Hydraulic and Geomorphic Impacts of Dam Removal on the Upper Baraboo River, Wisconsin

by

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Abstract

Over time, human interaction with space and place has led to shifts in cultural dominance and modes of subsistence. Societies depend on the access to particular natural resources for subsistence, mainly soil, water and timber. This research examines, 1) a brief history of human settlement within the Baraboo River watershed and the drivers behind the shifts of cultural dominance as related to the dependence on soil, water and timber, and, 2) an in-depth study of how society today adapts to a changing natural resources, namely water through the removal of small, hydropower dams. Often in human history, societies prosper and fail depending on their ability to adapt to climate-driven shifts in natural resource availability. However, with the arrival of modern Native Americans and Euro-Americans, shifts in natural resource availability results primarily from the exploitation of environmental services. An illustration of the human-driven alteration of a natural resource is the building and removal of dams along the Baraboo River. This research studies hydraulic and geomorphic responses to the 2001 removal of the La Valle dam from the Baraboo River. Examination of longitudinal profile adjustments and hydraulic response to a 500-year flood using stream surveys from the Flood Insurance Survey, Martin Doyle, the Sauk County Land Conservation Office, and the author show significant changes in channel form continued to occur several years after the removal of the dam. Between 36-39% of stored reservoir sediments were transported downstream since the 500-year flood, involving incision upstream of the dam site and aggradation downstream of the dam site. These bed adjustments created a smoother longitudinal profile; however, a grade control structure at the dam site further appears to strongly influence stream hydraulics and may result in renewed sediment storage within the old reservoir. This research reinforces the need for more studies which examine fluvial response to dam removal at larger spatial and temporal scales. With a better understanding of fluvial response to dam removal, watershed managers and planners can better protect our safety and the quality of our natural resources.

Acknowledgements

I am deeply grateful for the guidance, support, and wealth of knowledge offered by my advisor, Jim Knox. Additionally, I would like to thank Jena Krause for the several weekends spent in the field with me to collect data, regardless of the weather. Without the data, photographs, and advice given by Emily Stanley, Alicia Jepsen, John Vosberg, and Annette Humpal this project would not have been possible. The Wisconsin Department of Natural Resources and the Sauk County Land Conservation Office were also incredibly helpful in finding information regarding the dam removal. Last, I am thankful to the Trewartha Family Grant which funded my research.

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Chapter 1.0: An Introduction

Geographical thought focuses on the modes and drivers of interactions with and among space and place. Over time, human interaction with space and place has led to shifts in cultural dominance and modes of subsistence. In the Baraboo River watershed in southwest Wisconsin, there is evidence of the arrival of various cultural groups dating back to the late-glacial period 12,500 years ago. The survival of these groups depends on the access to particular natural resources, such as soil, water and timber. This research examines, 1) a brief history of human settlement within the Baraboo River watershed and the drivers behind the shifts of cultural dominance as related to the dependence on soil, water and timber, and, 2) an in-depth study of how society today adapts to a changing natural resources, as illustrated by the removal of small, hydropower dams.

During early human history in Wisconsin and the Baraboo River watershed, several different groups of pre-modern Indians settled and subsequently disappeared (McKern 1942 and Birmingham and Eisenberg 2000). Each new cultural group that arrived in the watershed apparently was attracted by the environmental services that the soil, water, and timber provided. However, it is the change in the availability of certain environmental services that drove several societal shifts within the watershed. As climate changed the type of resources available also changed; as societies failed to adjust to the new environment, they were replaced by other better adapted cultural groups. The initial groups which settled the watershed were likely nomadic hunters and gatherers, except for the last group known as the Woodland Indians. By the time Woodland Indians arrived, prehistoric agriculture had begun, allowing for permanent settlements (McKern 1942 and Lange 1976). Around 1200 A.D. the Woodland Indians disappeared and the modern inhabitants arrived, namely the modern Native Americans, such as Winnebago and Sac, who, in turn were followed by the Euro-Americans (McKern 1942).

Both modern Native Americans and Euro-Americans survived largely by creating communities along the Baraboo River where they grew crops. Most Native American tribes continued to hunt and gather along with practicing agriculture. The Euro-Americans, on the other hand, depended primarily on cultivation. As a result, settlers exploited the soil, water, and timber resources of the watershed to an extent unlike any earlier group (Doolittle 1992 and Knox 2001). The settlers transformed the natural landscape into a human landscape. Forests were cleared for fuel and building material, prairies were converted to agricultural fields, and hydropower dams were placed along the Baraboo River.

Today, the landscape remains characterized by cultivated fields and pastures. However, due to socio-cultural and socio-economic shifts within the watershed, the hydropower dams are no longer needed and are being removed. Several studies have looked at the immediate spatial and temporal hydraulic and geomorphic response to dam removal. However, there is a paucity of research that studies how longitudinal profiles and channels respond over several years, including responses to major floods. Considering that streams can take up to decades or even centuries to reach quasi-equilibrium (Pizzuto 2002) and that climate change may increase the intensity of flooding (Knox 2000; Lambert and Fyfe 2006; and Trenberth et al. 2007), there is a need for further research to explore these issues. With a better understanding of fluvial responses to dam removal, watershed managers and planners can better protect our safety and the quality of our natural resources. Considering the human drive to adapt to available natural resources and environmental services, this project tells the story of how human interactions with soil, water, and timber have changed over time, leading to the current environmental issue of dam removal.   To further our knowledge on the impacts of dam removal, this research examines how Wisconsin's Baraboo River longitudinal profile adjusted to the removal of the La Valle Dam and to the impact of a flood discharge approximated at the 500-year recurrence interval probability that occurred nine years later.

Chapter 2.0 Geographic Background of the Baraboo River Region

2.1 Geomorphology

To fully understand the cause and effect relationship between humans and the land, knowledge of the region's geology, soils, land cover, and climate is essential. It is the interaction among these four variables that make the Baraboo River watershed a unique natural resource, popular for its high quality agricultural soils, timber, and hydropower. The geomorphology and landscape evolution of the region results from interactions among geology, soil, land cover, and climate over time.

The upper Baraboo River watershed has an area of 575 square kilometers and is located in the geologic region known as the Western Uplands (Martin 1932). Located in the southwestern portion of the state, the Western Uplands is named for the rugged topography composed of broad, flat uplands and steep, valley slopes (figure 1). The high relief landscape of southwestern Wisconsin and the Western Uplands results from the absence of glaciers in the region during the most recent Pleistocene glaciations. Glaciers likely did not extend into the southwestern portion of the state mainly due to the deep topographic low of the Lake Superior syncline and the relatively low elevation underlying Lake Michigan; both had the net effect of diverting ice lobes away from southwestern Wisconsin (Irving 1877 and Cutler et al. 2001). Before the ice reached the Western Uplands, the climate warmed and the ice retreated north. Therefore, no glacial drift occurs in the Western Uplands, giving the region it's the more common name: the Driftless Area.

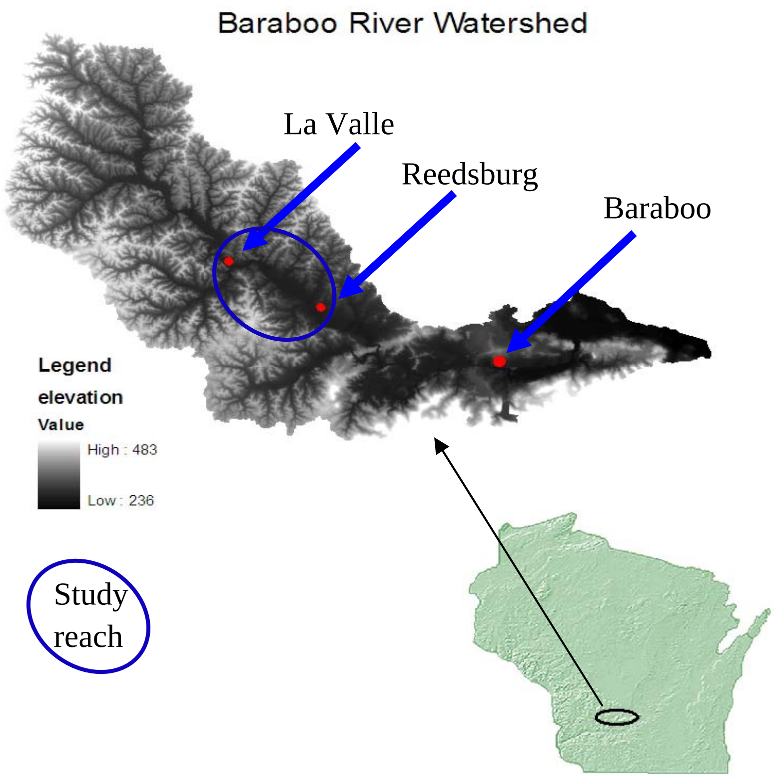

Figure 1 Relief map of the Baraboo River watershed and its approximate location in Wisconsin. The largest towns within the watershed include La Valle, Reedsburg, and Baraboo. The study reach includes the area between La Valle and Reedsburg and is outline on the map with a blue oval.

The lack of glaciers over the Western Uplands preserved the ridges from glacial erosion and flattening, allowing the Driftless Area landscape more time to develop its steep slopes and deep valleys. Glacial meltwater helped carve out the deep valleys as the melting ice formed braided, meltwater streams within major valleys that crossed the Driftless Area (Dott and Attig 2004). The braided streams abraded valley margins and contributed to the creation of the steep slopes that flank the rivers crossing the Driftless Area (Dott and Attig 2004).

2.2 *Geologic History of the Upper Baraboo River Watershed*

The collision, extension, and separation of tectonic plates contributed to the formation of the general topographic and bedrock structure of the Midwestern United States. The interior of the North American continent is relatively tectonically stable due to its location near the North American Craton, while the edges of the continents are more directly influenced by tectonic activities (USGS 2000). During the Paleozoic era, the western flank of the continent expanded westwards from the Craton while the eastern flank underwent extension followed by a series of orogenies due to collision with the African continent. Tectonic activity during the Appalachian (also referred to as the Alleghanian) orogeny on the eastern side of the continent likely created a series of basins and domes in the tectonically stable, interior continent (Gradstein and Ogg 2004). One dome formed around Lake Superior and northern Wisconsin, with a southern extension known as the Wisconsin Arch (USGS 2000 and Clayton and Attig 1990; figure 2).

The Wisconsin Arch is a broad, open fold extending southward from the Wisconsin Dome and positioned between the Michigan Basin to the east and the Forest City Basin to the west (Heyl et al. 1959; figure 2). The Arch produces a looping outcrop pattern for the erosion-resistant dolomite formations known as the Niagara and Galena-Platteville Cuestas starting at the Niagara Falls in Canada and continuing southwest into Wisconsin and Minnesota (Knox 2007; figure 2). Sauk County is located near the crest of the Wisconsin Arch, where the Paleozoic formations dip southward generally one to two meters per kilometer (Clayton and Attig 1990). However, this general trend is interrupted by the La Valle Fault in the present study area.

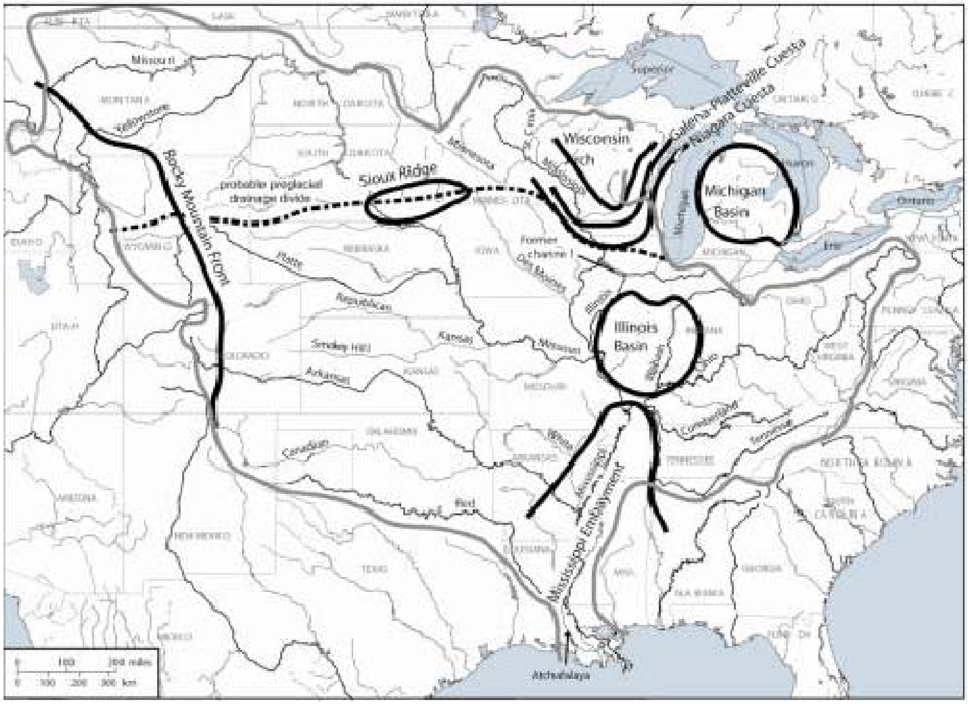

Figure 2 Map courtesy of Knox 2007. Map shows the location of the Michigan and Illinois Basins and the Wisconsin Arch. The location of the Galena-Platteville and Niagara Cuestas are also drawn.

The La Valle Fault is located near the village of La Valle and is at least 15 kilometers long (Clayton and Attig 1990). It trends east-west and curves slightly (Clayton and Attig 1990). The south side of the fault is downthrown and the rock bench associated with the Ironton member at the top of the Wonewoc formation (described in detail below) is about ten meters higher north of the fault than south of the fault (Clayton and Attig 1990).

The Wisconsin Arch is underlain by bedrock deposited during Cambrian times, dating 550-500 million years ago. At the beginning of the Cambrian Period, a shallow sea covered Wisconsin, depositing layers of sand. The upper Baraboo River watershed, located at the edge of this sea, experienced meters of pebble and sand deposition (Clayton and Attig 1990). The pebbles and sand later cemented into conglomerate sandstone several meters to tens of meters thick (Clayton and Attig 1990). As the shallow sea retreated in the middle to late Cambrian Period, the marine waters no longer reached the western side of the Wisconsin Arch to deposit sand and gravel. Instead, wind carried coarse to fine grained quartz sands and these aeolian deposits consolidated into sandstone. The quartz sand and sandstone layers form one of the lowest bedrock units called the Elk Mound Group (Dott and Attig 1990). While some do believe that the Elk Mound Group may have marine origins, the lack of marine fossils in the Wisconsin Dells area and the presence of adhesion ripples and adhesion-ripple bedding favor aeolian origin (Dott and Attig 1990).

The Elk Mound Group reaches a thickness of about 150 meters and contains the Mount Simon, Wonewoc, and Eau Claire Formations. The Mount Simon and Wonewoc Formations are characterized as more coarse grained quartz sand and sandstone. The Eau Claire Formation, which separates the Mount Simon and Wonewoc Formations, contains finer-grained, more dolomitic, more fossiliferous, and more glauconitic sandstone. Dott and Attig (1990) obtained sandstone core data from well records on file at the Wisconsin Geological and Natural History Survey (WGNHS) representing the Elk Mound Group near Dutch Hollow Lake, a few kilometers northwest of La Valle. The Elk Mound Group is described as consisting almost entirely of quartz grains. They noted that lithification is variable, but much of it is only slightly cemented, generally by silica.

The Mount Simon Formation is the lowest portion of the Elk Mound Group. Based on geological logs from the WGNHS, the formation consists primarily of medium-grained sand with considerable coarse-grained sand and smaller amounts of fine-grained sand. The coarse grains have undergone considerable rounding and consist mostly of quartz. No fossils exist in the Mount Simon Formation, supporting its hypothesized aeolian origin (Clayton and Attig 1990).

The Eau Claire Formation is a thinner portion of the Elk Mound Group and is thought to vary in thickness between 50 and 100 meters (Clayton and Attig 1990). The formation is located in the middle of the Elk Mound Group and consists of dolomite-cemented quartz sandstone, which is described as a very fine to medium sand with considerable dolomitic siltstone, dolomitic shale, and sandy dolomite. Glauconite and marine fossil fragments exist in many samples taken by the WGNHS; therefore, the Eau Claire Formation is considered a marine deposit. The presence of this thin marine deposit implies that the regressing shallow sea of the middle to late Cambrian Period experienced a short transgression. As the sea regressed again, new sand deposition occurred and subsequently became part of the Wonewoc Formation.

The Wonewoc Formation is composed of two members: the Galesville Member and the Ironton Member. The Galesville Member is the main bedrock unit in the Reedsburg reach of the Baraboo River (Clayton and Attig 1990). This member is the lower part of the Wonewoc Formation and is typically 15 to 20 meters thick in the study area. Clayton and Attig (1990) note that outcrops of the member generally consist of medium sand with considerable fine sand. WGNHS geologic logs note considerable coarse sand in the subsurface samples. Ostrom (1971) completed a laboratory analysis of 20 samples from northern Sauk County and found that the Galesville is generally fine to medium sand but includes coarser grains that tend to be well rounded and consist almost entirely of quartz.

The origin of the Galesville Member is not completely understood. No fossils exist in the Galesville Member, but burrows can be found near the top. Many suggest a fluvial and aeolian origin due to the lack of fossils (Dott et al. 1986; Stenzel 1983; and Clayton and Attig 1990). Fielder (1985) believes the presence of burrows indicates marine origin and Anstett (1977) believes that the burrows suggest a marine origin for at least the upper part of the member in Sauk County (Clayton and Attig 1990).

The Ironton Member represents the upper part of the Wonewoc Formation and can be identified along road cuts and natural cliffs in the study area (Clayton and Attig 1990). It is this formation through which the La Valle reach of the Baraboo River flows (Clayton and Attig 1990). The member is three to four meters thick and consists of fine to medium sand. The Ironton sandstone tends to be coarser and more poorly sorted than the Galesville sandstone, but the difference is not especially conspicuous in the study area (Clayton and Attig 1990). The sand grains are primarily quartz and tend to be more angular than those of the Galesville. The unit is well cemented with silica and much of the unit is nonglauconitic, noncalcareous, and nondolomitic. In addition, the Ironton sandstone is slightly fossiliferous, implying a marine origin.

The last geologic formation found in the study area is the Tunnel City Formation. The shallow sea that deposited the sand of the Ironton Member rose and deposited the sediments which make up the Tunnel City Formation (Clayton and Attig 1990). The Tunnel City Formation is typically between 30 and 45 meters thick and consists of the Lone Rock Member and the Mazomanie Member. Only the Lone Rock Member is thought to exist in the study region (Clayton and Attig 1990).

The Lone Rock Member is mostly sandstone, which typically consists of fine sand with some very fine sand and a smaller amount of medium sand (Clayton and Attig 1990). It is coarsest at its base. A few percent to a few tens of percent consists of glauconite. Dolomitic sandstone and sandy dolomite beds occur near the base of the formation (Clayton and Attig 1990). The dolomite grains are typically medium to coarse sand in size. The formation is slightly fossiliferous and burrows are generally present (Clayton and Attig 1990). Most of the Lone Rock Member is poorly lithified or unlithified and many parts have calcareous or dolomitic cement (Clayton and Attig 1990).

The different geologic formations in the study area have different levels of resistance to erosion. Those formations that are more resistant to erosion tend to have steeper cliff faces while those that are less resistant to erosion have gentler cliff faces. Of the formations described, the Mount Simon and Eau Claire Formation tend to be the least resistant to erosion, followed by the Tunnel City Formation and then the Wonewoc Formation (Clayton and Attig 1990). Within the Wonewoc Formation, the Galesville Member tends to be less resistant than the Ironton Member (Clayton and Attig 1990). The Ironton Member's strong resistance to erosion forms the steep bluffs found along the Baraboo River surrounding the city of La Valle.

2.3 Soils

During the last glaciations, Glacial Lake Wisconsin extended into the Baraboo River Valley, including the Reedsburg and La Valle basins (Clayton and Knox 2008). As a result, the soils of the valley floor are generally medium-textured soils underlain by sand or stratified loamy and sandy lacustrine deposits. In contrast, the uplands are generally dominated by fine-textured loamy soils. Howard F. Gundlach (1980) completed a soil survey of the region, documenting and mapping the soil types, their characteristics, and possible uses. The portions of the survey relevant to the Baraboo River study area are summarized below.

Fluvaquents dominate in the riparian lands bordering the stream in the La Valle and Reedsburg basins. These soils are found on flat, frequently flooded, poorly drained floodplains and drainage-ways. The soil surface layer ranges from silt loam to sand and may be locally organic. The soil below the surface layer is generally stratified sandy, loamy, and silty material. Permeability of the Fluvaquents range from moderate to rapid. The available water capacity, natural fertility and organic matter content of the surface layer vary. Often, surface runoff is slow or ponded and the water table tends to sit near the surface much of the year.

The high water table and frequent flooding of Fluvaquents result in generally poor soils for cultivated crops, recreational development, engineering uses, and forage species. Instead, most areas are used for woodland, wildlife habitat, or unimproved pasture. Some areas with adequate drainage and flood protection may support corn, soybeans, and small grain as well as legumes and grasses for hay and pasture. While artificial drainage may be feasible in some areas, it is not feasible in most; loose sand often enters the lines of tiles built for internal drainage and ditchbanks are easily eroded by flowing water or plugged by vertical banks that cave.

Overgrazing and other activities that remove vegetation destroy plant communities by encouraging the colonization of undesirable plants or increasing erosion. Fluvaquents tend to be restricted to cover by fast-growing species, making bare, overgrazed lands susceptible to invasion by unwanted pioneer species such as reed canary grass. Additionally, overgrazing increases the susceptibility of soils to erosion during periods of overbank flooding. Last, if grazing occurs when the soil is wet, soil compaction increases which decreases the soil quality for cultivation.

As one extends farther out from the riparian habitat, the soil types and topography become much more diverse. The La Valle basin has more variable topography and was impacted less by the Glacial Lake Wisconsin than the Reedsburg basin. This likely explains the greater variation in soil types across the landscape of the La Valle basin than that of the Reedsburg basin. The main soil association found in the La Valle basin outside of riparian lands is the La Farge-Norden-Gale, with most soils being either La Farge or Norden. These soils are generally found on ridgetops, side slopes, and valley floors in unglaciated sandstone uplands, such as the area surrounding La Valle. Depth to sandstone bedrock varies between 20 and 40 inches (50-100 cm). The soils of this series on gentle slopes are adequate for crop cultivation and pasture while the steeper slopes best support woodland.

La Farge soils are generally well-drained and moderately permeable, with a moderate available water capacity. They are found on slopes ranging from two to 30 percent and formed in loess and residuum from the underlying glauconitic sandstone bedrock. The surface layer tends to be silt loam about eight inches (20 cm) thick with a silt loam to clay loam subsoil about 25 inches (65 cm) thick. These silt upper horizons probably represent a thin loess mantle Glauconitic sandstone and siltstone bedrock is found at a depth of about 33 inches (85 cm).

Norden soils are similar to La Farge soils in that they are generally well-drained and moderately permeable, with a moderate available water capacity. They are often found on steeper slopes than the La Farge soils, ranging between two and 60 percent. Norden soils formed in loamy residuum from the underlying, fine-grained glauconitic sandstone bedrock. The surface layer tends to be loam with a thickness of three inches (8 cm), the subsurface layer is also loam with a thickness of about four inches, and the subsoil is about 21 inches (55 cm) thick. Glauconitic sandstone bedrock is at a depth of about 28 inches (70 cm).

Gale soils are well-drained and moderately permeable in the subsoil while rapidly permeable in the sand substratum; the available water capacity is moderate. They are found on slopes ranging from two to 30 percent and formed in loess and a thick layer of residuum from the underlying sandstone. The surface layer of the Gale series is silt loam about seven inches (18 cm) thick. The subsoil is about 24 inches (60 cm) thick. The substratum extends to a depth of about 60 inches (150 cm) and is mostly loose sand over soft sandstone. The soft sandstone bedrock begins at a depth of about 35 inches (90 cm).

The La Farge-Norden-Gale association is also present in the Reedsburg basin, but more often the Eleva-Boone-Plainfield association is encountered due to the stronger influence of Glacial Lake Wisconsin. Like the La Farge-Norden-Gale association, the Eleva-Boone-Plainfield unit is located on ridge tops, side slopes, and valley floors. More specifically, the Eleva and Boone series can be found on ridge tops, side slopes, and valley floors while the Plainfield soils are on foot slopes and valley floors. Soils of this association are often used for cultivation or pasture. However, the steeper areas best support woodland due to erosion hazards.

Eleva soils are somewhat excessively drained and moderately to rapidly permeable with a low available water capacity. They are found on gentle slopes ranging between zero and three percent and formed in loamy and sandy sediments over sandstone bedrock. The surface layer is a sandy loam about nine inches (25 cm) thick. The subsoil is about 22 inches (55 cm) thick, consisting of sandy loam in the upper part and loamy sand in the lower part. The substratum goes to a depth of about 60 inches (150 cm) and is loose sand over soft sandstone. The soft sandstone begins at a depth of about 36 inches (90 cm).

Boone soils are excessively drained and rapidly permeable with a very low available water capacity. Boone soils are found on slopes ranging between two and 30 percent and formed in sandy residuum from underlying sandstone bedrock. Boone soils tend to have less silt and clay and more sand than the Eleva soils. The Boone soils have a sand surface layer about seven inches (20 cm) thick and a loose sand substratum about 21 inches (50 cm) thick. Below the loose sand substratum, soft sandstone begins at a depth of about 28 inches (70 cm).

Like Boone soils, Plainfield soils are excessively drained and very permeable. The available water capacity is low. Plainfield soils tend to be found on the alluvial plains and stream terraces where slopes vary between one and 30 percent. These soils in the Reedsburg basin formed in deep deposits of sand associated with Glacial Lake Wisconsin shorelines. The Plainfield surface layer is typically loamy sand and about seven inches (20 cm) thick. The subsoil is sand with a thickness of about 23 inches (60 cm). The substratum extends to a depth of about 60 inches (150 cm) and is mostly loose, find sand over loose sand.

2.4 Climate

Climate is a principal driver in hydrologic systems. It strongly influences flood frequencies and magnitudes within river systems, eliciting hydrologic and fluvial geomorphic response to climatic events and climate change. Flood frequency and magnitude drive sediment movement through a watershed, thereby influencing a stream’s capacity to contain flood waters and ability to maintain an equilibrium channel form (Woltemade 1994). Studying trends in hydrologic and geomorphic response requires careful sorting of human and climatic causal factors since human land uses can also alter flood regimes and sediment budgets of fluvial systems by increasing surface runoff and erosion (Trimble and Lund 1982; Trimble 1983; Beach 1994; and Knox 2001).

Since significant human land use change in the study region did not begin until the mid-1800s, it is easier to sort out the human and climatic influences on hydrology and fluvial geomorphology. However, with projected changes in climate, it is important to consider how the human-caused changes to hydrology and fluvial geomorphology are or will be impacted by climatic-driven changes in the hydrologic cycle. The following section aims to give an overview of climatic trends over the past century in order to provide 1) a framework for the separation of human and climatic influences on the Baraboo River watershed from settlement to present and 2) to hypothesize potential impacts of projected climate change to the river channel response to dam removal.

The Baraboo River watershed is located in the temperate continental climate region of southwest Wisconsin, characterized by relatively cold winters and hot summers. Historical annual averages for temperature and precipitation are available starting in 1885 for southwest Wisconsin from the Wisconsin State Climatology Office. The average annual temperature data show a slight warming trend starting in the 1930s; however, there is little variability overall from 1885 to 2005 (figure 3). The average annual temperature for this time period is 45.6 degrees Fahrenheit (7.6 degrees Celsius). The total annual precipitation remains relatively constant from 1885 to the early 1970s. Then, from 1990 to present there is a slight increase in annual precipitation. However, starting in the 1940s through the 1970s, annual averages become more variable than in the period before the 1940s; there are more years with especially high and especially low annual precipitation totals (figure 4). The average annual precipitation for 1885 to 2007 is 32.86 inches (82.15 cm). Snow fall data for southwest Wisconsin begins in 1950. There has been no noticeable increasing or decreasing trend in total annual snow fall during the past half century (figure 5). The average annual snowfall from 1950 to 2005 is 39.0 inches (97.5 cm).

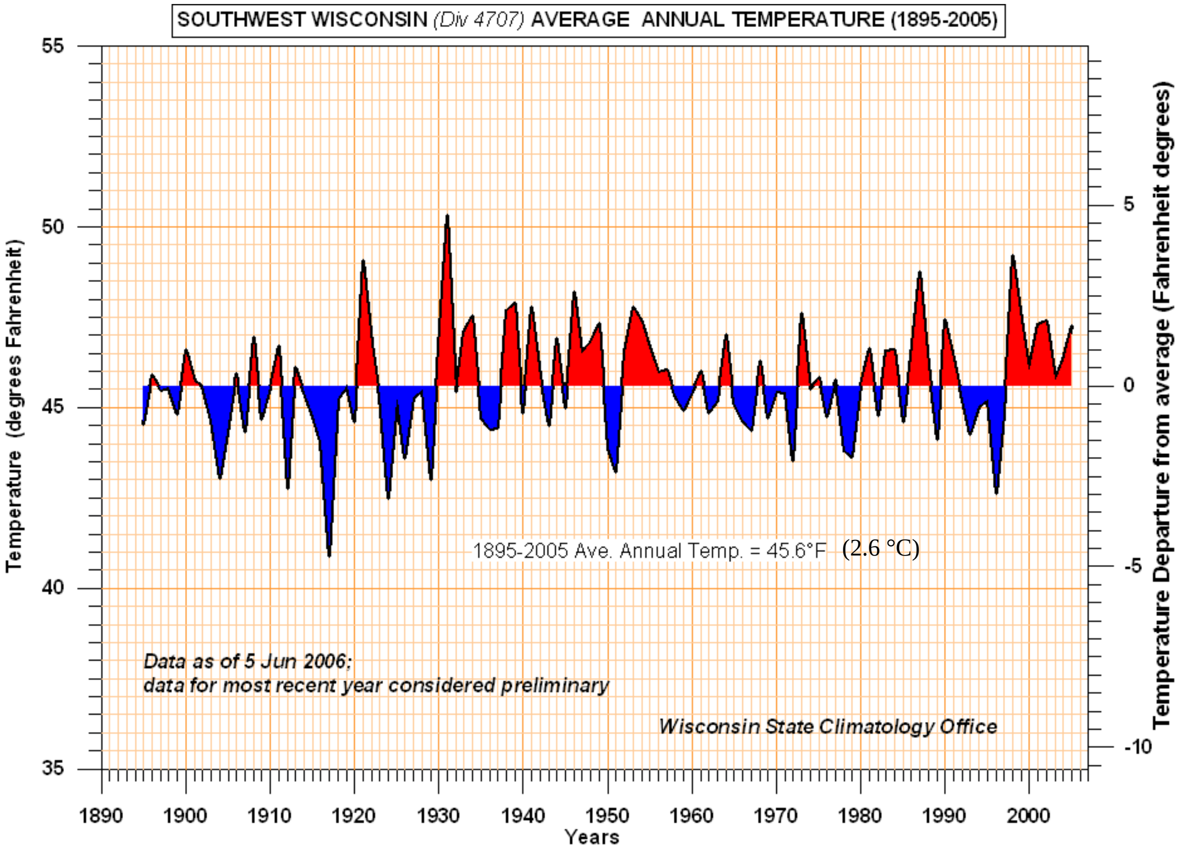

Figure 3 Average annual temperature for the years 1895-2005 in southwest Wisconsin. Temperature and temperature departure from average is measured in degrees Fahrenheit on the y-axis. The area in red represents years with above average temperature and the area in blue represents years with below average temperature.

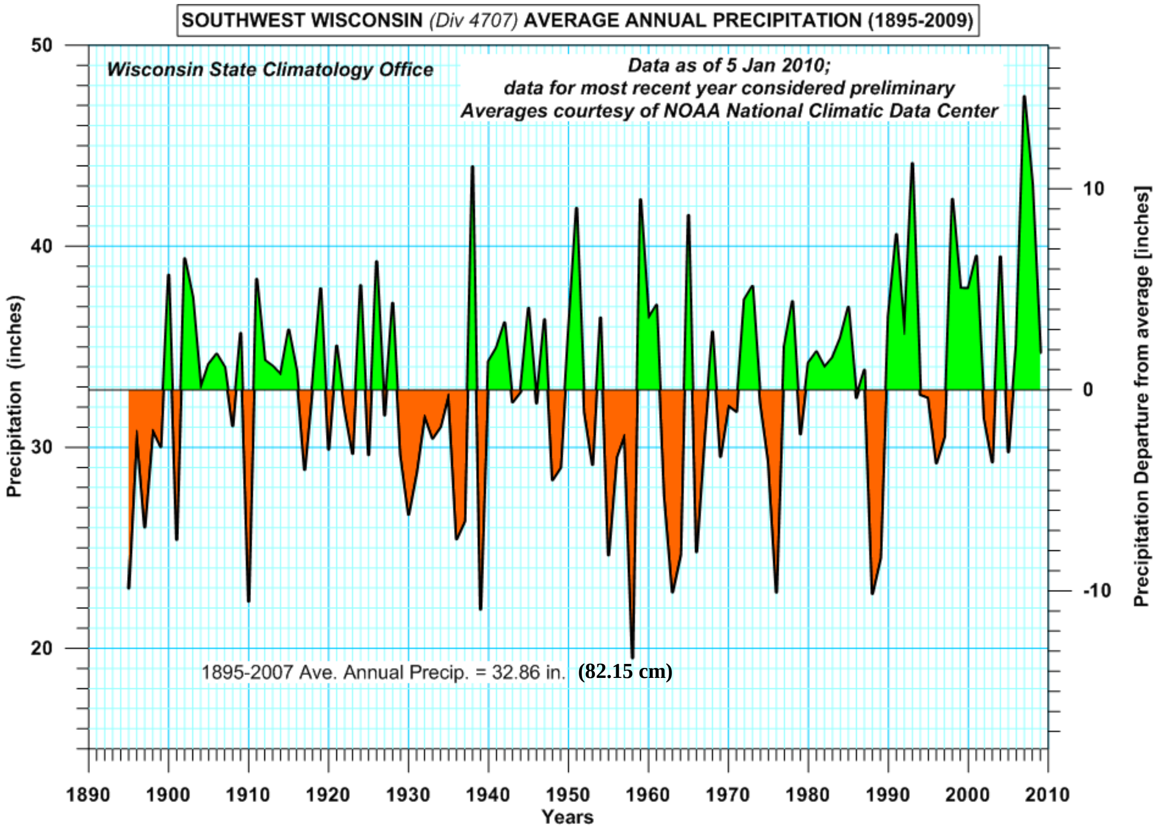

Figure 4 Average annual precipitation for the years 1895-2009 in southwest Wisconsin. Precipitation and precipitation departure from average is measured in inches on the y-axis. The area in green represents years with above average precipitation and the area in orange represents years with below average precipitation.

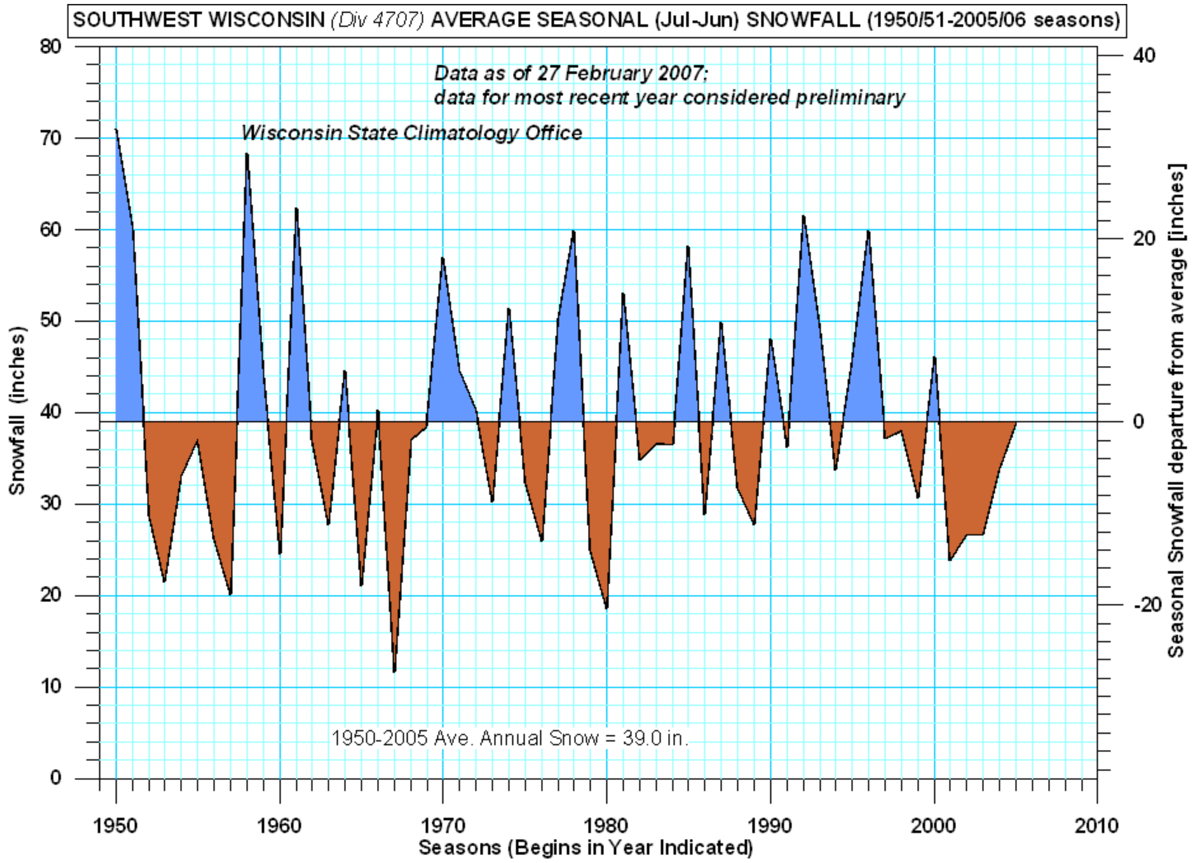

Figure 5 Average annual snowfall for the years 1950-2006 in southwest Wisconsin. Snowfall and snowfall departure from average is measured in inches on the y-axis. The area in blue represents years with above average snowfall and the area in brown represents years with below average snowfall.

The National Climatic Data Center (NCDC) calculated the climatic normal for southwest Wisconsin, defining it as the data average for the period 1971-2000. The NCDC calculated 45.7 degrees Fahrenheit (7.6 degrees Celsius) as the climatic normal average annual temperature and 33.92 inches (84.8 cm) as the climatic normal average annual precipitation. This shows little difference from the temperature and precipitation averages calculated for the years 1885-2006. The 1971-2000 climatic normal average annual snowfall is 41.8 inches (104.5 cm), slightly higher than the average for 1950 to 2007.

The temperate continental climate of southwest Wisconsin results in temperature and precipitation variations throughout the year. The climatic normal average winter temperature and precipitation is 19.7 degrees Fahrenheit (-6.8 degrees Celsius) and 3.44 inches (8.6 cm), respectively. Spring climatic normal average temperature and precipitation is 45.8 degrees Fahrenheit (7.7 degrees Celsius) and 9.24 inches (23.1 cm), respectively. Summer climatic normal average temperature and precipitation are 69.2 degrees Fahrenheit (20.7 degrees Celsius) and 13.14 inches (32.9 cm). Fall climatic normal average temperature and precipitation is 48 degrees Fahrenheit (8.9 degrees Celsius) and 8.10 inches (20.3 cm; table 1).

Table 1 Climatic normal averages of temperature and precipitation for the winter, spring, summer, and fall seasons. Data from the National Climatic Data Center (NCDC).

	Temperature °F	Temperature °C	Precipitation (in)	Precipitation (cm)
Winter	19.7	-6.8	3.44	8.6
Spring	45.8	7.7	9.24	23.1
Summer	69.2	20.7	13.14	32.9
Fall	48.0	8.9	8.10	20.3

The timing of precipitation events is extremely important in regards to how river systems transmit discharge from these events. In fact, the occurrence of larger floods generally result from early spring rains falling on winter snow (Knox 2000, Doyle et al.

2003b, and Fitzpatrick et al. 2008). NCDC data show an increase in spring and summer precipitation starting in 1990, the same period in which total annual precipitation begins to increase (figures 6 and 7). Fall and winter precipitation show little or no change over the past century (figures 8 and 9).

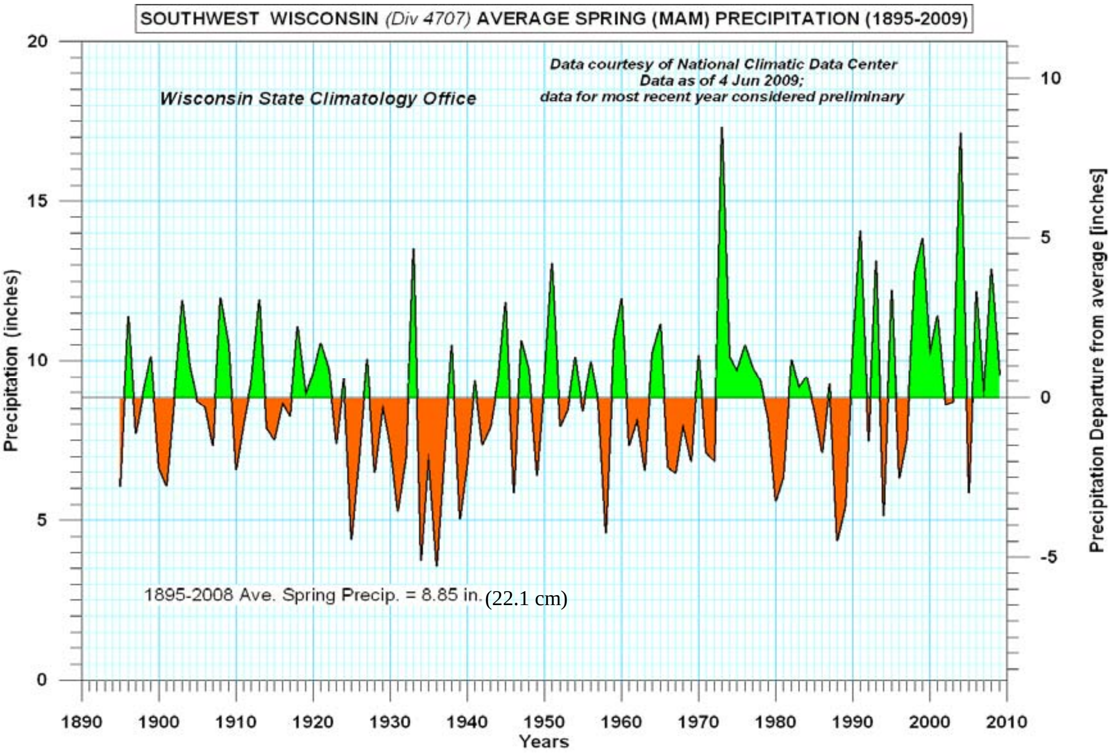

Figure 6 Average spring precipitation for the years 1895-2009 in southwest Wisconsin. Precipitation and precipitation departure from average is measured in inches on the y-axis. The area in green represents years with above average spring precipitation and the area in orange represents years with below average spring precipitation.

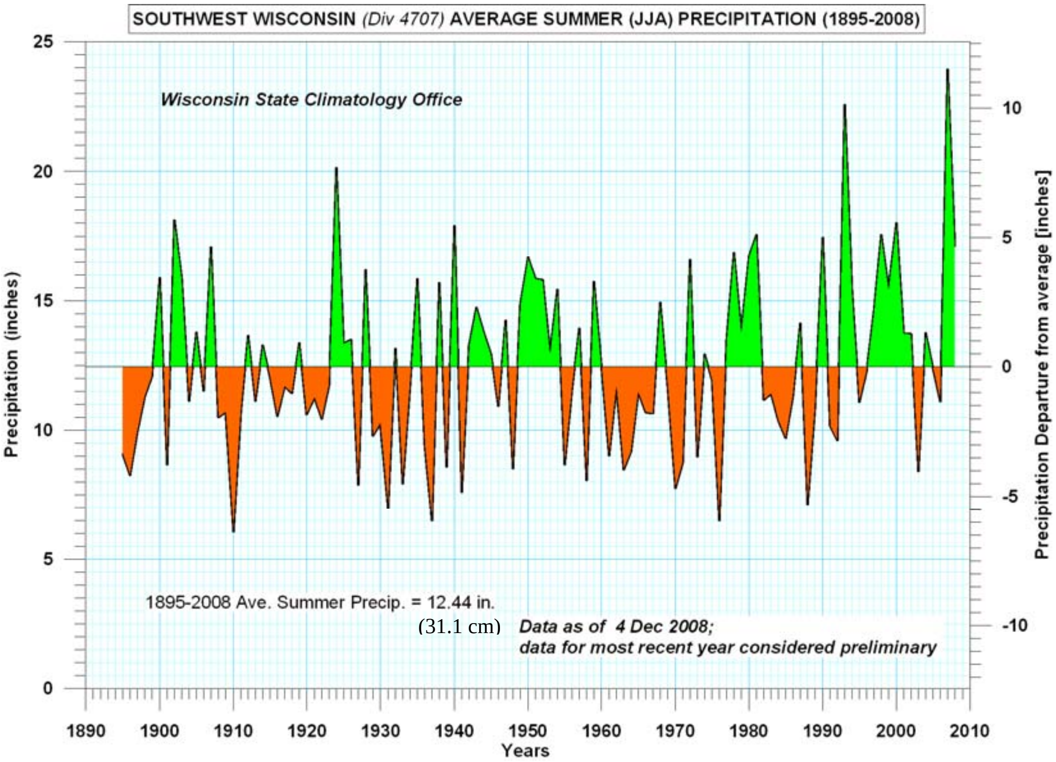

Figure 7 Average summer precipitation for the years 1895-2009 in southwest Wisconsin. Precipitation and precipitation departure from average is measured in inches on the y-axis. The area in green represents years with above average summer precipitation and the area in orange represents years with below average summer precipitation.

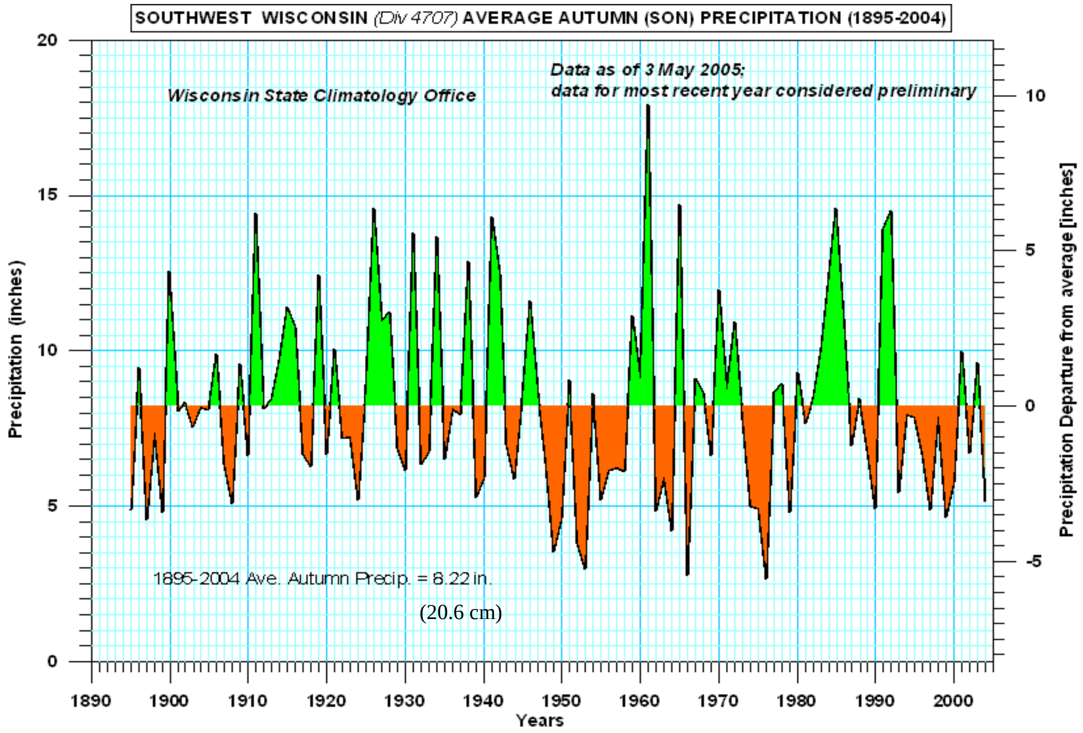

Figure 8 Average fall precipitation for the years 1895-2004 in southwest Wisconsin. Precipitation and precipitation departure from average is measured in inches on the y-axis. The area in green represents years with above average fall precipitation and the area in orange represents years with below average fall precipitation.

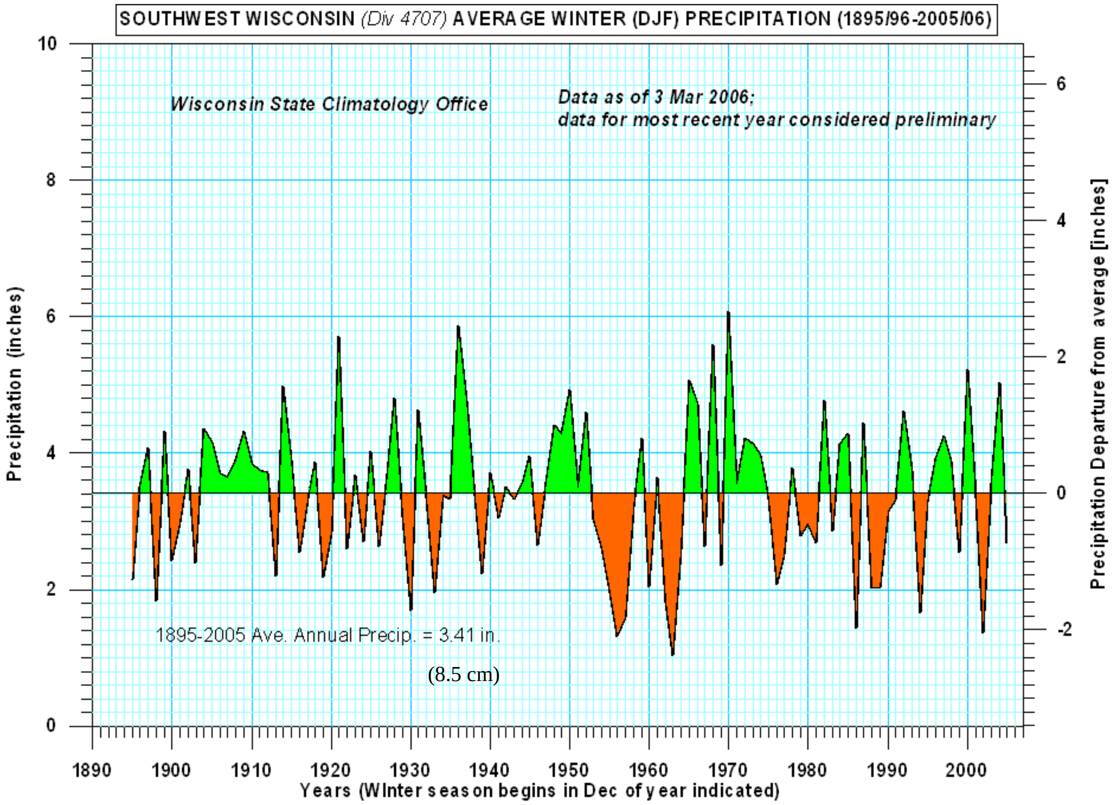

Figure 9 Average winter precipitation for the years 1895-2005 in southwest Wisconsin. Precipitation and precipitation departure from average is measured in inches on the y-axis. The area in green represents years with above average winter precipitation and the area in orange represents years with below average winter precipitation.

Temperature has also experienced some seasonal changes from 1885 to 2006. Spring temperatures appear to be warming beginning in the mid-1970s (figure 10). Summer and fall temperatures show little or no change from 1885 to 2006 (figures 11 and 12, respectively). Winter temperatures appear to increase beginning in the late 1970s or early 1980s to present (figure 13).

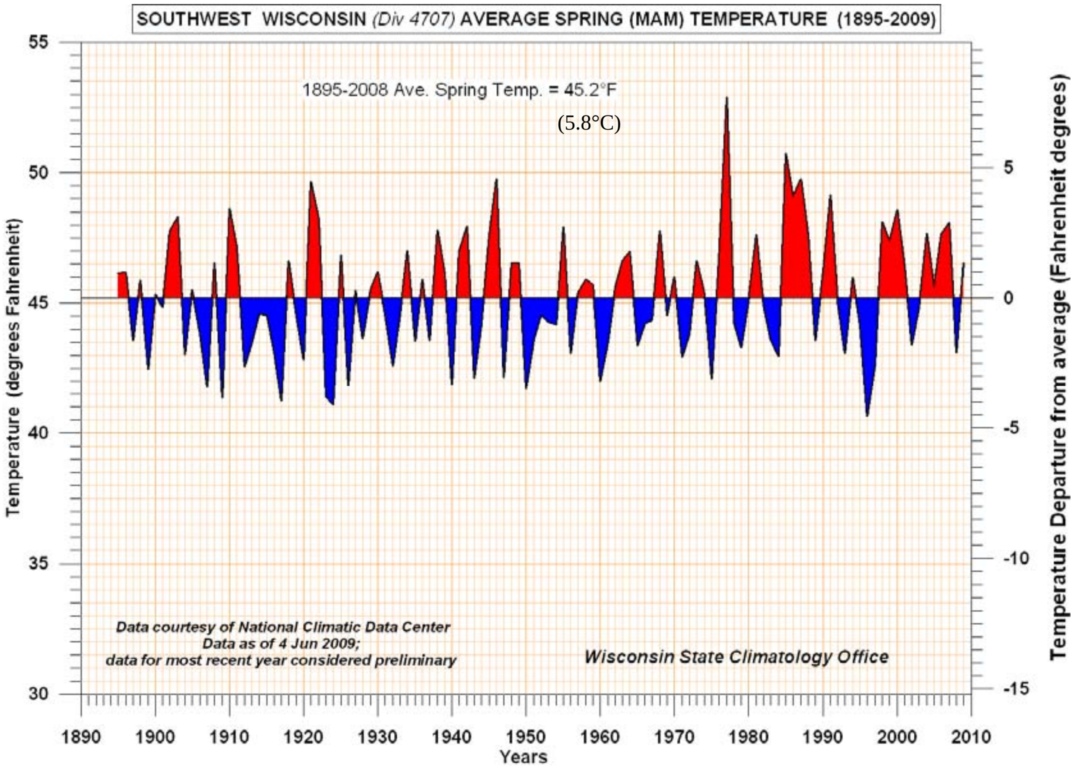

Figure 10 Average spring temperature for the years 1895-2009 in southwest Wisconsin. Temperature and temperature departure from average is measured in degrees Fahrenheit on the y-axis. The area in red represents years with above average spring temperature and the area in blue represents years will below average spring temperature.

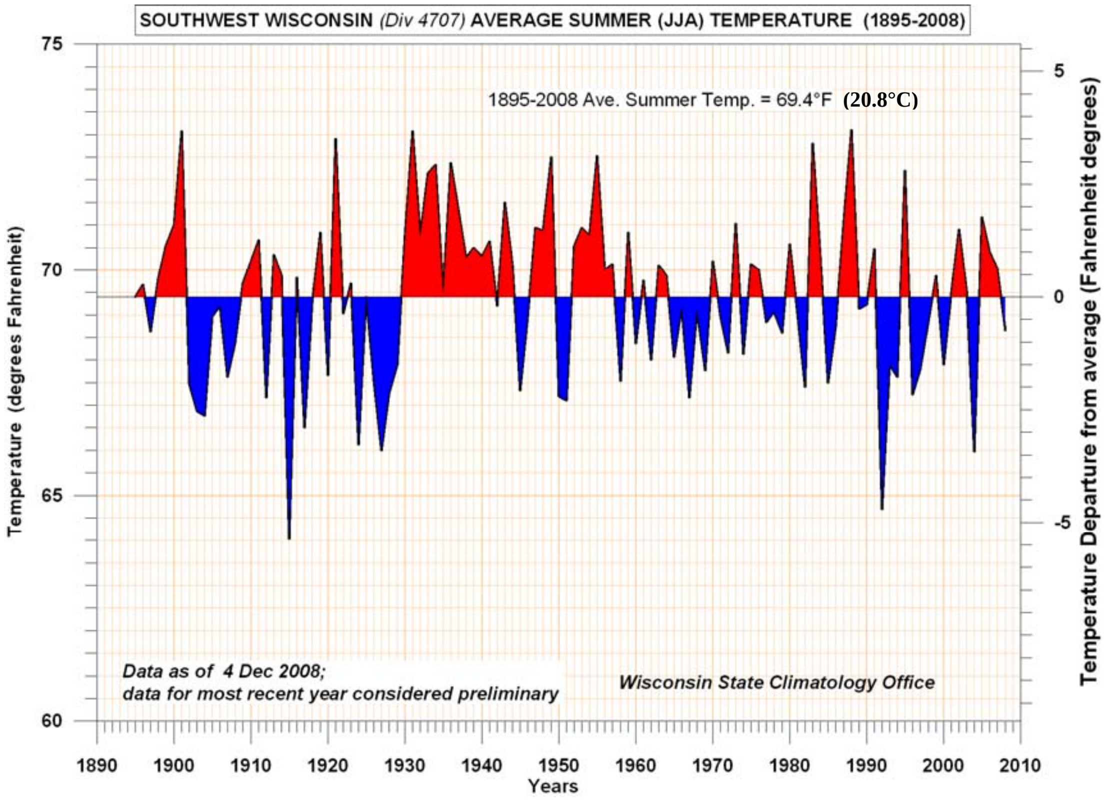

Figure 11 Average summer temperature for the years 1895-2009 in southwest Wisconsin. Temperature and temperature departure from average is measured in degrees Fahrenheit on the y-axis. The area in red represents years with above average summer temperature and the area in blue represents years will below average summer temperature.

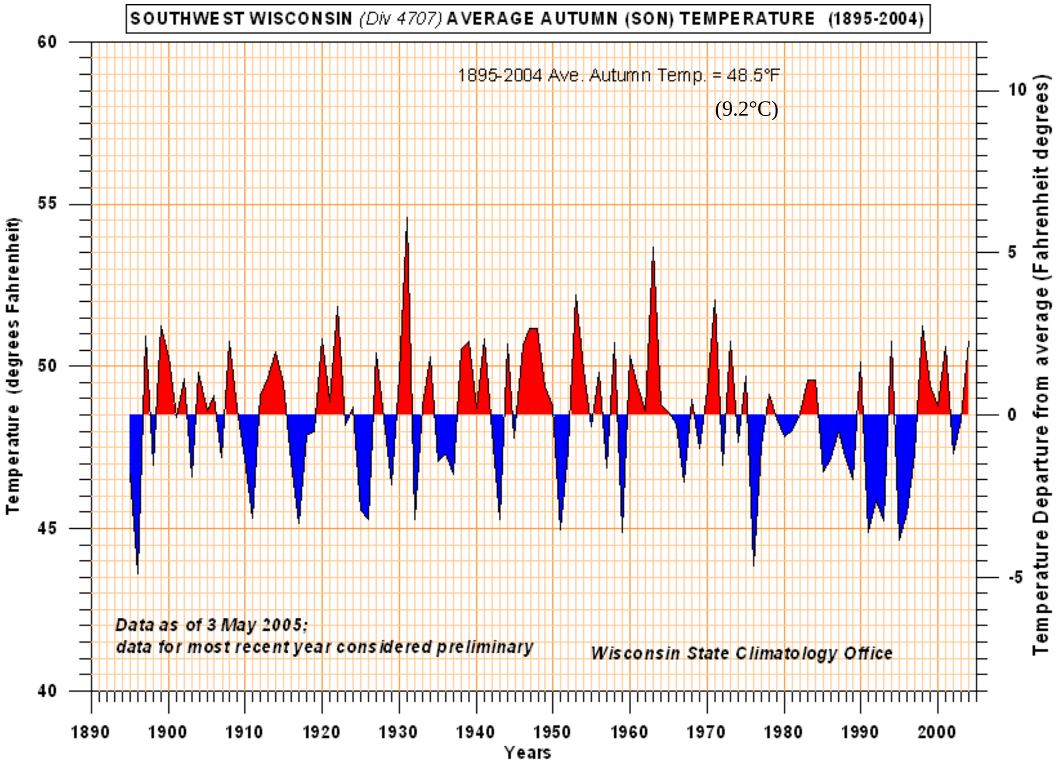

Figure 12 Average fall temperature for the years 1895-2004 in southwest Wisconsin. Temperature and temperature departure from average is measured in degrees Fahrenheit on the y-axis. The area in red represents years with above average fall temperature and the area in blue represents years will below average fall temperature.

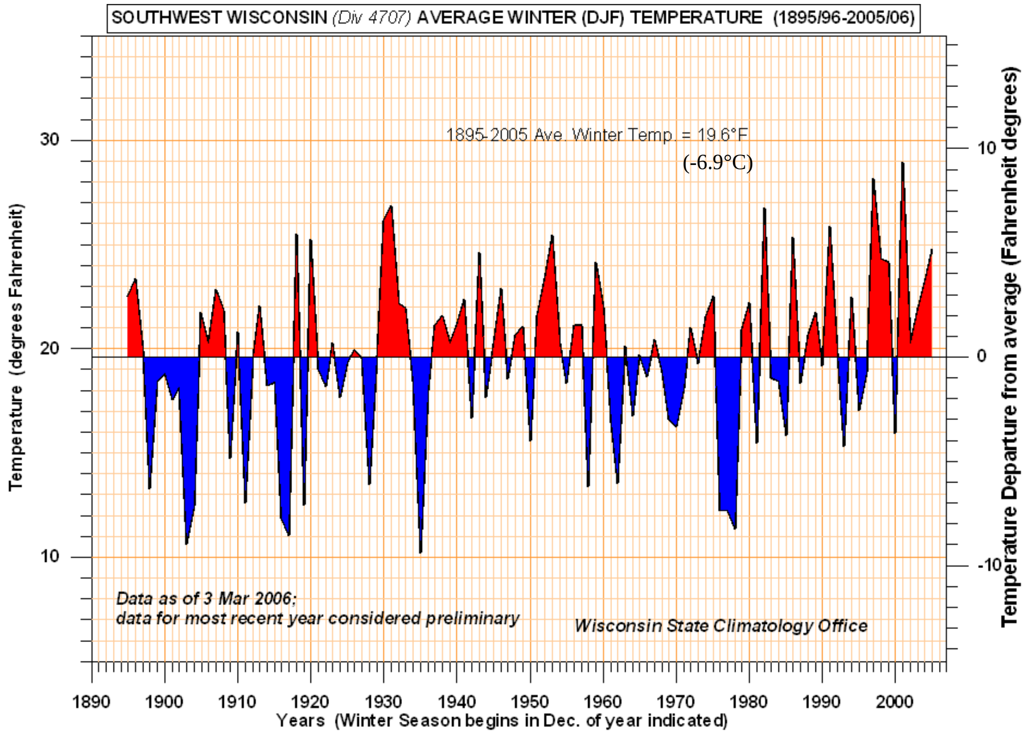

Figure 13 Average winter temperature for the years 1895-2005 in southwest Wisconsin. Temperature and temperature departure from average is measured in degrees Fahrenheit on the y-axis. The area in red represents years with above average winter temperature and the area in blue represents years will below average winter temperature.

Small changes in mean annual climate characteristics are often associated with important changes in storm track and air mass boundary patterns (Knox 2000). For example, temperature and precipitation from the Holocene to modern probably did not change by more than two degrees Celsius and 20%, respectively (Bartlein et al. 1984; Winkler et al. 1986; Baker et al. 1996). However, the corresponding changes in storm track and air mass boundary locations had large impacts on magnitudes and frequencies of floods (Knox 2000).

Large floods along rivers like the Baraboo tend to occur between March and June when the preceding summer and fall is especially wet, followed by an anomalously wet winter and spring, and below average annual temperature (Knox 2000). The wet conditions of the preceding summer and fall leave the soil highly saturated going into the winter, less able to absorb the melting snow. When the spring is also wet, then rain-on-snow events cause accelerated melting and runoff since the highly saturated soil has reduced capacity to absorb the moisture. It is the moisture content of seasonal air masses and the proximity of storm tracks which result from hemispheric atmospheric circulation patterns that influence whether the precipitation and temperature regimes will be wet and cool enough to produce these large floods.

Floods in southwest Wisconsin, including the Baraboo River watershed, tend to increase when the large, moist tropical air masses originating from the Gulf of Mexico migrate north meet with the cold, dry polar air masses at a well-defined front (figure 14). Cyclonic circulation on the downstream side of upper-level troughs produces northward advection of the warm, moist, and unstable air, and convective and frontal lifting associated with the cyclone produce heavy rain. Persistence of the storm track over southwest Wisconsin during the warm season increases frequencies of large floods.

Current climate change predictions state that large floods will become more common in the Upper Mississippi River watershed, including southwest Wisconsin (Knox 2000; Lambert and Fyfe 2006; and Trenberth et al. 2007). If this is accurate, the hydraulic and fluvial geomorphologic influences of these large floods to streams undergoing dam removals will be increasingly important. Therefore, this study considers the influence of the June 2008, 500-year flood on the hydraulic and geomorphic responses of the Baraboo River to the La Valle dam removal.

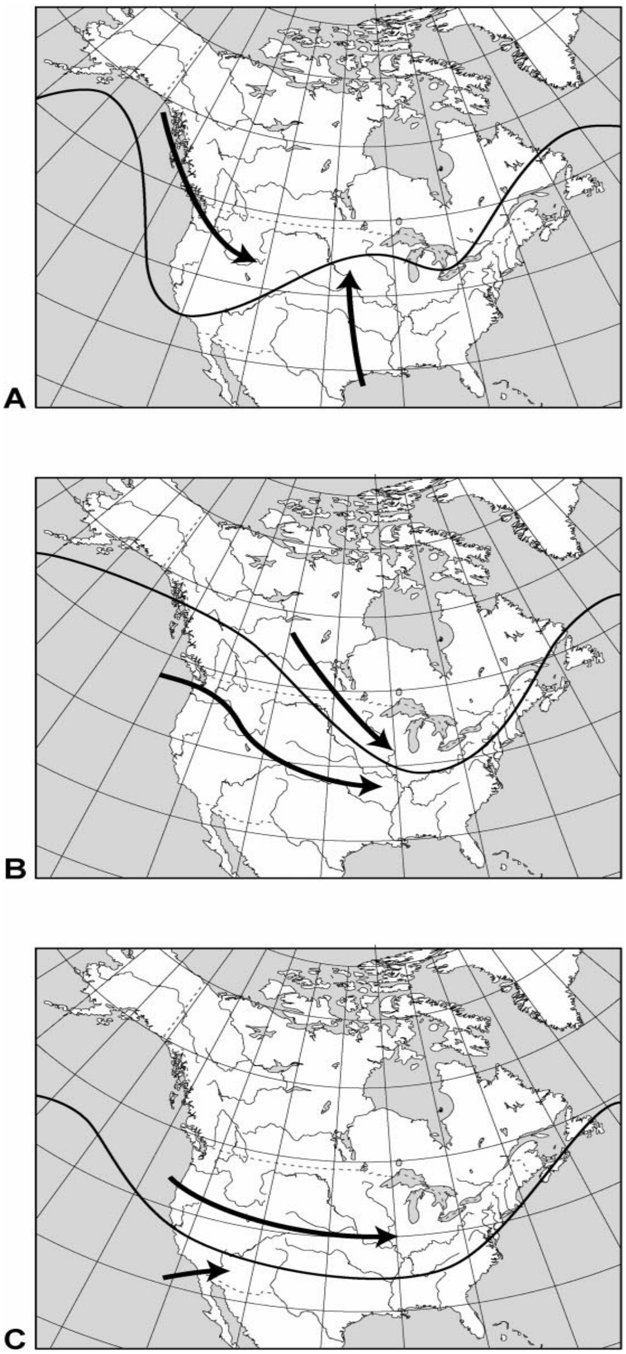

Figure 14 Arrows depict air mass trajectories and lines depict jet stream locations. The strong meridional flow in map A is associated with frequent large floods in the Upper Mississippi Valley as the moist tropical air masses enter the region and the storm track along the jet stream crosses the region. The circulation patterns in maps B and C bring relatively dry, stable air masses into the region which reduces the occurrence of large floods. Figure source: Knox 2000.

2.5 Land Use and Land Cover

The temporal interactions among geology, soils, and climate within a watershed produce unique land cover histories and influences land use. Plants cannot colonize a region until soil forms, and soil formation requires the physical and chemical weathering of bedrock by climate and organisms. Various biological and climatic drivers further impact the types of vegetation that dominate the landscape over time. Patterns of land cover change in the Baraboo River watershed can be split into two major intervals: the climate-driven shifts in vegetation and the human-driven shift in vegetation.

Since the last glaciation, several major plant communities colonized and disappeared as ecotones shifted to the north and east. Maher (1982) studied a soil core from Devil's Lake and recorded the type and abundance of pollen dating from 12,500 years ago to present (figure 15). Maher's (1982) core study shows that the plant community progression began with the boreal forest, followed by the northern conifers with mesic hardwoods, then the mesic forest, next the oak savanna, and last the oak forest and mesic forest (Lange 1990).

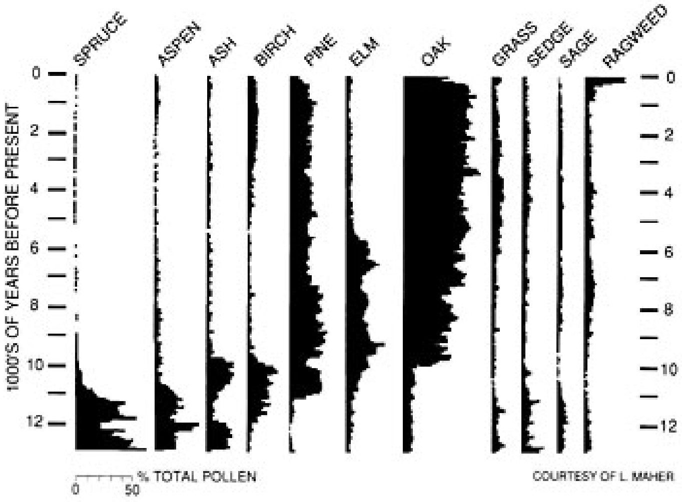

Figure 15 Graph of percentage of pollen from Maher's Devil's Lake core. Years indicated are radiocarbon years. Source: Maher 1982.

When glaciers covered most of Wisconsin between about 25,000 and 16,000 calendar years ago, the Driftless Area experienced tundra conditions but was soon colonized by coniferous forest (Knox et al. 1982). The conifer colonization was short-lived due to the rapidly changing climate as the Wisconsin Glacier receded (Maher 1982). White pine, jack and/or red pines, elm, maple, basswood, and ironwood colonized the region next. This post-glacial conifer and mesic hardwood forest dominated from about 10,500 years ago to 9,000 radiocarbon years ago. By 9,000 radiocarbon years ago, the climate was too warm for the pine woodland so the mesic forest dominated. Beginning around 6,500 radiocarbon years ago the climate became warm and dry, no longer favoring the mesic forest that requires moderate moisture. As a result, an oak savanna took over, populated by grasses and shrubs.

The last major climate-driven shift about 3000 radiocarbon years ago produced a plant community dominance that remained until the first Euro-American settlers of the Baraboo River watershed in the 1700s. Around 3,000 years ago, the climate cooled and precipitation increased. In response, the oak savanna transformed into an oak forest and the mesic forest reappeared in the lowlands (figure 16).

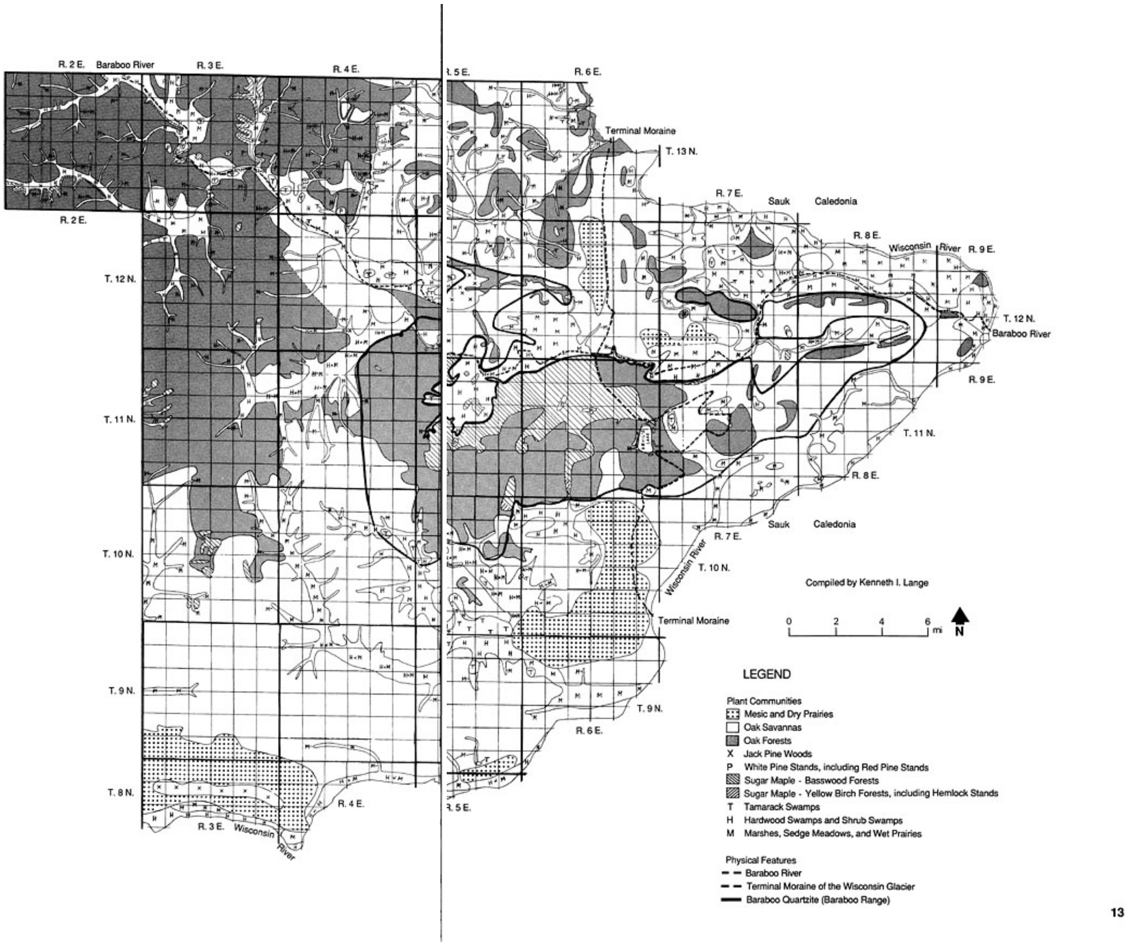

Figure 16 Map of pre-settlement vegetation in Sauk County, Wisconsin. Produced using data from the US General Land Office Public Land Surveys. Source: Lange 1976 and 1990.

The open forests coupled with the fertile soils formed over approximately the past 12,500 years made the Baraboo River watershed an attractive region for Euro-American settlement. As settlers colonized the watershed in the early 1800s, they quickly replaced the oak and mesic forests with cultivated fields. Today, cropland accounts for approximately

58% of the land cover and 90% of the land use within the watershed (USDA 2001; figures 17 and 18).

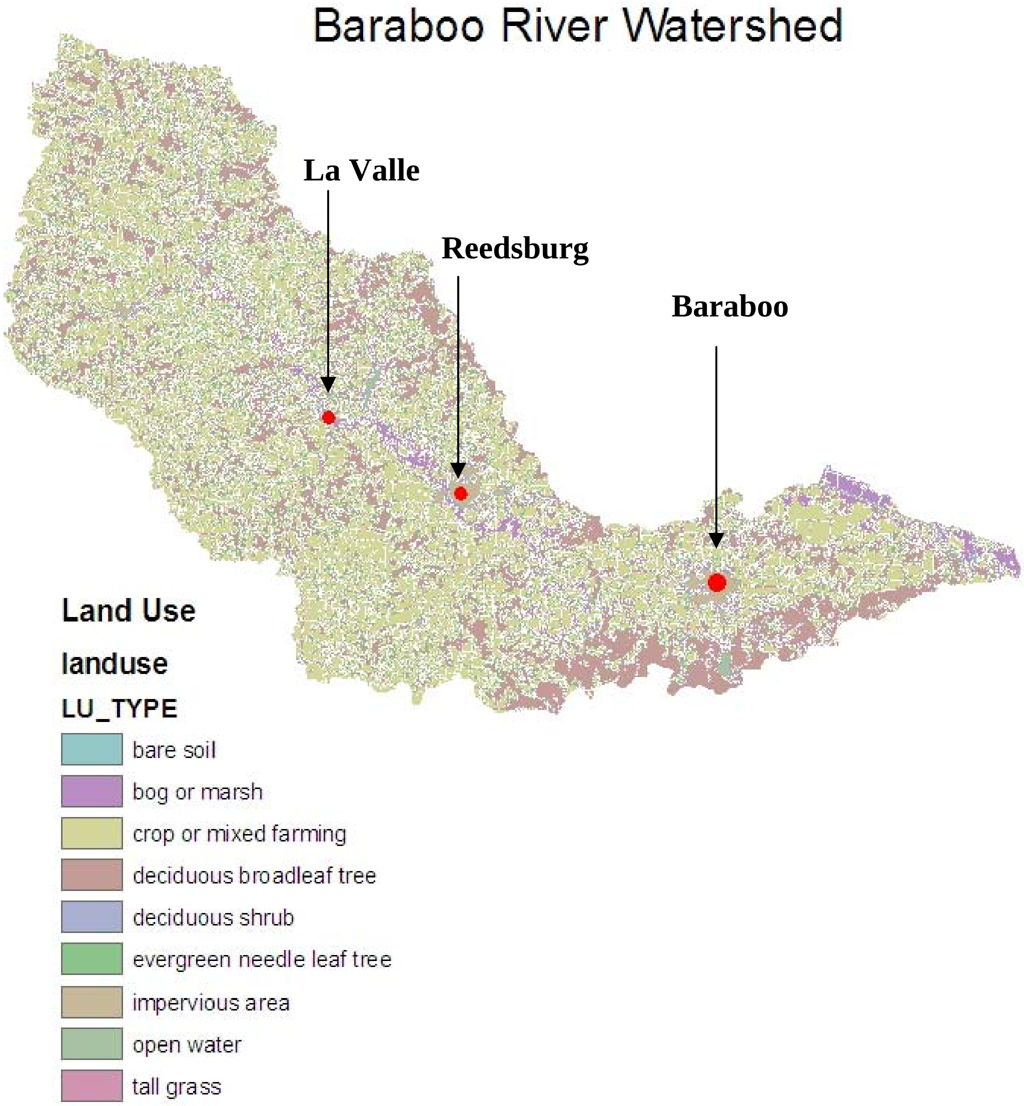

Figure 17 Data obtained from the USDA data gateway using the National Land Cover Data 2001. The towns of La Valle, Reedsburg, and Baraboo are shown in red.

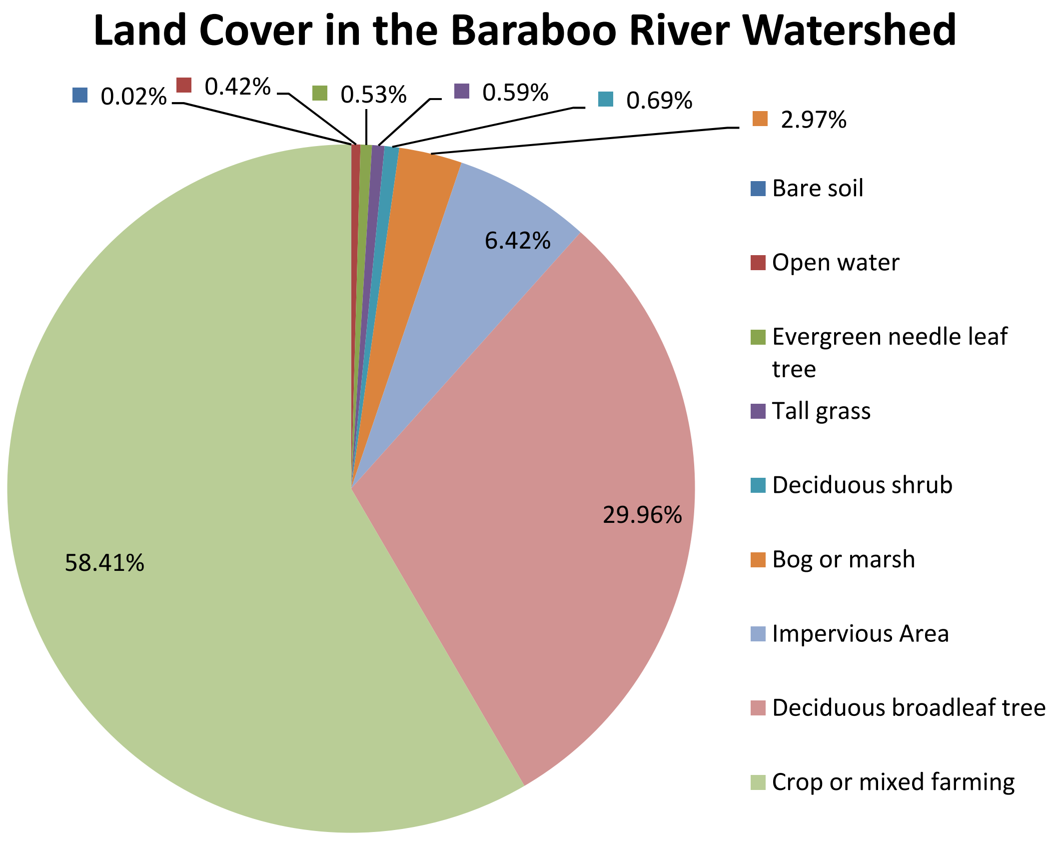

Figure 18 Data obtained from the USDA data gateway using the National Land Cover Data 2001.

Over the past 150 years of Euro-American agriculture, natural soil fertility has decreased, especially due to soil erosion and depletion of the existing pool of organic nitrogen and other nutrients; although, these nutrient losses are now largely offset by fertilizer application and liming. Farmers recognized reduced crop yields due to the loss of soil fertility in their fields as early as the mid-1800s (Johnson 1991). In response, several soil conservation methods were introduced throughout the first half of the 20th century that changed the type of crops planted and methods of cultivation (Johnson 1991 and Knox 2001). Despite soil conservation methods, soil erosion continues to be a problem as agriculture dominates the landscape of the Baraboo River watershed. In the future, projected changes in climate may require another shift in agricultural practices and crop species planted within the watershed (Ramankutty et al. 2002).

By and large, the changing interaction among geology, climate, soils, and vegetation drives changes in land cover and land use. Climate drove many of the shifts in vegetation from the late-glacial period until Euro-American settlement in the Baraboo River watershed. Once Euro-Americans settlers arrived to the watershed, human land use drove many of the observed changes in vegetation. As climate, soil, and land use continue to change over time, shifts in vegetation communities will continue.

Chapter 3.0 A Settlement History: Farming, Milldams, and Railroads

3.1 The First Arrivals

Human settlement, whether it is temporary or permanent, depends on the accessibility to basic natural resources that provide nutrition and shelter. Access to natural resources, such as good soil, clean water, and abundant timber, which provide sources of nutrition and shelter, has driven settlement patterns in the Baraboo River watershed since the first evidence of human presence in the region. Native Americans carefully established village locations based on the quality of soils to support animals and plants; access to drinking water sources and navigable streams; and quality of timber land for fuel and hunting. Similarly, Euro-American settlers established villages based on fertility of soils for agriculture and pasture; vicinity to drinking water sources and the navigability and hydropower capability of streams;

and quality of timber for fuel and shelter. While each cultural group, spanning from Paleo-Indians to Euro-American settlers, utilized soil, water, and timber resources differently, each group depended on these resources for settlement and survival.

Settlement in Wisconsin and likely along the Baraboo River began with Paleo-Indians about 10,000 to 12,500 radiocarbon years ago (Quimby 1958; Griffin 1956; Lange 1976, and Birmingham and Eisenberg 2000), soon after the Wisconsin glacier receded and forced a change in flow path of the Wisconsin River (Lange 1976 and Knox and Clayton 2008). During earlier glaciations Devil's Lake did not exist; instead, the Wisconsin River may have passed through the quartzite bluffs of the Baraboo Hills to form what today is called the Devil's Lake Gap (figure 19). As the Laurentide Ice Sheet reached its most western extent against the Baraboo Hills, it dammed the Wisconsin River and formed the impoundment in the central part of the state known as Glacial Lake Wisconsin (Clayton and Knox 2008). Subsequently, the ice dam failed and water drained westward to the Mississippi River via the Wisconsin River. After the glacier retreated, the Wisconsin and Baraboo Rivers took on their current flow paths through a marshy plain a few miles east of the east end of the Baraboo bluffs (figure 19). Its former route through the area of modern Devil's Lake was blocked by the terminal moraine of the last glaciation (figure 19).

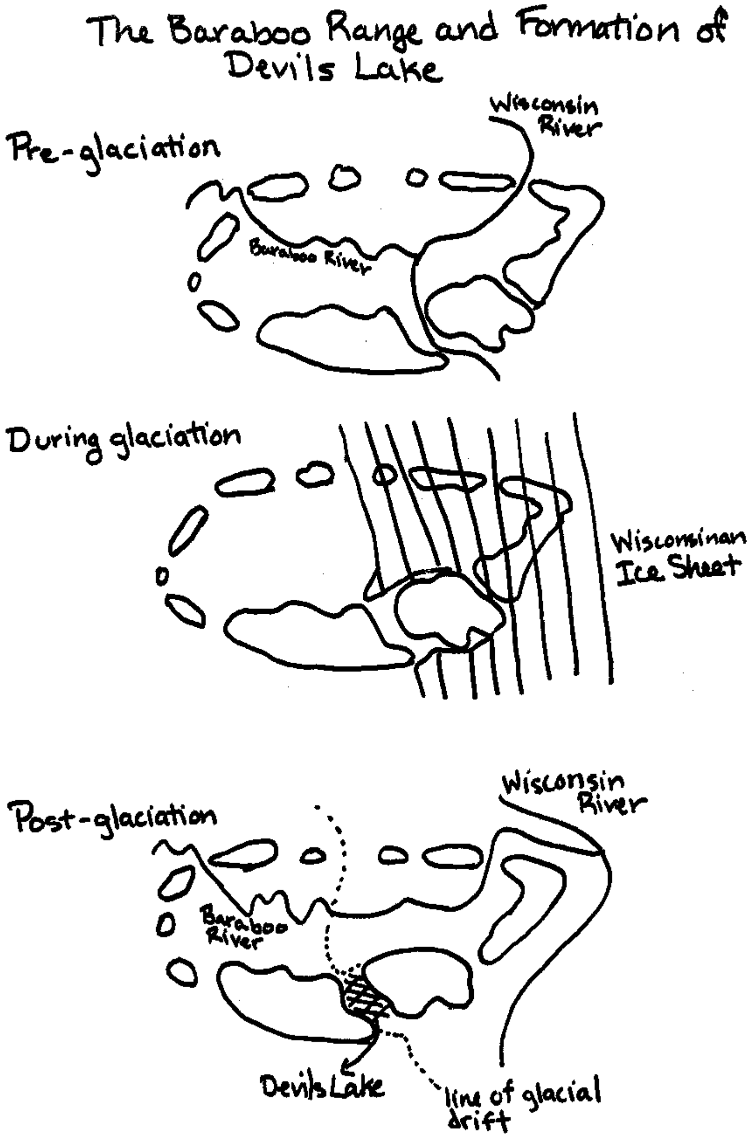

Figure 19 Paths of the Wisconsin and Baraboo River before and after the previous glaciation. Glacial drift in the third phase acts as the debris dams which formed Devil's Lake. Drawing adapted from Lange 1976.

As the climate continued to warm and glaciers disappeared from Wisconsin, the early spruce forest along the Baraboo River watershed was replaced by pines and hardwoods and mega-fauna disappeared (Lange 1990). In response to the changing environmental conditions, Paleo-Indians disappeared and a new group of nomads arrived called the Archaic Indians. As the climate continued to warm and vegetation and soils responded with a shift toward temperate deciduous hardwood and softwood species, several other groups of pre-historic Indians settled the region. The last pre-historic culture to settle the region was the Woodland Indians, who formed the first permanent settlements within the watershed (Lange 1976).

Woodland Indians primarily hunted and fished. In addition, they were one of the first groups to practice pre-historic agriculture along the Baraboo River (Lange 1976). Woodland Indians likely lived in the forests or at forest edges and are responsible for the vast landscape of effigy mounds found throughout Sauk County and southwestern Wisconsin (Birmingham and Eisenberg 2000).

Radiocarbon ages of the mounds indicate that the Woodland Culture survived for more than 1000 years, with a peak between 700 A.D. and the 1200's A.D. (Birmingham and Eisenberg 2000). William H. Canfield, Sauk County's first historian, estimated that the Woodland Indians built approximately 1500 mounds in Sauk County alone (Lange 1976). The location of mounds approximates where the Woodland Indians settled their villages. When mapping the distribution of mounds, they are concentrated around modern urban areas of Sauk County and all are within the Baraboo River watershed. Examples include La Valle, Reedsburg, and Baraboo. These sites offer a good source of water, fishing, and hunting, and a source of wood for fuel and building shelters along with good soil for raising crops. Therefore, the accessibility to these natural resources has drawn cultures to create permanent settlement in similar locations starting with the Woodland Indians through the Native Americans and Euro-American settlers.

Around 1200 A.D., the Woodland Indians disappeared from the Baraboo River watershed. Based on European settler accounts, the two most recent tribes that subsequently settled Sauk County were the Sacs, sometimes called Sauks, followed by the Ho-Chunk, referred to as Winnebago in earlier sources (Goc 1990).

When the first Euro-American pioneers entered Sauk County, Ho-Chunk Indians dominated the county. G. Richard Peske describes the Ho-Chunk settlement pattern as "… one of sedentary villages along waterways and having an adjacent cemetery and surrounding agricultural fields. They are located in regard to immediate access to water for drinking, fishing, wild rice gathering, shellfish collecting, hunting, and travel" (Lange 1976). An early settler notes "the fields extend a mile or more back from the villages and are interspersed with rock heaps derived from field preparation" (Lange 1976). Curtis (1959), Dorney and Dorney (1989), and early settler accounts tell of the use of fire by Native Americans. The Ho-Chunk burned to make good pasture land for deer, to drive game, and to provide for a renewed growth of blueberries and huckleberries (Lange 1976). They also communicated with fires and it is assumed that some of their signal fires likely escaped to become running fires (Lange 1976). Peske's quote along other settler and research accounts depict the Native American relationship with the environment as depending on fertile soils to grow crops; water for navigation, drinking, and wild food gathering; and timber for fire.

It was not long after the initial arrival of Euro-Americans in Sauk County that the settlers learned of the abundant natural resources and colonized the region. The first pioneers to enter Sauk County were Louis Jolliet and Father Jacques Marquette, two French explorers and their crews, in 1673 looking for a water route to the Orient (Lange 1976). However, they only came to the border and instead followed the Wisconsin River south.

After the first French expeditions by Jolliet and Marquette, other expeditions, fur traders, and eventually fur companies followed. In 1810, an English explorer, Thomas Nuttall, entered Sauk County as a naturalist, documenting new flora and marking the beginning of Euro-American interest in the land for settlement (Lange 1976). Between 1828 and 1830, Fort Winnebago was built and a party was sent to explore and document the maple, ash, and oak forest on the Baraboo River (Lange 1976). This was the first documented expedition of the Baraboo River valley.

Between 1840 and 1845 the United States General Land Office conducted land surveys throughout Sauk County, noting location and types of freshwater sources, identifying vegetation, and recording the quality of soil and timber. The goal of the surveys was to establish the township, range and section grid upon which land ownership and land use is based.

Based on the land surveys of Sauk County, Kenneth Lange (1976 and 1990) drew a map of the pre-settlement vegetation of Sauk County (figure 16). In addition, Finley (1976) published a vegetation map of pre-settlement vegetation in Wisconsin based on the public land surveys. Both maps depict similar vegetation patterns within the Baraboo River watershed. The Reedsburg basin was composed mostly of hardwood swamps including lowland thickets along the riparian region of the Baraboo River. Around the swamps were oak openings which were surrounded by oak woods. In the La Valle basin, the southern section was composed mostly of oak woods with some tamarack swamps and marshes. The middle section of the La Valle basin, starting from the southern end is mostly oak woods and hardwood swamps. Continuing northwest up the river, sugar maple-yellow birch forests that include hemlock stands, marshes, and tamarack swamps become more common, with areas of white and/or red pine. The northern section is a mix of areas dominated by hardwood swamps, oak woods, marshes, and on the outskirts some white and/or red pine stands. Overall, the county is dominated by regions of mesic and dry prairies, oak woods and oak openings.

Marsh existed along most of the riparian areas. In the center of the county there was a large region dominated by sugar maple-basswood forests. Lange (1976) calculates that during pre-settlement times, the 537,000 land acres in Sauk County consisted of about 2/5 oak openings, 1/3 woods and forests, 1/5 wetlands (marshes and swamps), and the remaining six percent was prairies. The diverse mixture of woodland provided plentiful timber for settlers to build homes and use as fuel and the fertile wetland and prairie soils provided abundant land for agriculture.

According to resident accounts in Sauk City, there was also plentiful game and fish in the region. Notes and letters from settlers of Sauk County speak of prairies with plentiful flocks of prairie chickens and passenger pigeons (Lange 1976). When William H. Canfield settled in Sauk County, he wrote “our waters filled with fish, and the air with game birds, and rock ledges with rattlesnakes, and the woods with large game…” Other mammals that used to inhabit Sauk County include bison, elk, timber wolf, porcupine, and snowshoe hare. The game birds and large mammals are mostly extinct. A few species, such as deer and striped skunk, are now more numerous. Some mammals that now inhabit the county were brought over by accident by the early pioneers, such as the Norway rat (Lange 1976).

3.2 The Arrival of Euro-American Settlers

Land was available in many places east of the Mississippi, yet a large number of people made the long trip to Wisconsin to settle. Pioneers, farmers, and a variety of opportunists arrived in Sauk County hoping to start a new life working the land. People often immigrated through Milwaukee via the Erie Canal in the 1840s and 1850s. Once in Milwaukee, many families continued west into the Driftless Area generally using a wagon pulled by oxen to haul their belongings (Lange 1976). Despite the diversity of origins and backgrounds of Sauk County's settlers, they all shared the common goal of "seeking a home where their hands may maintain them" (Fuller 1843).

The pioneers who entered Wisconsin could be divided into two groups: the Yankees and the continental Europeans. Yankees were people mostly of English background, but also of Irish, Scottish or Welsh origins, who came mainly from the eastern states (Lange 1976). The continental Europeans were primarily Germans and Swiss, but mostly German (Lange 1976). The Yankees tended to form a nucleus around Prairie du Sac while the Germans and Swiss settled around Sauk City (Lange 1976).

Farmers were the most common settlers in the Baraboo River watershed due to the array of cultivable land cover types. The fertile and open oak savannas of the uplands were nearly ready for the plow. The adjacent woodlands that covered the valley slopes provided a close source of timber for building and fuel. The low-lying wetlands and prairies offered good land for hay and pasture.

Many of the immigrants who took up farming were doing so for the first time; most were artisans or shopkeepers in their homeland (Butterfield 1919 and Lange 1976). The history of farming and resultant technological developments in Sauk County can be split up into three stages: wheat and hop growing of the 1800s, dairying of the early 1900s, and the large-scale livestock industry of the mid-1900s to present.

The first pioneers who arrived in the 1830s often believed that forests were superior to prairies, probably because they came from such areas and open land was strange to them (Lange 1976). In addition, property with trees was usually cheaper since the buyer had to clear the land before he could plow it. A number of settlers in those early days journeyed through the prairies until they found timbered lands with a dependable source of water. However, settlers soon found that prairie soils could be rich, too, and began settling the lowlands.

When families first arrived they lived in “shanties,” a “dry-goods box,” or camped out (Lange 1976). Often, the men and boys came first to build a temporary residence and then left to get the women, children, and possibly a cow or two. According to a settler’s letter from 1849, shanties were everywhere; Reedsburg even had a “shanty row” (Lange 1976). A primary task for pioneers of the woodlands was to cut the trees to make room for a cabin, crops, and perhaps a few animals. The trees numbered several hundred per acre and the men selected logs suitable for buildings and fences, saved some for fuel, and if a saw mill was nearby, may have taken some there (Butterfield 1919 and Lange 1976). However, most were piled into heaps and burned in huge conflagrations (Lange 1976).

Throughout the Baraboo River basin, wheat dominated as the principal crop and source of income through most of the 1800s (Butterfield 1919; Goc 1990; and Lange 1976). Wheat was cultivated as a monoculture, resulting in large chinch bug infestations by the 1860s (Butterfield 1919). Wheat dominated into the 1880's; in fact, throughout most of the late 1800s Sauk County was one of the largest producers of wheat in the state as well as the country (Goc 1990).

Wheat cultivation had a short break in the 1860s when the hops boom occurred, but the boom was quickly followed by a bust. Sauk County was the highest producer of hops in Wisconsin and in 1863 the demand for the product increased substantially (Butterfield 1919 and Lange 1976). People came from all over the state and even outside the state to settle in Sauk County and grow hop crop (Butterfield 1919 and Lange 1976). By 1865, most farmers in the county devoted some land to hops cultivation, when the price of hops rose to 60 cents per pound (Butterfield 1919).

In 1867, hops production hit its peak with Sauk County supplying a quarter of all hops grown in Wisconsin (Butterfield 1919). However, by 1868, the hop industry crashed as a result of the hop louse and the increasing market control in the East (Lange 1976). The price of hops crashed to between three and five cents per pound and many farmers abandoned hops for other crops as a result (Butterfield 1919). On the bright side, the hop boom did result in substantial farm improvements; the large and costly hop-houses made good barns once the hop bust commenced (Butterfield 1919).

In addition to agriculture, logging was common in the Baraboo River watershed. The upper reaches of the Baraboo River watershed, including La Valle and areas farther upstream, had dense forests of pine and a variety of oak that permitted the profitable harvest of timber (Butterfield 1919 and Goc 1990). In 1841, Archibald Barker and Andrew Dunn ran the first pine log drive on the Baraboo River (Goc 1990). By the 1880s, most of the timber had been harvested and sent to saw mills (Butterfield 1919).

3.3 Milldams

To process and sell the agricultural and timber products, mills were necessary. Since railroads did not yet exist to transport unprocessed agricultural and timber products to larger cities for milling, communities formed where water power was sufficient to run a small mill and fertile land for agriculture was abundant. In the Baraboo River watershed, the largest towns formed around the largest water power sources, which today are the cities of La Valle, Reedsburg, and Baraboo. During initial settlement, the Northwest Ordinance law limited milldam building by stating that all navigable waters leading into the Mississippi and the St. Lawrence Rivers were common highways and to remain free flowing. However, as settlement continued to increase in Wisconsin through the 1830s and the fur trader was replaced by the farmer, the Wisconsin Territorial Legislature recognized the changing economic conditions and changed the water policy accordingly (Schmid 1962).

In 1840, the Territorial Legislature passed the Milldam Act, which granted water-use preference to those riparian owners who built milldams. Under this act riparian land owners could flood the lands of other riparian land owners upstream, destroying the water power potential of the upper land. In addition, the act permitted the taking of land for flowage purposes without requiring the mill owner to obtain legal rights to the land. The riparian land owner upstream of the mill owner had no recourse except to sue for damages; therefore, Wisconsin violated the riparian doctrine of equal rights for all early in its history (Schmid 1962).

The Milldam Act also violated the established concept of free passage on navigable streams through an alteration of the interpretation of a navigable stream. While the Act only permitted the building of dams without a permit and without state supervision on non-navigable streams, the Territory, and later the State, generally ignored the test for navigability (Schmid 1962).

Initially, the courts defined non-navigable streams as those which would not float a saw log (Schmid 1962). However, the Territorial Legislature recognized that this narrow definition of “non-navigability” would have limited the building of milldams and also restricted economic development, and therefore, did not enforce the navigability test (Schmid 1962). Then, after more than half a century of ignoring the navigability test, the Wisconsin Supreme Court in 1908 decided the saw log test of navigability was never intended by the Territorial Legislature since a stream incapable of floating a saw log would also be incapable of furnishing sufficient water power to warrant a mill (Schmid 1962).

Given the several equal property rights issues that the Milldam Act of 1840 presented, it was continually challenged in courts resulting in repeals of and amendments to the law through the late 1800s and early 1900s (WDNR 2008). Assuming that the true goal of the

Act was to promote settlement and economic development, it appears that the Act was successful. By the time Wisconsin attained statehood in 1848, more than 100 water-powered grist and flour mills were built; by 1879 more than 700 milldams were built (Wisconsin Blue Book 1958). In Sauk County by 1860, about 60,000 acres, or 11% of the land cover, was converted to cropland (Lange 1976). Regarding Sauk County, the Illustrated Historical Atlas of Wisconsin reported in 1878 that "the prairies are all cultivated, many of the heavily timbered tracts have been cut off and reduced to a fine state of cultivation, but some portions of the openings have become good timber of second growth, while others have yielded to the plow." The abundance of milldams along Wisconsin's waterways allowed for the continual agricultural and economic development of the state throughout its early days.

3.4 The La Valle Milldam

In La Valle, the fertile soils and dense high quality timber noted by the surveyors made the area good for cultivation, logging, and the harnessing of waterpower. The early growth of La Valle was slow due to its location; it was situated in what was dense forest, scarcely accessible to the ordinary road wagons (Butterfield 1919). However, settlers gradually arrived into the hills and valleys and worked the land, increasing the need for a local mill and a hydropower milldam.

The La Valle milldam was initially built in 1849 as a saw mill (Jepsen 2009 and Butterfield 1919). In 1864, J.F. Sanford bought the mill property and established a flour-barrel factory in connection with the saw mill (Butterfield 1919). Both institutions carried on successfully for a few years and the manufacturing of broom handles quickly became a part of the enterprise (Butterfield 1919). In 1869, Sanford decided to build a grist mill propelled by the same waterpower running the saw mill, barrel factory, and broom handle factory (Butterfield 1919). As part of the grist mill, a large three-story building was erected just below the dam and was furnished with the necessary machinery to run a grist mill. This enabled the citizens of La Valle to use home-made flour and increased the popularity of La Valle for settlement (figure 20, Butterfield 1919).

Figure 20 Image of the La Valle dam from the late 1800s or early 1900s. Obtained from Martin Doyle at University of North Carolina, Chapel Hill.

In the 1870s, the grist mill ownership was acquired by Lyman Beery and Theodore Yager. The presence of the mill, coupled with the dense, high quality forests surrounding La Valle, provided a continual and abundant supply of material to local businesses that afforded lucrative employment to a large number of settlers (Butterfield 1919). As of 1881, the village of La Valle housed three general stores, one hardware store, one drug store, and one hardware and grocery store; one hotel, two blacksmith shops, one wagon shop, one livery stable, one shoe shop, one millinery store, one saloon, one stave mill, one hoop pole factory, one grist mill, one carding mill, one graded school, one church, one Odd Fellows’ Lodge, one Good Templars’ Lodge; and had one doctor (Butterfield 1919). However, with the increased settlement in La Valle, better transportation was needed to transport people and products in and out of the city.

3.5 Baraboo River Valley Railroads Driving Change in Agriculture and Mills

When cities first formed, wagons were the major mode of transportation of goods and products around Wisconsin. However, wagon transport was slow, limiting the types and quantities of products that could be transported. With the advent of the railroad, goods and products could be moved in much higher quantities and in much less time. For this reason, railroads became the maker and breaker of cities; if a city had a railroad, industry could keep expanding and the economy would keep growing at the expense of the towns without a railroad (Lange 1976).

By about 1850, leading citizens of Sauk County obtained a charter for a railroad through the Baraboo River Valley (Butterfield 1919). The corporate title was the Fort Winnebago, Baraboo Valley, and St. Paul Railway Company (Butterfield 1919). The railroad was planned to run from Chicago to Janesville and then the main line was to pass through Madison and the Baraboo River Valley to St. Paul (Butterfield 1919). The company charged with planning the railroad was the Chicago, St. Paul and Fond du Lac Company. This company had hopes of obtaining grant money from the government to help build the railroad, but opposition in congress grew due to indecision as to whether the railroad should connect to Milwaukee or Chicago (Butterfield 1919). In the end, the indecision defeated the grant bill.

In the winter of 1856-1857, negotiations began with the Chicago and Northwestern Railroad Company, of which William B. Ogden was then President (Butterfield 1919). President Ogden consulted with P.A. Bassett of Baraboo and they secured funds from the County of Sauk and the City of Madison to fund the rail line (Butterfield 1919). The surveying and rail work was supposed to begin that spring, but the economic crash of 1857 postponed this work (Goc 1990). After years of attempting to build the line with different companies and different plans for laying the railroad, the Chicago and North-Western Company finally surveyed the Baraboo Valley in 1870 (Butterfield 1919). The line to Baraboo was completed in September 1871 and to Reedsburg on New Year’s Day 1872 (Butterfield 1919).

When train companies chose station locations, they often chose communities with heavy forest cover, good water power, and good soil. The forest supplied timber for the tracks, water power supplied energy to process the timber and manufacture the tracks, and good soil ensured economic necessity of the line as a transporter of agricultural and timber products. In planning the completion of the rail line through the Baraboo River valley, Ironton was a prime location for the Chicago and North-Western Company to lay a line due to the dense hardwood forests and river rapids.

Ironton, a mining town located up the river valley of La Valle, feared that Chicago and North-Western Company would harvest the timber that miners used to fuel the mine furnace and foundry, did not want a station located in their town (Lange 1976). To protect the fuel source, the owners of the iron mine bought much of the land around Ironton, forcing the railroad officials to run the track through La Valle instead (Lange 1976). The Chicago and Northwestern main line was completed as single track through the Baraboo River valley in 1873 and a double track was then laid in 1896.

The introduction of the railroad through the Baraboo River valley allowed for the much needed change in agricultural production practices. Due to the long domination of monoculture wheat, pests became an issue as did soil fertility loss, primarily of nitrogen, and erosion (Johnson 1991). By the 1870s, farmers were urged to “substitute the cow for the plow” in hopes the manure would act as a nitrogen fertilizer to the worn out fields (Lange 1976 and Johnson 1991). However, the perishable dairy products required a quicker mode of transportation to distribute the products out of the river valley.

Railroads provided an efficient means to transport the perishable dairy products. Now with a mode of transportation that could distribute the dairy, agriculture diversified with dairying and the livestock industry and the diversification of grain crops. In addition, industry diversified with the spread of cheese factories and creameries (Lange 1976). The change in agricultural production also led to the building of feed mills in addition to the grist mills in cities such as La Valle and Reedsburg. This reinforced the need for waterpower by milldams in these agricultural towns.

The rail service though Sauk County allowed for the continual expansion of agricultural land through the early 1900s. During the Great Depression in the 1930s, the Wisconsin Department of Agriculture conducted county land economic inventories known as the Bordner Surveys. The Bordner survey found that over 3/5 of the Sauk County land was cleared for agriculture, while a third was in woods and forests, and 5% was marshes and swamps. In 1960, the WDNR listed the land cover types in Sauk County as: 31% woods and forest, 2% swamp and marsh, 56% agricultural land, and 11% industrial and urban areas (Lange 1976). However, by 1960, the dominant mode of transportation shifted towards domination of the car and truck and the economic structure of agricultural production had also shifted from small, family farms to larger, industrial farms due to post-depression politics.

The fall of the railroad in La Valle was also met by the fall of the milldam. As cars and trucks replaced railroads and large, industrial farms of the post-depression era replaced the small dairy farms, people decided to leave La Valle and head for bigger cities. While the mill and dam continued to grind corn and grain for local, small farmers and the Amish into the early 1990s, the dam owner Daryl Hansen, found it considerably harder to run the business (Jepsen 2009). When the DNR reported to Hansen that the dam needed extensive repairs to be brought up to state design standards in 1998, Hansen decided to retire and remove the dam. In July of 2000 the removal process began with the dewatering of the reservoir followed by the full removal of the dam structure in February 2001 (for pictures see Appendix).

3.6 Concluding Remarks: The Future of the Milldam Legacy

Settlement in Wisconsin was largely controlled by access to soil, water, and timber. Euro-American settlers arrived in large numbers, noting the abundant sources of fertile agricultural soils; water for drinking, fishing, and hydropower; and woodland for timber products and fuel. With the declaration of the Milldam Act of 1840, pioneer farmers and loggers quickly settled along the Baraboo River to harness the hydropower and locally mill their agricultural and timber products. Historical records report that up to eleven dams, including five milldams, were built during the 1800s along the entire length of the Baraboo River (WDNR 2008). While milldams stimulated settlement and economic growth in the river valley through the 1800s and early 1900s, production of cars coupled with post-depression agriculture brought the milldam era to an end. As a result many of the milldams were abandoned or left in disrepair.

There was a need for government regulation of the dams to ensure public safety and reduce environmental degradation. In 1967, jurisdiction over dams was given to the newly created Department of Natural Resources and standards for dam design, construction, and reconstruction were created to ensure public safety (WDNR 2008). In 1991, the DNR implemented a dam maintenance, repair, modification, or abandonment grant program (WDNR 2008). As of 2009, there existed more than 85,000 dams in the United States, of which at least 4,000 are rated unsafe and in need of rehabilitation, repair, or removal (American Society of Civil Engineers 2009; figure 21).

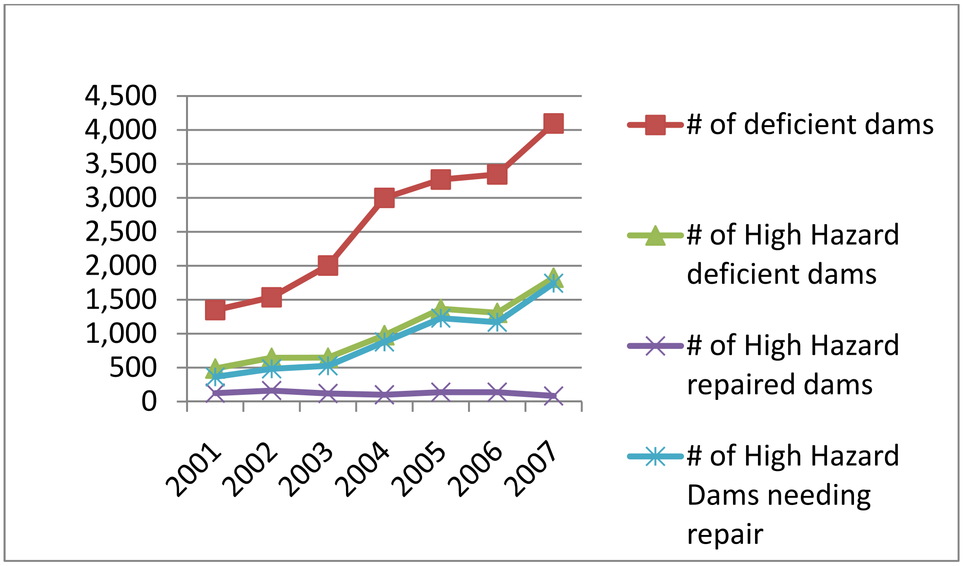

Figure 21 Data from the American Society of Civil Engineers (ASCE) Infrastructure Report Card. ASCE defines a deficient dam as harmful to the environment with a low threat to human safety. A high hazard dam is defined as threatening human life.

The functional lifespan of most dams ranges between 60-120 years, with repairs required an average of every five to ten years (Doyle et al. 2003). Gradual deterioration of the dam structure occurs as a result of degraded structural integrity or filling of the reservoir by sediment. By 2020, it is estimated that 20% of dams will reach the end of their structural design lives and either need to be repaired or removed (Doyle et al. 2003, Stanley et al. 2002). In addition, there is often a clear difference between the need for the dams at the time of their construction and the need for them decades later. This is especially true for the milldams built throughout the eastern and central United States, which powered the lumber and agricultural mills for the local loggers and small family farmers. Now that large companies have taken over the timber and agricultural industries, local communities no longer require the milldams to continue production (Doyle et al. 2003). Instead, local communities value these dams as historic structures due to the unique, although artificial, habitat that they provide (Doyle et al. 2003, Jepsen 2009). However, since the dams are no longer economically self-sustaining due to changes in industry structure, support for repair and maintenance declines, resulting in removal.

Waterways in Wisconsin support nearly 4000 dams, many being old milldams built in the 1800s (Stanley et al. 2002; figure 22). These milldams are low-head, run-of-river structures that create a hydraulic head of generally less than 7.5 meters; therefore, they do not substantially alter the natural flow regime of the river (Stanley et al. 2002). State and federal laws require the relicensing of dams on either a 10- or 50-year cycle. Inspections of Wisconsin dams have shown diminished economic returns, structural weaknesses, and environmental damage (Stanley et al. 2002). As a result, natural resource managers tend to favor the removal rather than the repair and relicensing of aging dam structures (Born et al. 1998, Stanley et al. 2002).

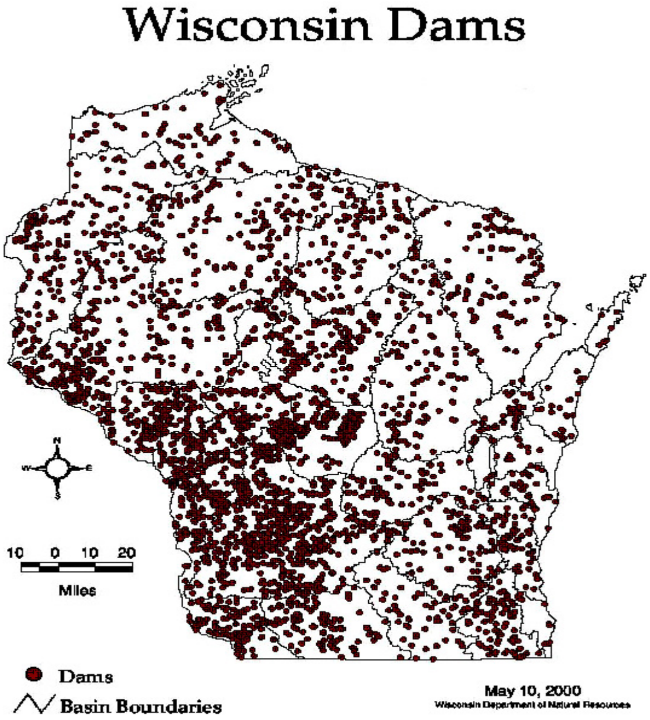

Figure 22 Dams present in Wisconsin as of the year 2000. Map courtesy of the WDNR.

Over the past 30 years there have been more than 70 dams decommissioned in Wisconsin, with 25 of these removals occurring since 1995 (American Rivers et al. 1999). The Baraboo River has led the dam removal effort, with all five milldam structures removed between the years of 1972 and 2001. The river now has 120 miles of free-flowing stream and is the first river to be fully undammed along its main reach in the United States (Jepsen 2009 and Exo 2006). Given the increasing popularity of dam removal as a river management option, determining the fluvial response regarding sediment transport and channel geomorphology is essential to minimize the negative impacts of future removal. To aid in this goal, the next chapter will discuss the current state of dam removal science followed by an analysis of the upper Baraboo River hydraulic and geomorphic response to the removal of the La Valle, Wisconsin milldam.

Chapter 4.0 Dam Removal: The Current State of the Science

4.1 Dam Removal and Ecosystem Response

Dam removal can both benefit and harm the local environmental system. The possible negative outcomes of dam removal are generally related to the fate of the reservoir sediments. For instance, one issue is that the dam removal could release a large quantity of stored sediment and nutrients into major river basins. Reservoirs act as a nutrient sink, trapping the eroded soils and agricultural and industrial runoffs (Stanley and Doyle 2002 and Doyle et al. 2003). In the Midwest where agriculture over the past 100-150 years has led to high rates of soil erosion and widespread application of large quantities of fertilizers and pesticides (Trimble and Lund 1982; Trimble 1983; Beach 1994; and Knox 2001), dam removal could significantly increase the sediment and nutrient load of Mississippi River Basin.

The movement of the large sediment storage out of the reservoir may also cause problems by disrupting already disturbed ecosystems downstream, such as macroinvertebrate communities and fish assemblages (Doyle et al. 2003). However, dam removal also restores the natural flow and temperature regimes and reconnects upstream and downstream reaches which can benefit macroinvertebrate communities and fish assemblages (Stanley et al. 2002). Stanley et al. (2002) found that in the Baraboo River, macroinvertebrate communities recovered within one year after dam removal, implying small and transient ecological changes in downstream reaches. Maloney et al. (2008) studied macroinvertebrate and fish response to a low head dam removal on the Fox River in Illinois. Their study finds that macroinvertebrate communities appear to fully recover within two years after the dam breach. In contrast, fish assemblage as measured through biomass, diversity, and density only recovered slightly by the end of the three year study, hinting the need for longer-term studies of fish assemblage response.

Other studies on fish population response to dam removal in Wisconsin report diverse responses to removal. Stanley et al. (2007) found little change in trout populations compared to pre-removal trout populations at the end of the two-year post-removal study. Catalano et al. (2007) studied fish assemblages at 35 sites surrounding four former impoundments along the Baraboo River over seven years. They found that biotic integrity for most sites increased within two years post-removal; however, the site-specific recovery appeared to vary based on river form. The Catalano et al. (2007) study concludes, similar to the Maloney et al. (2008) study, a need for further research as fish assemblage response varies based on channel morphology, hydraulic characteristics, reservoir characteristics, and distance to source populations of recolonizing taxa.

Dam removal may also result in positive or negative outcomes for riparian vegetation. The natural flow regime reconnects the stream with its floodplain, which could improve riparian habitat. In addition, the exposure of the bare reservoir surface may create the opportunity for increased riparian habitat. However, the newly exposed surface is also susceptible to invasion by invasive species. In studying revegetation patterns after dam removal, Orr and Stanley (2006) observed that of thirteen dam removal sites where the reservoir was allowed to revegetate without human interference, invasive species accounted for 75% of the colonized vegetation. Nonetheless, they commented that colonization occurs rapidly within one growing season, suggesting potential for riparian restoration at these sites.

Given the continual and severe loss of riparian habitat and ecosystems, the response of vegetation to dam removal is especially important and requires a deeper understanding to effectively restore riparian habitat to these sites (Orr and Stanley 2006)

Most studies of the ecological response to dam removal, including those previously discussed, state the importance of channel form and hydrology to ecosystem recovery. In addition, channel form and hydrology greatly influences the recreational and economic potential of a river through impacts of natural resources. Since physical habitat governs aquatic community composition and prospective human uses, studies of channel form and sediment characteristics are necessary to comprehend and predict the fluvial system response to dam removal (Stanley et al. 2002 and Power et al. 1988).

4.2 The Study of Geomorphic and Hydraulic Response to Dam Removal

Dams and their removal cause profound changes in river structure. The construction of a dam forms a reservoir directly upstream of the dam structure, within which water depth increases and sediment storage increases (Evans et al. 2007). As the reservoir traps sediment from upstream, downstream reaches degrade in response to a reduced sediment load, with a tendency to reestablish the former sediment load through the erosion of bed and bank materials. Erosion downstream of dam can cause incision and channel widening along with preferential transport of fine-grained material (Evans et al. 2007). The preferential transport of fine-grained sediment often results in channel armoring since the coarser grain sizes, such as pebbles, are not transported downstream. The most pervasive long-term downstream effect of dam construction is the attenuation of flood peaks, reducing the overbank flows which would transport sediment out of the channel and onto floodplains (Evans et al. 2007 and Orr and Stanley 2006). As a result, the downstream channel reach becomes disconnected from its floodplain. Therefore, dams have significant impacts on sediment transport and channel geomorphology both upstream and downstream of the structure.

Dam removal causes a transient disequilibrium in channel geomorphology and hydrology. However, little understanding exists of the physical system response, with most of the existing literature focusing on the administrative, legal, and socioeconomic aspects of dam removals (Burroughs et al. 2009). Studies which do focus on geomorphic and hydraulic aspects tend to look exclusively at low-head, run-of-river dams and are all short in duration, spanning one to two years after the dam removal (Burroughs et al. 2009). In addition, many geomorphic and hydraulic studies of removals provide insufficient descriptions of pre- and post-removal sediment storage and movement and lack quantitative data (Doyle et al. 2003 and Pizzuto 2002). However, studies are emerging which provide some clues as to the controls of reservoir sediment fate and the ability of the stream to reach quasi-equilibrium post-removal (i.e. Stanley et al. 2002, Doyle et al. 2003b, Evans et al. 2007, Schmitz et al. 2009, and Burroughs et al. 2009).

No set dam removal protocol exists to advise river managers in their planning, leading to the employment of a range of dam removal methods without proper understanding of either geomorphologic or hydraulic responses. The method in which a dam is removed tends to be chosen based on economic feasibility, goals for removal (i.e., removal primarily to preserve human safety or to restore stream ecosystems), knowledge background of the managers, and time frame available for the removal. The dam removal protocol employed greatly affects the extent and rate of the post-removal reservoir sediment erosion and transport, and the ability of the channel to reach a quasi-equilibrium form (Pizzuto 2002). Methods for dam removal vary in the phasing of structure deconstruction, reservoir drawdown, and methods of sediment removal in the drained reservoir.

The phasing of dam removal refers to the rate at which the structure is deconstructed and removed from the stream. A dam structure can be removed all at once or pieces can be taken away slowly over months or years (Doyle et al. 2003 and Burroughs et al. 2009). Phasing influences the rate of reservoir draining with the goal of reducing erosion of reservoir sediments and deposition of reservoir sediments downstream (Burroughs et al. 2009).

The drawdown of a reservoir before removal of the entire dam structure results in more gradual flushing of stored sediment downstream and allows fine-grained reservoir sediments to consolidate and strengthen (Doyle et al. 2003 and Pizzuto 2002). Without drawdown prior to dam removal, a higher volume of water will be released at the time of removal, increasing sediment transport out of the reservoir (Pizzuto 2002).

Sediment in the drained reservoir can be removed naturally, removed mechanically, or stabilized in place (Schmitz et al. 2009). Natural sediment removal allows the natural processes of erosion, deposition, floodplain development and channel evolution to distribute reservoir sediments with subsequent flood events (Doyle et al. 2003 and Schmitz et al. 2009). These processes result from base level lowering (Schumm et al. 1984) and depend on dam, reservoir, river, substrate, and watershed characteristics (Schmitz et al. 2009).

A range of case studies throughout the United States show the influence of dam, reservoir, river, substrate, and watershed characteristics on stream response to dam removal. Studies demonstrate that differences in characteristics such as channel geomorphology and hydrology, dam maintenance practices, watershed geology, and land use history all influence natural sediment erosion, transport and deposition post-removal (for examples, see Burroughs et al. (2009); Stanley et al. 2002; Neave et al. 2009; Doyle et al. 2003b, Evans et al. 2007). Overall, the case studies show that natural sediment removal is controlled by cohesiveness of sediments within the reservoir, grain size of sediments within the reservoir, and channel slope within the reservoir.

Mechanical sediment removal entails dredging once the reservoir is drained. Dredged sediments are then used elsewhere, such as on adjacent farm fields, in road bases, filling open pits, and as construction foundation material (Shuman 1995 and Schmitz et al. 2009). However, dredging can be expensive, and therefore, not always economically feasible. Methods for sediment stabilization include regrading, revegetating, and ripraping of the exposed dam fill (Pizzuto 2002; Doyle et al. 2003; and Schmitz et al. 2009). Sediment stabilization methods aim to reduce the extent and rate of erosion (Pizzuto 2002 and Doyle et al. 2003).

Researchers are creating several field and computer-based methods to study and predict the sediment movement and channel form response to dam removal. Most dam removal studies depend on field data to assess changes in sediment transport and channel form. While many studies utilize pre- and post-dam removal field data comparisons to evaluate sediment transport and changes in channel morphology (i.e. Stanley et al. 2002;

Doyle et al. 2003b; Burroughs et al. 2009; Neave et al. 2009), insufficient data on river geomorphology and hydraulics prior to dam building and dam removal limits conclusions.

Recent attempts have been made to study dam removal using a GIS and remote sensing approach (i.e. Lorang and Aggett 2005; Evans et al. 2007; and Schmitz et al. 2009), however, limited spatial data makes it difficult to assess the effects of dam removal. Additionally, GIS and remote sensing has only recently permitted the quantification of reservoir sediment storage, erosion, transport, and deposition through LIDAR. However, there is limited available LIDAR imagery for time periods before and after dam removals.

Conceptual stream channel models help predict channel evolution and sediment transport resulting from dam removal based on the assumption that channel response is controlled by base level lowering (i.e., Pizzuto 2002; Doyle et al. 2002; Doyle et al. 2003b; Doyle and Harbor 2003; and Lorang and Aggett 2005). A deeper understanding of the physical processes underlying stream response is necessary to improve the model accuracy and flexibility across fluvial systems (Doyle and Harbor 2003).

Overall, surprisingly little is known about the quantity of sediment that is eroded at these dam removal sites, the rate at which the erosion occurs, and how far and where downstream the sediment will be transported (Doyle et al. 2005). In addition, little is understood of how channel geomorphology, local soils and geology, and local slope influences and is influenced by sediment erosion, transport, and deposition following dam removal (Pizzuto 2002; Doyle et al. 2002; and Doyle et al. 2003). Important fluvial responses that still need quantification include the rates and mechanisms of sediment removal from reservoirs, how watershed geomorphology and hydraulics affect these rates and mechanisms, how far and quickly sediment will be transported downstream, and how downstream sedimentation will affect channel morphology and biotic communities (Doyle et al. 2003b, Catalano et al. 2007, and Maloney et al. 2008).

4.3 An In-Depth Look into a Dam Removal Case Study: The La Valle Dam, Baraboo River, Wisconsin

One of the first quantitative studies of sediment transport following dam removal was conducted by Doyle et al. (2003b) looking at stream response to the removal of the La Valle dam from the Baraboo River in Sauk County, Wisconsin. In July 2000, the La Valle Dam on the Baraboo River in Sauk County, Wisconsin was dewatered and subsequently removed in February 2001. Riprap was placed at the former dam site to create a long, steep riffle that acted as a grade control (WDNR 2001).

In talking to land owners, Doyle et al. (2003b) learned that in the early 1900s, impoundment was greater than two meters deep. However, due to a long history of agricultural land use which accelerated soil erosion within the watershed, sedimentation decreased the depth of the impoundment to less than one meter by the 1970s (Lange 1990; Johnson 1991; Doyle et al.2003b). In order to flush some of the stored sediment and to make repairs on the dam, the impoundment was dewatered by opening the dam gates every 5-10 years. Despite the effort to dewater the impoundment, the majority of sediment remained in the impoundment (Doyle et al. 2003b).

The study reach, which spanned approximately three river kilometers upstream of the La Valle Dam and three river kilometers downstream of the La Valle dam, contained a relatively uniform mixture of fine sand and silt and no gravel (Doyle et al. 2003b). By the time of the dam removal, the reservoir accumulated approximately 140,100 m^3 of sediment (Doyle et al. 2003b). The accumulated fine sediment throughout the reservoir varied in thickness from 1.4 to 1.7 m throughout the reservoir. Reservoir sediment was relatively unconsolidated due to the frequent dewatering transporting the silt downstream, which tends to be more cohesive than sand, while the fine sand remained in the reservoir (Doyle et al. 2003b).

Doyle et al. (2003b) found the greatest downstream transport of sediment occurred immediately following the dewatering of the reservoir, which Doyle et al. (2003b) define as the dam removal event. The dewatering resulted in the export of fine sediment from the reservoir and the conversion of the reservoir from a sediment sink to a sediment source. A subsequent storm event during the summer after removal remobilized fine sediment as well, but not to the degree observed immediately following removal (Doyle et al. 2003b). Post-removal total suspended solid concentrations were nearly always greater downstream of the dam than upstream, indicating net export of fine sediment from the reservoirs (Doyle et al. 2003b).

The net export of sediment from the upstream reach increased depth and cross-sectional area within and upstream of the reservoir (Doyle et al. 2003b). Incision occurred at all locations upstream of the dam site, but little or no change in channel width occurred throughout the upstream study reach.

Downstream of the dam site, the channel experienced deposition of fine sediment along channel margins and in backwater regions such as inside meander bends or near debris jams (Doyle et al. 2003b). During the first 10 months after the dam removal, a large quantity of sand was deposited within approximately the first 160 meters downstream of the dam site. This resulted in a channel depth decrease of about 20% (Doyle et al. 2003b). However, sediment transport downstream continued and this area returned to pre-removal elevation within three months (Doyle et al. 2003b). As downstream deposition continued during the study, there were observed increases in the size of channel point bars (Doyle et al. 2003b).

By the end of the study in November 2001, Doyle et al. (2003b) found that approximately 7.8% of the total reservoir sediments were transported downstream. This is a relatively small amount of mobilized sediment mobilization considering the quantity of sediment transported from reservoirs following dam removal generally ranges from10-80% of the stored reservoir sediment (Doyle et al. 2003b). Of this 10-80% of stored reservoir sediment, the majority is mobilized during the first year following removal (Doyle et al. 2003b).

The short duration and small, six kilometer study reach of the Doyle et al. (2003b) study limits the ability to assess drivers and rates of sediment transport as well as channel geomorphic response to the removal of the La Valle Dam in 2001. Therefore, the goal of this research is to improve the understanding of the drivers and rates of sediment transport after the removal of the La Valle Dam and to determine whether the stream has reached quasi-equilibrium. This will be achieved by studying the geomorphology and hydraulics of a longer river reach of 42.7 river kilometers for two surveys, one in completed 1984 while the dam was in place and the other completed in 2007 and 2009, 6-8 years after the dam was removed.

Chapter 5.0 Methods

In order to assess the influence of the La Valle dam removal on the upper Baraboo River hydraulics and geomorphology, I conducted a literature review, field surveys, Geographic Information System (GIS)-based research, and computer modeling. Through the literature review, I obtained historical information about the dam and the watershed. I conducted field surveys of the La Valle reach of the river channel and obtained additional field surveys taken in 2007 from the Sauk County Land Conservation Office, extending the river model through the city of Reedsburg, Wisconsin, and from the Flood Insurance Survey taken in 1984, provided by Flood Emergency Management Agency (figure 23). Using GIS, I recorded landscape and river characteristics, such as important geological features. I modeled stream flow for the upper Baraboo River using the HEC-RAS IV computer model. Through the combination of these four methods, I studied and recorded stream response to the removal of the La Valle dam.

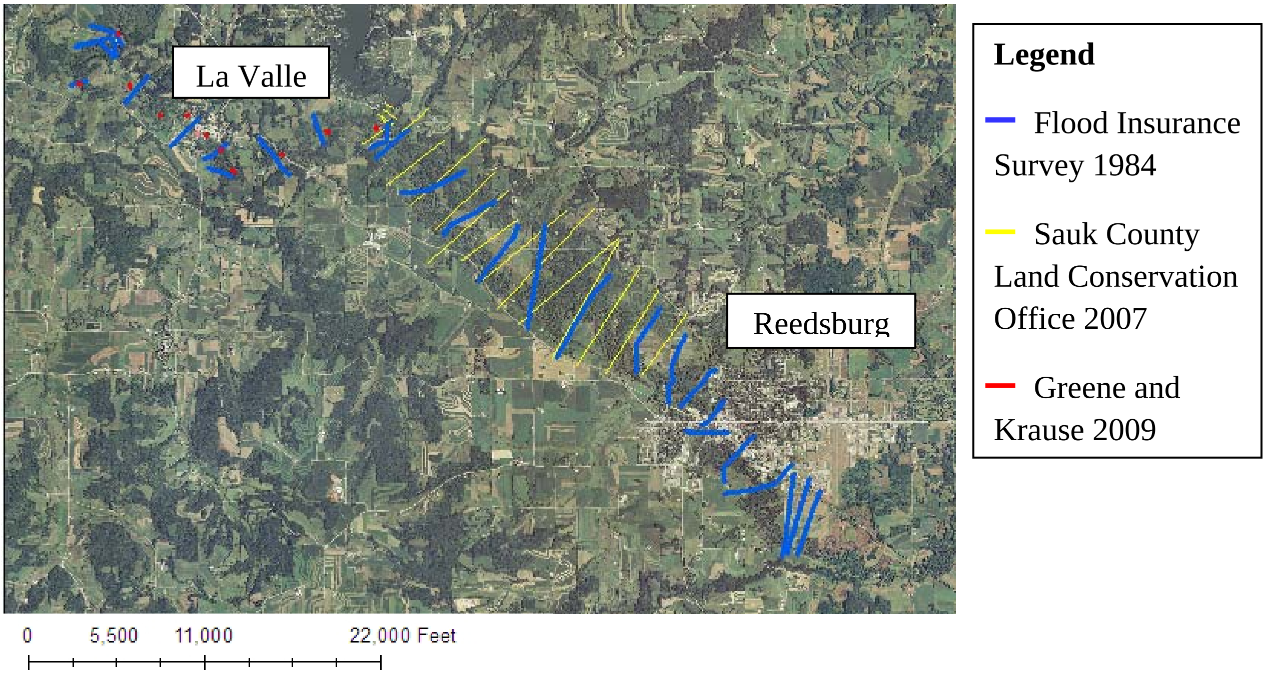

Figure 23 NAIP Imagery from 2008. Blue lines are locations of the Flood Insurance Survey cross-sections surveyed in 1984; Yellow lines are the Sauk County Land Conservation Office cross-sections surveyed in 2007; Red lines are the cross-sections surveyed by the author with the help of Jena Krause in 2009.

5.1 Literature Review

In order to understand the geography of the watershed, to accurately model the dam, and to analyze my results, I reviewed the literature surrounding the Baraboo River watershed and the La Valle dam. Since geomorphology of the river is connected to the bedrock geology and soil type in the Baraboo River system, I reviewed the Wisconsin Geological and Natural History Survey data on bedrock geology and soil. By knowing the bedrock stratigraphy and structure I inferred how bedrock erodibility changes throughout the upper watershed and identified the general location of a fault line within the La Valle reach.

Information on soil type within the watershed furthers the understanding of the sediment type in the river channel as well as how easily the soil may be eroded and carried into the stream by runoff. Understanding sediment load characteristics is necessary to comprehend sediment transport through the river system after the dam removal.

To accurately model the hydraulic influence of the dam and analyze the impacts of its removal, I reviewed historical records discussing the owner history and use of dam, the dam structure, the dam removal process, and the post-removal river engineering projects. I obtained information on the dam structure and post-removal engineering projects from Alicia Jepsen of the Sand County Foundation. The Sand County Foundation bought the dam with the goal of removing it and supervised the dam removal. I input dam structure data into the HEC-RAS IV computer model to observe river flow with the dam in place. To correctly identify the drivers of change in channel geomorphology, I obtained information regarding the post-removal engineering changes made to the river channel from the WDNR (1998 and 2001).

5.2 Field Surveys

Field surveys were taken of the Baraboo River channel, spanning approximately three river kilometers upstream of the dam site and approximately three river kilometers downstream of the dam site. The surveying was completed during September and October 2009 using an auto-level instrument. Twelve river cross-sections were surveyed along the La Valle reach (figure 23). Elevations at each cross-section were tied to a temporary benchmark created at each cross-section and then tied to a known benchmark on the State Highway 58 Bridge in La Valle.

5.3 GIS-based Research

Using ArcGIS I looked at spatial characteristics and temporal changes in channel form and flow. To record changes within the upper watershed in land use and channel flow that may impact the results I scanned and georeferenced aerial photographs of the La Valle reach for the years of 1937, 1947, 1978, and 1993/1994. I also downloaded the United States Department of Agriculture National Aerial Imagery Program (USDA NAIP) images for Sauk County for the years of 2004, 2006, and 2008. The NAIP imagery is a NAD 1983 HARN projection. I identified street cross-sections on the 2008 NAIP image as control points for the georeferencing of the historical aerial photographs.

To check for changes in channel location and changes in riparian vegetation I made shape files tracking the channel for each year of aerial data. To see how oxbow lakes changed from 1937 to 2008 I recorded their locations and how they changed over the study period. In recording oxbow lake changes, I took qualitative notes of their presence and whether they were filled with water, sediment, or vegetation. If the oxbows were filled with vegetation, I also noted vegetation type and density. I recorded type and density of riparian vegetation for each photographed time period to assess how it changed over the study period and where along the channel the change took place.

To look at topography within the watershed, I obtained LIDAR data from the USGS and uploaded it into ArcGIS. To note potential influences of bedrock on channel form, I recorded valley width and presence of bedrock walls along the channel for each surveyed cross-section used in the HEC-RAS IV computer model.

5.4 Computer Modeling

To study changes in the longitudinal profile and hydraulics due to dam removal, I used the HEC-RAS IV one-dimensional channel model. In the HEC-RAS IV modeling program, I prepared two models, one simulating conditions with the dam and one simulating conditions without the dam. To represent the channel profile and hydraulics with the dam in place, cross-section survey data from 1984 were obtained from the Flood Insurance Survey (figure 23). To model the current channel profile, I used cross-section survey data collected by John Vosberg during the summer of 2007 and the cross-section survey data I collected during the fall of 2009 (figure 23). After preparing the two models, I simulated a variety of different hydraulic conditions to test for model sensitivity and accuracy and to compare channel response between the models.

HEC-RAS IV is a one-dimensional stream model created by the United States Army Corp of Engineers Hydrological Engineering Center. HEC-RAS IV can compute hydraulic calculations for a complete network of natural and constructed stream channels. The HEC-RAS system can model flow states and conditions, sediment transport, and water quality. This is accomplished through four one-dimensional river analysis components, which include 1) steady flow water surface profile computations 2) unsteady flow simulations 3) moveable boundary sediment transport computations and 3) water quality analysis. In addition to these four river analysis components, the system contains hydraulic design features, such as inline structures, bridges, and culverts.

This project utilizes HEC-RAS IV to simulate steady flow. Steady flow simulations are conducted by solving the one-dimensional energy loss equation. Energy losses are computed through friction using the Manning's equation and expansion and contraction by multiplying velocity head by the expansion and contraction coefficients. The momentum equation is used in simulations where the water surface profile varies rapidly. Examples of such situations where the water surface profile could rapidly vary include mixed flow regime calculations, hydraulics of bridges, and evaluating profiles at river confluences. In the models of this project, mixed flow regime calculations are used and bridges are present, allowing the use of the momentum equation.

In order to run HEC-RAS IV for the Baraboo River near La Valle, Wisconsin, four pieces of information are necessary. First, field surveys of channel shape are required and are input as cross-sections. Second, channel slope is required to calculate the velocity head from one cross-section to the next in the downstream direction. Third, friction coefficients must be obtained to enter into the Manning Equation, which is used to calculate velocity head. Last, expansion and contraction coefficients are necessary to adjust the velocity head for major channel adjustments.

Field surveys of the channel shape for the 1984 model were obtained by the Flood Insurance Surveys as HEC-2 files and converted into HEC-RAS IV files. The Flood Insurance Survey cross-sections are of the entire length of the Baraboo River within Sauk County, Wisconsin. I extracted only the cross-sections within the study area; the study area begins three river kilometers upstream of the La Valle dam site and ends at Reedsburg (figure 23). Manning coefficients and expansion and contraction coefficients were obtained through aerial photograph analyses and field observations of vegetation structure, composition, and density, and the hydraulic models were validated using stream discharge and height measures. Manning coefficients vary between 0.035 and 0.1 and the expansion and contraction coefficients are 0.1 and 0.3, respectively.

For the present-day model without the dam, I used surveys taken in the summer of 2007 and the fall of 2009. During the summer of 2007, John Vosberg of the Sauk County Land Conservation Office surveyed and prepared a HEC-RAS IV model for a reach of the Baraboo River beginning at the confluence of Big Creek and ending at Reedsburg (figure 23). The Vosberg surveys were tied to true elevations using bridge benchmarks; the multiple benchmarks and a topographic map provided the model with channel slope. Manning friction coefficients were obtained through aerial photograph analysis and field observation and vary between 0.035 and 0.1.

During the fall of 2009, Jena Krause and I surveyed twelve cross-sections along a six kilometer reach of the Baraboo River, spanning three river kilometers upstream of La Valle and three river kilometers downstream of La Valle, ending at Big Creek where the Vosberg surveying began (figure 23). The cross-section surveys were tied to true elevations using the benchmark on the State Highway 58 Bridge in La Valle. More specifically, the cross-section obtained at the dam site next to the State Highway 58 Bridge in La Valle was tied to the bridge benchmark to obtain a true elevation. Then, to calculate elevations of the other cross-sections in the survey, channel slope over distance to each consecutive cross-section was used. Channel slope was obtained from USGS 7.5 minute topographic maps with contour intervals of twenty feet. The slope was calculated for each section of the fall 2009 survey reach where a topographic line crossed the channel. Channel slope averaged 0.000289 upstream of the old dam site and 0.000496 downstream of the old dam site. Since the elevation of my last cross-section matched the elevation of John Vosberg's first cross-section, which are both located at the confluence of Big Creek and Baraboo River, I assumed my elevations to be accurate.

The friction coefficients for the channel and the floodplain were measured through a combination of field and aerial photograph observations and by comparison with the Vosberg friction coefficients. I tested the sensitivity of the friction coefficients to reduce model error. Friction coefficients varied between 0.035 and 0.1, with values changing both among different cross-sections and horizontally across individual cross-sections. Smaller Manning coefficients are used for the La Valle basin of the study reach because the surveys do not extend into the thickly forested valley floor, unlike the Vosberg and Flood Insurance surveys. The larger Manning coefficients for the reach surveyed by Vosberg and the Flood Insurance surveys are for the valley floor where thick riparian forests exist. The expansion and contraction coefficients were estimated from a combination of the HEC-RAS Reference Manual and from the Vosberg model simulation estimates. The contraction coefficient was estimated at 0.1 and the expansion coefficient was estimated at 0.3. Again, a sensitivity test was conducted on the expansion and contraction coefficients to reduce model error.

I simulated several different discharge values for both the 1984 model with the dam and the 2007/2009 model without the dam until I obtained four discharge values for each model which represented the hydrology and hydraulics of the channel. For the 1984 model I simulated flows of 350 cubic feet per second (cfs; 9.91 cubic meters per second, cms), 444.19 cfs (12.58 cms), 5300 cfs (150.08 cms), and 11,000 (311.49 cms). The four flows represent the bankfull discharge for upstream of the dam, the estimated one-year recurrence interval flood, the estimated 50-year recurrence interval flood, and an estimate of the discharge at La Valle for the June 2008 flood, respectively. The flood that occurred in June of 2008 is recorded as a 500-year recurrence interval flood (Fitzpatrick et al. 2008). For the 2007/2009 model I simulated flows of 0.25 cfs (0.007 cms), 350 cfs (9.91 cms), 444.19 cfs (12.58 cms), and 850.49 cfs (24.08 cms). The four flows represent an extremely low flow, the estimated one-year recurrence interval flood, the bankfull discharge for upstream of the dam, and the bankfull discharge downstream of the dam, respectively. Flows larger than bankfull cannot be accurately modeled in the 2007/2009 model because the surveys do not extend far enough across the valley floor. However, the model still shows important post-dam removal geomorphology and hydraulics.

For each flow simulation I extracted values for water surface elevation, shear stress, velocity, and hydraulic radius to see how those hydraulic variables vary based discharge and between the two surveyed time periods. Last, using flow area calculations extracted from the model simulations I also estimated the amount of sediment transported out of the old La Valle reservoir as of 2009. To do this I ran simulations that calculated water surface elevation of the 2007/2009 stream model equal to the channel bed elevation of the 1984 longitudinal profile. I then extracted flow area calculations for each cross-section and extrapolated the flow area upstream to obtain volumes. Since the profile is not perfectly flat and smooth between cross-sections, some estimation error occurs. To reduce the errors in my estimation, I calculated conservative and liberal estimates, giving a range in percent of sediment removed from the reservoir.

Using the simulation outputs for the four variables as well as observations of the longitudinal profiles for the two time periods, I analyzed: 1) geomorphic changes to the La Valle and Reedsburg basins of the Baraboo River following dam removal and 2) the hydraulic drivers of the change in channel geomorphology.

Chapter 6.0 Results

Since the removal of the La Valle dam from the Baraboo River in 2001, the channel has undergone several geomorphologic and hydraulic adjustments. Channel simulations in HEC-RAS IV show many of these adjustments through changes in the channel longitudinal profile, channel water surface elevations, channel shear stress, channel velocity, and hydraulic radius under different flows.

6.1 Channel Longitudinal Profile in 1984

In 1984, much of the Baraboo River study reach appears to be a sediment sink based on the bed profile. Beginning upstream of the La Valle dam, which is located at a river distance of about 124,000 feet (37,795.2 meters; figure 24), sediment accumulation appears to aggrade the channel bed. Incision appears to occur in a portion of the channel upstream of the dam, around channel distance 136,000 feet (41,452.8 meters). At the location of this apparent incision the channel is constricted by sandstone rock walls on the channel margins (figure 24). The average channel slope upstream of the dam is approximately 0.00018. Immediately after the dam, the channel is scoured as a result of the dam trapping sediment on the upstream side and allowing clear, erosive water to flow downstream of the dam through the spillway.

Below the dam at a railroad bridge located about channel distance 110,000 feet (33,528.0 meters) there is a scour hole of about five feet (1.52 meters; figure 24). This likely results from the combination of the downstream scouring effect of the State Highway 33 Bridge immediately upstream at channel distance 118,000 feet (35,966.4 meters), the downstream scouring effect of the railroad bridge itself, and a natural channel constriction by sandstone rock walls at the railroad bridge.

Continuing downstream toward the western border of the city of Reedsburg, the flattening of the longitudinal profile suggests that the channel bed remains aggraded. The aggraded bed begins immediately upstream of State Highway 23/33 Bridge and neighboring railroad bridge (figure 24). While no natural constrictions occur at this location, the land use includes two sand pits, an industrial waste pond, and residential and urban developments which could supply large amounts of eroded sediment to the stream. Downstream of the State Highway 23/33 Bridge and the adjacent railroad bridge, no obvious channel bed aggradation or incision occurs. The average slope of the downstream reach is 0.00013.

Throughout the entire study reach, changes in profile slope indicate that stream structures influence channel bed aggradation and incision; aggradation takes place directly upstream of bridges and upstream of the La Valle dam while incision or scouring takes place directly downstream of bridges and downstream of the La Valle dam (figure 24). Channel structures also influence the water surface profiles in a similar pattern, where the water surface has a higher elevation immediately upstream of channel structures and a lower elevation immediately downstream of channel structures (figure 24). The average channel slope for the entire study reach is 0.000229.

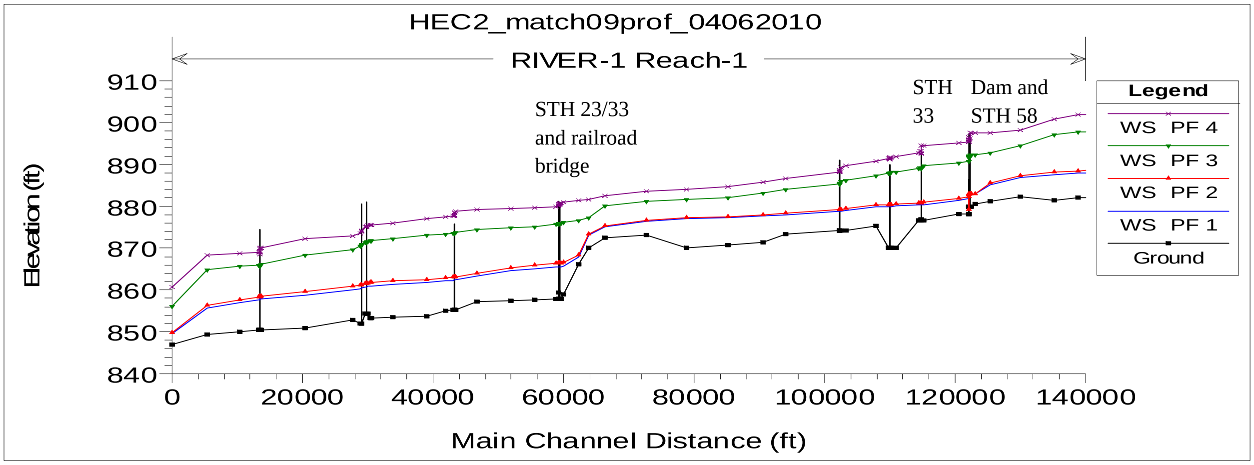

Figure 24 Simulation for 1984 FIS survey. Colored lines represent the water surface profiles at the four simulated discharges. The black line is the ground elevation so represents the longitudinal profile. The blue water surface is for a discharge of 350 cfs (9.91 cms); the red water surface is for a discharge of 850 cfs (24.08 cms); the green water surface is for a discharge of 5300 cfs (150.08 cms); and the purple water surface is for a discharge of 11,000 cfs (311.49 cms).

6.2 Channel Longitudinal Profile in 2007/2009

The channel longitudinal profile for 2007/2009 shows several channel geomorphic adjustments since 1984 based on the comparison of the two surveyed longitudinal profiles, especially for the reach between the bridges at the western border of Reedsburg through the town of La Valle. In general, the 2007/2009 profile shows several channel reaches where incision occurred into the aggraded channel bed described in the 1984 profile while aggradation occurred onto reaches with the incised channel bed described in the 1984 profile (figure 25).

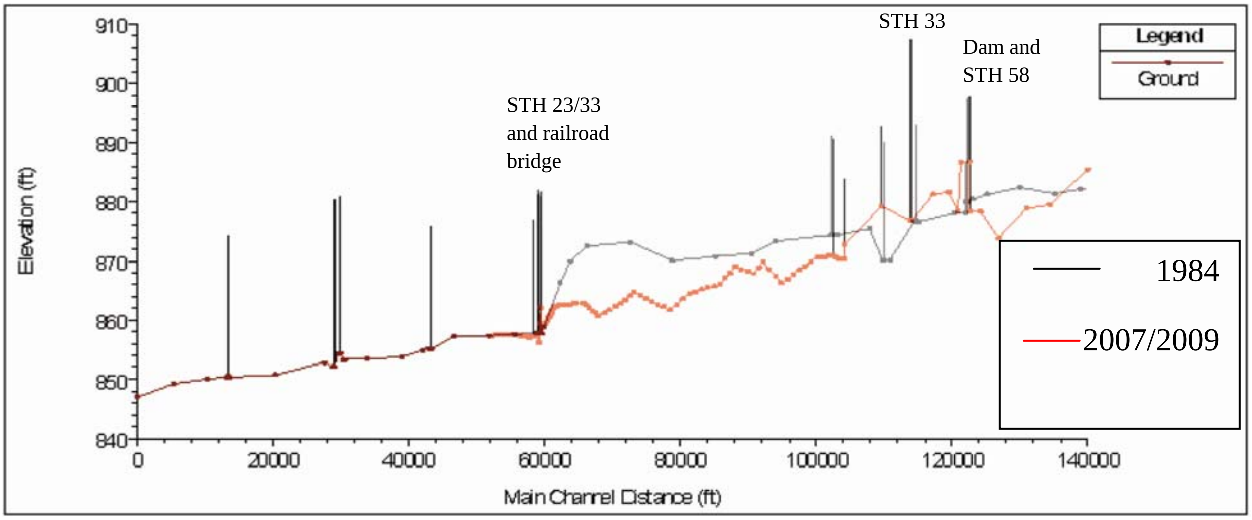

Figure 25 Comparison of the longitudinal profiles for 1984 and 2007/2009. The black line represents the 1984 survey and the red line represents the 2007/2009 survey.

Upstream of the La Valle dam the channel has incised into the reservoir sediments by approximately eight feet (2.44 meters) immediately upstream of the dam site and decreasing upstream to approximately three feet (0.91 meters). According to estimates of removed reservoir sediments obtained from the flow area estimates in the HEC-RAS IV model, the channel incision through the reservoir sediments has resulted in the transport of approximately 36-39% of stored reservoir sediment out of the reservoir.

The average slope of the channel upstream of the dam site is 0.000209, slightly steeper than in 1984. At the site of the dam, the river bed is artificially raised by about eight feet (2.44 meters) using rubble and concrete boulders (WDNR 2001; figure 26). The channel bed was artificially raised at the time of the removal of the dam structure to preserve the spillway as a grade control and protect the mill building (WDNR 1998 and 2001, communication with Alicia Jepsen, and Doyle et al. 2003b).

Through studying the shape of the channel bed in the 2007/2009 longitudinal profile, locations of channel aggradation and incision can be inferred (figure 26). Directly downstream of the dam site, channel scour occurs due to the grade control. After the grade control, net channel aggradation occurs between approximately channel distance 105,000 and 120,000 feet (32,004 and 36,576 meters). Channel aggradation between main channel distances of 105,000 and 120,000 feet (32,004 and 36,576 meters) is about two feet (0.61 meter), with the exception of the scour hole at the railroad bridge near channel distance 110,000 feet (33,528 meters) which has filled with about six feet of sediment (1.83 meters; figure 25). The scour hole at 110,000 feet (33,528 meters) still exists, however, likely due to the combination of the two bridges and the natural rock wall channel constriction.

Upstream of the State Highway 23/33 Bridge and railroad bridge at the western edge of the city of Reedsburg, the river incised into the sediments that were present in 1984 (figure 25). While the channel bed still seems slightly aggraded upstream of the two bridges, about eight feet of sediment has been removed since 1984. Downstream of the State Highway 23/33 Bridge and adjacent railroad bridge, no obvious channel bed aggradation nor incision occurs (figure 25). The average slope for the reach downstream of the dam site is 0.000183, slightly steeper than in 1984.

As in 1984, channel structures still influence channel bed aggradation and incision throughout the study reach; channel aggradation takes place directly upstream of bridges and channel incision or scouring takes place directly downstream of bridges (figure 26). The average channel slope for the entire study reach in 2009 is 0.000215, slightly gentler than in 1984. Channel structures still influence the water surface profiles as well, where the water surface is generally at a higher elevation directly upstream of channel structures and at a lower elevation directly downstream of channel structures (figure 26). A unique aspect of the water surface profile in 2009 is the high water surface elevation for low flows behind the grade control structure. Even for a discharge of 0.25 cfs (0.007 cms) the water surface elevation is particularly high for the reach directly upstream of the dam site's artificially raised bed in comparison to the rest of the profile.

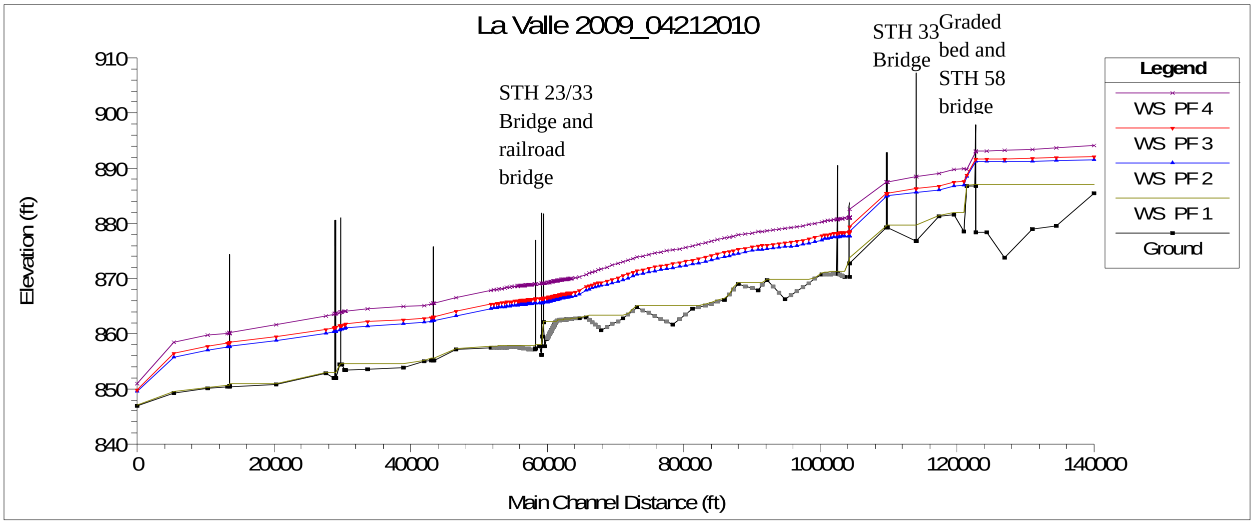

Figure 26 Longitudinal profile and water surface elevation simulations for 2007/2009 survey. Colored lines represent the water surface profiles at the four simulated discharges. The black line is the ground elevation so represents the longitudinal profile. The green water surface is for a discharge of 0.25 cfs (0.007 cms); the blue water surface is for a discharge of 350 cfs (9.91 cms); the red water surface is for a discharge of 444.19 cfs (12.58 cms); and the purple water surface is for a discharge of 850 cfs (24.08 cms).

Overall, the longitudinal profile is smoother in 2007/2009 than in 1984 (figure 25). The slope became steeper for the reach upstream of the dam site in 2009 relative to 1984 and steeper for the reach downstream of the dam site in 2007/2009 relative to 1984, while the total channel slope for the entire study reach, decreased in 2007/2009 relative to 1984. In both years, the slope of the upstream reach is steeper than the slope of the downstream reach; this is most likely due to the bedrock constriction that occurs upstream of the dam but is mostly absent downstream of the dam. Last, the presence of structures along the stream channel influences the longitudinal profile in both 1984 and 2007/2009. The removal of the dam in 2007/2009 appears to affect the longitudinal profile through incision upstream of the dam site and aggradation downstream of the dam site.

6.3 Changes in Cross-Section Characteristics, 1984 to 2007/2009

To see if any changes in cross-section width or depth occurred, identical cross-sections from the 1984 and 2009 surveys are compared. An analysis of a cross-section upstream of the dam shows that by 2009 the channel incised by approximately two feet (0.61 meters) along the thalweg and that the thalweg shifted towards the left bank (figure 27). The channel thalweg shift resulted in scouring of the left channel margin and aggradation on the right channel margin. No noticeable channel widening occurred.

Comparing the 1984 and 2009 surveys of a cross-section downstream of the dam shows the channel bed aggraded by approximately four feet (1.22 meters; figure 28). The channel margins and banks appear steeper and little or no change in channel bed width occurs.

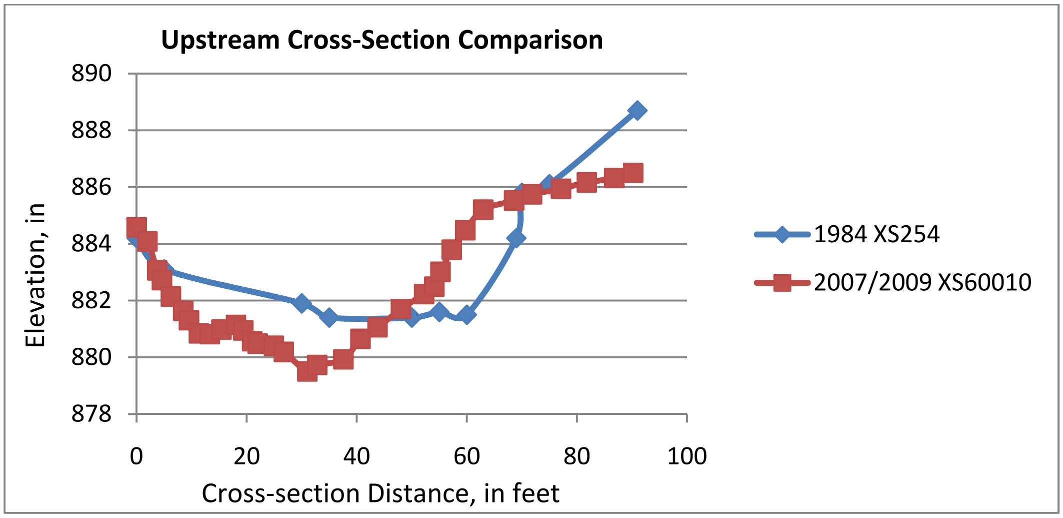

Figure 27 The blue line is the shape and position in 1984 and the red line is the shape and position in 2007/2009. XS number is the identification number of the cross-section within the simulation.

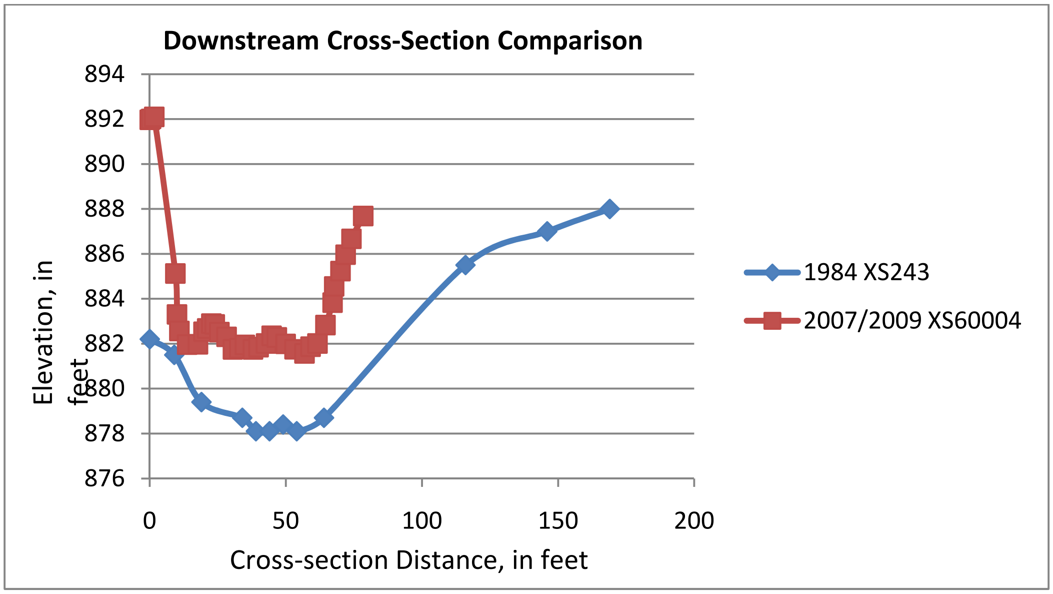

Figure 28 The blue line is the shape and position in 1984 and the red line is the shape and position in 2007/2009. XS number is the identification number of the cross-section within the simulation.

6.4 Hydraulic Variables: Channel Shear Stress, Channel Velocity, and Hydraulic Radius

To explain the observed changes in channel geomorphology, characteristics of key hydraulic variables are examined over a series of flow regimes. Changes in channel shear stress, channel velocity, and hydraulic radius occur for different discharges within the same modeled year and between the two modeled years that explain the observed change in channel geomorphology from 1984 to 2007/2009.

Channel shear stress and channel velocity for the majority of the study reach is relatively small for low flow stages as seen in both 1984 and 2007/2009 (figures 29-32). The low flow stages simulated range from 350 cfs to 444.19 cfs (9.91 cms to 12.58 cms) in 1984 and 0.25 cfs to 850 cfs (0.007 cms to 24.08 cms) in 2007/2009. In general, the shear stress and channel velocity do not exceed 0.1 pounds per square foot (0.49 kilograms per square meters) and 1.5 feet per second (0.45 meter per second), respectively. Exceptions in both time periods occur around river structures where shear stress and velocity decreases directly upstream of the structure and increases significantly directly downstream of the structure.

In the 1984 model of high flow simulations, shear stress and velocity significantly increase in several places along the study reach where significant increases are not observed during lower flows (figures 29 and 31). The high flow stages simulated in 1984 include discharges of 5300 cfs (150.08 cms) and 11,000 cfs (311.49 cms). Directly upstream of the dam where the stored reservoir sediments aggrade the bed, shear stress increases to nearly 0.5 pounds per square foot (2.44 kilograms per square meter) for a flow of 5300 cfs (150.08 cms) and 0.7 pounds per square foot (3.42 kilograms per square meters) for a flow of 11,000 cfs (311.49 cms). Likewise, velocity increases to nearly five feet per second (1.52 meters per second) for a flow of 5300 cfs (150.08 cms) and 6.25 feet per second (1.91 meters per second) for a flow of 11,000 cfs (311.49 cms). During the higher flows, shear stress and velocity also increase significantly to around 0.5 to 0.7 pounds per square foot (2.44 to 3.42 kilograms per square meter) and four to eight feet per second (1.22 to 2.44 meters per second), respectively, directly downstream of river structures. Overall, shear stress and velocity in 1984 is slightly higher downstream of the State Highway 23/33 Bridge and railroad bridge at the western border of the city of Reedsburg than in the reach upstream of the two bridges.

For the 2007/2009 simulations, shear stress and velocity are relatively constant throughout the entire study reach; there is no increasing or decreasing trend in the downstream direction as seen in 1984. However, shear stress and velocity behind the dam site in 2009 are small for all flow simulations in comparison to the rest of the study reach not impacted by channel structures. In addition, shear stress and velocity directly downstream of the grade control structure are especially high compared to the rest of the study reach and compared to the reach directly downstream of the dam structure in 1984.

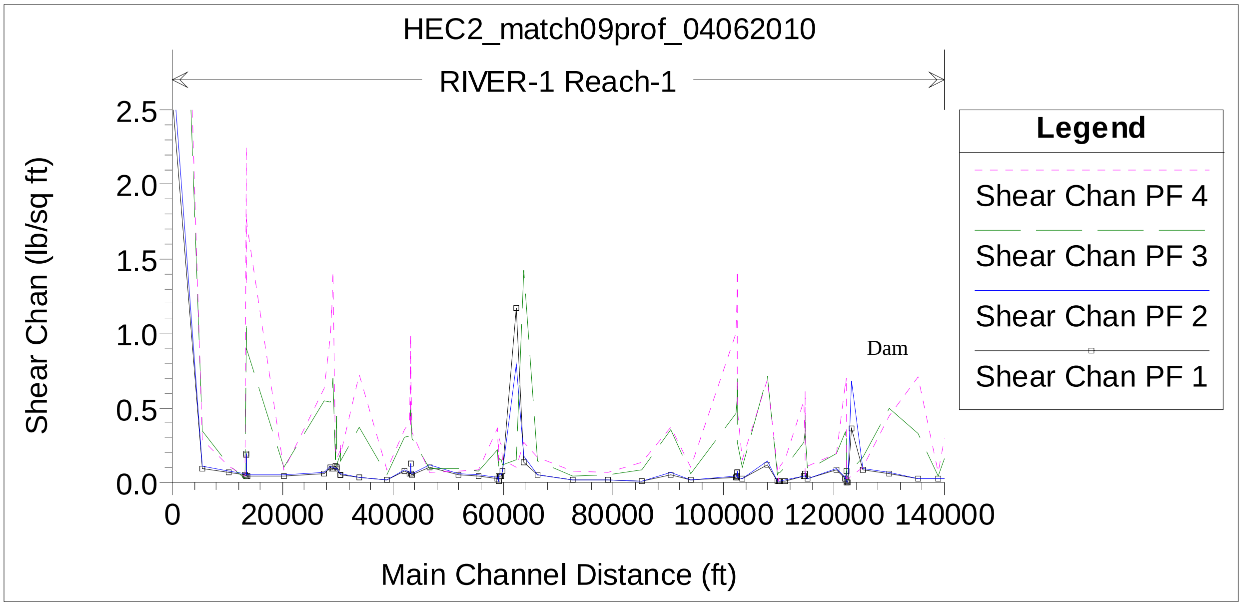

Figure 29 Simulation for 1984 channel shear stress. The black line is for a discharge of 350 cfs (9.91 cms); the blue line is for a discharge of 444.19 cfs (12.58 cms); the green line is for a discharge of 5300 cfs (150.08 cms); and the pink line is for a discharge of 11,000 cfs (311.49 cms).

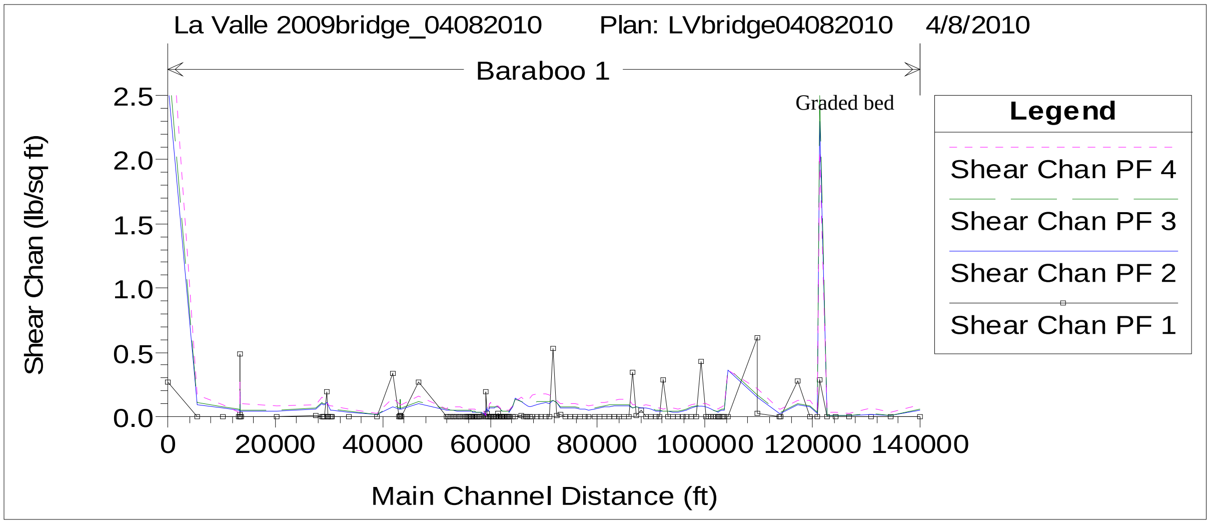

Figure 30 Simulation for 2007/2009 channel shear stress. The black line is for a discharge of 0.25 cfs (0.007 cms); the blue line is for a discharge of 350 cfs (9.91 cms); the green line is for a discharge of 444.19 cfs (12.58 cms); and the pink line is for a discharge of 850 cfs (24.08 cms).

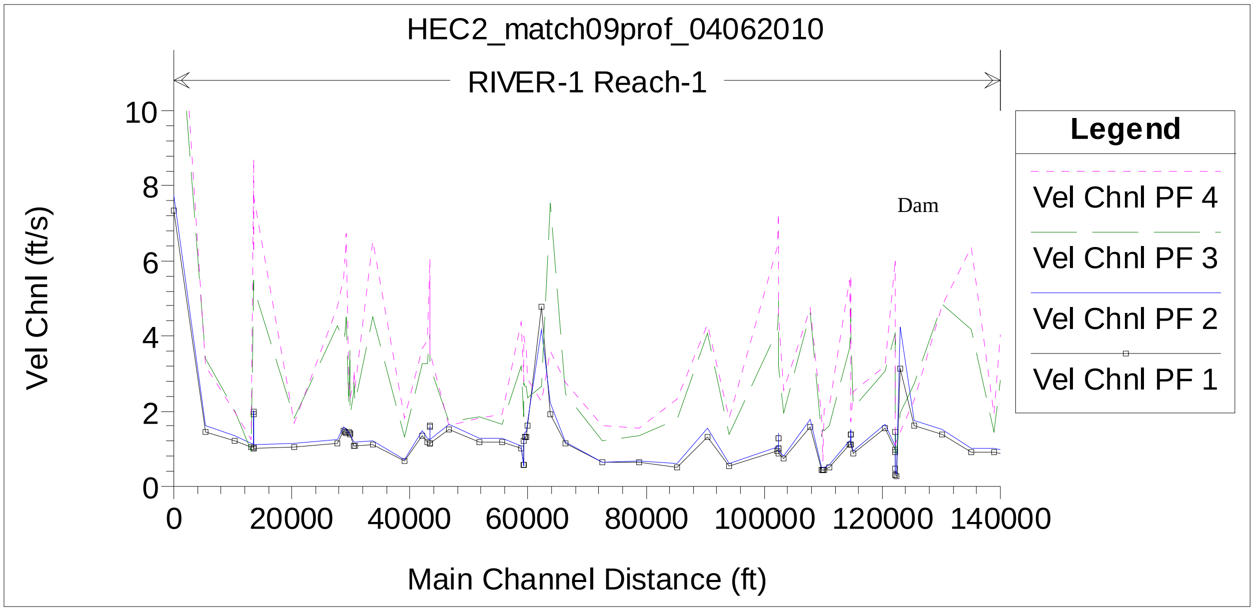

Figure 31 Simulation for 1984 channel velocity. The black line is for a discharge of 350 cfs (9.91 cms); the blue line is for a discharge of 444.19 cfs (12.58 cms); the green line is for a discharge of 5300 cfs (150.08 cms); and the pink line is for a discharge of 11,000 cfs (311.49 cms).

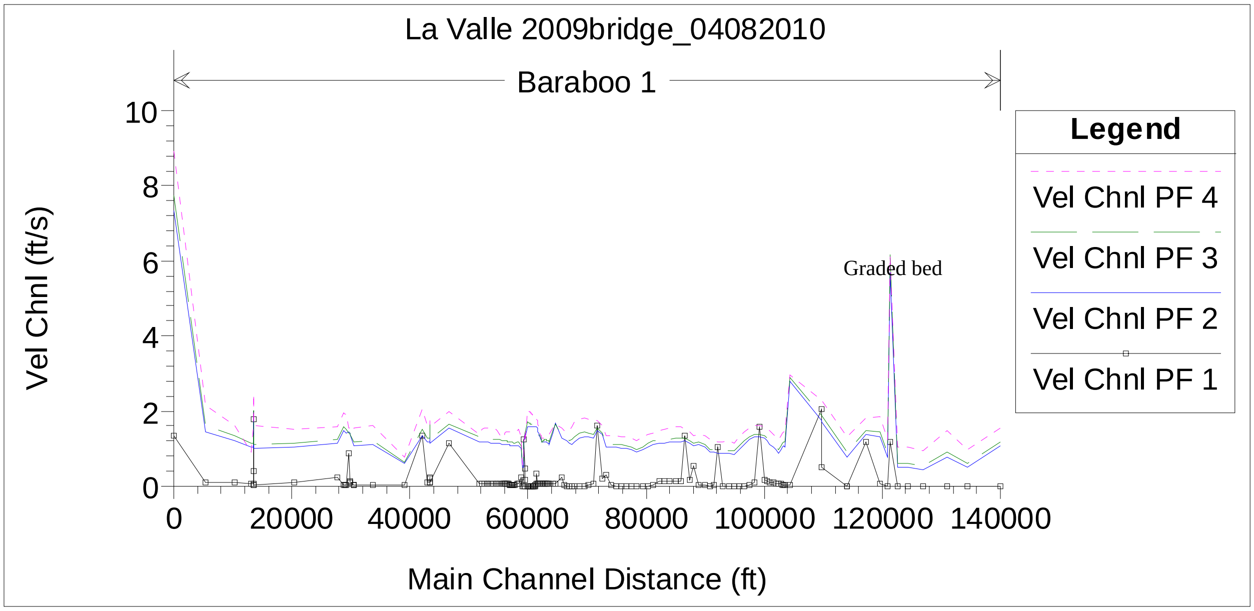

Figure 32 for 2007/2009 channel velocity. The black line is for a discharge of 0.25 cfs (0.007 cms); the blue line is for a discharge of 350 cfs (9.91 cms); the green line is for a discharge of 444.19 cfs (12.58 cms); and the pink line is for a discharge of 850 cfs (24.08 cms).

Hydraulic radius increases as discharge increases for both the 1984 and 2007/2009 model, as expected. However, the hydraulic radius changes at particular locations within the study reach in both model years and differences in hydraulic radius appear between the two model years for identical flows.

In the 1984 model, hydraulic radius near the La Valle dam is about two feet (0.61 meter), increases by one to three feet (0.30 to 0.91 meter) upstream of the La Valle dam, and decreases by about one foot (0.30 meter) directly downstream of the dam (figure 33). There is a general decreasing trend in hydraulic radius in the downstream direction until just after the State Highway 23/33 Bridge and the railroad bridge at the main channel distance of about 60000 feet (18,288 meters). Shortly after these two bridges hydraulic radius increases significantly by about five feet (1.52 meters), going from approximately one foot (0.30 meter) up to six feet (1.83 meters).

In the 2007/2009 model, hydraulic radius does not vary greatly throughout the study reach, with the exception of the reach near the La Valle dam site (figure 34). At the dam site, hydraulic radius fluctuates greatly. Upstream of the dam site the hydraulic radius increases by at least two to five feet (0.61 to 1.52 meters), reaching a peak of over ten feet (3.05 meters) directly upstream of the grade control structure. Hydraulic radius then falls drastically to about one foot (0.30 meter) directly downstream of the grade control structure. However, the hydraulic radius recovers quickly, and starting at a main channel distance of about 120,000 feet (36,576 meters) and continuing downstream there is little variation in hydraulic radius, with the hydraulic radius ranging between about three and five feet (0.91 and 1.52 meters).

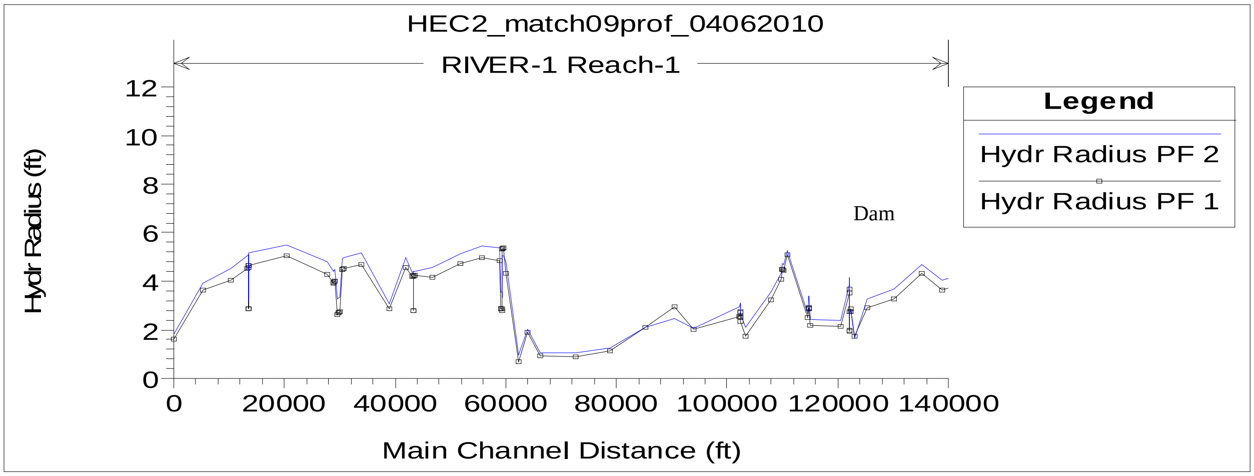

Figure 33 Simulation for 1984 hydraulic radius. The black line represents hydraulic radius at a discharge of 350 cfs (9.91 cms) and the blue line represents hydraulic radius at a discharge of 444.19 cfs (12.58 cms).

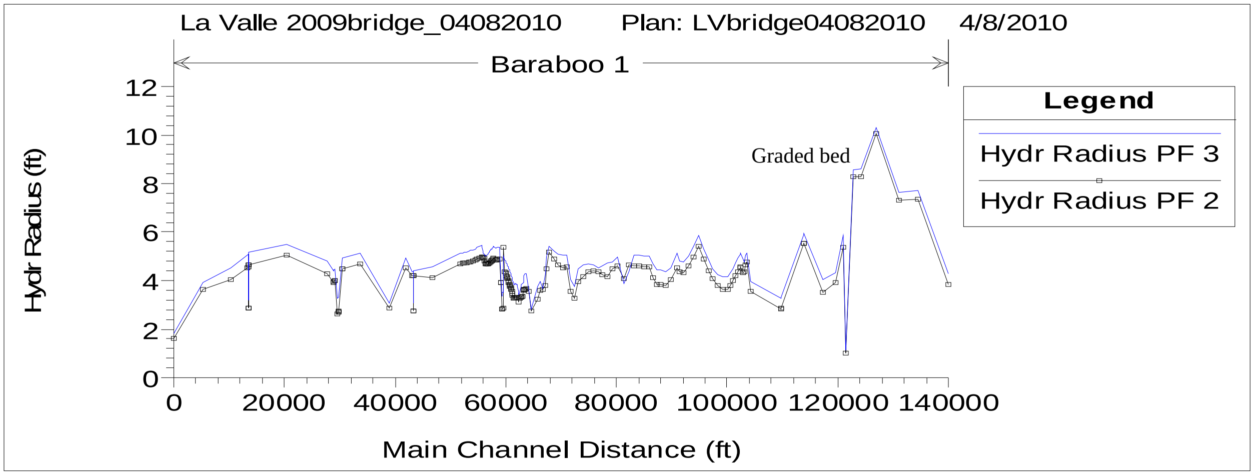

Figure 34 Simulation for 1984 hydraulic radius. The black line represents hydraulic radius at a discharge of 350 cfs (9.91 cms) and the blue line represents hydraulic radius at a discharge of 444.19 cfs (12.58 cms).

Chapter 7.0 Discussion

This study shows that during the past eight to nine years, the Baraboo River geomorphology and hydraulics continued to respond to the La Valle Dam removal. Variables used to identify fluvial adjustments include longitudinal profile, stream cross-section shape, channel velocity, channel shear stress, and hydraulic radius. These observations highlight the 1) significance of existing structures, post-removal stream reconstruction, and large flood events on stream response to dam removal and 2) the need for longer duration studies and longer study reaches to better comprehend and predict fluvial response to dam removal.

7.1 Impacts of Stream Engineering: Channel Structures and Post-Removal Reconstruction

The presence of several bridges and a culvert along the length of the Baraboo River study area impacts the river's form and flow. In regards to sediment transport, the structures act as small dams by storing sediment on the channel bed directly upstream of the structure and scouring the channel bed directly downstream of the structure. This alteration in sediment transport results from the structure constricting flow which backs up water upstream and deposits sediment. Then, potential energy increases at the structure and is transformed to kinetic energy immediately downstream of the structure. This allows flow to scour the stream bed and banks. While these structures prevent a smooth longitudinal profile from taking form, their impact on the geomorphology of the stream system is relatively small compared to that of a dam.

Post- removal stream reconstruction decisions appear to have a strong influence on channel geomorphology and hydraulics, especially in comparison to channel structures. After dam removal occurs, watershed managers often try to minimize the negative effects of the removal by stabilizing the channel banks and bed. In the case of the La Valle Dam, managers stabilized the banks through rip-rapping and seeding with vegetation. In reconstructing the channel bed, the goals were to create a grade control, divert the water away from the old mill building to keep it operable, and strengthen the highway bridge immediately upstream of the dam (Doyle et al. 2003b and communication with Alicia Jepsen). The grade control is located at the dam site toward the right bank along the old spillway, which both preserves the spillway and diverts the water away from the mill building (personal observation and communication with Alicia Jepsen). To strengthen the bridge, the pilings were armored with boulders (Alicia Jepsen).

While the reconstruction successfully prevents scouring of the stream banks and preserves the spillway, mill building, and highway bridge, it greatly impacts stream hydraulics and sediment transport and may adversely influence channel geomorphology. The grade control structure uses boulders and concrete to raise the river bed elevation by approximately eight feet (2.44 meters) above its natural grade. The raised stream bed acts as a barrier to water flow, creating a backwater effect behind the grade control structure. As a result, water depth increases and flow velocity and shear stress decreases directly upstream of the grade control. Over time, sediment may accumulate in this area due to the dissipation of energy and reduced transport capacity. However, the accumulation of sediment behind the grade control structure will primarily be of agricultural origin, and therefore, could store agricultural runoffs that would otherwise enter the greater Mississippi River system. At the same time, the storage area behind the grade control structure is relatively small compared to dam reservoirs so may not have a major influence on nutrient flux. In essence, they removed one dam and may have built another in terms of the stream sediment budget and transport.

7.2 Impacts of Large Flood Events on Sediment Removal and Downstream Sediment Transport from the Reservoir

At the end of the Doyle et al. (2003b) one-year study of the La Valle Dam removal, only approximately 7.8% of the stored sediment was removed from the reservoir and small adjustments to channel form occurred. Other studies that span only the first few years after removal find similarly small percentages of reservoir fill mobilization. For example, Doyle et al. (2003b) observed 14% removed from the Koshkonong Reservoir in Wisconsin, Evans et al. (2000) measured between 9-13% mobilized in an Ohio dam failure, and Burroughs et al. (2009) found 12% removed from the Stronach Dam reservoir in northern Michigan. It is likely that some of the remaining reservoir sediments are stored within stream terraces which are currently protected by vegetation, and therefore, may not be able to be eroded by the stream. Given that the transport of sediment downstream can influence ecological and human communities, sediment dynamics after dam removal is an important consideration.

Given the importance of sediment storage and transport for planning and management purposes, this study estimates the amount of remobilized sediment after a period of nine years following the dewatering of the reservoir. Based on estimates obtained using flow area calculations from the HEC-RAS IV model simulations, between 36-39% of stored sediment has been removed from the La Valle Dam reservoir since the removal of the dam during 2000 and 2001, nearly five times more than that transported by the end of the Doyle et al. (2003b) study.

The majority of the sediment transported out of the reservoir since the Doyle et al. (2003b) study likely occurred during the June 2008 flood. The June 2008 flood approximated the 500-year flood recurrence interval discharge on the Baraboo River (Fitzpatrick et al. 2008). Fitzpatrick et al. (2008) completed a peak flood height analysis and estimated the discharge in Reedsburg to have peaked between 11,500 cfs – 12,500 cfs (325.64 cms – 353.96 cms). According to the HEC-RAS IV model simulations, shear stress and flow velocity increases significantly within the reservoir during flows of the June 2008 flood. In fact, similar values of shear stress and flow velocity were calculated in the simulations for discharges as small as the estimated 50-year recurrence interval flood (figure 29). However, during the gage record for the Baraboo River there have been no floods with discharges equal to or greater than the estimated discharge for the 50-year recurrence interval flood. Therefore, the model indicates that the June 2008 flood had sufficient energy to erode and transport a significant volume of sediment out of the reservoir and is likely responsible for the majority of the sediment transported out of the reservoir since the dam removal in 2001.

Doyle et al. (2003b) took field measurements of the quantity of sediment transported out of the reservoir beginning with the dewatering of the dam and ending a year after the dewatering event. Doyle et al. (2003b) found that significant sediment remobilization in the reservoir occurred twice, once immediately after the dewatering of the reservoir and then several months later during a relatively small summer flood. However, the amount mobilized during the relatively small summer flood was only 0.5% of the total stored reservoir sediment, which is small in comparison to the amount mobilized by the dewatering of the reservoir.

Since the dam removal in 2001, the only extremely large flood that occurred within the Baraboo River watershed was the June 2008 flood. Between 2001 and 2008, there were two floods in 2004 and two floods in 2007 with discharges that exceeded the two-year recurrence probability, but were smaller than the five-year recurrence probability discharge (USGS 2009). The peak flows for each of the other years between 2001 and 2008 had recurrence probabilities of between one and two years (USGS 2009). Given that the Doyle et al. (2003b) study observed a small flush of sediment out of the reservoir during a relatively small summer flood, it is likely that the other small floods that occurred during the eight to nine years following the removal of the dam could produce water depths and shear stress capable of removing sediment from the reservoir. However, the amount of sediment removed from the reservoir during each flood would probably result in negligible changes in channel bed elevation and minimal downstream deposition of sediment on channel margins and floodplain.

In comparison, field observations of the downstream floodplain as well as conversations with landowners downstream of the dam site support the hypothesis that the June 2008 flood remobilized a major fraction of the reservoir sediments and deposited the sediments on the downstream floodplain. When surveying cross-sections downstream of the dam site, over a foot of sand was deposited on much of the floodplain. In addition, Carrol Czarnecki, an owner of floodplain property downstream of the dam, commented that the June 2008 Flood deposited copious amounts of sand on her property and that a large volume remains on the floodplain. Overall, channel model simulations combined with the findings of the Doyle et al. (2003b) study and field observations support the hypothesis that the June 2008 Flood eroded a large volume of sediment out of the reservoir.

7.3 Channel Profile Adjustments, 1984 to 2007/2009

In general, the channel profile in 2009 shows incision upstream of the dam through the reservoir and aggradation through the first three river kilometers downstream of the dam. The 2007/2009 survey shows steepening of the channel slope for the upstream and downstream reaches since the 1984 surveys. Similar results are observed by Doyle et al. (2003b) and other studies (i.e. Burroughs et al. 2009 and Neave et al. 2009) examining stream adjustment to the lowered base-level.

Although incision occurred upstream of the dam site after removal through 2009, no noticeable channel widening took place (figure 27). Doyle et al. (2003b) also observed no change in channel width upstream of the dam site, explaining this observation by the limited extent of channel bank mass wasting. This is counter to conceptual base-level lowering models for alluvial streams. A base-level lowering model created by Doyle and Harbor (2003) and used by Doyle et al. (2003b) in the La Valle Dam removal 2001 study is comprised of six stages, where incision occurs during stage three and is followed by channel widening in stage four and five before a quasi-equilibrium is reached during stage 6 (figure 35).

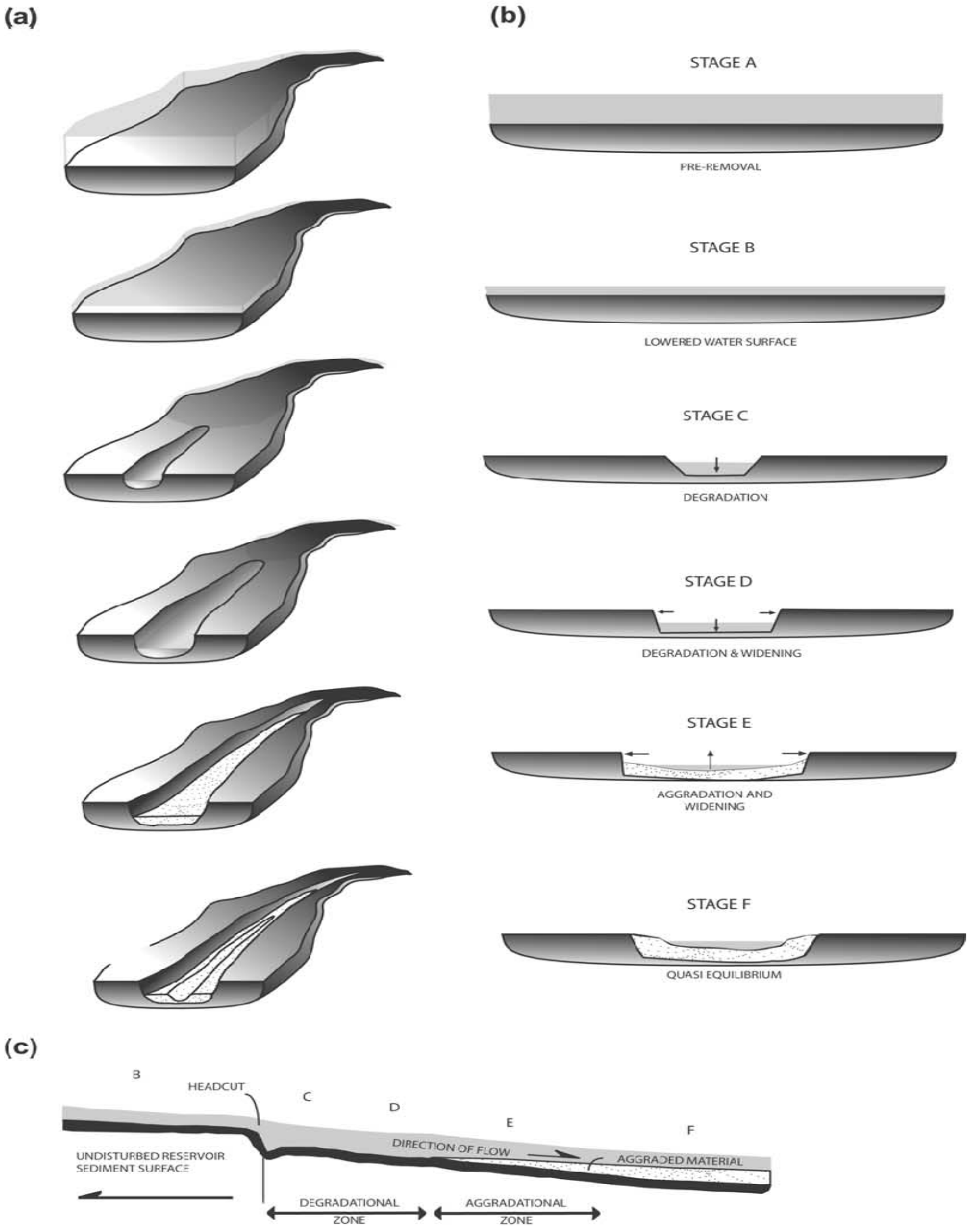

Figure 35 (a) and (b) depict changes that will occur over time in the reservoir as a result of base-level lowering. (c) depicts changes that will occur shortly after dam removal along the length of the channel. Source: Doyle et al. 2003b.

In the modeling study of Doyle and Harbor (2003), the authors examine the influence of channel widening and downstream aggradation on profile adjustments in an upstream reach responding to base-level lowering. The Doyle and Harbor (2003) study found that downstream aggradation reduced the time needed for a channel to reach equilibrium and that the influence of upstream channel widening on equilibrium time decreases as downstream aggradation increases. In this case, downstream sedimentation can be enhanced via grade control structures, further stabilizing the system. Therefore, the combination of the grade control structure installed after the dam removal and the downstream channel aggradation that occurred in 2009 likely played a role in limiting channel width adjustments within the upstream reach.

An important aspect of the present study on the La Valle dam removal is the utilization of a long study reach that extends past the immediately affected reach of the river. Most studies look at study reaches that span only a few river kilometers upstream and downstream of the dam. While study reaches of small lengths allow for the analysis of channel form adjustments through incision, aggradation, widening, and narrowing, they do not permit the analysis of adjustments in the longer longitudinal profile. Meanwhile, channel response is dependent upon adjustments that occur along the channel length and little is known as to how far downstream or upstream these adjustments will occur (Pizzuto 2002 and Doyle and Harbor 2003).

This study shows a smoother longitudinal profile in 2007/2009 than in 1984. In 1984, aggradation of the channel bed created a step-like longitudinal profile. By 2007/2009, channel bed adjustments, primarily through the transport of reservoir sediments, produced a smoother, concave longitudinal profile (figure 25). While it is still unclear whether the channel has arrived at quasi-equilibrium, the smoother, concave longitudinal profile may indicate a tendency towards a quasi-equilibrium form. In addition, the simulations for velocity and hydraulic radius have a smoother longitudinal trend in 2007/2009 than in 1984, which may further indicate a tendency towards a quasi-equilibrium form. However, due to the hydraulic impacts of the grade control at the dam site, the longitudinal profile may revert back to the pre-removal form through the trapping of sediment upstream of the grade control. The backwater effect caused by the grade control structure at the dam site may cause renewed storage of sediment in the old reservoir, reducing channel slope of the upstream reach. In turn, channel slope in the downstream reach may also decrease as it becomes sediment-starved and erodes its newly aggraded bed. Therefore, to assess the impact of the grade control structure on channel equilibrium form and related stream ecology, a future channel and sediment survey should be conducted.

7.4 Toward an Improved Temporal and Spatial Analysis of Dam Removal

The results of this study show that significant longitudinal and vertical channel adjustments may continue several years after dam removal and that post-removal channel engineering may greatly influence future channel adjustments. In the case of the La Valle Dam removal, renewed sediment transport resulted from a large flood with an estimated 500-year recurrence probability. While in many dam removal studies, the largest exportation of sediment occurs immediately after dam removal, present findings indicate continued potential for sediment remobilization given proper hydrological conditions. Moreover, given the likelihood of climate change to increase the occurrence of large-scale floods in the Midwest, more consideration should be given to the sediments that remain in the reservoir after the initial post-removal erosion occurs.

Despite the adjustments that occurred as a result of the June 2008 Flood, the post-removal channel engineering may reverse these adjustments through renewed sediment deposition in the reservoir. If the goal of dam removal is to restore a natural flow regime, care should be taken with post-removal engineering projects. This study shows how one type of channel reconstruction can affect channel hydraulics and geomorphology. The channel response to the grade control structure reinforces the need for more research regarding channel response to post-removal channel reconstruction.

Since the fate of reservoir sediments greatly impacts downstream ecosystems, watershed managers and planners should be aware of the possibility of continued sediment remobilization several years after dam removal and the potential for renewed storage within the reservoir depending on post-removal channel engineering projects. By improving our understanding of sediment transport out of reservoirs both temporally and spatially, scientists can better predict ecosystem response, and managers and planners can use better dam removal methods that minimize the adverse effects of dam removal.

7.5 Euro-American Environmental Impacts on the Baraboo River Systems

For the past approximately 12,500 years, humans have settled in the Baraboo River watershed. Each cultural group was attracted to the region by its abundant natural resources and related environmental services. Over time, environmental change forced groups to either adapt to the changing resources or disappear. Beginning over 150 years ago, Euro-Americans settled the watershed and greatly altered the natural landscape and resource availability through their land use practices.

While humans continue to alter the landscape of the Baraboo River watershed, climate change is also driving landscape change through increased precipitation. The coupling of these two drivers has profoundly affected the hydrology of the Baraboo River watershed, influencing the channel form, flood regimes and magnitudes, and sediment budget.

With the arrival of Euro-American settlement to the watershed, the natural landscape was transformed to a human landscape. Forests and prairies were replaced by cultivated fields and pastures and the free-flowing stream was altered by dams and bridges.

Widespread agricultural land use increased soil erosion and surface runoff through the change in vegetative cover and associated machinery. Agricultural crops generally provide less protection than prairie and forest cover against raindrop impact, which can destroy the natural soil aggregates (Knox 2001). As soil peds break apart, the particles can plug the natural pores within the soil column, reducing infiltration capacity and increasing surface runoff (Knox 2001). In addition, the loosened soil is then carried down slope by surface runoff and eventually enters the stream channel. Crops and cattle reduce the physical and chemical quality of the soil mainly through accelerated soil erosion and the removal of nutrients from the soil (Johnson 1991 and Knox 2001). In addition, cattle reduce the vegetative cover making it more susceptible to erosion from raindrop impact and surface runoff (Knox 2001). The machinery used on agricultural fields and the pasture-raised cattle compact the soil, further reducing the infiltration capacity of the soil and increasing the surface runoff. The combination of all these factors has likely led to increased flooding and sedimentation within the Baraboo River system since Euro-American settlement.

In addition to changes in land cover, the Euro-American construction of river structures altered the sediment budget and the hydrology of the river. Dams and other river structures reduce the downstream transport of sediment, storing much of the agricultural sediments within dam reservoirs and directly upstream of bridges. This occurred at the La Valle study site, where the pre-settlement channel surface was buried by meters of fine agricultural sediments (Doyle et al. 2003b). Cores from the Doyle et al. (2003b) study show the pre-settlement channel bed was likely fine sand. After approximately 150 years of Euro-American agriculture and the storage of agricultural sediment upstream of the La Valle dam, the pre-settlement channel bed at the study site was covered by finer sediment composed of a mixture of fine sand, silt, and clay (Doyle et al. 2003b). Even with the removal of the dam in 2001, a majority of the reservoir sediments are still stored within the old reservoir.

Euro-American stream structures also altered the pre-settlement channel form through channel incision downstream of the La Valle dam and bridges and channel aggradation upstream of the La Valle dam and bridges. This likely transformed the channel longitudinal profile from relatively smooth and concave to stepped and more linear. With the relatively recent removal of the La Valle dam, the channel profile appears to have returned to a form more similar to the pre-settlement form. Both the Doyle et al. (2003b) study and this study show that La Valle dam removal has resulted in increased sediment transport by removing stored sediment from the old reservoir. In addition, this study shows that expected increases in large storms may further enhance the transport of sediment through the system, which may result in a channel form similar to the pre-settlement channel form.

The existing bridges in the stream channel and the grade control structure built at the dam site continue to influence the hydraulics and sediment transport of the Baraboo River. The presence of these structures prevents the stream from returning to a completely free-flowing state. In addition, the agriculture-dominated landscape increases surface runoff and erosion. The increased runoff increases flood recurrence and magnitude within the Baraboo River watershed (USGS 2009b, figure 36). Therefore, while the La Valle dam removal appears to have allowed the river to return to a form more similar to that of pre-settlement, the bridges and extensive agriculture still influence the hydraulics and sediment budget of the Baraboo River watershed.

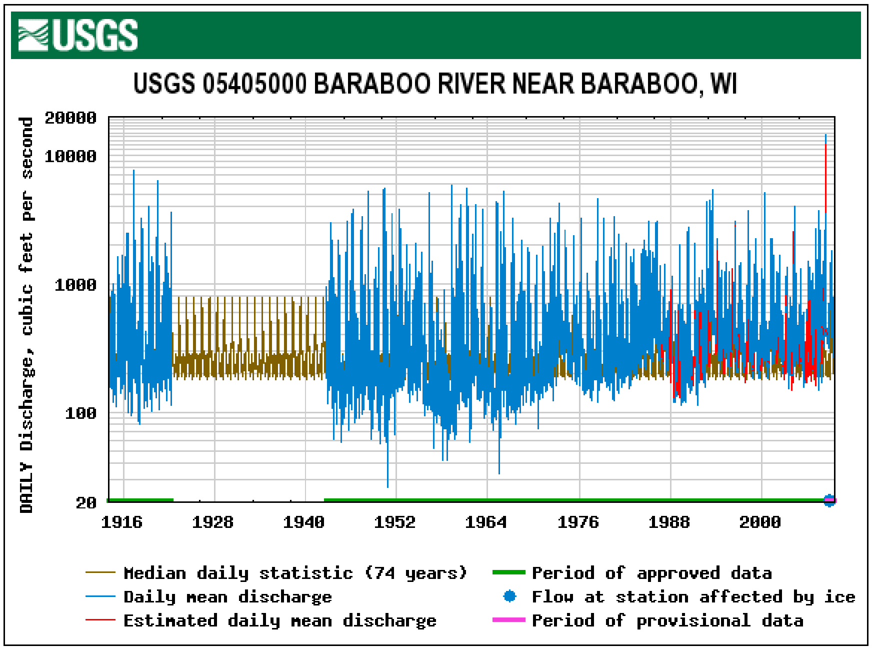

Figure 36 Baraboo River discharge, measured at a gage located near Baraboo, Wisconsin. Source: USGS 2009b.

Appendix

Figure 37 Photo courtesy of Emily Stanley and Martin Doyle. Picture of La Valle dam reservoir during the January 1999 drawdown, approximately one year before removal. River flows from left side of picture towards the right side of picture.

Figure 38 Photo courtesy of Emily Stanley and Martin Doyle. Picture of La Valle dam reservoir during the January 1999 drawdown, approximately one year before removal.

Figure 39 Photo courtesy of Emily Stanley and Martin Doyle. Picture of the dam site, looking upstream; taken after removal.

Figure 40 Photo courtesy of Alicia Jepsen. Picture of the preserved mill pond; taken in 2007. River flows from right side of the photo towards the left side of the photo.

Figure 41 Photo courtesy of Samantha Greene and Jena Krause. Picture of the dam site in October 2009, looking upstream.

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