegetation from deciduous forests to tallgrass prairie and savanna approximately 4,000 to 6,000 years ago.

Plant Communities

The vegetation of Walnut Creek watershed prior to Euro-American settlement was dominated by tallgrass prairie and open woodland or savanna (figure 2-4). Knowledge of pre-settlement land cover comes from General Land Office (GLO) Surveys of the region conducted by early surveyors, explorers, scientists, and land speculators (Anderson, 2000) and from written records from those who traversed, did business, or settled in the area. Additional insights are gained from characteristics of remnant natural communities still extant.

GLO surveys were established to provide a legal framework for land ownership boundaries and to promote settlements and agriculture. Surveyors recorded what they encountered when they first walked across the midwestern plains. The GLO survey of Walnut Creek watershed conducted in 1847 indicated that the flat-to-rolling landscape that existed in the northern half of the watershed was open prairie as no trees were reported in the GLO notes for the area. The southern portion of the watershed was probably a mosaic of prairie, savanna, and wet prairie or sedge meadow. The GLO data record timber in a wedge-shaped pattern with the broadest portion of the wedge near the southern end of the basin and a narrow tip that extended north into the middle of the basin (figure 2-4). Notes from this area indicate open prairie interspersed with timber dominated by bur oak (Drobney, 1994). One description of the prairie reported (Whitney, 1858):

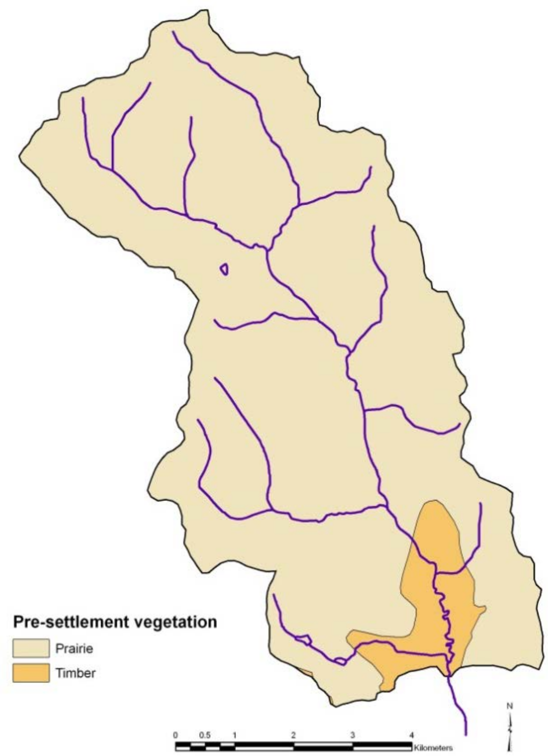


Figure 2-4: Pre-settlement land cover derived from GLO survey.

> "*The prairies are covered with a dense vegetation of grass and herbaceous plants, to the almost entire exclusion of trees, which occur only, under peculiar circumstances of moisture and soil, in scattered groups called groves, or along larger streams, or, occasionally, on low rocky ridges which sometimes are met with. This growth of timber in the river bottoms does not entirely disappear until we reach the border of the "plains." . . . In the swales, or depressions, which are comparatively humid, the grass grows very tall and rank; and the higher and drier the prairie the finer its growth, and more dense and closely interwoven the sod. Among the grasses of the prairies is interspersed a great variety of flowering plants, which bloom in constant succession from spring to autumn, and lend a peculiar charm to the landscape, giving beauty to might otherwise be called a monotonous scene.*"

In the quote above, Whitney (1854) observed that the location of groves or savannas was related to "peculiar conditions of moisture and soil" and was restricted to such areas. Although Whitney does not elaborate on precisely what that means, Wilhelm (2007) suggests that the location of savannas on the Southern Iowa Drift Plain was related to soil and moisture conditions and not to the quality or frequency of fire. Specifically he indicates that long-term soil organic matter inputs from and decay of deep and fibrous roots caused uplands to be poorly drained. Low wet areas were also wet and soggy, and under these conditions, growth is limited in most upland tree species. He concludes that:

> "*Trees were best developed on the drift plain dissections where the vadose waters were deeper below grade, and the abundant ground-cover sedges produced enough soil organic carbon in root mass degradation to keep in balance with the oxidation rate, which is important in sustaining good soil tilth*."

A district of five counties including Jasper (Tama, Marshall, Hardin, Jasper, and Poweshiek) was described as a ". . . gently rolling prairie traversed by numerous streams, skirted with timber, and dotted with occasional groves," (Whitney, 1858). The rolling, hilly topography of the Southern Iowa Drift Plain thus supported a rich diversity of grass, sedge, and forb species with nearly treeless tallgrass prairie punctuated by savanna. Savanna trees included bur, black, and white oak (*Quercus* spp.); hickory (*Carya* spp.), and scattered elm (*Ulmus* spp.). Sedge meadows existed in floodplains along streams and in uplands where seeps were expressed and were dominated by sedges (*Carex* spp.) and rushes (*Juncus* spp., *Eleocharis* spp.). Fens may have occurred where springs existed and are indicated by peaty soils. Larger rivers were often bordered by timbers. These natural communities blended and merged with one another imperceptibly without distinct boundaries, changing in response to hydrology, soils, and geology.

Fire was important in sustaining midwestern grassland ecosystems as were found in the Walnut Creek watershed. Fire swept across this landscape through prairie, woodland, and sedge meadow alike, influencing the vegetation, and thus availability of food, shelter, and water for wildlife and for the humans who ignited them. Accounts indicate that these fires were ignited annually and in the fall. Fires generated a fresh flush of vegetation providing good forage for game, and were usually followed by a hunt for meat needed to supply tribes through the winter. (Wilhelm, 2007). Several accounts by early Euro-Americans noted the annual fall burning practice of native people including this one by Whitney (1958):

> "*The idea is very extensively entertained, throughout the West, that the prairies were once covered with timber; but that this has been destroyed by the fires which the Indians have been in the habit of starting in the dry grass, and which sweep over a vast extend of surface every autumn."*

It was these fires that sustained the essential treeless character of prairie and the openness of savanna and woodland of the area. Surveyors' notes for the current refuge indicated some prairie areas were brushy and that "grubs" were present. When fire is hot enough to top kill an oak tree, resprouts occur giving it the appearance of a shrub. This shrubby looking oak is known as a grub and is evidence of frequent fire. Additional evidence is an early farm field noted by GLO surveyors as being located primarily within the timber. Settlers commonly believed that prairies could not support trees and therefore could not support a good crop. For these reasons, settlers gravitated toward timber. Smith (2012) who has extensively researched settlement patterns in Iowa relative to the character of the natural landscape notes that settlers chose open savanna and not forest to homestead, in order to reduce the work of converting it to a crop field. The broad spacing of trees recorded by surveyors also suggests timber with an open character. As such, the wooded areas noted as "timber" on the southern half of the current Neal Smith National Wildlife Refuge (NSNWR, refuge) were likely open and burned frequently and are appropriately categorized as savanna.

Water could be a limiting factor, particularly as water consumption needs by prairie exceeded water available through rainfall. This difference in water need and availability was mitigated by the process of metabolism and evapotranspiration when water was released back to the air. As temperatures fell in the evening, water condensed on the leaves and returned to the soil for use by roots. This cycle of condensation and resupply of water to the soil in cool temperatures was critical in maintaining native grasslands (Wilhelm and Rericha, 2007).

Pre-Settlement Hydrology

The pre-settlement hydrology of the Walnut Creek watershed largely reflects the geologic, climatic, and land cover history of the basin.

Water Balance and its Relationship to Vegetation

A simple water balance equation provides a convenient way to evaluate basin-scale hydrology. We consider the simple water balance of a basin to be:

$$P = ET + Q \pm \Delta S \qquad (1)$$

where P is precipitation, ET is evapotranspiration, Q is stream discharge, and S is water storage. Water storage can encompass many hydrologic components, including interception storage (water stored on plants or in mulch layer before infiltrating), soil moisture storage (water stored in the soil profile), channel storage (water stored in surficial depressions, wetlands, lakes, and/or in stream channels), and groundwater storage. But if we assume that over long periods of time that changes in S are equal to zero, then the water balance of a basin can be simplified. Discharge (Q) can be divided into two flow regimes, namely runoff (stormflow or Qs) and baseflow (groundwater seepage to streams or Qb). In a closed groundwater system like Walnut Creek where the unoxidized pre-Illinoian till serves as a barrier to deep groundwater percolation, baseflow is generally equivalent to groundwater recharge. We can use the simplified water balance equation:

$$P = ET + Qs + Qb \qquad (2)$$

to speculate on what the pre-settlement hydrology may have looked like.

We do not know how pre-settlement precipitation may have varied, but we can assume that annual rainfall was similar to the current long-term average for the area (about 33 inches; Schilling et al., 2006). ET typically accounts for 70–80% of the water budget in Iowa watersheds, but data on native tallgrass prairie/savanna water budgets are lacking. We know that native tallgrass prairie and savanna developed over thousands of years with a mix of cool season and warm season vegetation that was adapted to wide temperature and moisture extremes typical in the continental Midwest (Jackson, 2002). Native midwestern ecosystems were able to withstand extreme climate events, such as intense spring and summer rains; hot, dry summers; and cold and harsh winters. Because of the mix of cool and warm season vegetation, native prairie actively grows throughout the year, making highly efficient use of available water during all but the coldest months (Karlen et al., 2010; Dinnes, 2004). Beyond climate, the frequent and probably autumnal fires, large animal grazing, and other processes assisted to keep the area in grassland as opposed to other vegetation types.

Many studies compare prairie ET to cultivated crop systems. Annual ET generally increases from annual crops to grasslands to woodlands due to changes in rooting depth, leaf area index, and plant transpiration (Zhang et al., 2001). Prairie vegetation had massive below ground biomass with roots that consumed enormous amounts of water (Wilhelm, 2007; Weaver, 1958). Grass species dominated the tallgrass prairie (Curtis, 1971) and typically were sustained by dense, fibrous roots. Weaver (1958) reports that many of the forbs of the prairie were much more deeply rooted than grass species, and that 85–90 % of them were perennial. A species common to the Southern Iowa Drift Plain prairies was false boneset (*Brickellia eupatorioides* (L.) Shinners var. *eupatorioides*) and is among the most deeply rooted at 17 feet (5.2 meters). The variety in root architectural characteristics (Weaver, 1958; Fargione and Tilman, 2005), phenological differences, photosynthetic pathways (C^3 vs.C^4), and life history (annual, biennial, perennial) allow different species to exploit resources differently. Those with similar sets of the above characteristics are more competitive with one another. Others species co-exist because competition for resources is separated temporally, spatially, or physiologically (Fargione and Tilman, 2005). Spatial arrangements of prairie species can also be influenced by soil depth (Dornbush and Wilsey, 2009) and N availability (Crane, 2006). Ultimately the species composition and arrangement of prairie species thus influences water use and soil water content. Indeed, plot studies show that native prairie maintains greater soil water content in the soil profile, larger ET, and significantly less downward drainage compared to annual crops (Brye et al., 2000).

Rainfall interception by the above ground prairie residue, when it exists, is also a major component of the prairie water balance (Clark, 1940). In one plot study, 70% of the precipitation falling on an unburned prairie (five years since last burn) was intercepted and subsequently evaporated, leaving less water infiltration available for deep drainage (Brye et al., 2000). Deep roots of perennial grasses enable them to access deeper water supplies, which reduces volumetric water content and increases soil moisture storage (Hodnett et al., 1995; Huxman et al., 2005). A mulch layer of prairie vegetation serves to reduce evaporation losses and increase soil moisture levels (Lauwo, 2007). However, the degree that mulch is present varies depending on fire frequency. Annual burns of pre-settlement prairie would have resulted in less mulch on much of the landscape in any given year than many current prairies managed with multiple years between burn cycles. Thus, more of the water would have been available for infiltration and ET as opposed to evaporation. With longer intervals between burns, the mulch layer and thus the potential for high levels of evaporation from the deeper mulch, increases.

Pre-settlement prairie soils had high amounts of water-adsorbing soil organic matter that accumulated from perennial root systems (Karlen et al., 2010) leading to good infiltration characteristics (Knox, 2001). Prairie ecosystems are thought to function like a natural sponge—quickly infiltrating water and storing rainfall, slowing runoff, and lessening the kinetic energy of falling raindrops (Allen, 1993; Knox, 2001; Karlen et al., 2010). Infiltration capacity of prairie was described by Weaver and Noll (1935) as “impressive,” as the infiltration capacity and porosity of moist grassland soil accounts “. . . for the fact that on fully vegetated lands practically no erosion occurs except possible during storms of unusual violence, and then the erosion is seldom serious.” Thus, despite limited data on functioning native prairie ecosystems, we can be quite confident that annual ET rates from native prairies—including evaporation, infiltration, and plant transpiration components—were high, especially compared with current cropping systems. Rainfall that permeated through the mulch litter, when mulch was present, infiltrated quickly and was either transpired by the native vegetation or replenished soil moisture reserves. Soil moisture levels may have been high at the surface when prairie mulch was present, but they were drier deeper in the subsurface where the deep prairie roots were capable of reaching soil water reserves. Conversely, when mulch was absent and above ground vegetation was intact, surficial soils could be expected to be much drier.

With high ET under native vegetation, equation 1 indicates that streamflow discharge was lower in native prairie ecosystems. Unfortunately, there are no measured streamflow data available to document this, but we can infer streamflow conditions from other sources. Midwestern prairie is dominated by C4 grass species that are well adapted to hot, dry climates and as such, water runoff is relatively low, and intermittent streams are more abundant relative to perennial streams. Intermittent streams are characteristic of such grasslands globally (Dodds et al., 2004). Lower water yields are observed in basins with unburned prairie and high duff levels, because under such conditions much of the precipitation is diverted to interception and infiltration, and subsequently to ET and groundwater seepage (Heimann, 2009). Because high infiltration capacity and abundant surface roughness are associated with prairie residue and stubble, we can speculate that the runoff component of discharge (Qs in equation 2) was probably very low under tallgrass prairie. Flooding was probably unusual because the native soils, wetlands, and vegetation retained precipitation inputs and slowly released the water to streams with baseflow. A hydrograph of a prairie stream might have a relatively slow rise and fall with a high baseflow maintained by springs and groundwater (Menzel, 1983; figure 2-5). Grassland was found to reduce peak runoff in 5- and 25-year, 24-hour rainfall events by 50–55% and 40–45% respectively, compared to cropland (Gerla, 2007). It seems safe to conclude that streamflow discharge, particularly runoff, was very low under native tallgrass prairie.

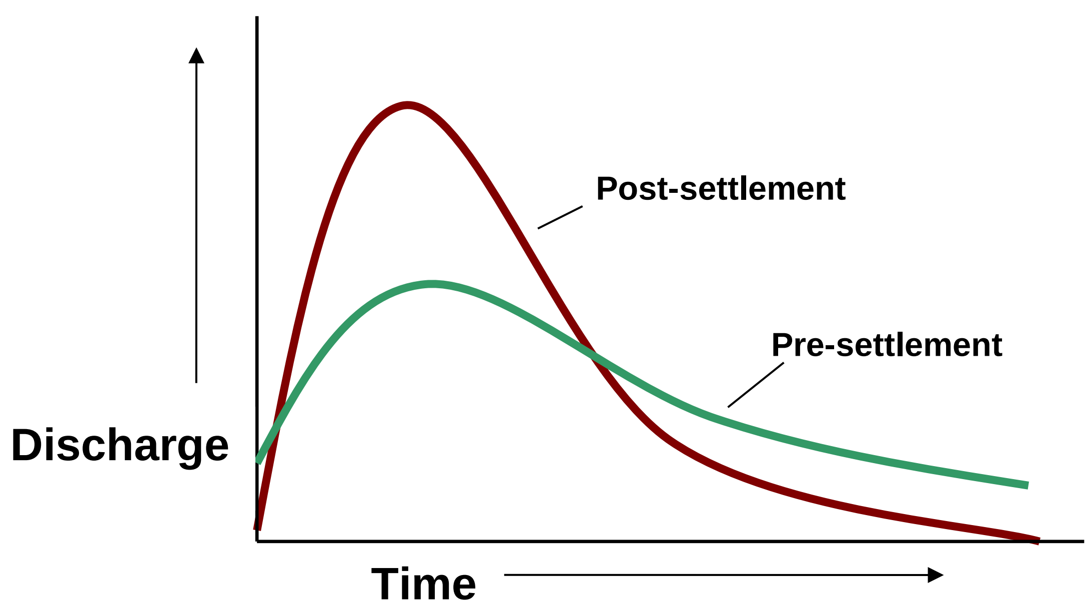


Figure 2-5: Historical alterations of stream discharge patterns in agricultural ecosystems (after Menzel, 1983).

With Qs low for native prairie ecosystems, equation 2 indicates that Qb (baseflow) must have been higher for a given discharge. The relation of baseflow to total discharge can be assessed as a baseflow percentage, and we suspect that the baseflow percentage of tallgrass prairie streams was much higher during pre-settlement times than observed today. The baseflow percentage in Walnut Creek from 1995 to 2005 was approximately 57% (Schilling and Spooner, 2006) but pre-settlement baseflow may have been on the order of 70 to 80%. So, while total streamflow was probably low, the percentage of streamflow due to groundwater seepage as baseflow was higher.

Higher baseflow percentage is consistent with the perception of how tallgrass prairie streams originated in southern Iowa landscapes underlain by pre-Illinoian till. Low elevation areas in headwater catchments were likely perennially wet or moist with vegetation dominated by wet prairie or sedges. Water would collect in these areas and coalesce into small intermittent or perennial streams before flowing downstream. There would not have been well-developed stream channels in headwater areas but rather a series of interconnected low wet spots that followed the present drainageways. We have evidence for wet prairie when Holocene-age Roberts Creek member alluvium is encountered in upland catchments (Schilling et al., 2007) and along the drainageways and floodplain of Walnut Creek (Schilling et al., 2004; Schilling and Jacobson, 2008). This unit developed under cooler and wetter (saturated) conditions and is largely composed of fine-grained organic matter typical of wetlands. We also see remnants of this hydrologic system in some areas of the refuge. During a basin-wide sampling event in 1999 (Schilling, 2001) creek discharge coming from upland catchments (flow rate of 7.5 liters/second) encountered a wide open area that became exceptionally wet and marshy, and the flow rate was substantially reduced in a barely visible channel (0.7 liters/second). Downstream, flow from the marsh area coalesced again, and channel flow exceeded 37 liters per second. The wide, flat marshy area encountered during this sampling was probably typical of much of the drainage system in Walnut Creek watershed prior to settlement.

An early geologic report records the hydrologic condition in Benton County (Savage, 1905) that was likely similar to Walnut Creek watershed:

> *"Their [prairie streams] beginnings can be traced back to the swales and marshy meadows of the Iowan drift plain. Out from those boggy sloughs the water slowly filters forming perennial springs. These unfailing fountains feed the larger streams with a constant supply of clear, pure water. From some distance from its source the water follows lazily along the shallow grassy depressions that are bordered by no erosion formed banks. Along a few miles each stream becomes established in a wide, partially filled valley. . . (p. 154)."*

Discharge from these marshy meadows was likely feeding the tallgrass prairie streams with consistent, clear baseflow.

Overall, in terms of a basin-scale water balance, ET was higher during pre-settlement tallgrass prairie and total streamflow was likely lower. Streamflow was probably dominated by baseflow, since surface water runoff from the well-vegetated prairie landscape was low.

Stream Network

Although a couple of farmed fields, and thus settlers, were already present on what is now NSNWR during the GLO surveys of 1846–1847, GLO notes provide information that can be used to infer characteristics of the pre-settlement stream network in Walnut Creek watershed. The surveyors recorded a description of stream and river crossing as they completed their rectangular grid of square mile sections. The GLO map of the Walnut Creek watershed suggests that Walnut Creek was highly sinuous and meandering over its floodplain (figure 2-6). Anderson (2000) conducted a Geographic Information System analysis of the pre-settlement stream network in the watershed (as delineated by the GLO surveyors) and quantified several key parameters, including total stream length, drainage density (total length of the channel system disregarding the meanders, divided by the area of the watershed), and channel frequency (total number of stream segments or visible stream tributaries per unit area). Based on the original plat maps, the 1847 Walnut Creek channel totaled 37,185 meters, and the drainage density of the watershed was 0.9. The channel frequency was 0.32 in 1847 (table 2-1). In chapter 3 we document how the stream network has changed since settlement.

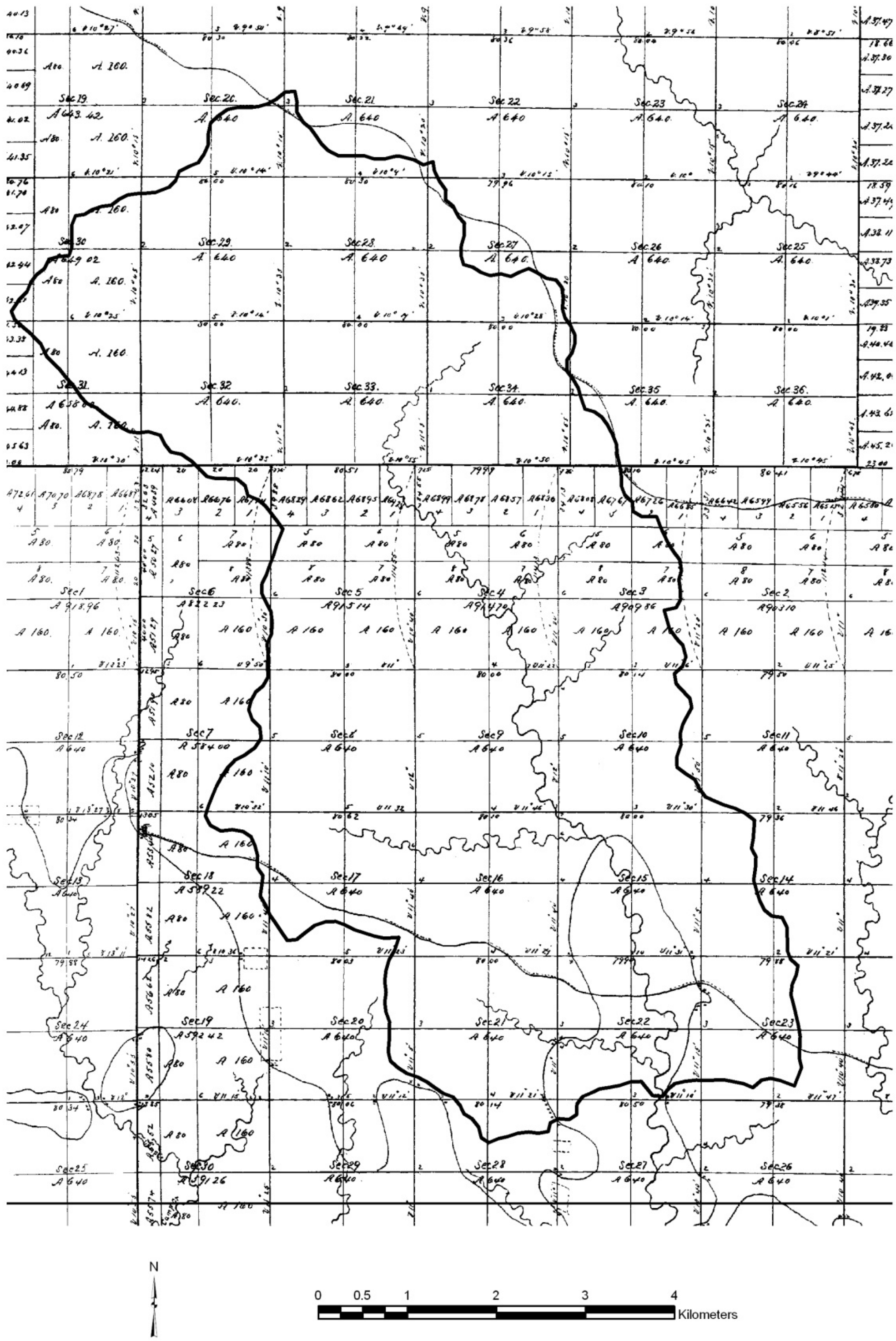


Figure 2-6: Stream channel delineated in 1847 GLO survey.

Table 2-1: Comparison of morphological characteristics of Walnut Creek watershed in 1847 and 1972 (after Anderson, 2000).

Property	GLO Survey (1847)	1972 USGS Streams
Stream length (m)	37,185	60,286
Drainage density[1]	0.9	1.52
Channel frequency[2]	0.32	1.20

[1]Total length of drainage system divided by watershed area.
[2]Total number of stream segments per unit area.

In the upper portion of the watershed, GLO surveyors in 1847 noted that Walnut Creek was two links wide (0.4 meters or 1.3 feet) and made no mention of difficult stream crossings (USGLO, 1847). Further downstream, the GLO notes indicate that Walnut Creek was 10 links wide (2.0 meters or 6.6 feet) and describes Walnut Creek as a clear stream running swiftly to the southwest on earth bed and banks. Many small brooks entering Walnut Creek ranged from two to four links (0.4 meters or 1.3 feet to 0.8 meters or 2.6 feet) wide. Streambanks were likely less than 0.2–0.4 meters (0.7–1.3 feet) high, and Walnut Creek probably overtopped its banks and flooded the riparian zone quite regularly. Hydrologic investigations and modeling of floodplain water table interaction with Walnut Creek suggest that artesian conditions (groundwater discharge to the land surface or springs) probably existed throughout the floodplain during pre-settlement times, with much of the floodplain probably perennially saturated and marshy (Schilling et al., 2004). These hydrologic conditions would be consistent with floodplain vegetation considered to be “wet prairie” in GLO notes. Assuming a stream width of two meters (6.6 feet) and a channel depth of 0.2 meters (0.7 feet), the width-depth ratio of the pre-settlement stream may have been around 10.

Groundwater

Upland loess and till eroded from uplands and deposited as silt in drainageways and floodplains consequently resulted in soil permeability characteristic of silt. Silt characteristics thus dominate groundwater conditions in the watershed. Hydraulic conductivity (K) measurements made in monitoring wells in the two landscape regions are similar, with K ranging from approximately 0.2 to 0.8 meters per day (0.7-2.6 feet/day) in the loess/till and alluvium, respectively (Schilling and Thompson, 1999, 2000; Schilling et al., 2004, 2007; Jindal, 2010). The K of the underlying unoxidized pre-Illinoian till is about two orders of magnitude less than the upper loess and oxidized till (0.001 meters/day or 0.003 feet/day) and thus acts as a confining layer to the overlying aquifer (Schilling and Wolter, 2001). Because of the low permeability of the silty aquifer, groundwater moves through the system very slowly. The average time needed for groundwater to travel from uplands to a stream is on the order of 20 years (Jindal, 2010; Schilling and Wolter, 2008). However, within this 20 year average, groundwater travel times range considerably, from less than a year near a stream to more than one hundred years at the upland divides.

Groundwater recharge is concentrated in the floodplain and upland areas (Schilling, 2009). A greater proportion of basin-wide recharge occurs in the floodplains because the floodplain has a shallow water table that responds readily to precipitation inputs. The floodplain comprises 17% of the land area but produces nearly 34% of the recharge in the watershed. In the upland, where the water table is much deeper, a much thicker unsaturated zone captures more infiltrating precipitation so less groundwater recharge occurs in upland areas. On side slopes in the basin, a greater proportion of precipitation is diverted to runoff so less groundwater recharge occurs in these areas (figure 2-3). The side slopes in the watershed occupy 54% of the land area but produce only 34% of the basin-wide recharge.

Early geologic reports for the region, including Jasper County, indicate water table depths for upland wells. Wells that were “sunk in the prairie” were considered shallow, with groundwater encountered from 15 to 30 feet in depth (Whitney, 1858). In several southeastern Iowa counties, groundwater conditions were described for future settlers. In Jefferson County, “an abundant supply of well-water is obtained on the prairies by digging from15 to 25 feet below the surface; on the timber lands it may usually be found at depths varying from 25 to 40 feet.” Similarly, in Washington County, “good wells of neverfailing water” are obtained from depths of 20 to 40 feet and in Wappello County, depth to water was reported from 20 to 30 feet (Worthen, 1858). The range of groundwater depths reported by early geologists for upland prairie are deeper than observed today. This would suggest that centuries of greater ET under tallgrass prairie lowered the water table in upland areas. Deeper water tables means a thicker unsaturated zone under prairie and greater capture of water infiltration by soils, which coupled with greater ET rates, resulted in less water delivered to streams.

Water Quality

Little is known about pre-settlement water quality in streams or in groundwater. Many early reports describe surface water in streams to be “clear,” “pure,” and “excellent.” However, these descriptions are hardly quantitative. Even prairie streams were turbid during storm events, so a term like “clear” probably represents a baseflow condition at the time of observation. Limited data exist in Iowa that describes early surface water quality conditions. An Iowa Geological Survey publication from 1955 reports surface water quality in three Iowa rivers in 1906–1907. This time period is after settlement began in Iowa, but it does provide an upper bound of water quality conditions prior to settlement (i.e., it was not any worse than reported at this time). Nitrate-nitrogen (nitrate) concentrations in the Iowa, Cedar, and Des Moines Rivers were very low at this time ranging from 0.06–0.07 milligrams per liter, as were chloride concentrations (3.4-4.8 milligrams/liter). It should be noted that nitrate and chloride are dissolved constituents that are typically discharged to streams with baseflow. Surface water conditions with respect to constituents delivered to streams with overland runoff (turbidity, total dissolved solids) were likely higher than pre-settlement concentrations by 1906–1907. Basin-wide sampling of streams draining reconstructed prairie at NSNWR also showed low concentrations of nitrate and chloride. Nitrate concentrations were less than one milligrams/liter and chloride concentrations were less than four milligrams/liter in water samples collected from small streams draining reconstructed prairie areas (Schilling and Wolter, 2001). These dissolved concentrations are similar to values reported for surface water quality in 1906–1907. Unfortunately, further quantitative assessment of pre-settlement water quality conditions is not possible due to the lack of monitoring data.

Chapter 3: Agricultural Intensification

In this chapter:

This section discusses the settlement history of the Walnut Creek watershed and the impacts of settlement on key hydrologic processes.

Settlement and Land Use History

Jasper County was established in 1846 and named after Sergeant Jasper of Revolutionary War fame (Williams, 1905). The area was ceded to the U.S. Government in 1842 by the Sacs and Foxes, and under the terms of the treaty, white men were allowed to enter the territory in May 1843. The first settlement in the county was made at the present location of the town of Monroe, which was designated the county seat in 1846. As far as it can be determined, the prairie that once covered the Walnut Creek watershed was converted to crop and pastureland soon after settlement. Land ownership records and plat maps show many 40 to 160 acre parcels being sold to individuals in the 1850s (Buitenwerf, 1996). In general, arable land (not too steep, rocky, or wet) was put into crops whereas the other non-arable areas were made into pasture.

Early geologic reports in Jasper County by the Iowa Geological Survey recorded active coal mining (above and below ground) in Section 22, in the lower portion of the watershed (see figure 2-1). Williams (1905) reported that in the north half of Section 22 along Walnut Creek, the William White and C.M Norris drifts were located on the west and east sides of the creek, respectively. The White seam was located 28 feet above the creek and averaged two to four feet in thickness with a low dip to the southeast. When reported in 1905, two acres were mined out, and the mine employed four to six men during five months of the year. The Norris mine located east of Walnut Creek was mined continuously for 22 years prior to the 1905 report, and 30 acres of coal were reportedly mined out. Williams (1905) reported that the occurrence of coal was similar on both sides of the creek and the quality was considered excellent and especially good for steam purposes. Near Walnut Creek, coal mines were also reported in Vandalia and other locations along creeks in the southwest portion of Jasper County (see figure 1-1).

Stream reconnaissance in the southern portion of Walnut Creek (north half of Section 22) identified the presence of sandstone bedrock and cobbles located in the channel (Schilling and Wolter, 2001). Substantial hillside erosion on the steep western side of Walnut Creek probably reflects coal mining activities that occurred in this area 100 years earlier (likely location of White mine). No evidence was observed of the former Norris mine located on the east side of Walnut Creek, although the creek bluff is quite steep in this area and may reflect post-mining land settlement.

Although we do not have land use records available specifically for Walnut Creek watershed, data are available for Jasper County and the State of Iowa. These land use records show how agricultural land use patterns changed throughout the late 19th and 20th centuries.

Soon after settlement, corn was quickly established as the dominant crop in Iowa with oats following closely behind (figure 3-1). In the early 1940s, soybean acreage began to increase significantly and around 1960 replaced oats as the largest secondary crop in Iowa. The rapid expansion in soybean acreage largely replaced untilled land (pastures) and other sod-based crops such as oats, alfalfa, and hay. While the balance of sod-based crops versus annual crops was about 50:50 throughout the 1950s (Jackson, 2002), after this time, annual crops of corn and soybeans dominated the agricultural landscape. Soybeans are rotated with corn production, so the two crops are often grouped together and designated as "row crop." Between 1940 and 2000, total row crop area in Iowa increased approximately 30–40% (Schilling and Libra, 2003; Schilling, 2005). Land use trends observed in Iowa are similarly noted throughout the upper Midwest (Zhang and Schilling, 2006; Donner, 2003).

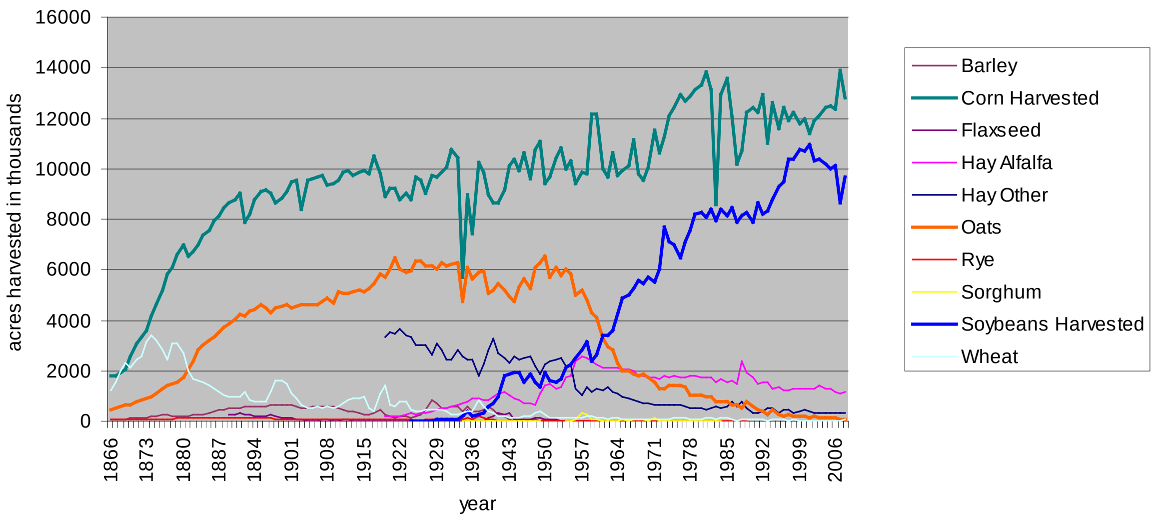


Figure 3-1: Changes in agricultural land use in Iowa, 1866-2008.

Data available for Jasper County echo these statewide trends (figure 3-2). Although the planting records for corn and soybeans only extend back in time to 1926, the significant increase in soybean production beginning in the mid-1930s is clearly evident. Soybean production increased from several hundred acres planted in the county to approximately 140,000 acres, whereas corn production during this time generally fluctuated between 140,000 to 180,000 acres. Oats and hay records are not available prior to 1973, but the downward trends in acreage beginning at this time are also apparent. By 1990 (prior to establishment of Neal Smith National Wildlife Refuge [NSNWR, refuge]), row crop in Walnut Creek watershed comprised 69.4% of the area followed by grass (20.8%), woods (5.1%), and other areas (farmsteads, railroads, roads, ponds, etc.; 4.7%) (Schilling et al., 2006).

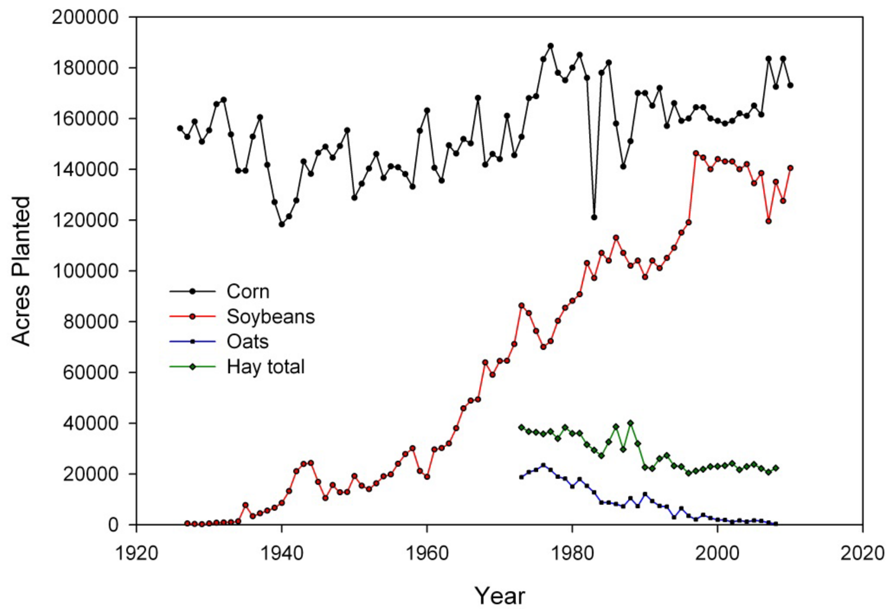


Figure 3-2: Changes in crop production in Jasper County, 1927–2010.

In addition to the land cover change, other agricultural production technology changed during the 20th century. Increased mechanization allowed the farmer to cover many more acres for the same length of time. No longer was there a need to feed and house animals on each farm, and there was less incentive to use feed crops in rotations. Nitrogen (N) fertilizer use rapidly expanded in the middle of the 20th century, which eliminated the need for meadow-type legumes in rotations. Cash-grain farming with anhydrous ammonia technology became widely utilized because the cost of N was low and its effects were profitable (Mahlstede and Hazen, 1983).

Landscape and Hydrologic Modifications

Other landscape and hydrologic modifications accompanied the land use/land cover change in the Walnut Creek watershed during the post-settlement agricultural intensification period, including stream channelization, artificial drainage, and conservation adoption.

Channelization

Stream channelization is the practice of straightening streams for controlling flooding, draining wet areas, increasing tillable acres, and squaring up farm plots (Schilling and Wolter, 2000; Hupp, 1992). Throughout Iowa, efforts to channelize larger streams decreased the original length of larger streams by 45% (Bulkley, 1975). Like many streams in Iowa, Walnut Creek was extensively channelized early in the 20th century. Aerial photographs from the late 1930s show a similar stream pattern as observed today, indicating that Walnut Creek was channelized prior to this time. In Iowa, it is thought that channelization efforts began in the late 1800s and were “vigorously pursued” through the mid-1930s (Menzel, 1983). Channelization and straightened streams in Walnut Creek watershed contrasts with the meandering stream channel described from General Land Office (GLO) survey (figure 3-3).

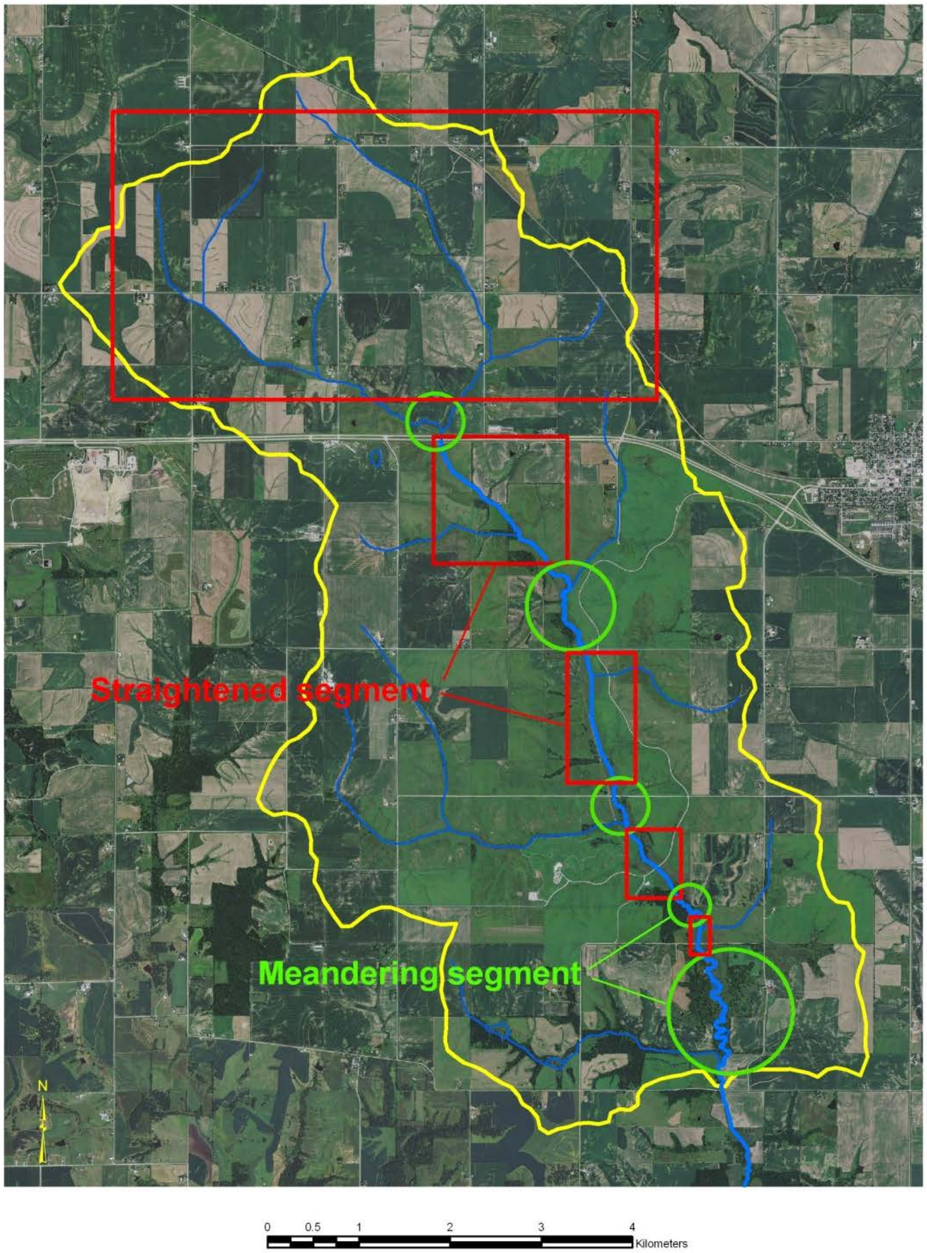


Figure 3-3: Locations of straightened and meandering reaches along the main stem of Walnut Creek are not evenly distributed.

Stream sinuosity is the actual channel distance between two points divided by the straight line distance, and a sinuosity of one is equal to a straight line. In Walnut Creek today, stream sinuosity in channelized segments is near one, whereas meandering stream segments show stream sinuosity between 1.5 to 2.0 (Schilling and Wolter, 2000). The locations of straightened and meandering segments of Walnut Creek are not uniformly distributed in the watershed (figure 3-3). Many stream reaches in the upper part of the basin have been channelized but several reaches in the lower watershed areas have not. Furthermore, many stream reaches shift from straightened to meandering and back again along the stream course.

Artificial Drainage

Accompanying the increasing row crop acreage in Walnut Creek watershed was installation of artificial subsurface drainage in the form of tiles installed about 1.2 meters (3.9 feet) below the soil surface. Subsurface drainage tiles are used throughout the Midwest to lower the water table and dewater soils that are seasonally or perennial wet. Tile drainage in Walnut Creek watershed differs greatly from the common perception of large integrated networks typical of those placed in recently glaciated areas like the Des Moines Lobe in north central Iowa. In these areas, tiles are placed at a regular spacing (patterned tile) across an entire field (10 to 100 meters; Strock et al., 2010), and these patterned field tiles are connected to larger drainage district systems that discharge drainage water into a stream through large bulkheads (30–50 inches). However, in Walnut Creek watershed, as well as in other basins dominated by hillslopes, tile drainage networks are primarily branched along the first order drainageways (drainages with no tributaries) and in poorly drained floodplain areas. Drainageway tiles are a recommended design practice for grassed waterways to prevent buildup of excessive wetness in these topographically low areas in order to maintain the vegetative cover, prevent formation of gullies, and facilitate the accessibility of farm equipment (Stone and McKague, 2009; Green and Haney, 2005; Natural Resource Conservation Service [NRCS], 2004). Floodplain tiling was also done to drain localized wet areas. Where observed, these tiles are usually small in diameter (4–6 inches) and empty directly into the main channel or larger tributaries.

Very little information is known about the actual tile drainage network in Walnut Creek watershed except from recent monitoring and mapping. Throughout the Midwest, artificial subsurface drainage systems were installed during the late 1800s to early 1900s (Zucker and Brown, 1998) to drain soils that were seasonally or perennially wet. In 1998, Schilling and Wolter (2000) conducted a GPS survey of the Walnut Creek channel and mapped a total of 52 drainage tiles along a seven-mile segment of the channel. Locations of tiles tended to be concentrated in agricultural areas of the watershed (row cropland use) with the highest density of tiles in the northern portion of the watershed where the landscape is more level and was historically prairie. Some tiles in this area were flowing between 30–60 liters per minute. However, many tiles mapped during this survey were not flowing and looked broken or filled with sediment. This suggests that tile drainage, particularly in the floodplain, may have been more extensive in the past. In 2004, another stream survey was conducted along the main stem and tributaries (Palmer, 2008). In this survey, 30 tiles were located along the main stem and 141 tiles were observed in the major tributaries. The latter survey indicated that tile drainage is more evident in the tributaries than in the floodplain of the main stem.

In 1999, discharge from many of the floodplain tiles were measured and gauged (Schilling and Wolter, 2001). In a snapshot event during a baseflow period on May 7, 1999, discharge into Walnut Creek from floodplain drainage tiles was estimated to be about 6% of the total flow in the channel (19.3 liters/second). During a follow-up study, flows from 19 drainage tiles emptying into the main channel and 16 tile discharging directly into tributary streams were not significant in terms of the total watershed discharge (Schilling, 2001). However, an important caveat is that the sampled tiles in these studies were only those that discharged directly into the stream channels from the streambanks. Schilling (2001) noted that these studies did not include tiles discharging from grassed waterways located in upland first-order catchments. Nearly all first order streams in the basin originate where subsurface tile flow is released above ground.

Jindal (2010) mapped the distribution of grassed waterways in the basin to derive an estimate of tile drainage extent in the watershed (figure 3-4). Using this approach, she estimated the drainage tile density to be 0.0027 m^{-1} in the basin. Using a calibrated groundwater flow model, Jindal (2010) further quantified the contribution of drainage tiles to baseflow in the watershed to be approximately 35%. That is, of the annual average baseflow that occurs in the watershed, 35% is derived from tile discharge rather than groundwater seepage. Tile drainage was found to decrease the groundwater travel time in the basin by about one-half (from 40 years to 19 years) by reducing the travel distance from recharge to discharge (Schilling et al., 2011). Beyond the wet floodplain areas and drainageways, there is little evidence to suggest that uplands and hillslopes are extensively tile drained. However, in watersheds like Walnut Creek, where much of the land is in hillslope, and side hill seeps can occur whenever the underlying till intersects the land surface, local tiles may be more numerous than accounted for in these studies.

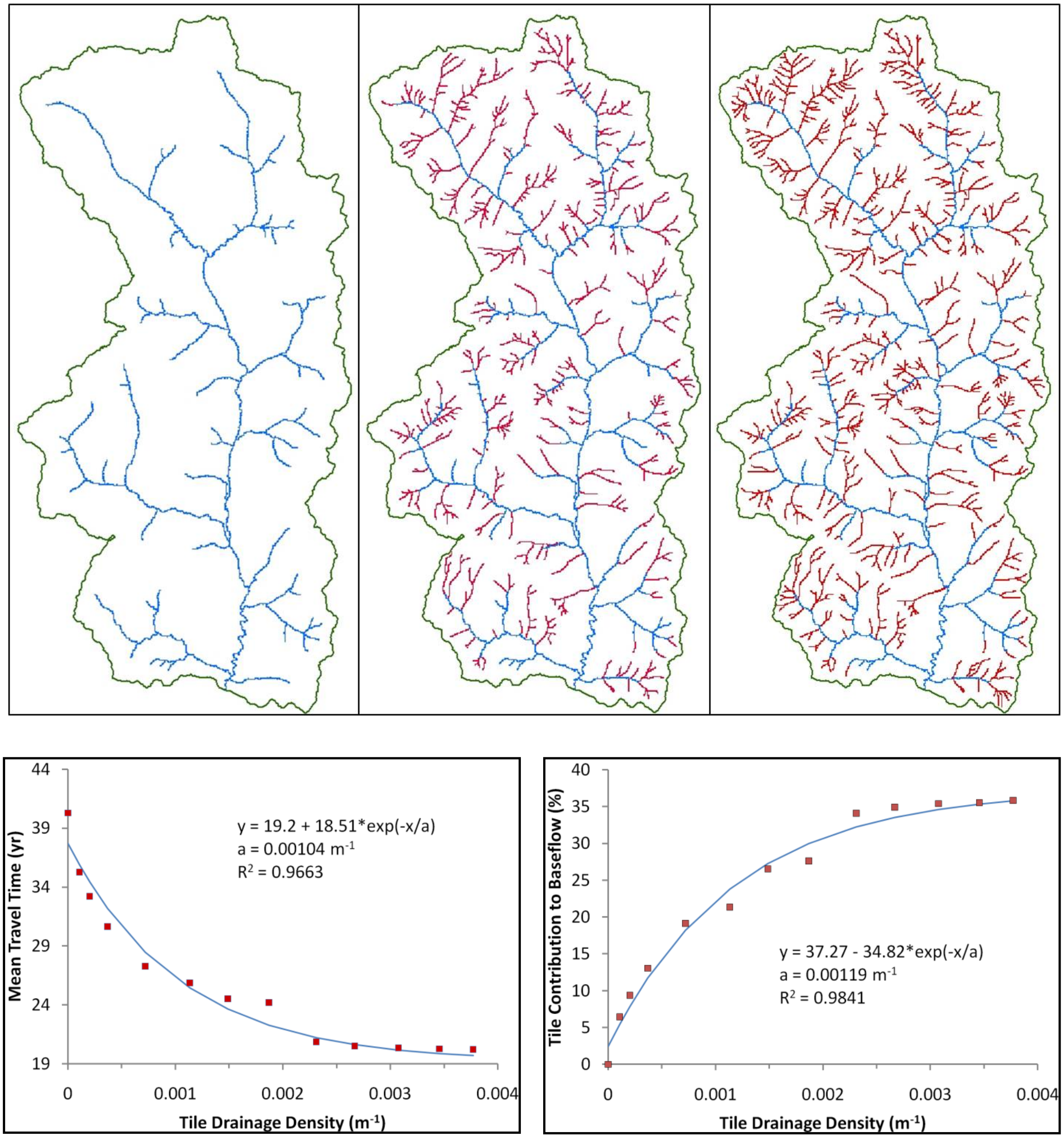


Figure 3-4: Hypothesized extent of tile drainage along grass waterways in Walnut Creek watershed (top middle). No drainageway tiling (top left) and maximum tile drainage extent (top right) were included as end members in modeling simulations. Increasing tile drainage density decreases mean travel time (bottom left) and increases tile flow contribution to baseflow (bottom right) (modified from Jindal, 2010 and Schilling et al., 2011).

Conservation Practices

With many conservation practices easily spotted on the landscape today, it is hard to imagine a time when there were none. It was not until the dust bowl in the 1930s that the need for soil conservation was evident and the Soil Conservation Service (now the Natural Resource Conservation Service or NRCS) was founded. The first soil and water conservation project in the United States was established in the Coon Creek (Wisconsin) watershed in 1933. Early settlers in Walnut Creek watershed farmed without any knowledge of soil conservation practices. Aerial photographs of the Walnut Creek watershed indicate that most of the watershed was cultivated by the late 1930s (figure 3-5). Many farm plots from this era appeared to be rectangular in shape with little regard for natural topography or stream boundaries. Moldboard plows common to the era turned over the soil in rows that were often oriented up and down the slopes. Land management practices during this time were further characterized by poor crop rotations, removal of crop residues, nutrient depletion, lack of cover crops, and very active erosion (Trimble and Lund, 1982). Concentrated overland flow from rills and gullies in cropped areas often dissected hillside deposits and eroded downslope. Organic-rich prairie soils once capable of infiltrating, storing, and transpiring rainfall were substantially eroded during the first 50–100 years of settlement.

Conservation practices were slowly adopted in the Walnut Creek watershed. Historical aerial photographs taken in 1940, 1950, 1967, and 1991 by the NRCS were examined to assess the history of conservation adoption in the area. The lengths of terraces and grass waterways and the area of land in contour farming were digitized from the photographs and georeferenced to a geographic coordinate system. Results indicate essentially no conservation implemented by 1940 and slow adoption by 1950 (figure 3-6). The greatest adoption of conservation occurred from 1950 to 1967, when the linear feet of terraces and grass waterways more than tripled, and contour farming area increased by a factor of 5.3 (figure 3-6). Additional adoption of conservation practices occurred between 1967 and 1991, when each practice increased by factors ranging from 1.2 to 1.7.

Throughout the Midwest, soil erosion in the uplands from intensive row crop agriculture mobilized a tremendous volume of sediment into the stream valleys, which remains stored on the floodplain (Knox, 1977; Trimble, 1983; Beach, 1994). Today, this “post-settlement alluvium” is termed the Camp Creek Member of the Holocene-age DeForest Formation (Bettis, 1992). In Walnut Creek watershed, the Camp Creek Member is a very dark grayish brown to yellowish brown silt loam to loam and is typically horizontally stratified. Post-settlement deposition mantles the entire floodplain and ranges in thickness from 0.5 to 1.1 meters (1.6 to 3.6 feet) (Schilling et al., 2009). Regionally, most of the Camp Creek Member was deposited between about 1890 and 1930 (Trimble, 1983; Baker et al., 1992, 1993; Bettis et al., 1992, Beach, 1994). The texture and nutrient content of the post-settlement alluvium in Walnut Creek watershed (Camp Creek Member) reflects the contribution of sediment from erosion of upland loess soils. Similar to the loess that mantles the watershed, the texture of the Camp Creek member is dominated by silt (71%) and clay (25%). The Camp Creek is particularly vulnerable to streambank erosion because historical post-settlement alluvium lacks internal structure, and erosion resistance provided by buried soil horizons developed in older alluvial units (Bettis and Littke, 1987; Kreznor et al., 1990; Beach, 1994).

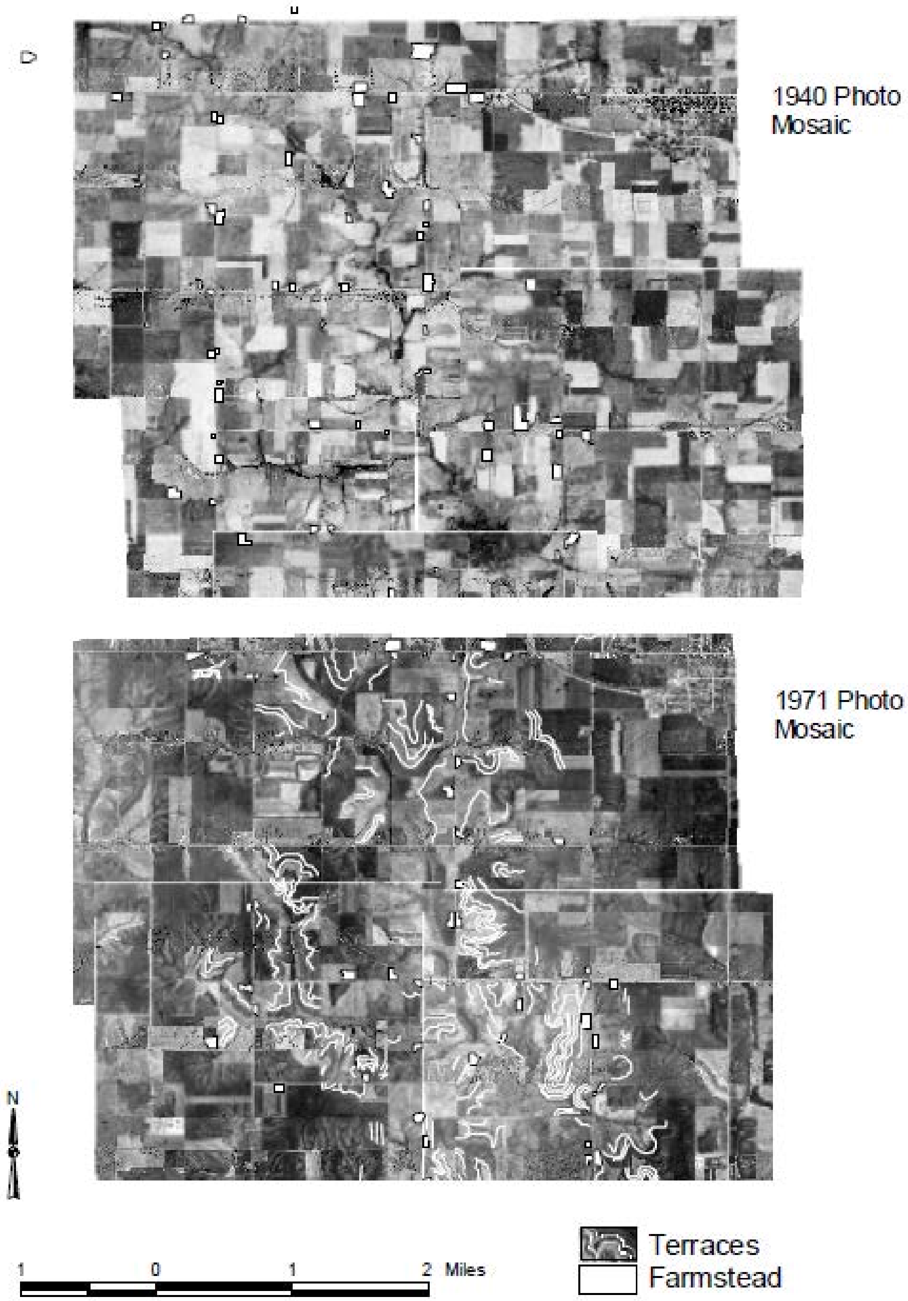


Figure 3-5: Historical aerial photographs of Walnut Creek watershed showing lack of conservation by 1940 and widespread adoption of terraces by 1971.

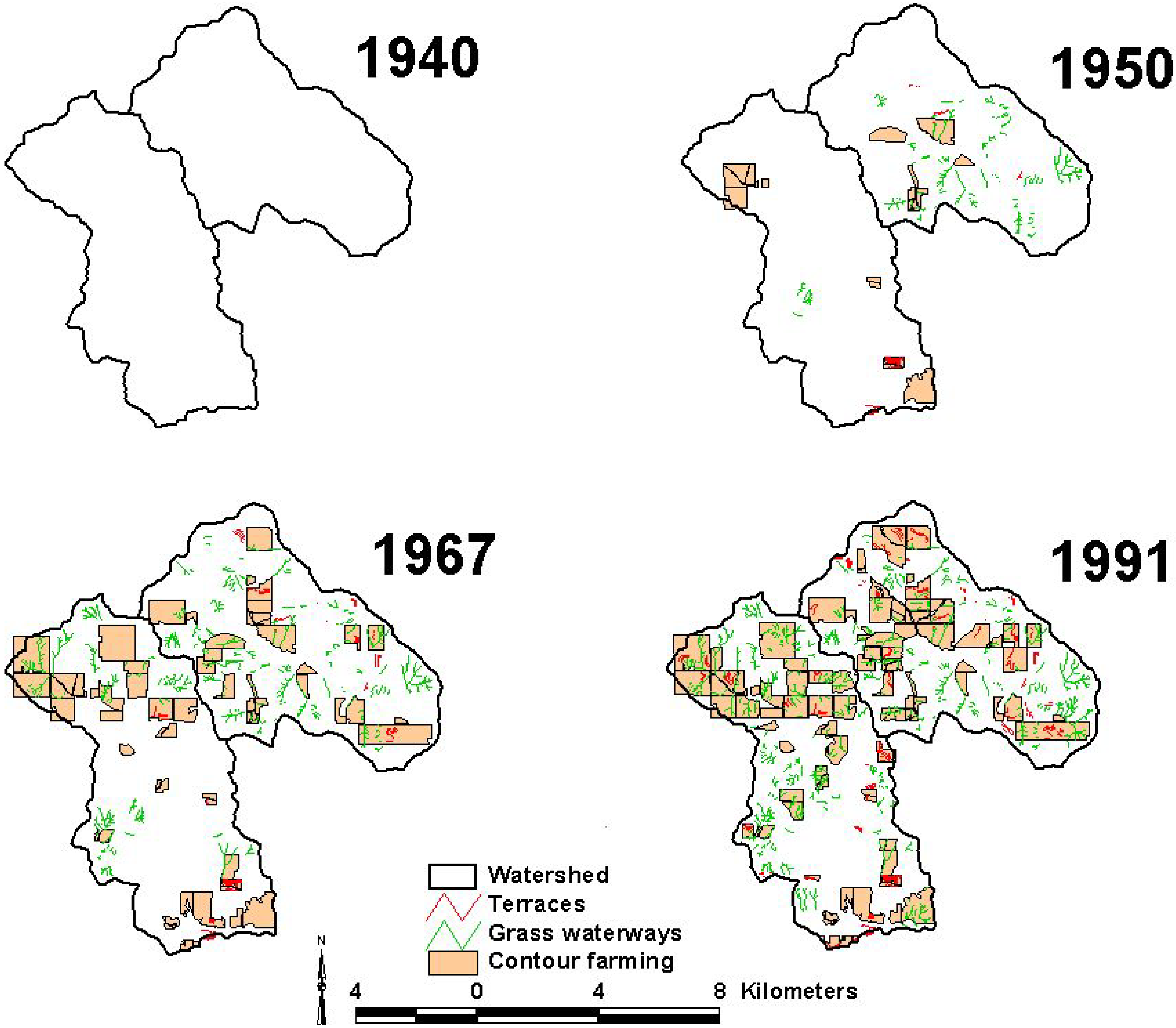


Figure 3-6: Conservation practice adoption in Walnut Creek and Squaw Creek watersheds from 1940 to 1991.

Hydrologic Effects

It has been well established that conversion of tallgrass prairie to cropland significantly affected many hydrological processes, including evapotranspiration (ET), infiltration, and streamflow (Knox, 2001). We return to the water balance equations to discuss the effects of settlement and landscape modifications on hydrology in the Walnut Creek watershed. Converting previously untilled land or other perennial cover crops to row crops increases available water for streamflow (Q) because annual crops have less annual ET. Gerla (2007) noted that croplands have higher surface albedo, low surface roughness, seasonally decreased leaf area, and shallower rooting depths compared to native grasslands, all of which contribute to less ET under cropland. While tallgrass prairie with its mix of cool and warm season grasses and forbs transpires throughout the spring, summer and fall, substantial transpiration from row crops typically does not occur until mid-growing season. For example, single crop ET coefficients (K_c) during initial, mid-season and late season growing periods vary substantially for different vegetation types. Initial, mid-season and late season K_c values for trees (walnut trees: 0.50, 1.10, 0.65, and 0.2 after leaf drop), rotational pasture (0.40, 1.05, 0.85) and fallow grass (0.85, 0.90, 0.90) compared to field corn (0.00, 1.20, 0.35) and soybeans (0.00, 1.15, 0.5) indicate much greater ET in the initial and late season growing seasons for the perennial vegetation types (Food and Agriculture Organization [FAO], 1998). Less ET in row crop fields in the spring and fall would make precipitation more available for discharge (Schilling and Libra, 2003).

Research from NSNWR clearly documents the effects of land use on ET. Prairie reconstruction activities have occasionally left some land bare and fallow prior to planting native vegetation and these opportunities have provided examples of how land use change affects the water balance. In one example, involving experimental sedge meadow reconstruction in a Walnut Creek floodplain (figure 3-7), one side of the floodplain was left in a dense cover of reed canarygrass while the other side was burned, mowed, and sprayed with herbicide in preparation for planting as a sedge meadow.

These management activities left the treated side of the stream as bare soil for several months (analogous to cropping conditions) (figure 3-8). Continuous water level monitoring from two monitoring wells over a period of 122 days revealed substantial differences in water table behavior under two land cover scenarios (Zhang and Schilling, 2005). The water level in the east grass well was generally lower and had much less response to rainfall events than the west no-grass well (figure 3-7). Grass cover lowered the water table, reduced soil moisture through ET losses, and reduced groundwater recharge and water yield.

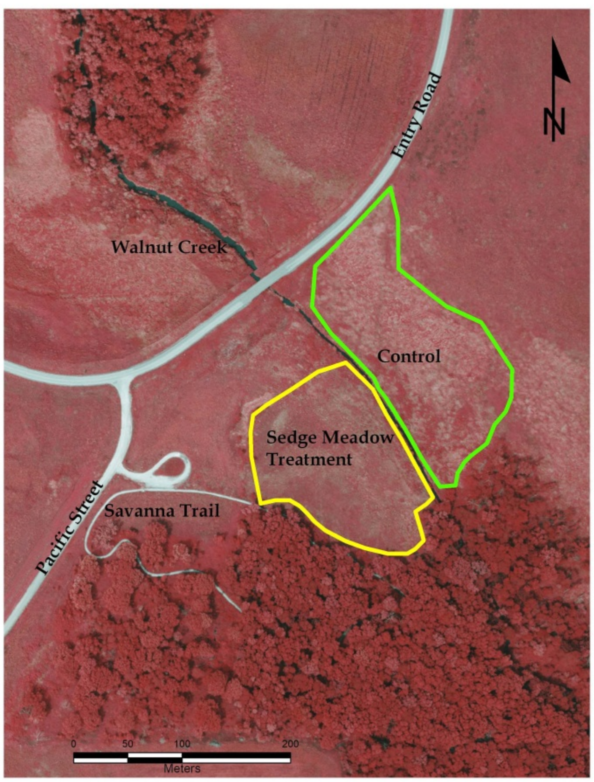


Figure 3-7: Experimental sedge meadow reconstruction treatment.

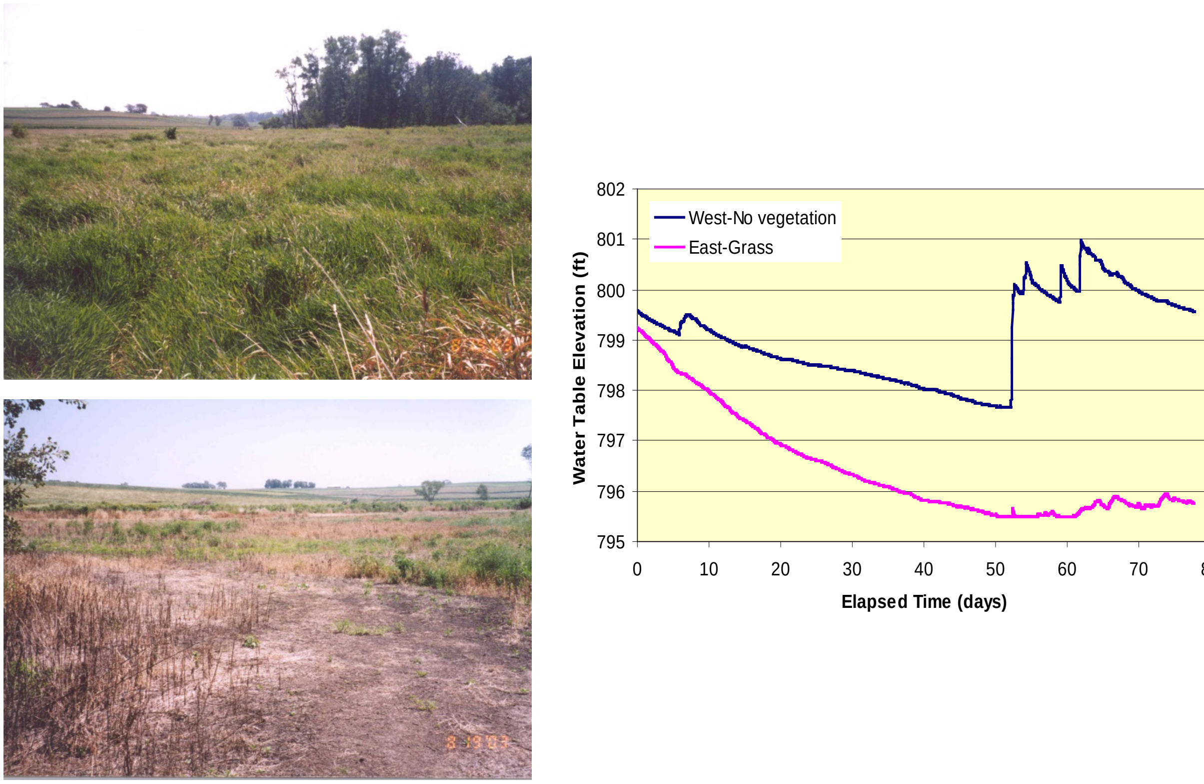


Figure 3-8: Water table behavior beneath grass cover on east side of Walnut Creek floodplain compared to groundwater below bare soil on west side during the July 21 to September 11, 2003 (modified from Zhang and Schilling, 2006).

In another study, water level fluctuations were used to estimate ET for riparian land covers of exotic cool season grass, dense woodland and corn (Schilling, 2007). Average daily ET rates were higher under woodland cover ranging between 4.8 to 2.7 millimeters/day, compared to exotic cool season grass (1.54 to 2.13 millimeters/day) and corn (1.25 to 1.64 millimeters/day). While maximum corn ET exceeded the grass in mid-July, grass ET rates were higher in the late summer and fall. These studies indicate that there are marked differences in ET according to land cover type, with substantially greater ET under grass and woodland compared to bare ground (i.e., typical for non-crop periods) and crop periods. Increasing the amount of cropland in a basin would therefore decrease annual ET.

Thus, changing from perennial vegetation to annual row crops would have the following effect on the water balance (where the arrows indicate whether the change is increasing or decreasing):

$$P = ET\downarrow + Q\uparrow \qquad (3)$$

Moreover, it is not just total Q that changes with land cover change, but the partitioning of streamflow into stormflow (Qs) and baseflow (Qb) components. Precipitation falling on the land surface in Walnut Creek watershed prior to 1950 would have encountered little to slow it down. Less infiltration occurs under row crops; for example, Bharati (1996) showed that infiltration under cropland was only two inches per hour compared to a six-year old planting of switchgrass that exhibited the infiltration capacity of more than 7.5 inches of rainfall per hour. Less infiltration of rainfall under cropland means more rainfall available for runoff. So, for the early part of the land use history in Walnut Creek watershed (from 1850 to 1900), the water balance likely changed:

$$P = ET\downarrow + Qs\uparrow + Qb\downarrow \qquad (3)$$

where stormflow increased and baseflow decreased. A stream hydrograph from early settlement probably peaked faster and higher compared to pre-settlement native grassland (Menzel, 1983; see figure 2-5). Loss of water storage capacity on the land with new plowed and intensively grazed land resulted in increased runoff, thereby producing an exaggerated seasonal flow regime and increasing the frequency, severity, and unpredictability of stream flows (Menzel, 1983). The consensus is that a majority of these alterations were well-established in the first 40–50 years of agricultural development (Trautman, 1957). For example, by 1893, naturalist Seth Meek reported:

> *“The streams of Iowa have undoubtedly changed much in character since the country has become so thickly settled. The soil, since loosed with the plow, is much more easily washed into the streams than when it was covered with the stiff native sod. The more thorough underdraining and surface ditches enables the water, after heavy rains, to find its way at once into the large creeks and rivers,” (Meek, 1893).*

More recently (from about 1940 to present), the water balance of many agricultural watersheds in Iowa appears to have shifted again. Evidence from many Iowa watersheds indicates that stormflow discharge has been relatively constant, but the baseflow component of the stream hydrograph has been increasing (Schilling and Libra, 2003). Where long-term records are available, annual baseflow, annual minimum flow, and the annual baseflow percentage were found to have increased over time in rivers draining watersheds ranging from 526 mi^2 to more than 14,000 mi^2. Reasons for these observed streamflow trends were hypothesized to include improved land management and conservation practices, increased and/or improved artificial drainage, and increasing row crop production. Improvements in land management practices, such as terraces, conservation tillage, and contour cropping played a role in modifying discharge variables in high relief agricultural watersheds like Walnut Creek. These conservation practices were implemented to decrease field erosion during stormflow and increase infiltration. Greater infiltration increases groundwater levels and sustains higher baseflow and minimum low flows in streams.

Discharge from drainage tiles also results in increases in baseflow discharge and a higher percentage of total discharge as baseflow (Schilling and Helmers, 2006). Schilling et al. (2011) modeled groundwater flow in Walnut Creek watershed and reported that increasing tile drainage extent increased the tile contribution to baseflow from 30% to 54%. Increasing row crop production in a watershed will also lead to increasing baseflow because less ET in row crop fields in the spring and fall makes infiltrating water more available for groundwater recharge, leading to higher sustained baseflow in streams (Schilling, 2005). In Walnut Creek watershed (like elsewhere in Iowa), soybeans began replacing perennial sod-based cropping systems in the middle of the 20th century and thus increasing the percentage of row cropland use in the basin and groundwater recharge.

So, from the middle of the 20th century onward, the water balance was again changing, with more precipitation directed toward baseflow discharge (Qb) in relation to stormflow runoff (Qs):

$$P = ET\downarrow + Qs\updownarrow + Qb\uparrow \qquad (4)$$

Equation 4 does not say that runoff was increasing or decreasing but rather it was variable, perhaps increasing in some areas with increasing row crop and poor conservation or decreasing in other areas with improved management. We suspect that the percentage of streamflow as baseflow was increasing in Walnut Creek as observed throughout Iowa during the second half of the 20th century (Schilling and Libra, 2003).

In sum, the water balance in Walnut Creek watershed during post-settlement was dominated by decreasing ET as annual crops replaced perennial native grasslands. Decreasing ET allowed more precipitation to be diverted into streamflow, which in the first half-century of agriculture, was dominated by stormflow runoff. Baseflow discharge began to significantly increase in the mid 20th century as cropping patterns, tile drainage and conservation practices began shifting the water balance toward increasing groundwater delivery to streams.

Stream Network

Changing the water balance early in the post-settlement history along with landscape modifications in Walnut Creek watershed had profound ramifications on the stream network and the natural communities of the landscape. Rapid runoff from newly plowed and drained agricultural land combined with increased gradients and faster flows in channelized stream networks greatly increased stream discharge peaks, stream erosive power, and sediment transport capacity leading to extensive channel incision (Menzel, 1983; Schumm, 1999). Channel incision results in streams being disconnected from their floodplains, so flood flows are contained within the channel rather than escaping the channel to dissipate energy and deposit sediment on slackwater floodplains. Hence, channel incision can be a self-perpetuating process, with ever-deepening channels containing larger and larger flood flows, eroding more bed and banks, and deepening the channel.

Walnut Creek probably began to down-cut into its floodplain soon after settlement began, as sediment hungry water (water containing less sediment than its carrying capacity) discharged to the stream in runoff and drainage. Williams (1905) reports an example of deep and rapid trenching in the Squaw Creek watershed (adjacent to Walnut Creek to the north) near the stream confluence with the Skunk River. Here, Williams (1905) reported that Squaw Creek ". . . was channeled into the Wisconsin drift . . . , forming a narrow gorge with precipitous walls for a distance of one-third of a mile leading into the valley of the Skunk River." In the same 1905 report, Walnut Creek was reported to have undergone "considerable downcutting" exposing the coal measures at various locations along its course.

Despite conservation adoption, it was evident that between 1940 and 1991, many stream channels were deepened and many gullies formed. Downcutting in the main stem would have had ripple effects in tributaries as base levels were lowered and tributary streams began to head up into their drainages. Stream networks appear considerably more developed by 1971, and the effects of channel incision in Walnut Creek are clearly evident today. Walnut Creek is incised approximately 10 feet into its floodplain from the upper portion of the basin to the lower end (Schilling and Wolter, 2000; Schilling et al., 2004). It should be noted that the incision is a result of both downcutting through the Holocene alluvium while simultaneously adding post-settlement deposits to the floodplain surface. Stratigraphic analysis of streambanks suggests that the responsibility for the incision appears to be about a 50-50 split between bed degradation (downcutting) and post-settlement aggradation (Schilling et al., 2009). Aggradation was likely due to several factors, including overbank sedimentation, sediment eroded from upland crop areas, and deposition of spoil piles from stream channelization.

Evolution of incised channels typically follows a trajectory (Simon, 1989) of initial disturbance in flow or gradient followed by channel degradation into the floodplain. This leads to a widening phase where the over-steepened and unstable channel banks collapse to a stable slope, and eventual formation of a new floodplain within the widened channel. In Walnut Creek and major tributaries, downcutting appears to have largely slowed, because the incising channel encountered more resistant Gunder Member alluvium or pre-Illinoian till. Because of this, most of Walnut Creek has transitioned to the widening phase over much of its channel length. Recent mapping suggests that various stages of channel evolution are present along the length of each stream, with areas of Stage III (degradation), Stage IV (degradation and widening), and Stage V (aggradation and widening) generally in the middle to lower stream reaches (figure 3-9). Variations in channel evolution appear related to channel sinuosity (i.e. channelized versus sinuous), adjacent land use, and time since disturbance (Palmer 2008).

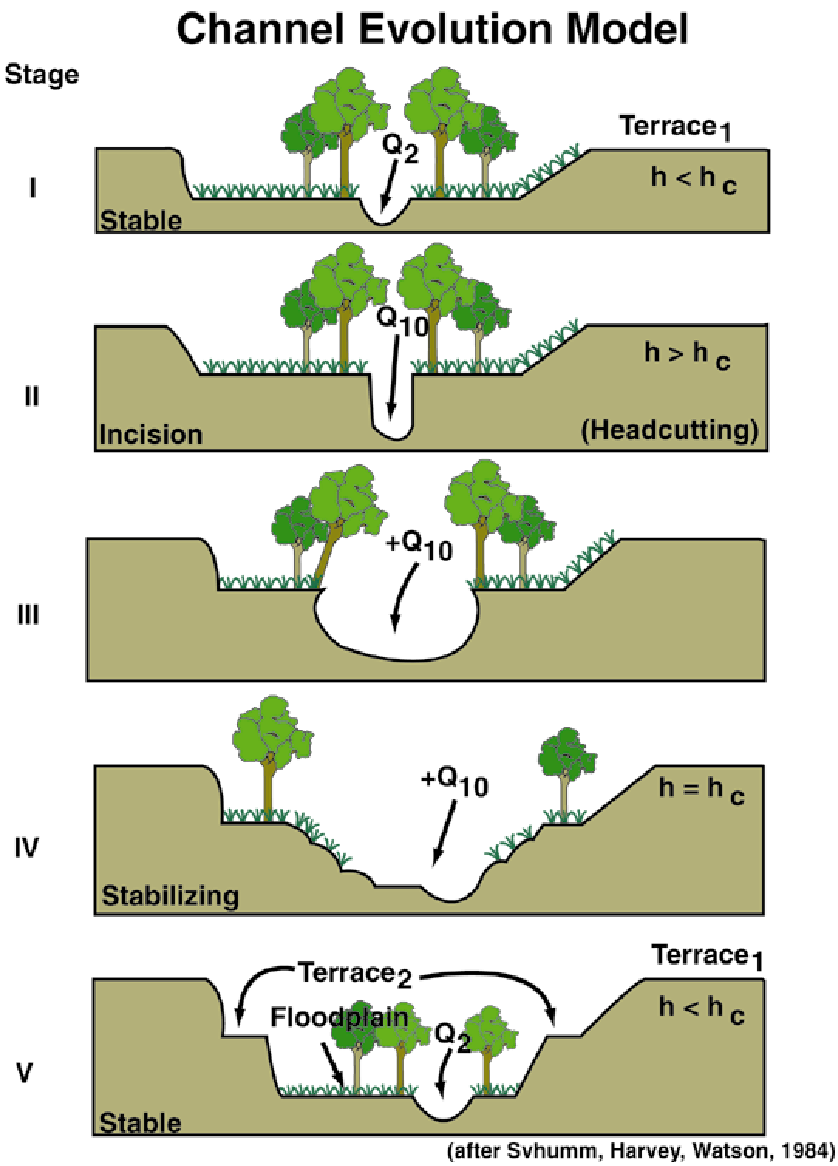


Figure 3-9: Stages of geomorphic evolution of an incised stream channel.

Channel incision destabilizes streambanks and results in increased contribution of streambank erosion to sediment loads exported from watersheds. In natural systems, meandering streams erode on channel cutbanks and deposit sediment on point bars located on inside meander bends. Although streambanks may be actively eroding on ~30% of the total stream length in natural systems, destabilized stream systems may have significantly more eroding streambanks and fewer depositional zones. Mapping conducted along the main channel of Walnut Creek in 2004 indicated that 57.4% of the streambanks were severely eroding (Palmer, 2008; Schilling et al., 2011). This corresponded to 19,200 feet of eroding streambanks along 33,473 feet of channel. The percentage of total sediment loads measured at the watershed outlet estimated from streambank erosion ranged from 51 to 85% (Schilling et al., 2005, 2011; Schilling and Wolter, 2000).

Changing riparian land cover in Walnut Creek watershed also contributed to degrading channel conditions. Pre-settlement savanna and tallgrass prairie lining the stream corridors had vigorous root systems that increased soil stability (Zaimes et al., 2008). Research is showing that row crop farming and grazed pastures along the stream riparian zone have greater streambank erosion rates compared to riparian forest buffers, perennial grasses, and managed grazing (Zaimes et al., 2004, 2008). While row crop farming within the refuge boundaries in Walnut Creek watershed has greatly decreased, the effects of pastures on streambanks have been evident. Cattle access to Walnut Creek was located in a one kilometer segment in the southern portion of the basin (see figure 1-1), and this area showed evidence for extensive channel modifications (Schilling and Wolter, 2000). Severe bank erosion and accumulation of streambed sediment were observed where cattle entered the stream by ramps located primarily at meander bends. Streambed sediment thickness often exceeded 0.3 meters (0.9 feet) where the cattle had trampled over the streambed. Historically, pasture was likely common to the Walnut Creek corridor and probably had similar effects on streambanks and bed materials.

Additional evidence of channel instability in Walnut Creek was obtained during detailed stream mapping in 1998 when a total of 81 debris dams were located in the stream channel between upstream and downstream locations (Schilling and Wolter, 2000). These dams ranged from fallen trees and beaver dams to several large debris dams, consisting of dozens of fallen trees blocking the channel and constricting stream flow. A second stream survey conducted in 2004 identified 72 debris dams along the main stem and 138 debris dams in the major tributaries (Palmer, 2008). Most of the woody vegetation in the channel consisted of fast-growing trees (elm, silver maple) that had fallen in the channel either from wind or streambank collapses. Trees, whose roots have been undercut by the stream, topple into the channel, increasing erosion potential and changing channel morphology.

Channel cross-sections measured at 34 locations along Walnut Creek indicated that stream channel width varied from 6.99 meters to 18.85 meters (22.9 to 61.8 feet) and averaged 10.64 meters (34.9 feet), whereas channel depth varied from 2.19 meters to 3.46 meters (7.2 to 11.3 feet) and averaged 2.77 (9.1 feet). Channel width to depth ratio varied from 2.71 to 7.76 and generally ranged between 3 and 4. This contrasts with a pre-settlement width-depth ratio that may have been around 10. Stream sinuosity was less than 1.1 in three straightened segments and greater than 1.5 in two meandering segments (Schilling and Wolter, 2000).

Streamflow in incised channels is characterized by flashy conditions whereby flows increase and decrease very rapidly during storm events. Incised channels contain all but the most exceptional flood flows and when coupled with straightened channels, resemble pipes that quickly route water downstream. While we do not have historical streamflow records from

Walnut Creek, recent streamflow monitoring indicates that discharge continues to be very flashy. In one example, stream stage observed during a runoff event in 2003 showed stream stage rising and falling nearly eight feet in the span of 12 hours (figure 3-10; Schilling et al., 2006). Rapidly rising and falling flows also carry a substantial load of sediment in the flood wave. During 10 years of monitoring daily sediment in Walnut Creek, the amount of sediment exported from the watershed in one day ranged from16 to 46% of the annual total (Schilling et al., 2006).

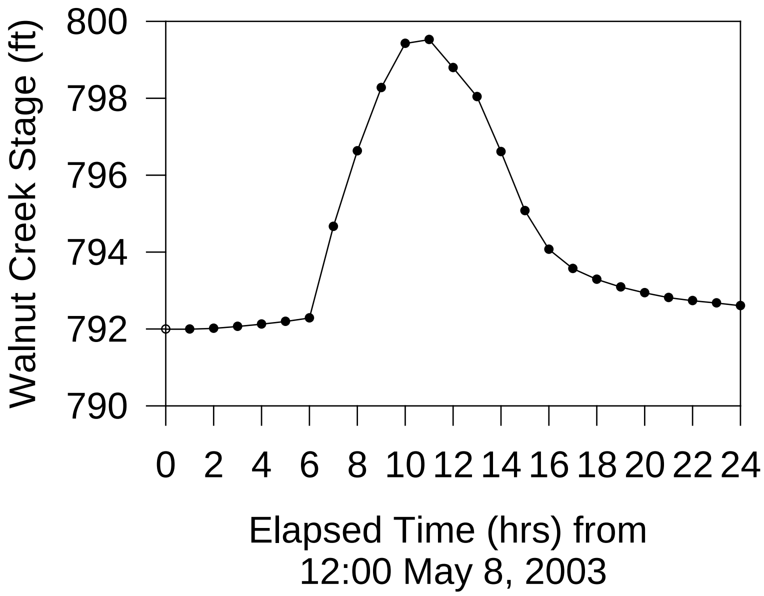


Figure 3-10: Hydrograph of Walnut Creek discharge that shows the flashy nature of streamflow in the incised channel. Discharge increased and decreased nearly eight feet during a 12-hour time period.

In conjunction with stream downcutting and widening, changes in the watershed stream network occurred as Walnut Creek adjusted to increased flow rates and volume after settlement (Anderson, 2000). The stream drainage density increased from 0.9 (1847) to 1.52 by 1972, and the channel frequency increased from 0.32 to 1.2 (see table 2-1). From 1847 to 1972 the total stream length in the watershed increased 76% from 37,185 meters to 60,286 meters. Greater drainage density and elongation of the stream network reduces the travel time for water moving off the watershed downstream. The watershed is able to shed water more efficiently. The expansion of the stream network in Walnut Creek was typical of other basins throughout Iowa (Anderson, 2000).

In sum, runoff from newly plowed and drained agricultural land combined with increased gradients and faster flows in channelized stream networks greatly affected the stream channel network in Walnut Creek. The channel network responded by deepening and widening into its floodplain and greatly expanding its total length and density in the basin. Early in the post-settlement period, Walnut Creek probably lost connection to its floodplain. Flashy flood flows were thenceforth contained within the channel, increasing streambank and bed erosion and contributing to widespread channel instability.

Groundwater

Agricultural intensification and channel modifications affected groundwater hydrology in Walnut Creek watershed. In areas converted to row crop, less ET compared to perennial systems can lead to increased water availability for groundwater recharge. If you consider the groundwater balance of a basin to be:

$$R - Qb = \Delta S \qquad (5)$$

where R is groundwater, Qb is baseflow and ΔS to be soil moisture storage, and consider ΔS to be equal to zero over long time periods, then R = Qb. More groundwater recharge will lead to more baseflow in streams, and, as noted previously, baseflow has been increasing in Iowa's rivers in the second half of the 20th century (Schilling and Libra, 2003). A decrease in ET rates under cropped systems will also lead to higher water table levels. Indeed, early settlers described good quality groundwater under prairie at depths ranging from 30 to 40 feet (9.14 to 12.19 meters), whereas today water table depths monitored under cropland in upland areas of Walnut Creek watershed average approximately three meters (9.8 feet) and typically fluctuate more than four meters (13.1 feet) in a year (reaching within one meter (3.2 feet) of the land surface) (Schilling, 2009; Schilling et al., 2007). Water levels in sideslopes and floodplain are substantially higher, averaging 1.9 meters and 0.3 meters (6.2 and 1 feet), respectively (Schilling, 2009). Although difficult to compare measurements made today with historical accounts, anecdotally, it would appear that water table levels became much higher following settlement.

Jindal (2010) varied groundwater recharge conditions in Walnut Creek watershed in a groundwater flow model and observed that increasing recharge in the uplands had a large impact on groundwater travel times in the basin. Modeling results suggested that increasing annual groundwater recharge by approximately 40 millimeters (1.6 inches) a year resulted in increasing water table heights in the uplands by 1.2 meters (3.9 feet) and decreasing watershed travel times by 9.2 years. Increasing recharge rates in the sideslopes and floodplains also increased water table levels and decreased travel times but not as much as upland changes. Hence, not only did land use conversion of prairie to row crop likely increase water table levels, the changes also resulted in decreasing groundwater residence times in the basin.

Along the disturbed stream corridor, a different pattern of water table change occurred. Along riparian zones adjacent to streams, water table depths are strongly influenced by surface water elevation (figure 3-11). In typical settings, shallow groundwater flows toward the stream according to a hydraulic gradient that generally mimics the land surface elevation (figure 3-11). The depth to the groundwater table (D_{gw}) is typically shallowest near the stream and increases with distance away from the stream. Incised streams are hydrologically disconnected from their floodplains as channel incision lowers the surface water elevation, which subsequently lowers the water table near the stream (Schilling et al., 2004). Along the Walnut Creek corridor, D_{gw} is actually greatest near the stream and shallower in more distal floodplain regions (figure 3-11). Channel incision was found to have lowered the water table from the stream edge to a distance of approximately 30 meters (98 feet), thus creating a large unsaturated zone in the near-stream riparian zone compared to more distant floodplain zones (figure 3-12; Schilling et al., 2004). Less groundwater recharge occurs near the incised channel, because the channel banks have been dewatered. Schilling (2010) used the term "hydrologic drought" of Groffman et al. (2003) to describe the near-stream riparian zone of an incised stream where the riparian zone within one meter (3.23 feet) of Walnut Creek received on average 17 to 35% less recharge compared to riparian areas located 20 to 40 meters (65.6 to 131.2 feet) away from the channel. Channel incision also limits the amount of groundwater–surface water exchange in the riparian zone. Monitoring results during a storm event indicate that bank storage of stream water during a storm event is limited to a very narrow zone (<1.6 meters) immediately adjacent to the channel (Schilling et al., 2006). Modeling suggests that should channel bed degradation continue in the future, a much greater proportion of the floodplain may become unsaturated in the future (Schilling et al., 2004).

In sum, groundwater levels in Walnut Creek watershed were influenced by agricultural intensification and channel modification. Water tables increased in areas where native perennial vegetation was replaced by annual crops but decreased in the riparian zone after channel incision lowered the base level of the stream.

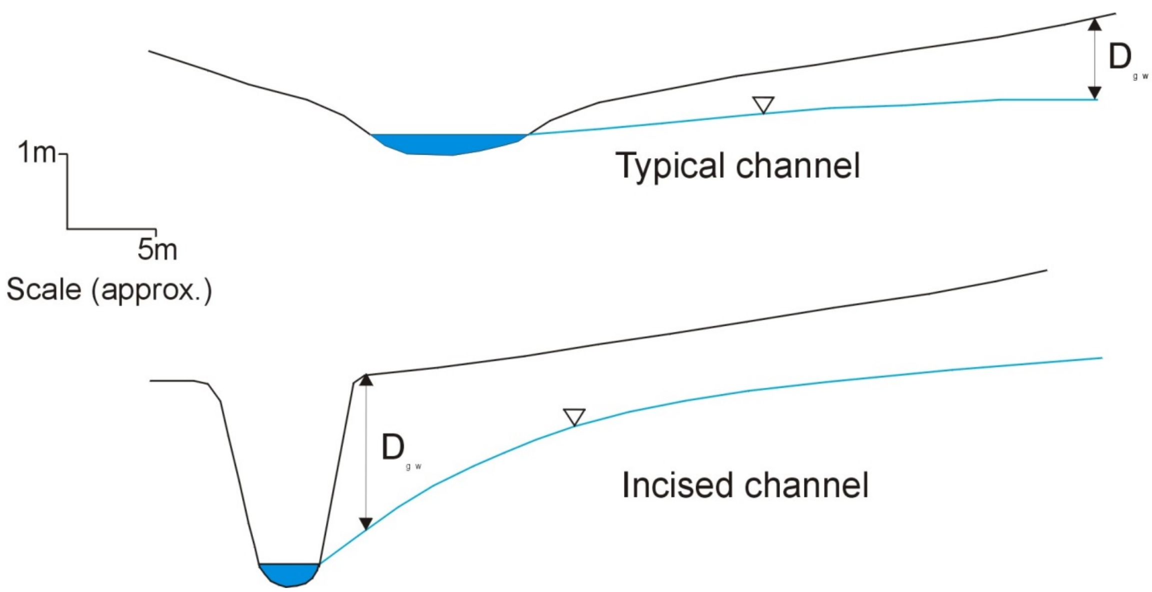


Figure 3-11: Comparison of riparian depth to groundwater (D_{gw}) in a typical floodplain and near an incised channel. Note how D_{gw} is greatest near the incised channel.

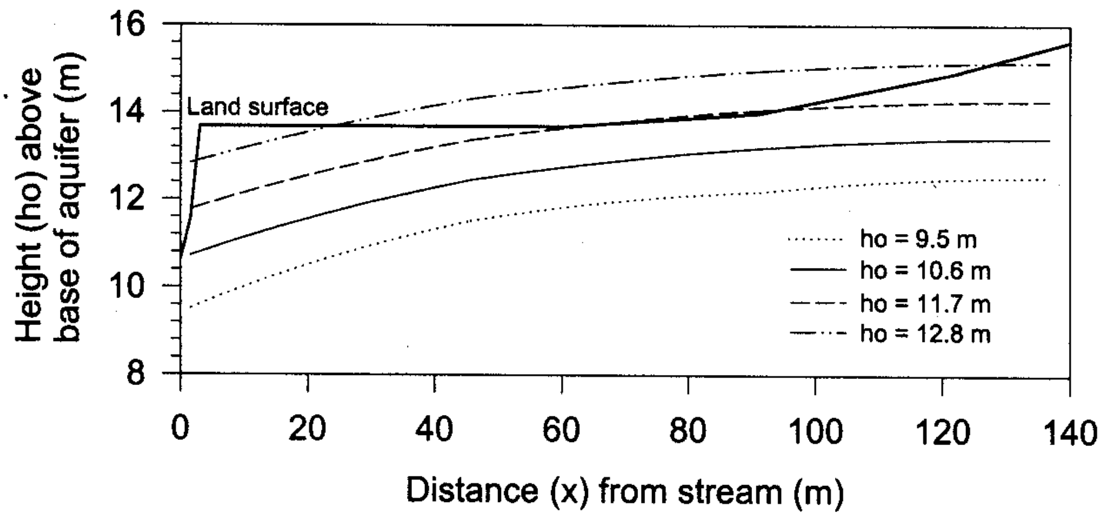


Figure 3-12: Effects of channel incision on water table shape in Walnut Creek riparian zone. Should Walnut Creek continue to incise deeper into its floodplain, riparian water table depths will likewise decrease and dewater a larger portion of the floodplain (ho = 9.5 meters). On the other hand, if channel incision were reversed and Walnut Creek aggraded, riparian water table levels would increase and more of the floodplain would be perennial saturated (ho = 12.8 meters) (after Schilling et al., 2004).

Water Quality

Although there is little pre-settlement water quality data available, we can be quite certain that surface water and groundwater quality conditions deteriorated under the post-settlement agriculture period. Land cover change towards increasing row crop production combined with the increasing and widespread use of N fertilizers and pesticides increased the vulnerability of water resources for pollution from nonpoint sources. Unfortunately, there is very little data available to track historic changes in water quality to agricultural intensification in the 20th century. In a rare example, water quality records from several large rivers in Iowa (Iowa, Cedar, Des Moines and Raccoon Rivers) indicate that average nitrate concentrations increased from less than 0.06 milligrams/liter in 1906–07 to 1.6 to 2.8 milligrams/liter in 1944–1956, to 6.1 to 7.2 milligrams/liter over the last 30 years (Iowa Geological Survey, 1955; Iowa Department of Natural Resources–Geological Survey Bureau, 2001). The increasing trajectory of nitrate concentrations certainly indicates an agricultural influence on regional water quality conditions. By the 1970s and 1980s, it had become recognized that modern agriculture was a significant source of water pollution (Duttwieler and Nicholson, 1983). Work continues today on strategies to reduce nonpoint source pollution impacts at local and regional scales, including the Gulf of Mexico (Agricultural and Biological Engineers, 2008).

Specific to Walnut Creek watershed, we can examine current water quality conditions to assess the cumulative degree of impact made by agricultural intensification over the last 150 years. Concentrations and loads of nonpoint source pollutants measured in Walnut Creek watershed during last two decades probably represent continued deterioration of water quality conditions that began when early settlers first broke the virgin prairie. With the onset of ecological restoration activities at NSNWR, some improvements in water quality are being made and the impacts of these restoration activities will be described in the next section of this report. What follows is an assessment of the water quality conditions that are assumed to represent “background” conditions; that is, water quality conditions that the U.S. Fish and Wildlife Service

(USFWS, Service) likely inherited when NSNWR was established. The water quality focus is on nutrients (N and phosphorus [P]) and suspended sediment, both of which have a detailed sampling record available to evaluate. Although post-settlement agricultural intensification undoubtedly affected pesticides and bacteria levels in surface and groundwater, less data is available to evaluate the spatial and temporal distribution of these parameters. Hence, for purposes of this report, the water quality focus will be on nutrients and sediment.

Nutrients – Sampling data available in Walnut Creek watershed indicate that post-settlement agricultural intensification has led to high concentrations of nitrate present in groundwater beneath cropped systems. For example, groundwater quality measured in monitoring wells installed in active farm fields located in upland areas have shown nitrate concentrations ranging between 8.5 and 12 milligrams/liter in one field (Schilling et al., 2007) and between 7.7 and 27.3 milligrams/liter in another field (Schilling and Jacobson, 2010). The average nitrate concentration in groundwater beneath both upland fields was approximately 11.2 and 14.8 milligrams/liter, respectively. Because baseflow reflects groundwater (and tile) discharge to streams, we can look at baseflow conditions measured in the watershed to also gauge impacts of groundwater discharge to streams from intensive row crop agriculture. In May 1999, a basin-wide synoptic sampling event in Walnut Creek watershed showed high nitrate concentrations (>15 milligrams/liter) in catchments dominated by row cropland use (Schilling, 2001). A watershed-specific relation between row cropland use and stream nitrate concentrations was developed based on this sampling effort, whereby stream nitrate concentration (in milligrams per liter) was a function of the percentage of the catchment in row cropland cover (NO3-N in milligrams per liter = 0.14*RC% + 1.1; Schilling, 2001; Schilling and Libra, 2000). A second synoptic survey conducted during a fall baseflow period in October 2001 similarly showed that nitrate concentrations were highest (>12 milligrams/liter) in catchments dominated by row cropland use (Schilling, 2001). Overall, the sampling data indicate that post-settlement row crop agriculture resulted in high nitrate concentrations present in groundwater beneath cropped upland areas that are delivered to streams with baseflow.

Along many upland drainageways, nitrate concentrations are known to be significantly lower due to biogeochemical processing that occurs in the saturated, organic-rich alluvial deposits. For example, nitrate concentrations in groundwater were observed to decrease from >10 milligrams/liter in upland groundwater to <0.5 milligrams/liter in a drainageway (Schilling et al., 2007). A groundwater flow model suggested that denitrification was capable of removing all upland groundwater nitrate contribution to the drainageway (Weisbrod, 2005). However, this work highlighted that tiles commonly placed in low drainageways to drain grass waterways short-circuit the natural denitrification process available in the sediments. Considering that nearly all first-order streams in Walnut Creek watershed originate with tile flow, we suspect that denitrification in the low drainageway soils is not a dominant fate of nitrate in the basin.

Along the Walnut Creek riparian zone, potential for biogeochemical processing of groundwater nitrate is also evident in the Holocene alluvium, but the effectiveness was compromised by the channel incision. In 2001, a series of 35 shallow, nested groundwater monitoring wells were installed in a 550-meter transect across the Walnut Creek floodplain (Schilling et al., 2004). Groundwater samples showed elevated nitrate concentrations (up to 20 milligrams/liter) in riparian groundwater near the incised stream where the unsaturated zone was thickest (recall the unsaturated wedge that develops near incised channels). Nitrate concentrations were then found to decrease with distance away from the stream as the water table became shallower and perennially wet conditions were maintained. Groundwater nitrate concentrations were observed to decrease to concentrations typical of pre-event concentrations over the two-month period that followed the runoff event due to dilution and denitrification processes.

Subsequent investigations of the floodplain focused on background nutrient concentrations in various alluvial members and the effects of land management (Schilling and Jacobson, 2008). Although one side of the transect was impacted by land management activities during the monitoring period, the other side was covered with a near monoculture of reed canarygrass, a cool season exotic species. Except for a high flow event where nitrate was detected in a shallow near-stream well at 3.7 milligrams/liter, nitrate concentrations measured in alluvium were generally less than 0.5 milligrams/liter, and many wells showed non-detectable concentrations less than 0.1 milligrams/liter (Schilling and Jacobson, 2008). Soluble N under a grass cover was primarily in the form of reduced ammonium (NH4-N) in the Holocene alluvium, with a common range of ammonium concentrations in alluvium between 0.05 to 0.2 milligrams/liter. Some exceptionally high concentrations were measured in several wells, with the highest single concentration of 22.6 milligrams/liter found in one deeper well. Average ammonium concentrations were nearly two milligrams/liter in Roberts Creek and Gunder member alluvium.

On the other side of the stream, the grass cover was removed during reconstruction activities (figure 3-7), which would seemingly preclude it from representing agricultural background conditions. However, if we consider the reconstruction process of removing invasive cover to be similar to cropping (both procedures leave the soil bare for extended periods of time, although it should be noted that cropping leaves the soil bare year after year compared to the one-year reconstruction), we can see what happens to the alluvium when “cropping” is done along the near-stream riparian zone. After grass removal, groundwater nitrate concentrations within the channel incision wedge increased from less than 0.5 milligrams/liter to greater than 20 milligrams/liter during a spring rainy period. The source of the nitrate was the N-rich Holocene alluvium. With the perennial cover of grass removed, N was mineralized in the unsaturated soils to nitrate, and vegetation was not present to reduce the accumulation of nitrate. In contrast, at locations 20 to 40 meters away from the channel, nitrate concentrations remained low (Schilling and Jacobson, 2008). Later in the summer and fall, additional monitoring of near-stream wells indicated that, like the upland drainageways, groundwater nitrate concentrations were observed to rapidly decrease via denitrification.

Phosphorus (P) concentrations have been monitored less than nitrate, but concentrations measured in groundwater beneath active farm fields in upland areas ranged between 0.01 and 0.67 milligrams/liter and averaged 0.09 milligrams/liter (Schilling and Jacobson, 2010). Dissolved P concentrations in groundwater differ from those of nitrate, as concentrations were often greater in saturated drainageways than in the uplands (Tomer et al., 2010). Concentrations in upland wells averaged 0.024 milligrams/liter whereas average concentrations in footslopes and drainageways were 0.147 and 0.109, respectively. Tomer et al. (2010) suggested that one reason for this is that accumulation of P from eroded sediment (post-settlement alluvium) in drainageways may be a continuing source of P to groundwater. In the riparian zone of Walnut Creek, soluble reactive phosphorus (SRP) concentrations in alluvium ranged from less than 0.1 milligrams/liter in upland wells to as high as 1.42 milligrams/liter in riparian wells, although most concentrations were less than 0.3 milligrams/liter (Schilling and Jacobson, 2008). Similar to the upland drainageway, P concentrations were significantly higher in groundwater beneath post-settlement alluvium (0.26 milligrams/liter) than beneath loess and till (0.04 milligrams/liter).

High concentrations of N and P in groundwater contribute to high concentrations measured in surface water. On a watershed scale, we can look at surface water quality measured upstream of the current refuge and in a paired control watershed (Squaw Creek) to gauge the current impact of post-settlement agriculture on surface water resources. Approximately 200 water samples collected from both areas from 1995 to 2005 indicate that nitrate and P concentrations are very high in surface water draining these watersheds that contain ~80% row cropland use (Schilling et al., 2006). Nitrate concentrations upstream of the refuge and in neighboring Squaw Creek averaged 11.1 milligrams/liter and 9.5 milligrams/liter, and exceeded the 10 milligrams/liter drinking water standard for nitrate approximately 65% and 74% of the time, respectively. Average export of nitrate mass in water (chemical load) averaged 26.1 kilograms per hectare in Squaw Creek and 30.3 kilograms/hectare in upper Walnut Creek. Much of the nitrate export occurs with baseflow discharge of groundwater (61–68%; Schilling, 2002). If N fertilizer rates are assumed to be about 140 kilograms/hectare, then the amount of nitrate N export from these areas represents about 20% of the N applied as fertilizer.

Phosphorus concentrations and loads measured upstream of the refuge and in a paired control watershed (Squaw Creek) also indicate substantial export of P to surface water from these heavily cropped basins. Over 100 water samples collected from 2000 to 2005 showed P concentrations averaging 0.29 milligrams/liter in Squaw Creek and 0.23 milligrams/liter in upper Walnut Creek, while P loads averaged 0.98 kilograms/hectare and 0.66 kilograms/hectare, respectively (Schilling et al., 2006).

In sum, water quality monitoring data collected from intensively row-cropped areas indicate significant impacts of N and P on surface and groundwater resources after more than 150 years of agriculture. Nitrate concentrations have likely increased more than 100-fold from pre-settlement to the late 20th century, from <0.1 milligrams/liter to more than 10 milligrams/liter in both surface and groundwater. Although we do not have pre-settlement P concentrations, it is evident that P concentrations measured today are also elevated. These high nutrient concentrations represent the background condition for NSNWR ecological restoration.

Sediment – Conversion of perennial native prairie and savanna to predominantly row crop agriculture unleashed a massive volume of sediment to Walnut Creek. While a substantial portion of sediment remains stored on the floodplain as four to six feet of post-settlement deposition, a large volume of sediment is also exported from the watershed. Although we do not have sediment records that extend to early post-settlement, we can look at long-term records from the Raccoon River watershed in west-central Iowa to identify general patterns (Jones and Schilling, 2011). These records indicate that sediment concentrations were much higher in the early 20th century despite drier conditions and less discharge and that sediment concentrations declined as the century progressed. Against a backdrop of increasing discharge in the Raccoon River and widespread agricultural adaptations by farmers, sediment loads increased and peaked in the early 1970s and then have slowly declined or remained steady throughout the 1980s to present. These patterns may be similar to Walnut Creek considering that adoption of conservation practices occurred mainly in the 1960s and 1970s. As such, these temporal trends suggest that sediment concentrations and loads measured in upper Walnut and Squaw Creek watersheds may be less than what they were historically.

Daily sediment concentrations and loads measured in Walnut and Squaw Creek watersheds from 1995 to 2005 provide data on recent patterns of suspended sediment transport. Pre-settlement surface water in GLO notes was described as “clear,” but today turbidity values in Walnut Creek range from clear (<5 Nephelometric Turbidity Units [NTU]) to very turbid (>1000 NTU) (Schilling et al., 2006). Annual mean sediment concentrations in Walnut Creek ranged from 78 to 153 milligrams/liter and averaged 104 milligrams/liter, whereas nearby Squaw Creek ranged from 47 to 129 milligrams/liter and averaged 90 milligrams/liter. Sediment concentrations typically ranged between 20 to 50 milligrams/liter in surface water but maximum values exceeded 3,000 milligrams/liter in both basins (Schilling et al., 2006).

We speculate that the source of sediment in Walnut Creek may have shifted from dominantly sheet and rill erosion during early post-settlement record to in-channel bed and bank erosion today. As indicated earlier, most of the post-settlement alluvium (PSA) was probably deposited between about 1890 and 1930. Sedimentology work in Walnut Creek suggests that most of this PSA was likely derived from erosion of upland loess soils rather than overbank sources (Schilling et al., 2009), so the timing and deposition implicate overland flow sediment transport early in the agricultural period. However, recent monitoring suggests that while upland soil erosion may be slowing, sediment contributions from streambank and bed sources are increasing. The sediment contributions to Walnut Creek from streambank erosion were estimated to range from 2,934 to 4,900 Megagrams (3,233 to 5,400 tons) per year and comprise 38.6% to 64.4% of the total sediment export (Schilling et al., 2011).

Additionally, the contribution of resuspended streambed sediment to sediment loads are likely contributing to sediment losses. Sediment that accumulates in the channel behind logs, beaver dams, or other impediments can provide temporary storage sites of sediment that can then become available for transport during storm events. Schilling and Wolter (2000) estimated sediment storage in Walnut Creek to be 14,726 tons, which would require nearly 10 years to flush from the watershed under average streamflow and sediment concentrations.

Overall, sediment concentrations and export from Walnut Creek are significantly higher compared to pre-settlement conditions but may be less than what was experienced in the first few decades after settlement. Late in the 20th century, sediment contributions appear to be increasingly dominated by streambank and bed erosion. Sediment contributions coming from in-stream sources reflect historical channel instability and subsequent channel evolution over time.

Chapter 4: Restoration of Hydrologic Processes at NSNWR

In this chapter:

From chapters 2 and 3, it is clear that the Walnut Creek watershed is a product of its history, containing a legacy of the geologic and native tallgrass prairie past that was greatly modified with the arrival of settlement and agricultural intensification in the 19th and 20th centuries. It is against this backdrop of history that the U.S. Fish and Wildlife Service (USFWS, Service) entered the watershed with Neal Smith National Wildlife Refuge System (NSNWR, refuge) in the early 1990s. In chapter 4, we begin with an assessment of vegetation that existed when the refuge was established in 1991. We then synthesize current research to show how the refuge is making progress on restoring key hydrologic processes in the Walnut Creek watershed.

Vegetation Characteristics at Refuge Establishment

The landscape the refuge inherited in 1991 was primarily cropped, with some grazed and Conservation Reserve Program lands occupied by cool season exotic plant species and small areas of remnant prairie, savanna, and sedge meadow that survived agriculture and exotic species dominance (USFWS, 1993). Faint shadows of the former natural landscape existed prior to any Service conservation management, and expression of elements of native flora was directly related to hydrology.

Native vegetation still existed in upland seeps, for example where glacial till and paleosols can be wet and soupy in moist spring weather but in drier summer weather can become sunbaked and hard. Although agriculture is often tried in seeps, conditions are unsuitable for farming, and efforts are soon abandoned.

When such areas were tilled, and native vegetation was largely removed, plant establishment was likely slow and difficult. In 1991, prior to refuge management, Coneflower Prairie Remnant (figure 4-1), supported a limited number of native species with greater cover existing in areas that remained perennially moist (Drobney and Bryant, 1991). Part of the prairie was bisected by a horizontal line across hillslopes formed by two vegetation types. Large patches of the northern section supported only sparse vegetation mostly consisting of native species that were deep rooted or rhizomatous. Extreme moisture conditions apparently suppress or eliminate most exotic species, although native species more tolerant of harsh conditions can survive. In Coneflower Prairie Remnant, examples of native species that survived harsh conditions included deep-rooted pale purple coneflowers (*Echinacea pallida* (Nutt.) Nutt.) compass plants (*Silphium laciniatum* L.), and a matrix of the rhizomatous rough dropseed (*Sporobolus compositus* (Poir.) Merr. var. *compositus*).

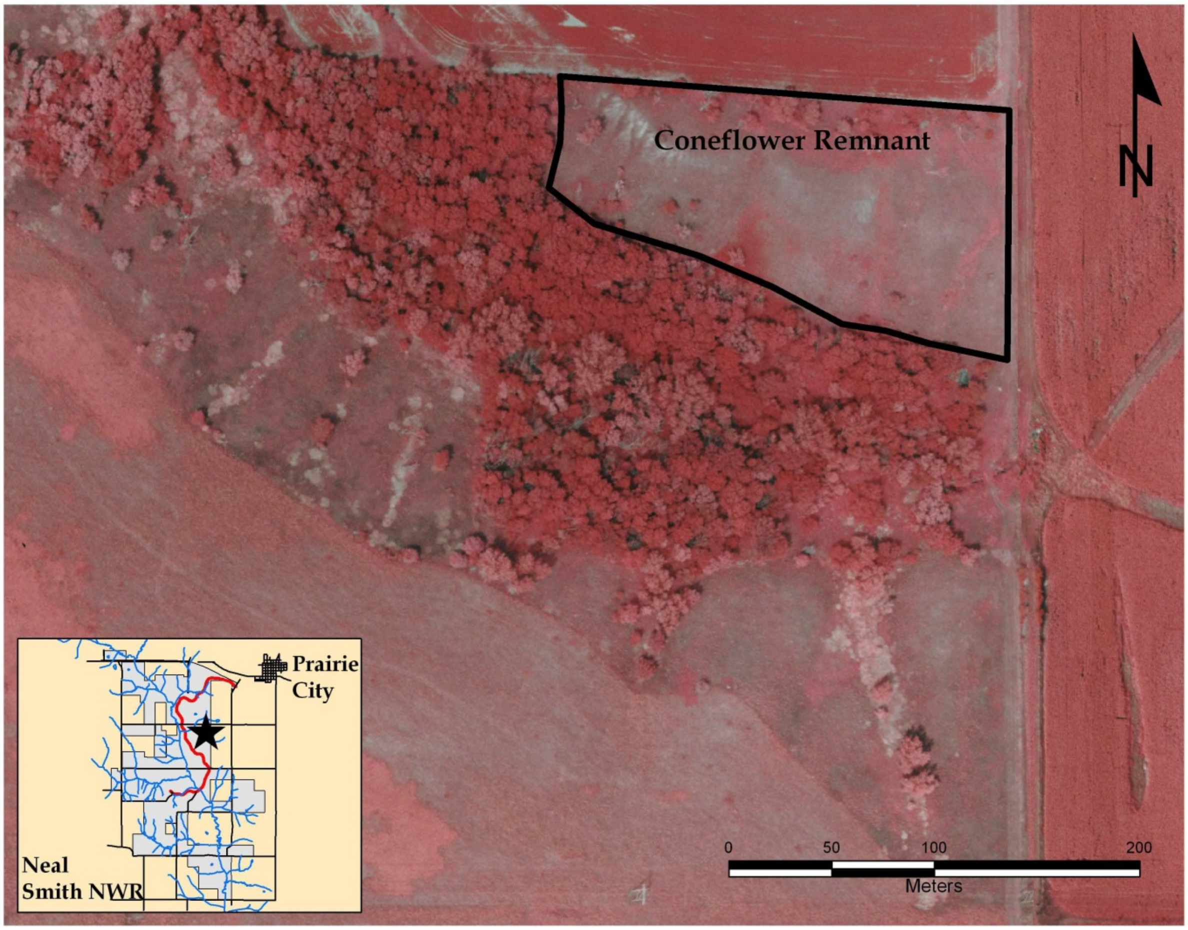


Figure 4-1: Although heavily damaged, Coneflower Prairie Remnant was obvious as a remnant prairie in prior to refuge management in 1991 because of the presence of a large population of pale purple coneflowers (*Echinacea pallida*) among other prairie species.

In contrast, dominant vegetation in perennially moist areas of the prairie remnant in 1991 included sedges (*Carex* spp.), rushes (*Juncus* spp.), and other native species dependent on water near the soil surface. Vegetation patterns existing in Coneflower Prairie Remnant in 1991 signaled a past land use, with farming probably having been more intensive north of the line where it was drier in summer, possibly making it more accessable to farm equipment.

Except for a couple of sites, most prairie remnants were obscured by trees that had grown opportunistically on areas poorly suited for commercial use or for use as homesteads. In the case of the most diverse remnant prairie named “Dogleg,” a stagecoach trail was reported by a local resident to be among past land uses, and each land use of extant remnants of natural communities contributed subtly or profoundly to the current condition.

Savanna remnants were more obvious because the presence of old (> 100 years) oaks with a branching pattern horizontal to the ground indicated that trees had grown in open sun instead of the distinctive upward branching pattern typical of trees developing under intense competition for sunlight. These savannas were densely overgrown with tree species that were absent under historic fire regimes but opportunisitically established due to deposition of seed by animals or wind. Without fire to limit them, the canopy closed, and conditions became too dark to support a healthy savanna understory. A mix of native and exotic woody species often included dense growth of thorny species such as multi-flora rose (*Rosa multiflora* Thunb.), honey locust (*Gleditsia triacanthos* L.), and black locust (*Robinia pseudoacacia* L.) indicating a history of grazing, as livestock avoid eating thorns. However, in rare areas where light penetrated the dense canopy, savanna species including leather flower (*Clematis* pitcheri.), Turk's cap lily (*Lilium michiganense* Farw.), Penn sedge (*Carex pensylvanica* Lam.), and woodland twayblade orchid (*Liparis liliifolia* (L.) Rich. ex Ker Gawl.) indicated a former diverse savanna understory. In addition to light deprivations, many savanna herbaceous species that languished in the understory also suffered from reduced soil moisture, due to massive water use by non-savanna trees.

Both fire and tree removal contribute to a more open savanna condition. Savannas have traditionally been a source of wood for local residents, and the presence of tree stumps suggests this has been the case in the relatively recent past. Furthermore, the presence of char on one or more trees in Thorn Valley is evidence of past fire. However, at least within the decade prior to Service ownership, it is unlikely that fire would have moved very deeply into these dark woodlands with only sparse grass and sedge to carry the fire. In fact, prescribed fires lit deliberately by refuge staff in unthinned savannas have met with poor success.

Conversations with local residents, indicated that wooded areas in the vicinity of Thorn Valley were popular for weekend picnics and that Thorn Valley had been named because of the thorny character. Rows of walnut trees of fairly uniform age and spacing present in both Thorn Valley and Coneflower Prairie Remnant also indicate use for forestry projects. In addition, Old Game Farm Savanna Remnant was being used as a private hunting preserve when the refuge started.

Sedge meadows that had once blanketed the land within the floodplain had nearly succumbed to reed canarygrass by the time the refuge began in 1991 (Drobney and Bryant, 1991). Examples existed in very small pockets within reed canarygrass monocultures. The best example was found in the southern portion of the refuge in a unit called Sedge Wren. Amazingly, an area approximately 10 to 20 meters in diameter persisted in fairly good condition with a complement of native species despite being surrounded by reed canarygrass. Reasons for its survival are unknown, although we speculate it may be related to the density of the native species within the patch or to a large enough patch size to continue to be competitive. Alternatively, it may be because of a unique hydrological condition present in that particular area or a combination of these possibilities.

In summary, remnants of the natural landscape persisted at NSNWR when it began despite harsh treatment from an ecological perspective. Remaining remnant natural communities were not preserved because they were a part of a rare native ecosystem but rather, they were preserved incidentally because they proved relatively useless for economic gain, or because they had aesthetic value. All had been used for one or more purposes through time including farming, pasture, silviculture, hunting, and recreation. Despite the degraded condition of remnant prairies, savannas, and sedge meadows, they contained native flora and fauna and provided the potential for restoration of natural communities. As such, remnant prairie, savanna, and sedge meadow are highly valuable in the overall goal of ecological restoration.

Restoring the Water Balance

The water balance of the watershed changed from a pre-settlement evapotranspiration (ET) and infiltration-based landscape to a water-shedding landscape involving elevated surface water runoff and baseflow. Restoration of the water balance in the Walnut Creek watershed means increasing plant water demand (i.e., ET) relative to annual crops and increasing the water infiltration and soil moisture storage. Increasing ET and infiltration will ultimately decrease surface water runoff.

On a watershed scale, converting large areas of land from annual crops to native prairie would have been expected to reduce the water yield in the basin (total Q in equation 1). However, during the 10-year monitoring project when 3,023 acres of native prairie were planted in the watershed (representing 25% of the basin), Walnut Creek streamflow was not significantly different compared to streamflow in the paired Squaw Creek watershed (figure 4-2; Schilling et al., 2006).

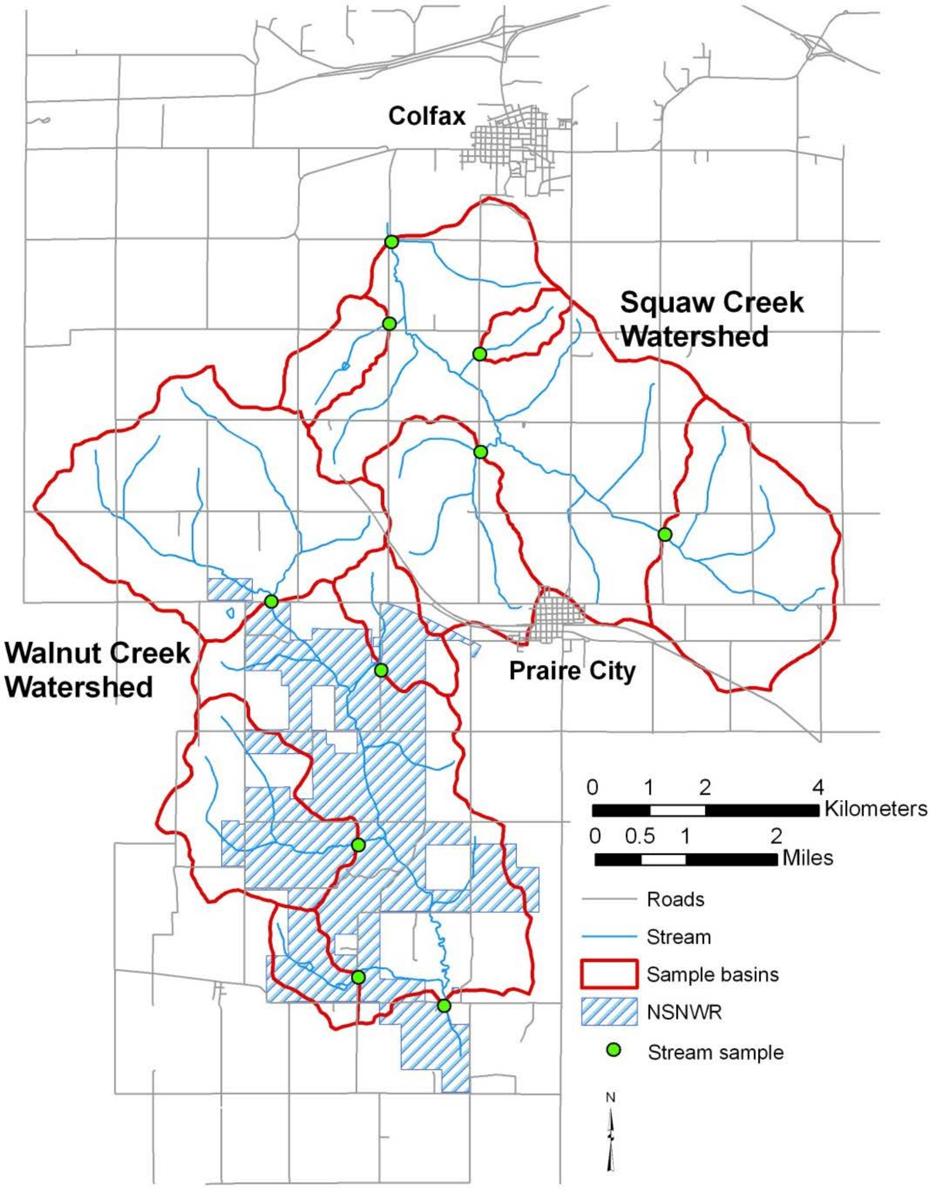


Figure 4-2: Location of paired Walnut and Squaw Creek watersheds.

There was evidence, however, to suggest that streamflow patterns were different among the watershed areas monitored during the project. Maximum daily discharge was often higher in Squaw Creek than Walnut Creek, and Squaw Creek and upper Walnut Creek (north of refuge boundaries) had higher annual baseflow and a higher percentage of streamflow as baseflow than lower Walnut Creek (portion within the refuge study area) containing NSNWR (Schilling, 2002). Elevated baseflow in the highly row-cropped regions of Squaw Creek and upstream Walnut Creek suggest that these areas may have lower annual ET and greater tile drainage compared to reconstructed prairie areas. Lower baseflow in lower Walnut Creek is consistent with the hypothesized ability of prairie reconstruction to increase ET and reduce drainage of water from the soil profile. Nonetheless, at a watershed scale, significant changes in the water balance have been difficult to detect and measure.

Research conducted at the plot or field scale has isolated hydrologic changes and suggests that restoring aspects of the water balance are possible at NSNWR. Guzman and Al-Kaisi (2011) measured soil organic carbon (SOC), soil bulk density, and water infiltration in croplands, prairie reconstructions at NSNWR, and in remnant prairie at the nearby Rolling Thunder Prairie in Warren County. The study found that increasing SOC in prairie soils promoted soil aggregate stability, lowered bulk density, and increased soil permeability in reconstructed prairies. Infiltration rates were found to be much greater in toe-slope landscape positions where eroded soils historically accumulated (legacy affect). While the prairie remnant site had the highest infiltration rate, the year since prairie establishment was a significant factor in increasing SOC and decreasing soil bulk density that resulted in more permeable soils (Guzman and Al-Kaisi, 2011). In other words, infiltration rates appear to be increasing in reconstructed prairie soils, but there are some variations based on landscape position.

As part of a long-term experiment assessing the performance of vegetative filter strips at NSNWR, 12 ephemeral catchments in the Walnut Creek watershed are being monitored for testing the effectiveness of prairie filter strips (PFS) in trapping sediment from agricultural runoff (Helmers et al., 2012). As part of this monitoring effort, discharge from two 100% prairie catchments planted in December 2003 (Cabbage site; see figure 1-1) is also being monitored. Average annual runoff from the two 100% prairie watersheds was approximately 49% lower than runoff in the watersheds with PFS and nearly 70% lower than watersheds with 100% crop. During a single event in August 2011, total runoff and sediment export from the native prairie watersheds was 44% and 62% lower than in the watersheds with PFS (Helmers et al., 2012). While these results are preliminary and part of a long-term study, the data suggest that upland prairie reconstruction can have a significant affect on reducing overland runoff (Qs in equation 2).

Understanding how plant communities use water differently also provides insights into restoration of the water balance at NSNWR. Asbjornsen et al. (2008) used stable isotopes to infer depth of water uptake for contrasting a selection of annual and perennial plants at the refuge. Species of perennial plants tested, including native prairie, woody shrubs, and trees, extracted soil water at much greater depths than annual crop plants including soybeans and corn. Perennial plants showed much greater plasticity in extracting water from a variety of depths, whereas corn and soybeans were restricted to the surface 20 centimeters of the soil profile. The authors note that establishing a diverse ecosystem of perennial plants will enhance hydrologic functions by ". . . recycling water from deeper depths in the soil profile back to the atmosphere and increasing soil water holding capacity" (Asbjornsen et al., 2008). Other research focusing on restoration of remnant upland savannas demonstrated large differences in stand-level transpiration rates and water table levels between adjacent thinned and unthinned study sites in a savanna encroached by elms (Asbjornsen et al., 2007). Oaks in thinned areas had greater sap flow than oaks and elms in unthinned areas. However, the unthinned savanna's overall stand transpiration was greater than the thinned savanna, possibly contributing to deeper water table depths under the unthinned savanna. The research provides clues regarding restoration of savanna remnants that were once plentiful during pre-settlement times.

In the floodplain, reconstruction of sedge meadow and wet prairie communities is hampered by reed canarygrass competition. This invasive species is adapted to wide extremes in soil moisture and nutrients (Mahaney, Wardrop, and Brooks, 2004; Galatowitsch et al., 1999), and is of serious management concern in moist to wet areas where it is especially competitive (Lavergne and Molofsky, 2004; Mahaney, Wardrop, and Brooks, 2004; Lyons, 1998). Its occupation can lead to ecological degradation and loss of native plant and insect diversity (Lavergne and Molofsky, 2004). Alterations in the hydrological regime, soil disturbance, and nutrient inputs from offsite sources enhance reed canarygrass spread. As such, the lowlands of Walnut Creek watershed are ideally suited for tenacious reed canarygrass occupation, and based on 2010 aerial imagery, approximately 330 acres of lowland are dominated by this species (NSNWR CCP 2012).

In floodplains where reed canarygrass is most abundant, Schilling and Kiniry (2007) estimated ET by reed canarygrass using field observation and model simulations and reported that total water use by this species was approximately 500 millimeters from April to October. This value is similar to those reported for floodplain oaks on a site in southwest Iowa (Schilling and Jacobson, 2009) and warrants concern, because reed canarygrass is competing for the same groundwater resources as reconstructed native vegetation. However, in a water-rich environment like the Walnut Creek floodplain, water availability is not a limiting factor in reconstructing sedge meadow except in the hydrologic drought zone. Rather, nutrient levels in soil, groundwater level fluctuations, and periodic floodwaters likely favor the competitive success of reed canarygrass in Walnut Creek floodplains, as it thrives and suppresses sedge meadow species under nutrient enrichment (Perry, Galatowitsch, and Rosen, 2004; Green and Galatowitsch, 2002).

Experimental sedge meadow reconstruction was undertaken in 2002 in near-monocultures of reed canarygrass on both sides of Walnut Creek (see figure 3-7). Project implementation included tree clearing along both sides of the stream, with no treatement on the control (west) side. In the treatment side, reed canarygrass was treated with glyphosate and the area was planted with a seed mix and established plants of sedge meadow species. In the first two years, areas reinfested with dense reed canarygrass were again treated with glyphosate.

Vegetation monitoring suggests that sedge meadow reconstruction of reed canarygrass areas may be related, in part, to groundwater hydrology. The most rapid and persistent recovery of sedge meadow community has been in a “Distal” zone located farthest from the stream (also nearest a savanna remnant). The Distal zone corresponds with a relatively stable hydrology more characteristic of historic conditions and may explain the more rapid and complete recovery in the sedge meadow community.

In the “Middle” zone between the stream and the “Distal” zone, water levels fluctuate dramatically after rainfall events and result in unstable water level conditions. This may explain the advantage reed canarygrass has in this middle floodplain area and the subsequent difficulty in establishment and maintenance of native plants.

Near the stream (“Streamside”), channel incision has lowered the water table (see figure 3-11) and affected sedge meadow reconstruction. Based on historic condition, this area should be the wettest portion of the floodplain supporting wetland to sedge meadow communities. Streamside vegetation has been “weedier” throughout the years including Canada thistle (*Cirsium arvense*) and other exotic species, and species symptomatic of soil disturbance such as giant ragweed (*Ambrosia trifida* L.). Weediness in the Streamside zone is likely to be further exacerbated by occasional flooding of Walnut Creek.

To some degree, sedge meadow is recovering (figure 4-3). Distal zone sedge meadow vegetation is vigorous and seemingly expanding toward the Middle zone. In the Middle, reed canarygrass appears less vigorous and shorter in 2012 than in past years, and forbs are beginning to invade the reed canarygrass. Streamside, vegetation still consisted of reed canarygrass but it was shorter than it has been in past years and was heavily interspersed with sunflowers in some areas. One reason for increases in native plant occupation in the Middle and Streamside zones may be related to several weeks of dry weather patterns beginning fairly early in the 2012 growing season that lowered the water table and stabilized it to some degree, causing reed canarygrass to decline concurrently with stimulation of native plant species more tolerant of hydrologic conditions.

Figure 4-3: Recovery of sedge meadow vegetation in the floodplain (photograph credit: Jennifer Anderson-Cruz).

In the end, restoring the water balance in the Walnut Creek watershed means returning to a hydrologic system dominated by infiltration and ET. At a plot scale, research indicates that prairie reconstruction is increasing infiltration and reducing stormflow runoff (Qs). Vegetation and water depth controls on ET are being assessed to provide guidance on how best to manage newly established prairie, savanna and sedge meadows against competition from annual crops and non-native perennials.

Restoring Streamflow Hydrology

Discharge in Walnut Creek is currently very flashy as stream stage rises and falls rapidly with every runoff event. Nearly all flood flows are contained within the incised channel, and the hydrograph is dominated by sharp peaks and valleys. This is in contrast to the pre-settlement hydrograph that shows a relatively slow rise and fall with a high baseflow maintained by springs and groundwater (see figure 2-5). Is there progress being made to restore the natural streamflow hydrology in Walnut Creek and its tributaries?

While plot scale studies indicate that prairie reconstruction will help to reduce runoff (Qs), at a watershed scale these small plot scale changes are currently lost against the backdrop of stormflow discharge derived from non-refuge lands. Water delivered to the stream network via runoff and tile drainage from cropland areas is quickly routed to the incised stream system, resulting in flashy stream discharge. Channel incision restricts the discharge to the channel itself with no opportunity for flood flows to escape to the floodplain and dissipate energy. Based on monitoring data collected during the ecological restoration process thus far, there has been no change in streamflow hydrology detected (Schilling et al., 2006). Hence, it would appear that little progress has been made in restoring stream hydrology.

Restoring Groundwater Levels in the Uplands

In the uplands, prairie reconstruction appears to be making progress towards restoring historic groundwater levels. Although largely anecdotal, early settler accounts suggest that water table depths were deeper under native prairie than those measured today. Lower prairie water tables would be consistent with greater ET occurring under perennial grass compared to annual crops. In a study of a chronosequence of prairie plantings and current crop fields, groundwater depths were significantly lower in older reconstructed prairie plantings (1993 and 1994 plantings) compared to younger plantings (2003 and 2004 plantings) and the existing farm field during field sampling conducted in 2007 and 2008 (Schilling and Jacobson, 2010). Groundwater depth decreased from about 0.09 to 0.15 meters per year of the chronosequence, although the trend was not significant during a wet sampling period. Fewer differences in groundwater depth were noted between the new prairie planting and the cropped field compared with the older prairie planting.

Although the average groundwater depth under the reconstructed prairie chronosequence was greater in old plantings compared to new plantings and row crop, this trend was only evident when conditions were dry. During dry periods, roots of established tallgrass prairie plants like big bluestem (*Andropogon geraldii*), little bluestem (*Schizachyrium scoparium*), and Indian grass (*Sorgastrum nutans*) that extend deeper in the soil profile can tap soil water reserves unavailable to shallow rooted vegetation and new prairie plantings. Roots from established tallgrass prairie can directly tap deeper groundwater and deplete deeper soil moisture reserves (Dahlman and Kucera, 1965; Hodnett et al., 1995). Depleting soil moisture reserves would limit the amount of infiltrating precipitation available to recharge the groundwater. In newer prairie plantings less than three years old, isotopic investigation indicated that the prairie plants obtain most of the their water from the upper 20 centimeters of the soil profile, essentially no different from that of corn (Asbjornsen et al., 2007). Hence groundwater depths under newer plantings may more closely resemble current cropped fields than older established prairie sites. When water was plentiful during a wet period, the groundwater depth beneath old and new prairie and cropped systems behaved similarly. This suggests that perhaps only when conditions are dry does the competitive advantage of deeper tallgrass prairie roots particularly reveal itself.

Restoring Groundwater Levels in the Riparian Zone

Incision of Walnut Creek into its floodplain has altered the natural riparian hydrology in the near-stream riparian zone making it difficult to restore floodplain hydrology to pre-settlement conditions. Findings from several studies (Schilling et al., 2004; 2006; in prep.) revealed that channel incision lowers the water table near the stream compared to more distant floodplain areas resulting in unsaturated conditions in the near-stream riparian zone. If channel bed degradation continues in the future, a much greater portion of the floodplain will become unsaturated in the future. On the other hand, if channel incision was arrested and the channel bed began to return to historical conditions, riparian water table levels would increase, and the near-stream riparian zone would become more saturated (Schilling et al., 2004; see figure 3-12). Research conducted at Walnut Creek has largely focused on documenting the effects of channel incision on water levels and quality rather than restoration.

Restoring water table levels in the riparian zone will be difficult. If Walnut Creek is allowed to evolve over time, the channel evolution model (Simon, 1989) predicts that Walnut Creek will widen sufficiently to accommodate bankfull stream flows, and the streambanks will collapse to form stable vegetated banks. Walnut Creek will meander within the new widened channel and form a new floodplain, while the old floodplain will form a floodplain terrace. The “new” floodplain will be connected to the stream stage, but the abandoned floodplain, especially at the terrace edge, will continue to be largely unsaturated. While this picture of floodplain hydrology hardly resembles “pre-settlement,” the evolution of the channel could be considered a natural, albeit slow, process in the context of 150 years of agricultural perturbations. The new floodplain could be populated by pre-settlement vegetation (sedges, wet meadow), whereas the old floodplain terrace could be populated by mesic prairie. The timeframe for restoration of the riparian hydrology using natural stream evolution processes would be on the order of decades to centuries.

Since groundwater depths near Walnut Creek are controlled by stream stage, raising the stage of the creek would also restore water table levels in the riparian zone. We see some evidence for this effect by looking at riparian groundwater levels measured in wells located near the watershed outlet on the studied portion of the stream. Because of a weir installed across Walnut Creek to measure stream discharge and large woody debris present in the channel restricting flows, stream stage is, at times, higher in this downstream reach of the channel compared to other areas. As a result, groundwater levels in riparian wells located in the vicinity of the higher stream stage appear to be higher than observed elsewhere. Water level depths measured over a 2.5-year period were 0.2 to 0.7 meters (0.6 to 2.3 feet) higher than average water table depths observed at seven other riparian well sites (Schilling et al., in prep.).

At other locations in Walnut Creek there is evidence for other temporary base level control by flow constrictions and beaver dams. During the stream reconnaissance studies conducted in 1998, debris dams were found to be blocking the channel and constricting stream flow (Schilling and Wolter, 2000). These flow constrictions are, to varying degrees, capable of backing up stream discharge, creating slackwater pools, and temporarily raising stream stage. Similarly, raising the stream stage with other in-stream structures (pool-riffles structures, low-head dams, etc.) would result in maintaining higher water table levels in the Walnut Creek riparian zone. Allowing base level controls to develop in Walnut Creek either naturally (beaver dams) or artificially (low head dams) could be accomplished or encouraged relatively quickly compared to natural channel evolution (on the order of years rather than decades). Research results indicate that raising stream stage would raise riparian water table levels and re-saturate the floodplain. If this were to occur, floodplain locations further removed from the channel edge would probably become perennially wet and form wetlands and marshes along the bluffs.

Restoring the Stream Network

The stream network lengthened, widened, and incised during post-settlement agricultural intensification such that restoration of the network to pre-settlement conditions is, in all practicality, not possible. The channel length is now defined by an integrated network that primarily originates as tile discharge from grass waterways. While it appears that channel downcutting has largely ceased, stream mapping indicates that the channel has entered a widening phase (Schilling and Wolter, 2000; Schilling et al., 2011). As noted earlier, the Walnut Creek stream channel will continue to evolve over time and eventually form a new channel within a new floodplain.

Channel instability results in streambank erosion and more than 50% of the streambanks in the Walnut Creek watershed are severely eroding. Restoration of eroding streambanks is not being performed by the Service at NSNWR and rightfully so, since restoring or armoring one eroding segment of the channel would not address the underlying cause of the problem and quite possibly make the problem worse somewhere else. Within the refuge boundaries, perennial vegetation planted along the riparian corridor is serving to strengthen streambanks by controlling soil moisture fluctuations and providing soil stability with deeper roots.

Cattle once roamed a large riparian pasture within the southern portion of the refuge acquisition boundary, but the cattle were removed in 2010, and there is evidence that many streambanks in this historically degraded pasture are recovering. Several erosion pins placed in this former pasture to measure streambank erosion rates are now covered with vegetation, and portions of the streambanks are no longer considered severely eroding (Palmer et al., unpublished data). However, bison grazing continues along a tributary stream channel that feeds into Walnut Creek (see figure 1-1). Palmer (2008) observed that nearly 1,400 meters of streambanks located in the bison enclosure were severely eroding, representing 16% of the total bank length.

Overall, the channel network will be difficult to restore to pre-settlement conditions, but continued management of riparian land cover and land use will aid in the recovery. The stream network will continue to evolve over time toward a new equilibrium.

Restoration of Water Quality

Perhaps the greatest improvement in returning to pre-settlement conditions has been restoring aspects of water quality, particularly nitrate.

Nitrate

Nitrate concentration reductions have been observed at the plot scale and watershed scale in the Walnut Creek basin, representing the most observable improvement in hydrology associated with NSNWR. At a plot scale, the effects of prairie reconstruction on subsurface water quality have been measured at a single site and across a chronosequence of prairie plantings. Soil-water and groundwater monitoring during six years of prairie reconstruction within a single catchment (Cabbage site) showed NO_3-N concentrations declining within five years of planting (Tomer et al., 2011). A lagged response was observed and this response varied by landscape position. Along drainageways, non-detectable NO_3-N concentrations dominated within three years, but in upland areas, it took five years for NO_3-N concentrations to stabilize near two milligrams per liter.

In a study of a 13-year reconstructed prairie chronosequence, groundwater NO_3-N and chloride concentrations significantly decreased with time since prairie planting (Schilling and Jacobson, 2010). Nitrate concentrations were observed to decrease approximately 0.6 milligrams/liter per year since planting across the chronosequence, but the rate of NO_3-N concentration reduction measured in the basin-wide chronosequence study was less than that measured in the single field. This comparison attests to the variability that exists within agricultural starting points prior to reconstruction. Variations in historical land use and land cover and fertilizer and manure management history add complications for comparing nitrate concentrations across the chronosequence. Additional soil-water sampling beneath the chronosequence further suggests that prairie reconstruction may be affecting nitrogen (N) concentrations in soil-water more rapidly than water observed in shallow soil or in groundwater. (Schilling et al., 2010). This probably is due to higher rates of microbial metabolism in organically rich root zone relative to the groundwater present in the loess.

Additional impacts of prairie reconstruction have been observed during several synoptic sampling events. Synoptic sampling conducted in Walnut and Squaw Creek watersheds on two occasions in 1999 (Schilling and Wolter, 2001; Schilling, 2001) and 2001 (Schilling, 2002) indicated that the refuge is having a major impact on nitrate concentration patterns. In 1999, a baseflow survey of 81 tributary creeks and tiles showed major differences in pollutant loading rates within the Walnut Creek watershed. Concentrations of nitrate and chloride were lowest in creeks and tiles draining reconstructed prairie areas (<1 and <3 milligrams/liter, respectively) compared to concentrations of water draining row crop areas (>10 and >12 milligrams/liter, respectively). Results indicated that nine headwater areas consisting of 90% row crop contributed more than half the total nitrate export from the watershed while comprising only one-third of the land area (Schilling, 2001). A second synoptic survey in 2001 that included both Walnut Creek and Squaw Creek watersheds revealed that water flowing from prairie reconstructions in the interior watershed of Walnut Creek had substantially lower nitrate and chloride concentrations than water flowing from cropped portions of Squaw Creek and upper Walnut Creek watersheds (Schilling, 2002). Furthermore, the study completed during an October 2001 low flow period indicated that nitrate concentrations at that time decreased from upstream to downstream locations in Walnut Creek but increased in heavily cropped Squaw Creek watershed. Data from both synoptic surveys show that the portion of the Walnut Creek watershed containing the refuge clearly contributed less nitrate and chloride loads to the watershed.

Effects of prairie reconstruction are also observed at the watershed scale, although the effects at the larger scale are less easily detected. Results from the 10-year watershed monitoring project (Schilling et al., 2006; Schilling and Spooner, 2006) indicated that planting 25.4% of the Walnut Creek watershed in native prairie resulted in a reduction of nitrate of approximately 1.2 milligrams/liter over 10 years in the main stream (table 4-1). In subbasins where land use changes comprised a greater proportion of the watershed area, nitrate concentrations decreased as much as 3.4 milligrams/liter in 10 years. Evidence from chemical loads support less nitrate contribution to streamflow from the lower portion of the Walnut Creek watershed containing the refuge (Schilling, 2002). Losses of nitrate and chloride were substantially less in the lower Walnut Creek watershed than in the upper Walnut Creek watershed and Squaw Creek watershed. Nitrate reductions are thought to be the result of several factors, including reduced water and nitrate flux through the soil under perennial cover compared to row crop systems, reduced fertilizer N inputs on refuge-owned croplands, and reduced overland flow N contributions during runoff events (Schilling and Spooner, 2006; Schilling and Jacobson, 2010).

Table 4-1: Comparison of nitrate concentration reductions measured at different scales. Note that concentration decreases are greater at smaller scales.

Scale of Monitoring	Area (ha)	Model type	NO3-N decrease per year (milligrams [mg]/liter [l] per year)	NO3-N concentration after 10 years if starting at 15 mg/l
Watershed	5218	linear	-0.12	13.8
Subbasin	201-795	linear	-0.12 to -0.34	13.8 to 11.6
Plot[a]	7	linear	-1.9	<1
Chronosequence[b]	<10 (each plot)	linear	-0.58	9.2
		Exponential	$e^{-0.23}$	1.5

[a]Single upland monitoring site (Tomer et al., 2011).
[b]Plot scale sites sampled across chronosequence within watershed (Schilling and Jacobson, 2010).

The fact that watershed scale reductions were not as high as anticipated sheds light on the difficulty of detecting nitrate concentrations changes in predominantly agricultural watersheds. Upstream contributions from tile-drained, row crop areas have a significant effect on downstream water quality. Prairie reconstruction occurring in the core of the watershed is primarily diluting upstream nitrate contributions. Furthermore, the time needed for observing water quality change is largely governed by the hydrogeology of the watersheds. Since nitrate leached from soils moves with shallow groundwater to discharge to streams, slow groundwater flow velocities in the watershed limit speed of the contributions from upland prairie reconstructions to stream water improvement. The timeframe needed for detecting groundwater quality improvements from prairie reconstructions was evaluated using a Geographic Information System (GIS)-based hydrologic model (Schilling and Wolter, 2007). Results suggested that groundwater from only half of the prairie plantings reached the stream in the 10 years of surface water monitoring. The proportion of land in the watershed with prairie groundwater reaching the stream (11%) was similar to the measured reduction of stream nitrate (14.8%). In subbasins, groundwater from 60 to 74% of the prairie plantings reached the stream network, consistent with greater measured stream nitrate reductions. The proportion of subbasin land area with reconstructed prairie groundwater reaching the stream (10 to 22%) was also similar to measured nitrate decrease (11 to 29%). This research indicates that effects of prairie reconstruction on water quality will likely continue in the foreseeable future as more low-nitrate groundwater beneath prairie plantings reach the stream network.

Along the stream corridor, research is showing that perennial vegetation reduces the potential for nitrate leaching near the incised Walnut Creek channel (Schilling, 2009; Schilling and Jacobson, in prep.). As noted earlier, riparian water tables near incised streams are deeper than the surrounding floodplain. Deeper water tables expose nutrient rich Holocene alluvium to aerobic conditions and create conditions favorable for nitrate leaching. During occasions when overlying vegetation has been removed, nitrate concentrations in the near-stream riparian zone of Walnut Creek have exceeded 20 milligrams/liter while concentrations in the floodplain remained less than 0.5 milligrams/liter (Schilling et al., 2006; Schilling and Jacobson, 2008). Recent groundwater sampling of riparian wells installed one meter, 20 meters and 40 meters from an incised channel under four replicated land covers (cool season grass, warm season grass, woods, pasture) indicates that maintaining perennial vegetation in the stream riparian zone prevents nitrate mineralization or leaching (Schilling and Jacobson, in prep.). Research is showing that while deeper water tables near the channel edge have high dissolved oxygen (DO) and oxidation-reduction potential (ORP) levels, perennial vegetation is serving to keep riparian nitrate concentrations low. We know from early studies that when the perennial cover was removed, riparian soils are capable of generating nitrate concentrations from 20–40 milligrams/liter in riparian groundwater (Schilling et al., 2006; Schilling and Jacobson, 2008). When perennial vegetation covers the nutrient rich alluvial soils, infiltrating soil water is captured by soil moisture reserves, and excess N is scavenged by plant roots in the vadose zone.

Overall, nitrate concentrations are being impacted by prairie reconstruction at NSNWR. Groundwater concentrations are being lowered beneath upland prairie plantings and beginning to impact surface water concentrations measured at the watershed scale. Along the stream corridor, nitrate concentrations are being kept low by perennial vegetation that scavenges excess water and nitrate delivered in groundwater recharge.

Phosphorus

Phosphorus (P) is primarily transported to streams with surface water runoff, so reducing runoff with prairie reconstruction should reduce P concentrations over time. However, P concentrations in Walnut Creek and three tributaries did not show evidence for water quality changes during a five-year monitoring program (2000 to 2005; Schilling et al., 2006). One possible reason for the lack of detection of P concentrations improvements may have been inadequate sampling design that failed to characterize the episodic transport of P (Schilling et al., 2006).

In contrast to NO_3-N, groundwater P concentrations show little evidence of improvement due to prairie reconstruction, which may reflect the legacy of long-term agriculture. In this way, detecting improvements in P concentrations is challenged in the same way as sediment. In groundwater sampling across the reconstructed prairie chronosequence, P concentrations ranged from <0.001 to 0.671 milligrams/liter and averaged 0.063 milligrams/liter in 107 groundwater samples. Concentrations did not show any statistically significant differences in groundwater beneath prairie sites (Schilling and Jacobson, 2010). Similarly, groundwater sampling at a single site (Cabbage site) showed no detectable trends in P concentrations measured five years after prairie planting (Tomer et al., 2011). Concentrations were higher in footslope landscape positions than uplands, due, in part, to the history of sediment deposition along the drainageways that provides a supply of soil P that could leach into shallow groundwater at these positions.

Across the Walnut Creek floodplain, P concentrations in alluvium ranged from less than 0.1 milligrams/liter to 1.42 milligrams/liter, but most concentrations were less than 0.3 milligrams/liter (Schilling and Jacobson, 2008). No systematic variation in P concentrations was detected in wells installed in the Roberts Creek and Gunder and pre-Gunder alluvium. In general, P levels in alluvial units (0.16 to 0.29 milligrams/liter) were higher than concentrations measured in upland wells (0.04 milligrams/liter) and in surface water (0.1 milligrams/liter). P concentrations were higher under grazed pasture and lowest under riparian woods but do not appear to be impacted by channel incision (Schilling and Jacobson, in prep.).

Overall, P concentrations show minimal effect relative to prairie reconstruction thus far at NSNWR.

Sediment

By reducing surface water runoff and increasing infiltration, prairie reconstruction should result in decreasing sediment transport from the Walnut Creek watershed. Recent monitoring and modeling suggest that sediment reductions are likely occurring in some locations. In small upland catchments, the average annual sediment export from two 100% prairie watersheds (Cabbage site) was significantly less (0.24 Megagrams per hectare or 0.11 tons per acre) than sediment export from 100% cropped catchments (8.11 Megagrams/hectare or 3.6 tons/acre) (Helmers et al., 2011). Visual evidence for reduced sediment transport from reconstructed prairie watersheds is stunning (figure 4-4). Even cropped catchments with 10 to 20% reconstructed prairie placed as filter strips have substantially reduced sediment transport (0.26 to 0.47 Megagrams/hectare or 0.11 to 0.21 tons/acre) (Helmers et al., 2011).

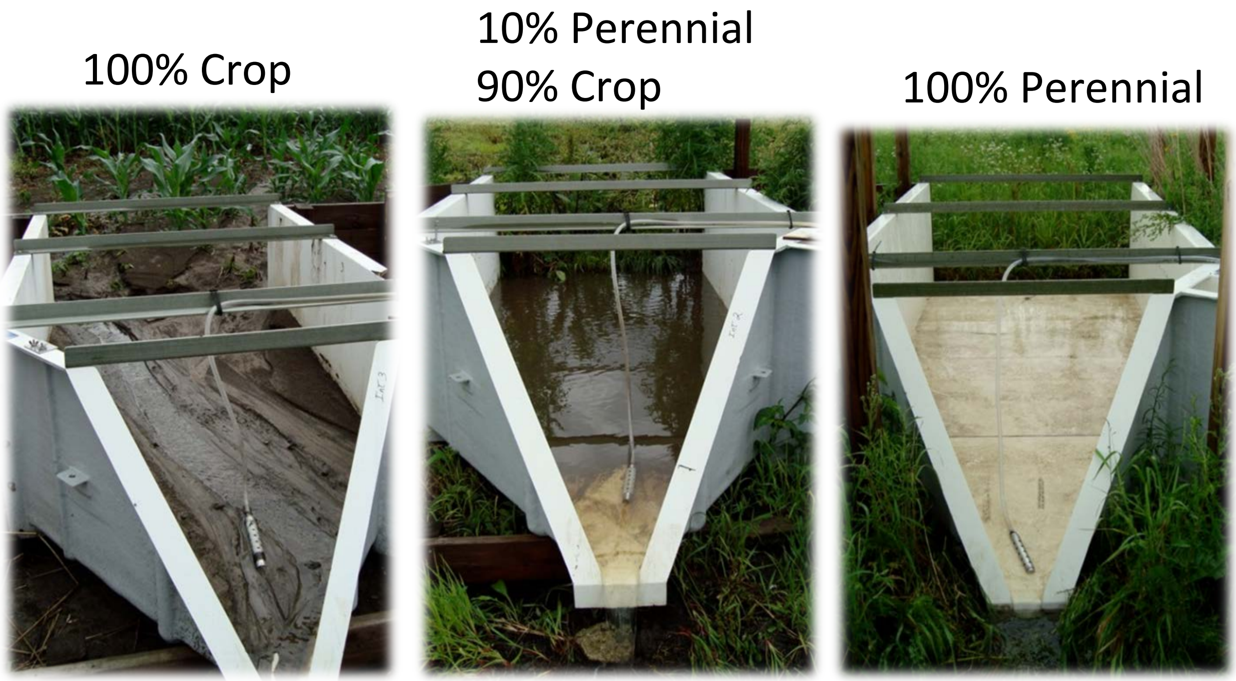


Figure 4-4: Visual examples of sediment loss from three small catchments in Walnut Creek watershed after a four-inch rainfall event in June 2008. The 10% perennial catchment had reconstructed prairie planted at the catchment outlet.

At a watershed scale, the Revised Universal Soil Loss Equation (RUSLE) was used to estimate the changes in gross sediment erosion occurring in Walnut Creek watershed from 1990 to 2005 resulting from prairie reconstruction at NSNWR (Schilling et al., 2006; Schilling et al., 2011). The RUSLE model is a method for calculating the average sheet and rill erosion under specified conditions and was developed by the U.S. Department of Agriculture. The GIS-based model calculated the erosion rate for a 30-meter grid cell using the 1990 and 2005 land cover grids, the Iowa Soil Properties and Interpretations Database soil grid and the Natural Resource Conservation Service Rainfall Erosion Index. It should be noted that results from the RUSLE model represent total annual gross erosion from the watershed and does not account for actual sediment delivery to a stream. Sediment erosion modeling suggested that land use changes in upland areas of Walnut Creek watersheds have affected sediment erosion potential. In Walnut Creek watershed, the RUSLE model predicted that 35,871 tons of sediment eroded from the landscape in 1990 prior to NSNWR establishment. By 2005, following conversion of 23.5% of the landscape to native prairie, total gross erosion in the watershed was reduced to 22,591 tons. Thus, prairie reconstruction reduced gross sediment erosion by 13,279 tons, or 37% between 1990 and 2005. Combined, the catchment monitoring results and watershed scale modeling suggest prairie reconstruction is reducing sediment transport in Walnut Creek watershed.

However, we have not been able to detect reductions in sediment transport at the watershed outlet. For a 10-year period (1995 to 2005), daily suspended sediment concentrations and loads in Walnut Creek were monitored as land use changes were implemented at NSNWR, but no significant changes in sediment export at the watershed outlet were detected (Schilling et al., 2006). Sediment contributions from streambanks and beds appear to be responsible for the lack of detectable improvements. Hence, while data suggest that prairie reconstruction is reducing upland sheet and rill erosion in the watershed, flashy stream discharge in the incised channel continues to erode streambank and bed materials. Only by reducing stream power within Walnut Creek and its tributaries, either by reducing water discharge or energy slope, will sediment export from the watershed be reduced over the long-term. Prairie reconstruction is assisting with this, but contributions from artificial subsurface drainage within headwater areas and runoff from the steeply sloping pre-Illinoian glacial landscape will continue to deliver water to the incised channel at rates that will continue to erode streambanks. Once water is delivered to the channel, the incised banks are particularly vulnerable to collapse with rapidly rising and falling stream stage and poor soil structure in the exposed banks. Research is indicating that a lag time of decades may be needed to detect changes in sediment export resulting from prairie reconstruction in order to overcome variable climate and historical sediment storage.

Overall, prairie reconstruction is reducing sediment loss in areas where prairie has been planted, but at a watershed scale, these reductions are being overwhelmed by sediment contributions from other sources.

Summary of Progress Made Toward Restoring Hydrologic Processes

The impacts of prairie reconstruction at NSNWR on key hydrologic processes in the Walnut Creek watershed are mixed and, for the most part, underwhelming given the amount of land use change that has occurred. Of the major hydrologic processes discussed in this report (water balance, streamflow hydrology, groundwater, stream network, and water quality) it is evident that there remains a gulf between the current state of hydrologic restoration at NSNWR and the goal of returning the watershed to a closer approximation of pre-settlement conditions. However, there is measurable progress being made in restoring key hydrologic processes in some areas, a hint of progress in other areas, and no observable progress in restoring several key hydrologic attributes (table 4-2).

Table 4-2: Degree of progress being made toward restoration of key hydrologic processes at the NSNWR.

No progress	Hint of progress	Measureable progress
Decrease Qs (watershed)	Increase ET	Increase infiltration
Restore hydrograph	Decrease Qb	Decrease Qs (plot scale)
Reduce channel length	Increase %Qb	Groundwater depth (uplands)
Reconnect channel with floodplain	Channel morphology (widening phase)	Reduce nitrate concentrations (plot scale)
Groundwater depth (riparian zone)		Reduce nitrate concentrations (watershed scale)
Reduce P concentrations (watershed scale)		Reduce P concentrations (plot scale)
Reduce sediment export (watershed scale)		Reduce sediment export (plot scale)

Qb = stream baseflow, Qs = stormflow runoff, %Qb = percentage of streamflow as baseflow

Research performed over the last few years has documented increasing infiltration, deeper water tables, and reduced pollutant discharge in plot scale studies conducted in upland areas. However, while nitrate concentrations are decreasing at the watershed scale, no other pollutant reductions have been observed at larger scales. We have observed indirect evidence (i.e., hints of progress) that prairie reconstruction is changing the water balance at NSNWR, inasmuch as less baseflow and greater baseflow percentage has been observed in the lower Walnut Creek watershed containing the reconstructed prairie. Indirect evidence is also suggesting that perennial vegetation, including prairie and savanna, have greater ET and use groundwater differently than crop systems. Where perennial vegetation has remained in place or has replaced crops, less deep drainage and nitrate leaching has occurred. Although the channel of Walnut Creek remains highly disturbed, it has entered a widening phase that will eventually lead it to recovery.

No measurable progress has been observed in some key hydrologic processes (table 4-2). At a watershed scale, the hydrograph remains very flashy and dominated by stormflow runoff events. Relatedly, the channel of Walnut Creek continues to be incised and considerably longer than it was during pre-settlement. Channel incision and extensive aggradation has left the floodplain disconnected from the channel and resulted in substantial dewatering of riparian groundwater. Unless the relationship of the channel to the floodplain changes, and there is no evidence for this using current management strategies, the hydrograph and channel will continue to reflect post-settlement disturbances. Due to the lack of progress in restoring channel conditions and runoff hydrology, export of pollutants carried with stormflow discharge is also not improving. Despite reduced sediment and P transport measured in upland plots, flashy discharge will continue to erode these pollutants from streambank and bed materials, and no progress will be made in reducing overall watershed scale export until streamflows are reduced. Hence, the lack of progress being made toward restoring hydrologic processes is primarily confined to the main channel and tributaries.

We can look closer at the degree of hydrologic restoration by examining how the degree of progress varies based on spatial scale of evaluation, landscape position, and, in the case of water quality, pollutant type. Each of these factors is described below.

Scale of Ecological Restoration

Research at NSNWR indicates that the hydrologic effects of ecological restoration are more easily observed at small spatial scales compared to a larger watershed scale (figure 4-5). At the individual plot or field scale, or a small ephemeral catchment (Science-based Trials of Rowcrops Integrated with Prairies or STRIPs project), progress toward hydrologic restoration is being observed. At a small-scale, prairie reconstruction has been shown to reduce surface water runoff, increase infiltration, lower groundwater levels, and reduce nitrate concentrations and sediment export. All of these improvements are observed at the Cabbage site, which is serving as a 100% prairie reconstruction for the STRIPs project. In fact, if this was the scale of ecological restoration at NSNWR, it would be justifiable to consider the hydrologic restoration approaching pre-settlement. However, NSNWR is much larger than a single field, and the degree of restoration of hydrologic processes decreases substantially at a larger and larger watershed scale. Although research has not focused much at a subbasin scale, we do observe greater reduction of nitrate concentrations compared to the larger watershed. At the scale of the entire Walnut Creek basin, with the exception of decreasing nitrate concentrations, we have not observed improvements in restoring hydrologic processes.

Several factors account for the challenges involved with observing hydrologic improvements at the watershed scale. First, the legacy of historical agriculture intensification left a long-lasting imprint on the watershed hydrology. Land use patterns changed to annual crops, drainageways were tile drained, streams were channelized and straightened, and soil erosion left low areas blanketed by post-settlement alluvium. All of these legacy effects are present within the entire watershed but may be limited in isolated fields or catchments. This makes the case for strategically planning management actions to achieve the greatest cumulative benefit.

Second, NSNWR does not encompass the entire watershed so water and pollutants derived from non-refuge land are a continuing source of inputs. For example, nearly all first-order streams originate in the watershed at a tile outlet draining a grass waterway. Rather than low, marshy areas slowly releasing groundwater to streams during pre-settlement times, tile water and overland runoff from crop areas contribute to higher and flashier streamflows. Evidence from the chemical load data, two synoptic surveys, and the 10-year monitoring program indicate that headwater regions in Walnut Creek watershed dominate the nitrate concentrations at the watershed outlet. Once delivered to the stream network from row crop-dominated headwater regions, pollutants are diluted by the downstream watershed area containing the reconstructed prairie. Finally, simply the amount of land area planted to prairie is probably insufficient to change hydrologic conditions at a watershed scale. Small scale improvements at the field or catchment scale are lost against the noise of hydrologic signals generated in the remainder of the basin. For example, variable precipitation occurring in the basin will obscure detection of subtle hydrologic trends. We see this in trying to measure changes in suspended sediment transport against variable climate patterns. Regardless of the mechanism, we observe major difficulties in scaling up hydrologic improvement observed at the field or catchment scale to the third-order watershed.

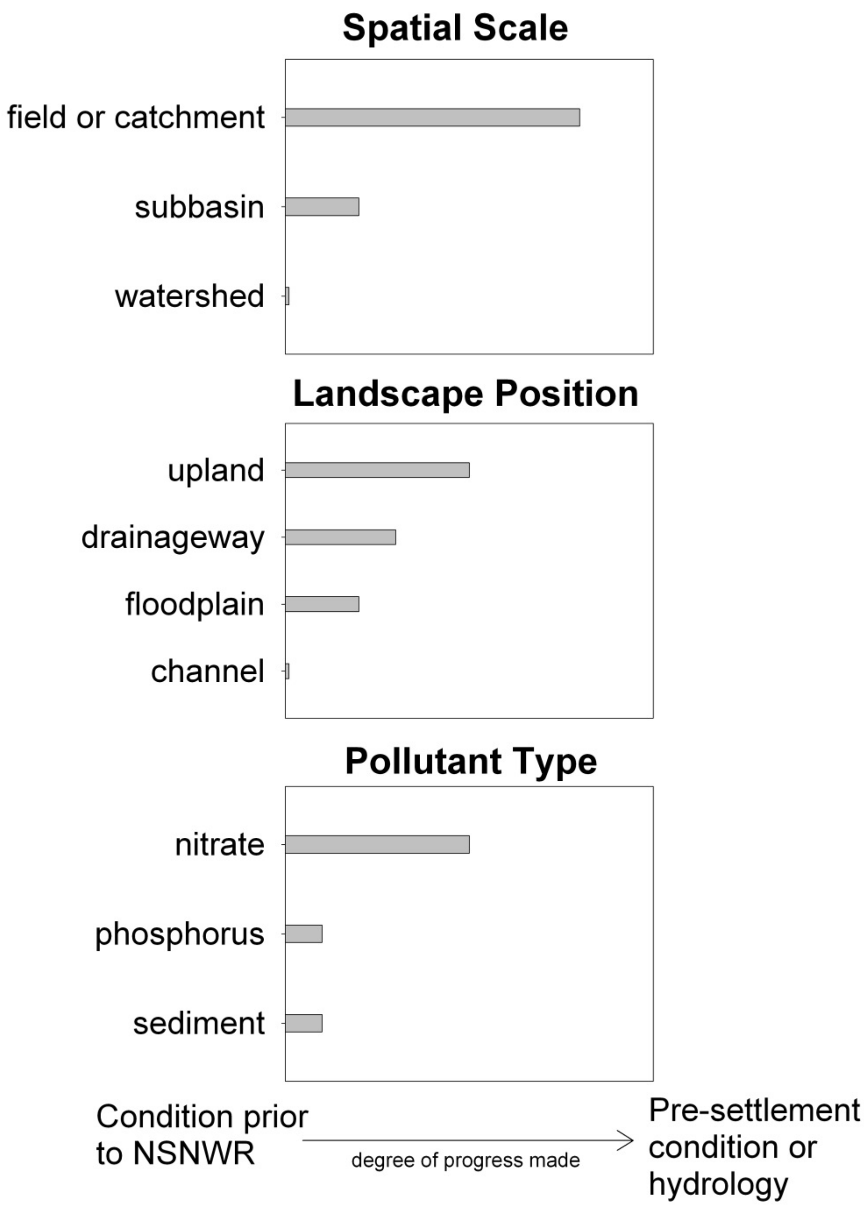


Figure 4-5: Summary of progress being made toward restoring hydrology to pre-settlement conditions specifically related to three key attributes. At what scale is progress being made (top panel)? Where on the landscape are changes being seen (middle panel)? What pollutant type is responding more readily to hydrologic improvements (lower panel)? The degree of progress attempts to be independent of other factors.

Landscape Position

If we consider where hydrologic improvements due to prairie reconstruction are most readily observed, uplands offer a much greater opportunity for restoring hydrologic processes than drainageways, floodplains, and the channel (figure 4-5). Upland areas are dominated by infiltration and groundwater recharge, and research has shown that prairie reconstruction is making changes in these processes. In the uplands, groundwater levels are deeper under reconstructed prairie plots where deep rooted vegetation is tapping deeper groundwater reserves and showing greater plasticity to accommodate water table fluctuations. Nitrate concentrations are also decreasing beneath reconstructed prairie in upland areas where downward percolation of soluble nitrate is being captured.

In contrast, it will be more difficult to restore hydrologic processes in the drainageways, floodplains, and the channel. Drainageways are commonly tile-drained, and accumulated sediment stored in them is contributing to high concentrations of P in alluvial groundwater. Floodplains are also storing sediment derived from upland soils and overbank deposition, which is a continuing source of sediment and P to streams and groundwater. Near the stream, riparian water table levels are deeper near the incised Walnut Creek stream channel, and groundwater hydrology has been severely impacted. In this area, restoration of pre-settlement hydrology will not be possible unless the channel is reconnected to the floodplain or stream stage increases. On the positive side, by planting and maintaining perennials in the drainageways and floodplains, NSNWR is improving the water balance by reducing concentrated overland flow and increasing water infiltration. Soil infiltration rates beneath reconstructed prairie were highest in footslope landscape positions. Thus restoration of drainageways and floodplains may be the key to watershed scale hydrologic change.

Perhaps the most challenging for restoration will be the Walnut Creek channel. The channel has integrated the accumulated legacy of historical changes that have occurred throughout the basin and has been completely altered from pre-settlement condition. The channel is now deeper, wider, straighter, and more prone to bank and bed erosion than at any time in its post-settlement history, and it will take more time for a return to pre-settlement hydrology than any other landscape position. The channel will not return to a pre-settlement equilibrium until sometime after hydrologic changes are fully implemented throughout the watershed.

Pollutant Type

Nitrate concentrations in groundwater and surface water baseflow have been the most receptive to progress toward approximating the pre-settlement conditions (figure 4-5). Beneath reconstructed prairies, nitrate concentrations are decreasing by about 0.5–1.5 milligrams/liter per year since prairie planting and have shown concentrations less than 0.5 milligrams/liter after a decade or so. Given sufficient time for impacted groundwater to flow to the streams, baseflow delivery of nitrate to streams is also decreasing, although as noted above, these improvements are more easily detected in smaller basins. Nitrate concentrations have also been shown to be susceptible to denitrification occurring in the organic-rich Holocene alluvium in the drainageways and floodplains. While nitrate concentrations remain high in areas overlain by row crops, reconstructed prairie locations are decreasing substantially to levels approaching pre-settlement conditions (<0.5 milligrams/liter).

Although sediment transport (and presumably sediment-bound P as well) is being reduced in reconstructed prairie areas, improvements in P and sediment concentrations and loads have not been observed at the watershed scale due to legacy effects and altered streamflow hydrology. Streamflow discharge will continue to erode streambank and bed sediments and deliver downstream P and sediment loads until the stream hydrology becomes less flashy and the stream channel is reconnected to its floodplain. Observing changes in water quality in Walnut Creek will probably be limited to nitrate concentrations for the long-term.

Timeframe for Hydrologic Restoration

Hydrologic research conducted at NSNWR over the last two decades clearly demonstrates that restoring hydrologic processes in the Walnut Creek watershed will take a long time. But, how far along is the hydrologic restoration at NSNWR located relative to pre-settlement hydrology? The timeframe for restoration can follow several different trajectories but we highlight four different conceptual models (figure 4-6). These models are idealistic representations of how the pace of hydrologic restoration may vary with time. Ultimately, the goal of the restoration is to approximate as nearly as possible, the pre-settlement condition so we consider this goal to be "100%" in the models. The models assume that the Neal Smith Refuge continues on its current rate of ecological restoration activities within the congressionally-approved acquisition boundary (8,654 acres; see figure 1-1). By 2005, 3,023 acres of prairie were planted, representing about 35% of the total acquisition limit. Using a planting rate of about 220 acres per year (Schilling et al., 2006), it will take approximately 25 more years of active reconstruction to plant the entire area within the final acquisition boundary to native prairie. Given the rate of reconstruction and the starting year of 1992 for the initial reconstruction plot, planting within the acquisition goal boundary could be achieved in approximately 40 years (year 2032). Of course, this scenario is unrealistic since there are numerous uncertainties in purchasing remaining lands within the boundary and managing new plantings with current appropriations. Nonetheless, the benchmark of 40 years gives us a target timeframe to evaluate the future trajectory of ecological restoration.

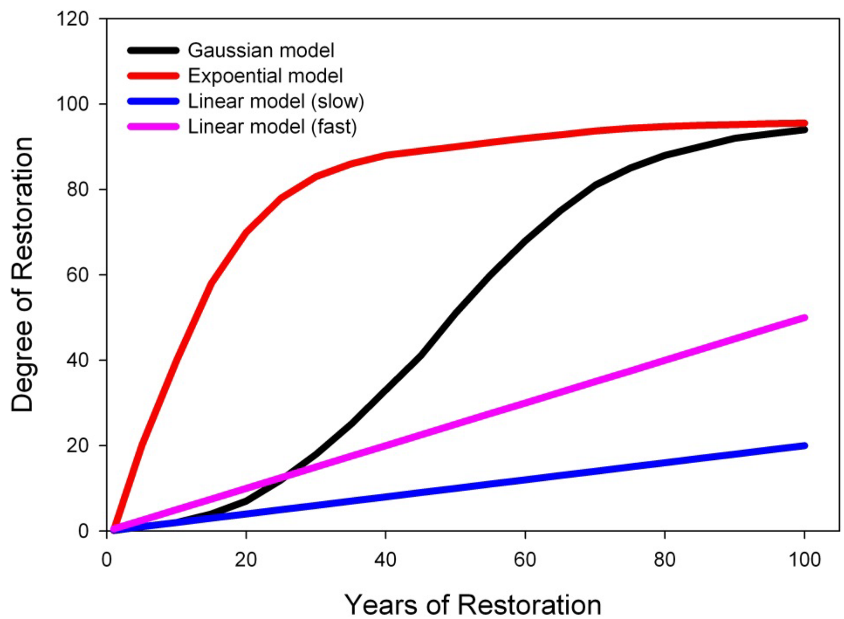


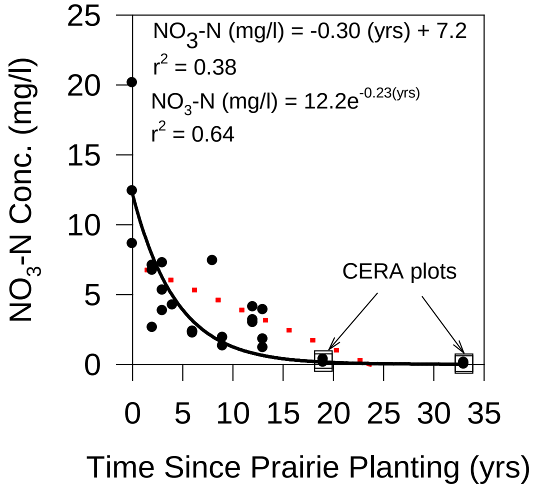
Figure 4-6: Hypothetical trajectories for restoring hydrological processes at Neal Smith National Wildlife Refuge. See text for explanation of the assumptions and details regarding each curve.

In a simple linear model of ecological restoration, the progress made toward restoring hydrology will continue to occur slowly and incrementally over time. In figure 4-6, there are two linear models shown that span a range of possible restoration trajectories, a slow rate and a faster rate. The slow rate argues that hydrologic changes occurring at NSNWR are making little progress toward restoring pre-settlement hydrology, and that after 20 years of restoration, we are no better than 4% of the way toward our final goal. After 40 years of prairie reconstruction, watershed hydrology may be restored to about 8% of the pre-settlement condition. The slow linear rate of reconstruction will continue in the future as watershed hydrology adjusts to additional prairie plantings. A century after the first prairie planting at Neal Smith, watershed hydrology may be returned to 20% of its pre-settlement condition.

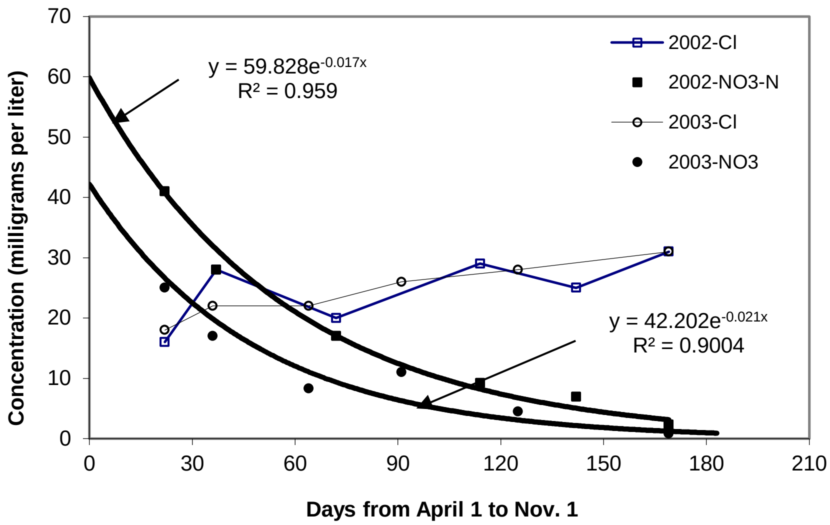
In the faster linear model, we assume that the planting rate has doubled to over 440 acres per year, and the entire acquisition boundary would be planted in about 12 years. We would expect the trajectory of reconstruction to change as well, with a faster rate of reconstruction resulting a more time available for the hydrology to adjust in later years. After 70 years of hydrologic adjustment, the linear model would predict hydrologic restoration to be at 50% of the pre-settlement condition.

Based on research conducted to date, the linear models seem to apply best to the watershed scale reconstruction effort. We have not seen much progress made on a watershed scale or within the stream channel in shifting toward the historic hydrologic condition. The lack of progress can be traced, in part, to the location of NSNWR in the central core of the Walnut Creek watershed. The current refuge boundary and the future acquisition area do not include any headwater areas of the watershed, so even complete restoration of the acquisition area will not eliminate the overriding influence of headwater regions on watershed scale hydrology. Stream discharge will continue to be dominated by flows originating by cropped and tile-drained headwater areas, and this stream discharge will continue to slow channel recovery. Nitrate concentrations discharged from tiles and sediment and P eroded from streambanks will confound detection of progress being made to restore pollutant levels. Because of the lack of headwater control in the watershed, prairie reconstruction occurring in the core of the watershed at NSNWR will only serve to slowly dilute concentrations from upstream areas and reduce area-weighted discharge. Recovery to a closer pre-settlement approximation of hydrologic conditions will be slow and gradual (i.e., linear model) without removing the hydrologic influence of headwater areas. The unaltered flow regime of the headwaters of the watershed will also have impacts on riparian processes that will always remain.

The exponential and Gaussian models of restoration do not assume a linear response of hydrologic recovery to ecological restoration. In the exponential model, hydrologic recovery occurs quickly after prairie is planted, with the hydrologic recovery tapering off with additional time. Based on two decades of research in the Walnut Creek watershed, this model does not appear to be applicable to the scale of the entire basin. Although the model might predict a 70% recovery after 20 years, we remain a long way from approximating pre-settlement hydrology in the watershed. However, a case could be made that the general shape of the model might be appropriate at the scale of a plot. For example, simply establishing prairie strips within cropped basins resulted in a 96% reduction in sediment transport within a four-year period (Helmers et al., 2011). The 100% prairie catchment (Cabbage site) resulted in nearly a 50% reduction in annual runoff less than a decade after planting. We speculate that in upland catchments, a rapid change in runoff hydrology (Qs) and runoff-delivered pollutants may occur soon after prairie planting is established in formerly cropped fields. An exponential model also describes decreasing nitrate concentrations observed in groundwater. Across the reconstructed prairie chronosequence, nitrate was observed to decrease exponentially with time since prairie planting (figure 4-7; Schilling and Jacobson, 2010). Nitrate concentrations in groundwater were also observed to decrease exponentially following fertilizer application on drainageway soils (figure 4-7; Schilling et al., 2007) and in floodplain sediments following flooding (Schilling et al., 2006). While nitrate concentrations followed an exponential decay at the plot scale they were not evident at the watershed scale.



Comparison of trend lines fitted through chronosequence plots with a linear and exponential model using NSNWR data and chronosequence plots from restored prairie plots (Conrad Environmental Research Area or CERA) near Grinnell, Iowa (from Schilling and Jacobson, 2010)



Observed nitrate decay in monitoring well D-4S located in drainageway during 2002 and 2003. Chloride concentrations are shown as a conservation-ion reference (after Schilling et al., 2007)

Figure 4-7: Exponential decrease in plot scale nitrate concentrations observed in chronosequence study (top) and in drainageway soils at the Cabbage site (bottom).

The Gaussian model predicts that while hydrologic changes may be slow at first, the rate of hydrologic restoration will increase substantially in later years and then slow over time. At this point in the hydrologic restoration at NSNWR, we do not know if we are on a Gaussian trajectory, but we do know that changes have been difficult to detect. The trajectory of the model would lead us to believe that after two decades of watershed scale restoration we have progressed little toward hydrologic restoration. However, within the next few decades, the model would predict that the rate of hydrologic restoration will increase greatly. After 50 years, the Gaussian model predicts that watershed hydrology may have returned to 50% of the pre-settlement condition, and after 100 years, the entire watershed may be approaching 95% restoration.

The Gaussian trajectory toward hydrologic restoration is appealing because while changes may be discouragingly slow initially, we might be able to expect substantially greater progress in the next few decades. We suspect that changes in the water balance may become more evident in the future as increasing ET beneath reconstructed prairie reduces water levels and increases soil moisture storage. As prairie restoration expands and matures, we would expect greater influence on water and nutrient export. Reduced water export from reconstructed prairie areas will reduce water and pollutant delivery to streams. At some point, a threshold amount of reconstructed matured prairie may be reached that may result in a non-linear change in watershed scale hydrology. While nitrate concentrations are slowly decreasing at the watershed and subbasin scale, travel time analyses suggest that future changes may be more pronounced as low nitrate groundwater from upland locations arrives at the stream network (Schilling and Wolter, 2007). Given the slow groundwater flow velocities in the watershed, it will take time for changes in subsurface flow and concentrations to manifest themselves in watershed scale export.

Each of the three conceptual models of restoration timeframes appear to apply to certain aspects of the hydrologic restoration. The linear model appears to best describe the trajectory of watershed scale restoration. The current pace of prairie reconstruction may be the best predictor for future changes, in which case, we suspect that the degree of hydrologic restoration will continue slowly, determined in part, by the overriding influence of row cropped headwater areas. The exponential model appears to describe hydrologic changes that occur beneath a single plot or in a single first-order catchment. Hydrologic changes appear to be rapid following planting compared to hydrologic conditions in row cropped fields. However, these exponential changes in hydrology are lost in the watershed scale perspective. The Gaussian model attempts to bridge the linear and exponential differences by describing a condition where hydrologic progress may be slow at first, but when a critical threshold is reached, widespread hydrologic progress is observed. It is unknown whether ecological restoration throughout the entire acquisition boundary will be enough critical mass to result in rapid progress made toward pre-settlement hydrology.

Overall, the timeframe for hydrologic restoration in a single plot may be less than a decade, but the timeframe for restoration of the watershed hydrology will be at least a century or longer unless control of important headwater areas is obtained. Hydrologic restoration of the entire watershed will be slow and gradual over time as current prairie plantings mature and more areas are planted in the future.

Chapter 5: Lessons Learned from Hydrologic Monitoring

Presented here are lessons learned resulting from two decades of conducting hydrological research at Neal Smith National Wildlife Refuge (NSNWR, refuge) in the Walnut Creek watershed.

It is important for ecological restorations to address hydrology. Restoring the hydrology of the Walnut Creek watershed is the key piece needed to restore the land to approximate pre-settlement conditions. Pre-settlement hydrology was based on rainfall infiltration and evapotranspiration, but post-settlement hydrology became focused on shedding water from the landscape. Returning the landscape to an infiltration-based system will enable marshy wet meadows to return to the upland drainageways and floodplain, and streams to return to consistent baseflow and clear, high quality water. Restoring the water balance and streamflow hydrograph will have cascading effects on restoration of native prairie flora and fauna throughout the watershed. Reconstruction of plant communities and restoration of hydrology is synergistic. Diverse, conservative plantings affect the water table and contribute to a more natural hydrology. Likewise, more natural hydrology contributes to greater ecological restoration potential.

Monitoring hydrologic restoration is best suited at the plot or catchment scale. Improvements in hydrology have been difficult to detect and measure at the watershed scale, but hydrologic changes have been observed in small plots and first-order catchments within a few years. Detecting hydrologic changes in small plots or catchments may provide the incentive needed to pursue making similar hydrologic improvements elsewhere. Since these small plots or catchments comprise part of larger and larger watershed areas, the cumulative effects of hydrologic restoration will have an increasing downstream impact. Demonstrating that hydrologic systems can be restored at a small-scale is important information for selling the idea of ecological restoration and prairie reconstruction to other stakeholders.

Headwater areas must be restored before hydrologic conditions in downstream areas are restorable. Lack of headwater control in the Walnut Creek watershed has probably been the largest factor contributing to the lack of hydrologic improvements observed at the watershed scale. Since flows and pollutant loads originate in headwater areas, downstream areas are heavily influenced by upstream contributions. Restoring upland areas that feed headwater drainages should be targeted if stream channel improvements and improved watershed scale water quality are primary goals. These actions would contribute to stability of recovering natural communities, preventing incremental erosion and degradation.

Restoring the stream channel is a long-term project. Walnut Creek was severely impacted by agricultural intensification and bears witness to the cumulative hydrologic changes that occurred over time throughout the basin. As such, restoration of the channel will lag behind other hydrologic improvements made in the watershed. The stream channel continues to evolve over time as it adjusts to the historic alterations in channel morphology and flow that occurred over the last 150 years. Restoration of the stream channel should be a natural evolution process. Active channel restoration involving strategies such as armoring streambanks or installing channel meanders is terribly expensive and not likely to work until the water balance and hydrology are restored. On the other hand, allowing natural processes to occur in the stream network (beaver dams, debris jams, etc.) do not cost anything and encourage stream evolution and readjustment. Modest investment in carefully placed weirs could help in natural reconnection of the stream to the floodplain. Vegetation has a role in the process of stream readjustment or recovery. Understanding the role that vegetation has in the process of stream readjustment and recovery includes consideration of changes in populations and communities of both native and introduced species as the ecology changes. This is a subject to consider for future research.

Hydrologic monitoring is not easy but should be conducted. Understanding the hydrologic changes that occur in response to prairie reconstruction is important to assess the short- and long-term success of any project. Monitoring can involve strategies such as following a single site through the recovery process (Cabbage site) or measuring hydrologic changes across a chronosequence of plantings. While some water balance components can be monitored easily, such as rainfall or groundwater levels (provided a well is installed), other components are more difficult to measure, including soil moisture and runoff. Water quality improvements can be assessed with a sampling program but laboratory analyses can be cost prohibitive. Partnering with agencies and universities, as was done with U.S. Fish and Wildlife Service support at NSNWR, may provide one mechanism for establishing hydrologic monitoring. At a minimum, recognition of the importance of hydrologic restoration and local field observations will alert people to hydrologic changes that may be occurring.

The timeframe for hydrologic restoration should be realistic. In this report, we documented the changes in hydrology that occurred during 150 years following settlement and speculated that hydrology, especially at the watershed scale, will take at least this long to recover. Patience is needed by restoration professionals to frame restoration of hydrology in realistic terms and not over-promise on future benefits. Results from studies conducted in Walnut Creek watershed show that hydrologic changes at a small-scale are observable within a decade, but detecting changes at a larger scale will need a much longer timeframe.

Chapter 6: Land Management Implications

This chapter is a discussion of land management insights gained from consideration of results of hydrologic research in the context of ecological restoration and research experiences spanning the history of Neal Smith National Wildlife Refuge (NSNWR, refuge). Perhaps the most profound insight relative to management and conservation design is that synergy exists between hydrology and natural community development or recovery. Prairie planting incrementally stimulates hydrologic recovery, and hydrologic recovery provides new opportunities for refinement of the natural community. Understanding this synergy leads to insights about developmental phases of prairie reconstruction and restoration suggesting that a more holistic approach to management and conservation design could be more efficient in achieving goals. It also provides some provocative insights about how to most effectively design, prioritize, and phase management areas and strategies for ecological restoration. The following discussion topics are generally organized as one moves from uplands to lowlands, although all topics, including management concerns and actions, are ecologically interrelated.

A feedback loop exists between groundwater and developing prairie. Agrarian settlers on the Southern Iowa Drift Plain prairie landscape described good quality groundwater in uplands at depths of 30–40 feet (9.1 to 12.2 meters), although today's water table depths under crops are about 10 feet (~3 meters) and can be as shallow as 3 feet (~1 meters). With prairie reconstruction at NSNWR, groundwater depths are similar to that of croplands for the first few years after planting. Deepening water tables signals a shift both in prairie development and hydrologic function. During this time, the prairie flora typically shifts from a dominance of annual and biennial plants during the first two years, to a greater preponderance of mature perennial species in the third year. In the process of maturation of the perennial prairie flora, the characteristically dense network of prairie roots develop, with capacity to penetrate deeply into the soil. At this critical phase of prairie development, evapotranspiration (ET) demands increase, and water table depths increase. Continued decline of groundwater will stimulate growth of longer roots in many species and may also stimulate a change in growth patterns, competition and possibly species distribution as water supplies near the surface are more limited seasonally.

Although this deepening of the water table with prairie planting occurs at all landscape positions, it is most dramatic in uplands. In plantings next to cropped fields, it is likely that water table depths are greater in the center and shallower near the edges where the effects of reduced ET by crops come into play. It is thus possible under these circumstances that greater potential for ecological recovery occurs in the center of the planting where greater hydrologic function is likely. Greater water availability due to a higher water table occurring near the interface with cropped field may create conditions that favor invasive species with shorter roots, thereby causing greater difficulty in their control. Potential for greatest synergy between flora and hydrology and thus for greatest ecological recovery is likely where plantings are concentrated on large blocks of the landscape. Indeed, at least some aspects of hydrologic recovery, such as increased impact on stream water quality, demonstrate that this is the case.

Spring flora is necessary for greatest hydrologic function throughout the growing season. Although spring flora was well represented in pre-settlement prairie, current plantings on NSNWR typically have poor vernal species representation. The synergy between vegetation and hydrology described above is thus likely functioning deficiently during cooler portions of the growing season when the dominant native C_4 plants are not as actively functioning. A few C_3 exotic grass species with relatively shallow roots such as smooth brome and reed canarygrass dominate some areas, but as surrogates for a richly diverse native cool season catena of species, ecological function of these species is anemic at best. Installation of a greater compliment of vernal forbs, grasses, and especially sedges, which were abundant on the intact natural landscape, would facilitate a more natural and probably a more functional relationship between flora and hydrology.

Management actions affecting hydrology can be used to achieve specific site level objectives. Managers influence site level characteristics such as duff layers, surface soil moisture, ET, and infiltration potential by choosing to burn, graze, or rest and by selecting the length of interval between treatments. Increased duff tends to increase evaporation, and because it intercepts rainfall and absorbs water, it decreases infiltration potential (Brye et al., 2000). Duff also increases the potential for the surface soil to be moist (Lauwo, 2007). Fire and grazing decrease duff and thus increase infiltration potential. Fire stimulates biomass production above and below ground and consequently increases ET and water storage potential (Hodnett et al., 1995; Huxman et al., 2005). Management actions related to hydrology can be applied to achieve particular goals or objectives such as enriching floristic diversity, tailoring habitat conditions, and suppressing exotic species.

Differences in past farm management influence development of prairie reconstructions. Farm management decisions regarding type or amount of fertilizer applied or amount of cover maintained varied, and these decisions have resulted in different nitrate concentration starting points for prairie reconstruction. As a result, rates of nitrate decrease are variable among fields. Variability in amounts of residual farm nutrients and other chemicals probably accounts, in part, for differences observed in prairie reconstruction development even among fields planted with the same seed mix, using the same equipment, and in the same season. Among differences that could be related to variable nutrient loading are time that annuals and biennials continue to be a major part of the flora, exotic species pressure, species expressed, floristic quality, and the amount of time needed to meet management objectives.

Phosphorus tends to concentrate in footslope position. Prairie reconstruction did not significantly reduce phosphorus (P) levels, which is mainly carried to the stream through surface runoff. A reason for this could be inadequate sampling design, but it likely is due to legacy effects of agricultural land use. P concentrations were higher in footslope than upland positions (Tomer et al., 2011). Thus, exotic species that tend to increase with greater P availability could be more problematic at these topographic positions.

Legacy effects can be present in the system for long periods of time. The time for groundwater to travel from uplands to the stream at NSNWR can be as long as 100 years. Although nutrients are metabolized in carbon rich waterways, herbicides and insecticides or their breakdown products could be more persistent in areas with longer travel times. This means that persistent chemicals delivered to the system since 1950 could be affecting water quality in some areas until 2050. Although it may not be possible to change this situation, it is a sobering reminder that practices that deliver chemicals to the landscape could have long-term and unknown effects, possibly including cascading impacts on soil biota, wildlife, and ecological health in general. It is a thought provoking detail regarding the long-term and complicated nature of ecological recovery, particularly in the context of a rapidly changing climate.

Strategically incorporating prairie plantings into landscape designs could achieve hydrologic improvement of high value to society. Prairies are planted for a variety of reasons, including to: simulate historic conditions, buffer remnant natural communities, provide wildlife and pollinator habitat, reduce sediment and nutrient export in cropland, and increase visual aesthetics. Given the hydrologic benefits, prairie plantings could be used in a larger conservation design strategy to achieve the above purposes and to decrease flooding along rivers and streams and naturally dry cropland (reducing need for tiling). Strategic installation of prairie plantings could also be used to increase recreational and drinking water quality, and to buffer sensitive conservation areas and water reservoirs from negative impacts of adjacent land use. Ultimate benefits to society could include reduced cost for municipal water filtration and reduction of distant impacts such as hypoxia in the Gulf of Mexico.

Savannas may be sustained in somewhat different locations than historically due to changes in hydrology and soil conditions. Savannas are primarily located in places conducive to upland tree species, primarily oaks. Wet, soggy places are unfavorable to most upland woody species characteristic of savanna. Wet conditions existed in the sedge meadows along the stream and arguably in the uplands where, according to Wilhelm (2007), dense root mass generation and decay impeded drainage, creating wet conditions on the pre-settlement landscape. Using this perspective, savannas in the Southern Iowa Drift Plain were located on slopes where abundant sedges produced a balanced soil organic carbon to oxidation rate and sustained a good soil tilth. Current savannas should thrive under conditions that favored pre-settlement savannas. Although agriculture and other land uses certainly influenced where savannas currently remain, drastic changes in hydrology and in root biomass conditions may explain to some degree why savannas are not always in the same places they occurred in the early 1800s.

Floristic diversity is important on side slopes to deter runoff and erosion. In uplands there is a much greater unsaturated zone to accommodate infiltrating precipitation, and with greater storage there is less recharge to the stream and thus less contribution to flooding. Although floodplains are 17% of the land cover, they contribute 34% of the recharge to the stream. Side slopes (54% of the land cover) contribute only 34% of the recharge with a greater proportion of precipitation diverted to runoff. Planted vegetation on slopes must establish quickly and provide a variety of structural characteristics to deter the increased potential for runoff on these vulnerable slopes. Morphological diversity inherent in a native plant community that includes bunch grasses, rhizomatous species, vines that act as “weavers” to bind plants together, stiff and soft stemmed species, broadleaved/branching, and graminoid-type growth forms serves to reduce rainfall impact on the soil, slow water movement on the soil surface, and promote infiltration. Sedge species have special utility on slopes and in drainageways where snow melt and spring rains can cause erosion early in the season, expose and allow germination of weed seeds, and contribute to flooding. Inclusion of species that are actively growing in early, middle, and late times of the growing season armors the soil, and a diversity of root structures contribute to greater infiltration.

Tile removal and prairie reconstruction stabilizes soil, reduces runoff and rehydrates waterways. The majority of water flowing in Walnut Creek originates from headwater areas off-refuge and is collected and transported via tiles that empty from upland drainageways. Nearly all tributaries begin as first order (unbranched) streams originating from these tiles. Increased water discharge from tile outlets throughout the last century has eroded channels into areas previously occupied by upland swales. The development of these erosional channels has effectively lengthened the stream and reduced sinuosity compared to the natural condition.

Many additional tiles drain floodplains laterally and empty directly into the stream, but these contribute only 6% of the total flow in the stream channel. Although tiles in both positions dewater the land and contribute to erosion, the impact of tiles emptying directly into the stream on hydrologic function is miniscule compared to the large impact of tiles from headwater uplands that deliver into the stream. Refuge ownership, conservation partnership, or private conservation effort in the headwaters is needed to resolve or mitigate the enormous impacts of headwaters on hydrologic function and thus ecological restoration.

Although the impacts of tiles existing directly on the refuge have a minor impact relative to off-refuge headwater sources, their removal or deactivation is important for several reasons:

- Tiles that drain prairie reconstructions no longer contribute high nutrient or sediment loads to the stream. They remove water that would contribute to a more nuanced upland natural landscape replete with seeps and springs, and they would particularly allow restoration of heavily vegetated swales in drainageways.
- Tiles move water more quickly to the stream than would have occurred on the natural landscape, depriving the land of sustained baseflow. Reinstating natural baseflow with tile removal contributes to greater hydrologic stability in lowlands located near the base of hills and distant from streams. These areas could be among the best sites to reconstruct and sustain sedge meadow communities.
- Tiles emptying in uplands continue to aggravate old erosional scars making native plant establishment difficult, and in some cases, sustains early successional or exotic vegetation. Tile removal in these areas allows reinstatement of vegetation and greater hydrologic function.
- Lowland tiles remove water from formerly wet areas and reduce hydrologic function that could support hydric natural communities. These tiles are often sources of soil destabilization and erosion causing gullies to extend into the floodplain.
- Tiles that drain only refuge land can be removed.

Many tiles exist on the refuge. Table 6-1 is a decision framework suggested for prioritizing tile removal and includes rationale that supports each potential priority decision. This allows refuge staff to weigh decisions based on current refuge circumstances and management ability.

A possible starting point for a process of identifying tiles and implementing tile removal is as follows:

- Locate all tiles emptying in uplands using aerial photographs and ground reconnaissance.
- Locate all lowland tiles emptying into tributaries and the main stem of Walnut Creek using research data and ground reconnaissance.
- Contact former landowners or renters of current refuge land to gain information that might be available about the location of tile lines.
- Locate tiles on Geographic Information System maps that include aerial infrared imagery, topography, ownership, and land-use layers.
- Determine which tiles drain only refuge land based on the map. For example, tiles draining an upland area that is completely owned by the refuge can be removed, because removal will not provide negative impact to neighbors.
- Prioritize tile removal based on refuge needs. Table 6-1 provides examples of rationale for prioritizing tile removal.

- Select method of tile removal, and implement.
- Stabilize soil disturbance using prairie planting techniques and special erosion control methods if needed in highly vulnerable areas.
- Monitor effectiveness of the implemented strategy, and adjust during future efforts as necessary.

Table 6-1: Examples of potential high priority tile removal targets and rationale for their consideration. These factors can be weighted and used to prioritize tile removal on NSNWR.

Potential High Priority Tile Removal Targets	**Rationale for Consideration as a High Priority Site**
Tiles present in high concentrations	Major improvements in local hydrologic function occurs by removing many tiles in a local area.
Tiles present in low concentration	These areas represent "low hanging fruit"; that is, objectives that would be relatively easy to achieve. Removal of tiles completes this phase of hydrologic recovery with relatively little effort and may represent the last mechanical disturbance for the site (thus also completing a phase of prairie reconstruction).
Tiles in areas already planted to prairie	Established prairie will help hold soil as tiles are removed. Removal of tiles may represent final soil disturbance needed in long-term management.
Tiles in areas slated for future planting	Pro-active tile removal happens in the planting phase so plantings will not need to be disturbed as prairie matures.
Tiles that empty in uplands	Surface water flow and related erosion diminish or cease; water infiltrates and hydrates waterways, slowing movement to the stream; an artificially lengthened portion of the stream (due to flow from tiles) shortens; hydrologic function increases; and greater capacity exists for higher quality prairie reconstruction. This target coupled with prairie reconstruction on erosional features stabilizes, repairs and rehydrates uplands.
Tiles that empty into the stream	Rehydrates drainageways and other tiled areas; allows for some stabilization of erosion that may be related to tile outlets in this position. (Reducing erosion along the stream can be difficult due to the process of undercutting by the stream.)
Tiles located in floodplains	Rehydrates floodplains and increases potential for sedge meadow reconstruction.
All tiles in a targeted subwatershed	Increases function of a hydrologic unit and if coupled with completion of natural community development, increases efficiency in achieving overarching refuge goals; management is usually more efficient on a single larger unit instead of several smaller ones (fewer burn lines, for example); increases habitat quality by increasing diversity and block size; and accelerates progress in ecological restoration due to synergy between upland and lowland and between vegetation and hydrology.

Prairie planting is important in tile erosion repair. Although erosion is associated with active tiles, the process of tile removal can also stimulate erosion. Active farming practices such as tillage often masks the degree of severity of erosional patterns as soil is smoothed for the next season's farming. With prairie planting, erosional problems can sometimes be revealed to be bigger than expected. In the long-term, prairie vegetation can halt minor to moderate erosion, repair erosion scars, and contribute to restoration of the intermittent quality of some tributaries. In the early stages of prairie reconstruction on a field newly removed from agriculture, however, erosive forces can generate soil instability and areas devoid of vegetation especially in high rainfall years. Special attention given to stabilizing upland erosion prior to or during the planting process can reduce investment needed later to repair damage resulting from unchecked erosion.

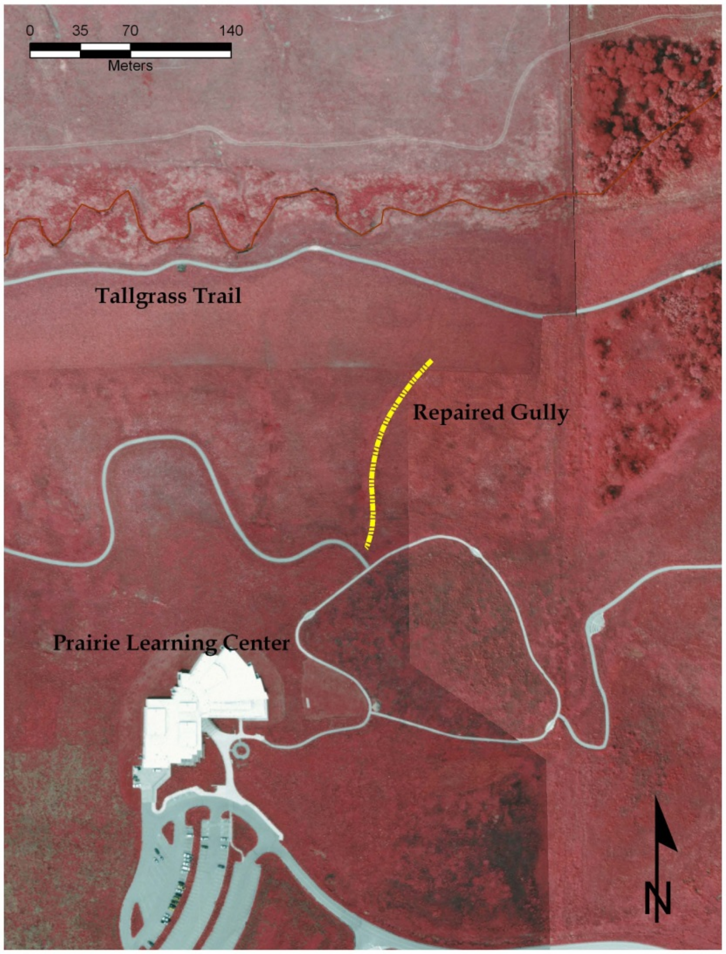


Figure 6-1: Experimental gully repair was accomplished with NSNWR staff and volunteers who filled a gully with waste soil and planted established plants in 2000.

An experimental alternative in stabilizing high profile problematic erosional areas was undertaken at NSNWR in 2000 (figure 6-1). Plants were installed in greenhouse waste soil and other soil used to fill the gully working from the upland to lowland. Although there was insufficient soil and plants to complete the lower reach of the project, the approximately 80% that was completed has remained secure for many years. This gully could be a high priority area for evaluation and completion to avoid possible future destabilization.

Nutrient levels may indicate timing of waterway removal. Installation of cool season exotic grass such as smooth brome, Kentucky bluegrass and reed canarygrass in highly erosive drainageways was a common farm practice on the Walnut Creek watershed. Known as "grassed waterways" these areas were a low priority for removal in most reconstruction efforts at NSNWR because of high pressure to plant acres quickly, limited seed availability, and lack of resources for detailed reconstruction efforts. It was also believed that successful prairie plantings would eventually out-compete exotics in these narrow strips. In some cases, particularly where fire has been frequent to near annual, significant progress has been made to this end, but a decade or more later, many if not most of these waterways are still clearly dominated by cool season exotic plant species and their signature is obvious on aerial infrared photographs.

Weed pressure radiating from waterways dominated by exotic species can impede recovery of the natural community within a local area, especially if native species most appropriate to a soggy waterway and most successful in performing needed functions relating to infiltration were not planted. Thus, active conversion of exotic vegetation to a hydrophilic native plant community in these areas is worthy of consideration.

Hydrologic studies provide some insights about timing for this process. Studies of nitrogen (N) at the Cabbage Site indicate that in drainageways, NO_3-N resulting from farming was metabolized within three years of prairie planting, although it took five years for levels to be stabilized at two milligrams per liter in uplands (Tomer et al., 2011). Most exotic species that dominate local grassed waterways and most annuals that establish when soil is disturbed are stimulated by high N inputs, whereas germination of many prairie species, notably legumes, is inhibited by high N levels (Kitajima and Tillman, 1996). After years of occupation by exotic species, the seed bank is likely well loaded with exotic species propagules in grassed waterways. Thus, conversion of these areas to native vegetation may be most successful three years after planting the surrounding slopes. By this time, the water table should have deepened under the planted prairie. If cool season exotic species are favored by moist conditions, even some drying in this normally moist area may confer a modicum of competitive advantage to the native flora.

Additional approaches to conversion of waterways to prairie in the same year as the surrounding field include: 1) planting native annuals, biennials, and opportunistic species that thrive under higher N conditions and increase diversity through time, or 2) planting a diverse seed mix of hydrophilic species and in later years interseed with species that failed.

Conversion of reed canarygrass to sedge meadow likely depends on stable hydrology. Reed canarygrass occurs nearly exclusively along the stream and in floodplains throughout the refuge where sedge meadow and other hydric plant communities historically occurred. In these areas, high nutrient levels in the soil, groundwater, and floodwaters tend to favor reed canarygrass and tend to suppress sedge meadow species (Perry, Galatowitsch, and Rosen, 2004; Green and Galatowitsch, 2002).

Reducing N in floodwaters or groundwater is the ultimate method for reducing N levels in floodplains in preparation for sedge meadow reconstruction. This would require significant dilution or removal of N from farm sources (i.e., tiles and crop field runoff), particularly from the headwaters north of Iowa Highway 163 (see figure 1-1). As we have found, even large prairie plantings in uplands result in small increases in water quality at the watershed scale, so without mitigation of offsite influences of agricultural waters infused into the system via headwaters and tributaries, removal of N from streamwaters is not an option. Although efforts to reinstate fully functioning sedge meadow communities to the floodplains of Walnut Creek are disabled by disconnection of the stream to the floodplain, ecological function can at least be increased by reconstruction of sedge meadow communities in parts of the floodplain where the hydrology is most stable.

Nitrogen depletion in hydric areas can be a tool for land managers to control cool season exotic species and reconstruct or restore sedge meadow. Several methods available include the following:

- Introduction of carbon sources such saw dust or wood chips to deplete N via the decomposition process.
- Harvest of vegetation several times in a season (Perry, Galatowitsch, and Rosen, 2004), although it may take as many as five harvests in a season for depletion sufficient to control reed canarygrass (Wilkins and Hughs1932) in preparation for sedge meadow establishment.
- Livestock grazing to accomplish vegetation harvest (Lyons, 1998; Martin, Jordan, and Hovin, 1976). This method is problematic, because some species such as reed canarygrass have poor palatability, can cause illness in livestock, and can damage wet areas. In addition N is returned to the soil via urine and feces, reducing effectiveness.

- Burning (Ojima, Shimel, Parton, and Owensby, 1994). Although late spring fires can damage both exotic and native cool season species, dormant fires are reported to be useful (Henderson, 1991). A bonus in using fire to reduce N is that it can invigorate native species (Wilhelm and Rericha, 2007), while simultaneously weakening exotic species (Hutchison, 1992).

Using a combination of these tools in conjunction with a grass herbicide or glyphosate treatment, and planting a sedge meadow seed mix and/or plants may be most effective in suppressing reed canarygrass and successfully reconstructing sedge meadow. The sedge component of the sedge meadow community may have some utility in reducing N. Based on a greenhouse study, sedges appear to have greater N uptake efficiency than reed canarygrass, and thus in N poor conditions, sedges have a competitive advantage (Perry, Galatowitsch, and Rosen, 2004). Sedges are also tolerant of at least some chemicals used in reed canarygrass control. Thus, when reed canarygrass is sufficiently suppressed so that sedges could survive, their introduction could be useful in continued N reduction and creation of an environment for further development of a competitive sedge meadow community.

In experimental efforts to replace a monoculture of reed canarygrass with a diverse sedge meadow community along a deeply incised portion of Walnut Creek, greatest success was achieved in the zone most distant from the stream. This area is adjacent to a hilly savanna remnant that provided baseflow to support more stable hydrologic conditions. The middle zone is dominated by reed canarygrass, but it appears that a limited number of species, and particularly an aster species, is persisting or perhaps even invading the reed canarygrass. Monitoring in this zone after glyphosate treatment and devoid of vegetation showed large fluctuations in the groundwater hydrograph after rainfall events. Unstable hydrology in this area may explain difficulty in sedge meadow community establishment. The long-term ability to establish native vegetation in this area is unknown.

Along the stream, conditions do not support sedge meadow. The stream incision characteristic of Walnut Creek extends below the water table causing it to drain and resulting in a wedge shaped zone along the stream that is unnaturally dry. Although we did not initially understand the cause of this hydrologic drought zone or how it functioned, symptoms of it were observed at the outset of the project. A slight elevation near the stream caused by sediment deposition probably exacerbates drying conditions.

During rainfall events, the incised streambanks are scoured causing bank collapse and destabilizing or removing vegetation on the side or top of the bank. On rare occasions, the volume of water exceeds the capacity of the incision to contain it, and the stream floods (figure 6-2). Fast moving floodwaters are severely detrimental to vegetation closest to the stream, and receding water leave behind damaging deposits of sediment and seed, probably mostly exotic.

Figure 6-2: An image of Walnut Creek flooding in 2010 on NSNWR and photographed from a bridge on Pacific Avenue looking east. The sedge meadow reconstruction treatment area is on the right side of the photo, and the control on the left. The right edge of the streambank can be faintly detected by a slight riffle running from the bottom left corner through the center of the photo. Forces were great enough to remove a portion of the road.

We believe the best course of action in this harsh zone is to thoughtfully select a set of native species that will thrive, deter erosion, and rapidly recolonize when soil is destabilized. For the unsaturated zone, invest in species with roots that will clone and knit together creating greater soil stability. Trees and tall shrubs should be avoided for two reasons: 1) as they become denser, light levels decrease, excluding the herbaceous understory and leaving the soil vulnerable to erosion, and 2) uncontrolled woody species will become a management control issue as they spread into the sedge meadow. Some lower statured woody shrubs could be used along the streambank if they are not overly invasive in the recovering sedge meadow environment. Smooth rose (*Rosa blanda* Aiton) is a nearly thornless rose that can easily be transplanted and established, probably is not a threat to sedge meadow, and its roots could provide structural support in the bank.

Although a true sedge meadow community will not thrive along the margin of the stream, selected native species, perhaps from multiple natural community types, could do well. Establishment of such an assemblage of native species with desired characteristics is not a natural community reconstruction, because it has no context to the historic natural landscape. A more appropriate term is “native species construction.”

Species selections for use in the hydrologic drought zone should be based on specific characteristics, including ability to: 1) form a tight network of roots to stabilize soil and resist erosion, 2) facilitate rapid reestablishment of vegetation after extreme erosional events, 3) be tolerant of extreme moisture conditions, and 4) provide a buffer between the stream and the developing sedge meadow. Only species that do not contribute to degradation of the recovering sedge meadow community should be selected.

We gained several insights from sedge meadow reconstruction and monitoring, which are listed below:

- Success in early establishment probably depends on having a relatively stable water table near the soil surface.
- Water table fluctuations approximately in the middle of the sedge meadow reconstruction site may produce conditions that impede or prevent sedge meadow reconstruction.
- A hydrologic drought zone near the edge of the stream is too dry for true sedge meadow establishment and needs a special assemblage of species.
- A dormant burn may provide greater advantage in sedge meadow reconstruction in the long-term by invigorating the native plant community than performing a spring burn to suppress reed canarygrass.
- Introduction of hemiparisitic plants could provide natural reduction of reed canarygrass vigor and competitiveness.
- Rare stochastic combinations of weather patterns, management actions, and plant responses probably create conditions favorable in shifting the advantage to native species if strategic and appropriate management actions are applied, but land managers must be informed, observant, prepared, and able to act.

Degradation of hydrology and the floodplain has been long-term and severe, and reconstruction of natural communities will take time, patience, and management wisdom. There is much more to be learned about this complex process, and continued research coupled with needed management will be key to greater understanding.

Reconstruction blocks, including uplands and lowlands where stream and floodplain are connected, could be most efficient in restoring ecological function. Prior to European settlement, prairie streams on the Southern Iowa Drift plain, like prairie streams in many other areas, were shallow, meandering, and intermittent for long stretches, particularly in the upper watershed. Heavily vegetated swales in upland drainageways absorbed most rainfall before it reached the stream, and marshy areas replete with springs were stream sources. Where stream channels appeared, their margins were characterized by wetland or sedge meadow.

In some localized places at NSNWR, the stream still exists in the absence of a deep incision. In these places the stream channel is shallow or indistinct, and the vital connection between the stream and the floodplain exists. Although rare on the refuge landscape, these areas bear some functional resemblance to the natural hydrologic condition not found along most of Walnut Creek floodplain. With a more stable lowland hydrology, sedge meadow reconstruction has a better chance to be successful than along deeply incised streams. Because there is no hydrologic drought zone, the wettest part of the floodplain can be in a more natural position at or near the stream margin. As uplands in these areas are planted to prairie and the groundwater deepens, more infiltration is possible and thus more water will be released as baseflow instead of stormflow.This facilitates greater reinstatement of springs and seeps. Because there is still connection between the stream and floodplain, baseflow will not be lost in a deep stream incision, and the interaction between hydrology and native vegetation established in both lowlands and the uplands will generate synergy not fully possible in other areas.

These areas may offer the best opportunity for more complete reconstruction of a suite of connected natural community types—for hydrologic recovery and for greater wildlife habitat quality in relatively large blocks. In short, these areas may provide the best opportunity to restore ecological functionality and sustainability. They are also likely to have the greatest management efficiency, because in these locations, hydrology has more potential for recovery.

An example of rehydration of lowlands through prairie reconstruction in uplands occurs in the floodplain north and west of the Prairie Learning Center building. This low, flat land was farmed until refuge ownership and clearly was dry enough to sustain cropping practices. A north facing hillside just upland of this farmed land supported a dense growth of trees of mixed species that was uncharacteristic of the historic natural condition in terms of floristic composition, density, and geographic location. A small remnant of sedge meadow was identified adjacent to the northwest corner of the woods and nearing the bottom of the slope, indicating the presence of a seep. Trees remove enormous amounts of water, and the presence of a small, dense upland woods area dried the hillside seep. When the trees were later removed, the sedge meadow expanded, and water became available to rehydrate the lowland. The lowland was planted with a wet prairie mix and now is an example of a recovering sedge meadow in the floodplain.

Holistic recovery in this area is impossible, however, as deeply incised banks contain and disconnect the adjacent stream to the north from its floodplain creating massive erosion along the unstable hydrologic drought zone that is the stream margin. Undercutting and bank collapse lead to destabilization and persistence of a weedy border that is compounded by dry conditions present at the stream margin, an area that was once the wettest portion of the floodplain. Bison use likely contributes to erosion in this tributary to Walnut Creek.

Two sections of the stream with shallow stream conditions (and thus an absence of deep incision) and that are connected to the floodplain exist on the northern third of the refuge and are indicated in figure 6-3. We recommend consideration of these areas as high priority management blocks, with special focus on sedge meadow reconstruction. The southeast site is within Coneflower Management Unit, and close examination of a high resolution aerial photograph reveals two thin meandering waterways with a marshy delta between them. Springs likely still feed this wet place, and reconstruction of adjacent uplands, especially those to the east has probably increased upland infiltration and thus delivery of baseflow water to springs and seeps in the lowland.

A second area recommended as a high priority management site is shown in the northwest section of figure 6-3. Although the stream has been straightened, the channel is shallow, and the surrounding floodplain tends to be wet and soggy. Exotic species suppression and sedge meadow establishment here would not require restructuring of stream morphology, flow, or meander, but evaluation of potential off-refuge inputs of water and needs for mitigation are important to maximize ecological benefit. Because all of the farm fields in this local area have been retired, gullies are "obsolete" and are excellent candidates for repair. We recommend evaluation of the refuge to discover and prioritize additional stretches of shallow stream where connection to the floodplain exists. Highest priorities are areas that are completely or nearly completely contained within refuge boundaries where water input from offsite tiles, if they exist, can be reasonably mitigated. These areas can be expected to be associated with first order streams. Stretches of stream appearing as thin lines on aerial photographs will usually indicate that they are shallow. Presence of the signature of a wet soggy or marshy area offers evidence of active baseflow.

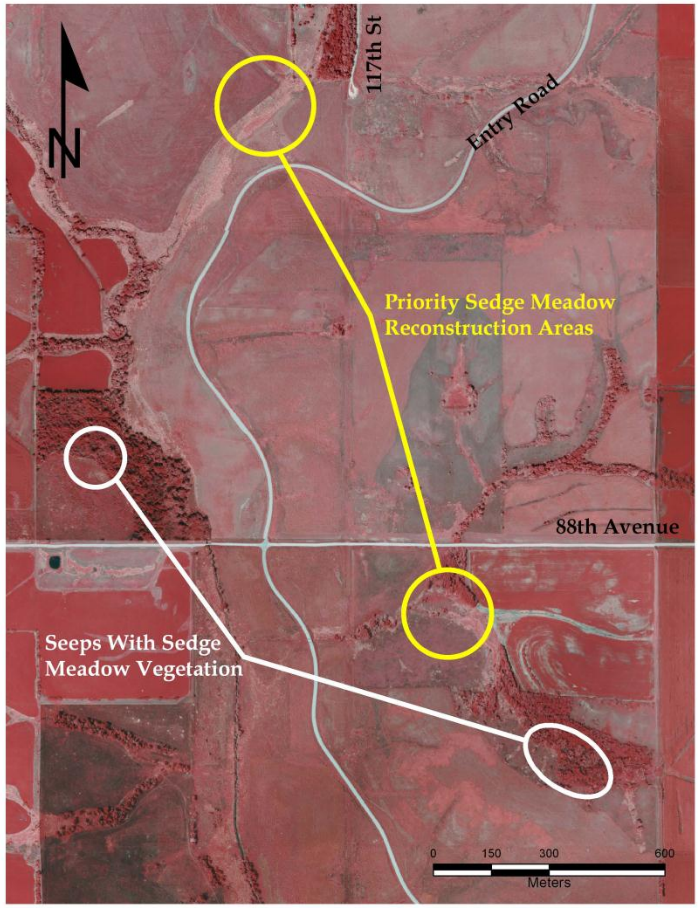


Figure 6-3 Examples of areas on NSNWR where wet soggy areas exist. In some cases, remnants of a historic sedge meadow community persists, including tussock forming sedges. Greatest potential for successful sedge meadow reconstruction may be in areas where the stream is still connected to the floodplain and thus supports a more natural streamside hydrology. Such areas are recommended as high priority sedge meadow reconstruction sites.

Strategically placed weirs and natural structures can help reconnect stream to floodplain. If degradation of the stream bed continues, the drought zone near the stream (formerly the wettest area of the floodplain) will continue to enlarge. If the stream incision does not deepen but instead widens, as it appears is happening, bank collapse and associated erosion will continue to destabilize the streambank. This will stimulate a cycle of exotic and weedy species generation as the seed bank is exposed, especially under unstable soil conditions. Ability for stream ecology to recover under these conditions is low, and ecosystem function, including hydrology, will be continually and critically impaired. Planting native vegetation with dense interlocked rhizomes and roots may help slow bank collapse, but vegetation alone will not remedy this situation. Erosion is a symptom; disconnection of the stream from the floodplain is the root of the problem.

Information from a downstream weir on Walnut Creek installed to measure water discharge indicates that installation of weirs at strategic positions would have potential to raise the stream stage. Water levels measured over a 2.5-year period at the established weir were 0.2 to 0.7 meters higher than average water table depths observed in seven other riparian well sites (Schilling et al., 2013). Water obstructions currently caused by beaver activity and debris dams also create pools and temporarily elevate the water table in portions of Walnut Creek.

Informed and thoughtful placement of low head dams or weirs, coupled with natural processes like beaver dam creation could obstruct water flow and create a more natural floodplain. Using this approach, soils near the stream margin, formerly in the hydrologic drought zone, could rehydrate, making wetland and sedge meadow reconstruction possible. Recommendations on placement of low head dams or weirs could be developed by a team including refuge staff, NSNWR hydrology researchers, and the Regional Hydrologist, using information from hydrologic research, this document, and other pertinent sources. Recommendations should address refuge management concerns and address the need to avoid negative impacts to neighboring landowners.

Changes due to low head dam or weir installation could be expressed as greater ecological function at all landscape positions, although the greatest magnitude of change would likely happen in the stream and floodplain where periodic flooding could begin to occur horizontally instead of being contained vertically within steep and incised banks. Stream ecology could finally improve, providing habitat for fish, invertebrates, amphibians, birds, and aquatic vegetation. In addition, wet meadows could be developed in the floodplains, sustained by hydrated soil. Using this method, the process could be accomplished in a matter of years rather than decades and at a moderate cost. Continued hydrologic monitoring, integrated with vegetation and wildlife monitoring would be important in understanding the relationship of hyrologic changes to the recovering prairie landscape and adjustments in course regarding stream recovery.

Sufficient information exists to explore steam restoration options. The long-term and intensive study of hydrology of Walnut Creek watershed provides a powerful base of information rarely available to refuge managers. Stream restoration recognized as important in early refuge planning, was wisely deferred by NSNWR staff until there was enough information to have a reasonable discussion about options. The wealth of hydrologic data and this synthesis of hydrologic research pave the way for assembly of a team including refuge staff and experts in stream restoration, hydrology, and ecological restoration to develop options for a realistic, phased plan for stream restoration. Possible questions to consider could include the following:

- To what degree can the stream be restored? What is impossible?
- What would be a reasonable starting point?
- Could stream restoration be accomplished without negative impact to neighbors?
- What would be the best way to phase the stream restoration process?
- What is the projected cost of phased stream restoration?
- What partners would be needed to assist in the process, and what would be their roles?
- Would stream restoration make land management more efficient in any way, and if so, how? What would the hinderances be?

- What types of monitoring would be necessary, and who could do it?

The discussion and results of such a meeting could not only inform the refuge about what future course of action is possible and reasonable, but it also could help inform future conservation planning in the U.S. Fish and Wildlife Service (USFWS, Service) and partners in the Midwest.

Incremental management actions can improve hydrologic function. Although restoration of refuge hydrology is daunting, incremental actions at specific locations can improve hydrologic conditions, and partners can be aligned to help address larger issues beyond the scope of refuge staff alone. Targeted reconstruction efforts, tile removal, erosion repair, specific seed mix design, and technique development serve multiple purposes of hydrologic restoration, recovery of natural communities (prairie, savanna, and sedge meadow), and improvement of wildlife habitat. In applying management actions, it is important to keep in mind that biotic and abiotic elements of the landscape are synergistic and thus progress made today toward ecological recovery will change the starting condition for future actions. For example, planting a prairie seed mix on farmed land will change hydrology after a few years, and a later interseeding will be subject not only to different plant community conditions but also to a different water table configuration. A strong message from this synthesis is that a changing hydrologic condition changes the plant community, and conversely, a changing plant community changes the hydrology. Thus, improvement in ecology through the time considering changing starting points caused by this synergy may be depicted more like a spiral rather than a linear progression.

A summary list of recommendations discussed in this document to improve both hydrologic and the larger ecologic condition of the refuge, and the degree that they can be accomplished by refuge staff, is shown in table 6-2.

Table 6-2: Management actions for improved hydrology, wildlife habitat, natural community quality, and ecological function indicating actions that can be accomplished with refuge staff alone, and actions requiring regional staff or partner participation.

Management Actions for Improved Hydrology, Wildlife Habitat, Natural Community Quality, and Ecological Function

1. Identify, prioritize, and implement management of holistically designed project areas that include stretches of shallow stream connected to the floodplain and adjacent uplands. (refuge staff)
2. Continue experimental sedge meadow reconstruction, including research and management. (refuge staff, Zone Biologist, and researchers)
3. Introduce a diverse cool season native plant component, including sedges to refuge plantings at all landscape positions. (refuge staff, volunteers, Friends group, and commercial seed producers)
4. Remove onsite tiles drainage ditches and berms, and plant native vegetation. (refuge staff)
5. Convert exotic waterways on slopes to native vegetation. (refuge staff)
6. Repair upland erosion features. (refuge staff)
7. Continue natural community reconstructions suited to specific landscape positions. (refuge staff)
8. Develop and implement plan to install low head dams or weirs to reconnect the stream and floodplain. (refuge staff, Regional Hydrologist, Zone Biologist, and research partners)
9. Explore potential to mitigate offsite water quality and quantity inputs. (multi-partner assistance)
10. Explore potential for phased stream restoration. (refuge staff, Regional Hydrologist, Zone Biologist, and researchers)

Innovative partnerships and strategies could mitigate issues from off-refuge water sources and become a model for other conservation projects. A majority of water entering Walnut Creek originates from nine headwater subbasins and especially from those subbasins located north of Iowa Highway 163. Additional inputs come from tributaries from the east and west sides of the refuge. High volumes of water laden with nutrient and sediment loads seriously impair ecological restoration and the ability to provide quality wildlife habitat at NSNWR, especially in lowlands. These impacts cannot be mitigated simply by working within established refuge boundaries. Although it may not be realistic to consider expanding ownership boundaries to capture the entire Walnut Creek watershed, it is possible to engage in innovative partnerships involving a variety of stakeholders.

Several possible themes for partnership approaches are possible. Some examples include the following:

- Develop a model for current agricultural practice that includes an emphasis on clean water and greater water infiltration such as the Iowa State University project entitled "Science-based Trials of Rowcrops Integrated with Prairie Strips." Stakeholders could include local landowners and farmers, farm and conservation organizations, and organizations designed to work with private landowners such as the USFWS Iowa Private Lands Office.
- Develop a more intensive model for an agriculture/conservation partnership that includes alternative crops such as biofuels, organic crops, or other innovative business models to more fully achieve infiltration and clean water goals. Partners could be the same as those above.
- Develop a green infrastructural project in central Iowa that includes the Walnut Creek watershed. A possible focus could be to connect Chichaqua Bottoms Greenbelt (Chichaqua), an 8,000-acre multi-partner conservation area, to the refuge via the headwaters of Walnut Creek. Chichaqua is a Skunk River oxbow restoration project and has been designated a Bird Conservation Area jointly with NSNWR by the Iowa Department of Natural Resources and thus makes sense as a green infrastructural project. A larger project area could include the 65,500-acre Lake Red Rock, an U.S. Army Corps of Engineers project with a maximum pool that stretches to the southern end of the refuge along Walnut Creek. Partners could be the same as in the last two projects but could also engage the nearby metropolitan Des Moines area, currently expanding toward the refuge.

Chapter 7: Final Thoughts

Two decades of hydrologic research at Neal Smith National Wildlife Refuge (NSNWR, refuge) in the Walnut Creek watershed has led to new insights on the relation of hydrology to ecological restoration. We have found that hydrology and ecology are intricately linked at a variety of spatial and temporal scales with an ambitious ecological restoration like NSNWR. We have learned that it is not possible to isolate individual components of the hydrological cycle and ask how prairie reconstruction and hydrological change have affected each one. Rather, the hydrologic components overlap and interact with ecological restoration along entire hydrologic pathway, from rainfall droplet to stream water export. Research at NSNWR has emphasized the interconnectedness of hydrological processes and ecological restoration.

Hydrologic research at NSNWR has been ongoing for 20 years, which in comparison to many research projects, is a long time. However, in the context of undoing and rebuilding a natural landscape, it is a paltry amount of time. Understanding the history of hydrologic changes that occurred in the Walnut Creek watershed is critical for evaluating the success of an ecological reconstruction like NSNWR. The process of ecological restoration is in its infancy, and our knowledge has grown in ways we could not have predicted when Walnut Creek National Wildlife Refuge began. In the future, changes on the refuge, changes in the agricultural land use around the refuge, urban expansion, and global climate change may all affect progress toward achieving refuge goals. It will be imperative to establish clear research questions and directions to assess how these future changes will affect hydrologic restoration.

We hope this report catalyzes discussion and opens doors to new kinds of thinking about the relations of abiotic and biotic aspects of ecological restoration. Our goal is that this contribution will provide a springboard for new collaborations among scientific disciplines that are often isolated from one another. We have emphasized hydrology in this report, but the case could be made for other ecosystem-based approaches for ecological restoration of an entire landscape. In our case, we have endeavored to advance the cause of prairie, savanna, and sedge meadow conservation in the context of hydrologic restoration. We hope this document is the beginning of a larger ongoing discussion of conservation and hydrology and invite feedback on ideas and insights from readers.

Chapter 8: References

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