An Assessment of Land Use Impacts on Channel Morphology in a Western Minnesota Watershed

A dissertation submitted to the Faculty of the Graduate School of the University of Minnesota

By

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Dedication

This dissertation is dedicated to my wife Kristine. No married graduate student goes through this alone, and if they say they did they're lying. Our spouse's experience everything the graduate student does and more. They are the person providing support behind the scenes. Kris's support throughout this process never diminished. She was willing to sacrifice much for this effort. I truly could not have completed this work without her by my side; and I am a better person because she is a part of my life. She is my foundation. This dissertation is as much her's as mine. I am a lucky, lucky, guy.

Abstract

This research is a comprehensive investigation encompassing land use changes in an agricultural watershed and corresponding changes to the rainfall-runoff relationship and stream channel morphology. The Lac qui Parle (LqP) watershed is one of eleven major watersheds within the Minnesota River Basin (MRB). Agriculture is the dominant land use within the MRB occurring on more than 90-percent of the landscape. This research investigates the spatial and temporal changes in channel morphology and land use between 1965/66 and 2002/03. Historical data were obtained from the US Army Corps of Engineers for the South Fork Lac qui Parle (SF LqP) River. Sixty-five cross-section sites were re-surveyed and evaluated. Current channel morphology was assessed through a second year of data collection. Additional data were collected and analyzed for crop history, riparian vegetation, agricultural drainage, annual discharge, annual peak discharge, and monthly and annual precipitation.

Results indicate crop diversity within the SF LqP River has diminished and is currently dominated by corn and soybean. Surface and subsurface drainage of agricultural lands was documented on 37-percent of the sub-watershed area evaluated. Analysis of the discharge and precipitation records indicates an increase in the Q/P ratio and average annual runoff volume post-1960.

The analysis indicates land use changes within the SF LqP watershed have impacted the channel morphology of the SF LqP River post-1965/66. Significant changes in channel cross-sectional area were noted in the Middle and Upper watersheds. Results corresponds to a channel enlargement ratio (CER) of 1.02 – 1.30. Changes in cultivation practices and drainage activities correspond with higher CER of 2.32 – 2.6. Similar increases were noted for peak discharge (1.30 – 1.35). CERs match values developed for storm sewered streets in urbanized areas. All changes were significant at the 95-% confidence level.

A separate investigation evaluated the use of natural channel design for agricultural ditches. Results indicate natural channel design provides more efficient sediment

transport, increased channel diversity/complexity, and may reduce channel maintenance costs.

Key Words: Lac qui Parle River, channel morphology, Rosgen classification, channel evolution model, channel enlargement ratio, agricultural drainage, bankfull, grazing, annual discharge, peak discharge, climate change, Q/P ratio.

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Chapter 1: Introduction

Non-point source pollution (NPS) from the Upper Mississippi River Basin has been implicated as a principal cause for the expanding hypoxic zone that develops each spring and summer in the Gulf of Mexico (Rabalais et al., 1999). Agricultural practices have been cited as the major contributor to NPS pollution (US-EPA, 1996). The Minnesota River Basin (MRB) is the largest single contributor of NPS pollution to the Mississippi River in the state of Minnesota. Agriculture is the dominant land use within the MRB occurring on more than 90 percent of the landscape. Greater than 80% of the wetlands in the MRB have been drained since European settlement (Leach and Magner, 1992). A 2001 article in the Minneapolis Star Tribune examined the environmental conditions in the state and found wetland drainage increased by more than 700 acres in 2001 (Anderson, 2001); adding to those previously drained primarily for agriculture. Those that remain are either filling due to increased sedimentation rates, or have been adapted as modified retention basins (Anderson, 2001).

A modeling study of the Little Cobb watershed showed a reduction in wetland acres altered the hydrologic regime of the MRB producing more total runoff with a higher peak discharge (Miller, 1999). An altered hydrologic regime can produce an accompanying alteration in stream channel morphology (Lane, 1955; Lane et al., 1996; Legleiter et al., 2003; Leopold et al., 1964). The altered stream channel morphology may result in unstable channels and streambank erosion. Since stable channel design is an important component of a successful watershed restoration plan, knowledge of land use impacts on stream channel morphology is an essential factor. Most research in the MRB has focused on nutrient loading, climate change, and agricultural management practices. This research will investigate land use impacts on stream channel morphology in an agricultural watershed of the MRB.

Background

Prior to European settlement, the MRB was a prairie pothole landscape containing a “rich sea of grass” and oak savannah (Moyer and Dale, 1916). The organic rich soils were the foundation supporting the agricultural industry during the past century. Stable channels, that provide floodplain access at low probability flows (1.5-yr recurrence interval), play an important role in sediment loading, nutrient attenuation, and flood peak reduction. Stable channels exist in a dynamic state of equilibrium responding to the amount and type of precipitation, vegetation, geology, and land use conditions within the watershed (Dunne and Leopold, 1978; Leopold, 1997; Leopold et al., 1964; Rosgen, 1994, 1996). These factors also determine the amount of energy a stream has to move sediment along with the type and amount of sediment (Brooks et al., 2003). Land use practices within a watershed that change the vegetation also alter the hydrologic regime. Any change in sediment supply and/or stream flow upsets the dynamic equilibrium in a watershed resulting in changes in stream channel morphology (Lane, 1955).

Early settlers in the MRB viewed prairie pothole wetlands as obstacles to agriculture spurring the advancement of drainage to expand cultivation. Cultivation replaced the natural oak savannah and riparian vegetation with annual row crops and altered the hydrologic regime in the watershed. Perennial vegetation transpires more water, for longer periods of time in the year, than annual row crops (Brooks et al., 2003). Transpiration losses are greatly reduced after harvest providing more water for infiltration and runoff. The cultivation of annual row crops leaves more water in the soil profile in the fall and spring, resulting in more potential for runoff.

Prairie potholes formed in the Wisconsin glaciation when large blocks of ice separated from the main glacier and slowly melted. Today these landforms provide added storage within their watersheds. These self-contained sinks were largely unconnected to surface water streams but would fill with water that either evapotranspires or slowly percolates into groundwater aquifers. They did not contribute directly to surface water streams until their internal storage capacity was exceeded. Agricultural drainage modified this process and altered the hydrologic regime of the prairie pothole landscape.

Agricultural drainage increases the contributing area within a prairie pothole watershed by connecting isolated wetlands to the main waterways (Schilling et al., 2007). This hastened conveyance of water previously stored within the basin and decreased watershed storage capacity. These factors combined to alter the hydrologic regime within prairie pothole watersheds producing higher runoff volumes sooner in response to precipitation events. This in turn, upset the dynamic equilibrium in the watershed resulting in channel degradation. Channel degradation is a sign of an unstable stream and will continue until a new equilibrium is obtained (Rosgen, 1996; Schumm, 1999).

Channel morphology is a reflection of watershed characteristics, stream flow, sediment regime, land use, and direct channel disturbance. A stable channel is able to transport the sediment and water delivered to it, while maintaining its dimension, pattern, and profile, over time without aggradation or degradation (Leopold, 1997; Rosgen, 1996). This "stable" channel morphology is developed and maintained by the bankfull, or channel forming discharge (Dunne and Leopold, 1978). Bankfull discharge is associated with the average annual flood with a recurrence interval (RI) generally between 1-2 years. The cumulative effects of wetland drainage, conversion from prairie-oak savannah to annual row crops, and stream channel and riparian zone modifications have all led to higher water yields and higher peak flow discharges associated with more frequently occurring rainfall and snowmelt events. Furthermore, higher water yields increase the bankfull discharge and alter the stable morphology in a channel.

Channel degradation, in the form of incision and channelization, disconnects a stream from its floodplain and results in a higher, more erosive, discharge flowing in the incised channel. Channelization increases the hydraulic efficiency of a channel by eliminating natural stream morphology (pools, riffles, and sinuosity) and increasing in-stream velocities (Hupp, 1992; Steiger et al., 1998; Wyzga, 2001). Increased conveyance in upland tributaries can increase in-stream velocities of downstream reaches that have not been channelized causing streams to down-cut their channels and/or undercut their banks (Poff et al., 1997; Schumm, 1999; Simon and Rinaldi, 2000). The result is an incised channel hydraulically disconnected from its floodplain. The discontinuity between the stream and its floodplain has several negative impacts.

Floodplains provide a stream with a mechanism to decrease the discharge velocities associated with flood flows. When rivers overtop their banks flow velocities decrease due to the increased area of the floodplain allowing flood flows to dissipate naturally with minimal changes in the shape, slope, and sinuosity of the channel. Floodplains provide temporary storage within the watershed prolonging infiltration to groundwater, water uptake by riparian vegetation, and attenuation of flood peaks (Hughes et al., 2001). Floodplain interaction is both effective at nutrient attenuation and essential to stable stream channel morphology (Galat et al., 1998; Sparks et al., 1998). However, for nutrient reduction to occur in the floodplain, a stream needs to interact with its floodplain on a frequent (annual) basis. Interaction with a floodplain left high by channel incision from accelerated flood flows may be less frequent in many of the tributaries to the Minnesota River (Leach and Magner, 1992; Magner and Steffen, 2000). This research investigates the relationship between the amount of land artificially drained (i.e. surface tile inlets and sub-surface tiles) and changes in stream channel morphology.

Justification

Agricultural drainage has progressed at a fairly steady rate in the MRB, but advances in technology with the introduction of plastic saw this rate increase in the 1960s. In the fifteen year period between 1983-1998, the amount of agricultural land drained in Minnesota doubled from twenty to forty percent (USDA-ERS, 1987; Zucker and Brown, 1998). A study by Magner and Steffen (2000) analyzed stream flow data from eleven tributaries to the Minnesota River over two time periods, 1936-1955 and 1979-1998. They report a 55% increase, on average, in the 1.01-year annual peak flow between periods. Although the authors suggest the increased discharge was the result of wetland and prairie-lake drainage, the result was inferred and not conclusive. A modeling study of the Little Cobb River, a tributary to the Minnesota River, suggested that stormflow volumes and peak flows associated with the 1.5-year to 2-year recurrence interval events have more than doubled as a result of wetland drainage and associated channel changes (Miller, 1999). Miller also compared pre-settlement conditions to current conditions and estimated bankfull flow rates increased at least four times due to wetland loss since European settlement. More recent research indicates the bicarbonate and water flux increases in the Mississippi River over the past 50 years are due to an increase in discharge from agricultural watersheds that has not been balanced by a rise in precipitation (Lins and Slack, 1999; Raymond et al., 2008). However, research conducted by others attributes the increased discharge solely to a wetter climate (Mallawatantri et al., 1996; Johnson et al., 2009). If the cumulative effects of wetland drainage, conversion from oak-savannah to annual row crops, and riparian zone modifications have led to higher water yields and higher peak flow discharges associated with the more frequently occurring rainfall events, then the morphology of the stream channels should reflect these changes. This research uses a unique set of circumstances to investigate the hydrologic effects of agricultural drainage on channel morphology.

On May 28, 1956, the United States Department of Agriculture (USDA) initiated the Soil Bank Act. This act authorized short and long-term removal of land from production with annual rental payments to participants. The program allowed producers to retire land on an annual basis in return for payments. After the program expired in 1966, over 80% of the land was eventually put back into production, much of it during the 1970-export boom (Muir, 2002). Soon afterwards improvements in drainage technology made it possible to greatly increase crop yields. New plastic tile in long coils and improved trenching techniques converted previously marginal land into crop production (Wilson, 2000). Research by Anderson (1998) shows a significant increase in the number of ditch liens filed during the 1960s in Sibley County, MN (Figure 1.1). Ditch liens are filed by the county against landowners when public monies are used to construct agricultural ditches on their property. If this trend was maintained in other agricultural counties in the MRB it had the potential to alter the hydrologic characteristics of the watersheds and channel morphology. The U.S. Army Corps of Engineers (COE) flood control survey provides a set of baseline data needed to assess channel morphology prior to accelerated drainage in the basin. Beginning in the late 1940s, and continuing on through the late 1960s, the COE conducted a series of flood control studies (surveys) on several streams in the MRB collecting detailed data on stream plan form, longitudinal profile, and cross-sectional area. The existence of these data prior to the repeal of the Soil Bank Program, combined with the increased installation of agricultural drainage systems over the past forty years allows for the investigation of agricultural drainage and stream morphology changes.

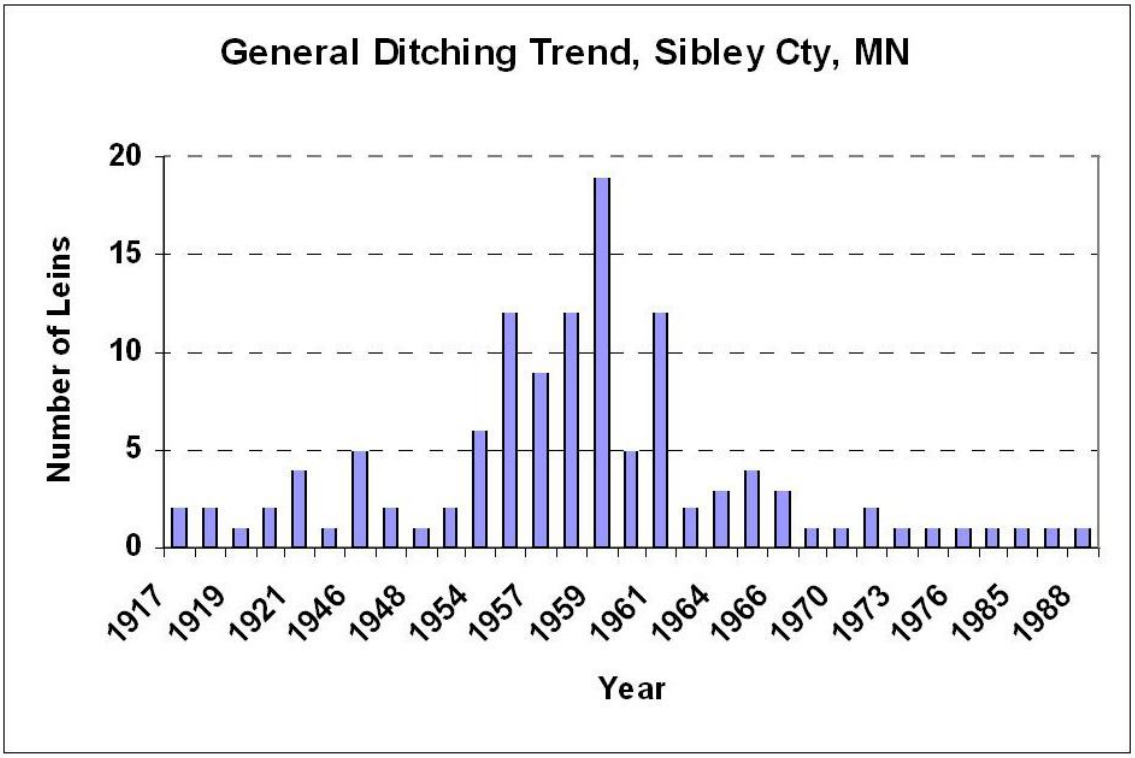

Figure 1.1. Number of ditch liens filed in Sibley County, MN.

Objectives of the Proposed Research

This research investigates the relationship between land use changes in an agricultural watershed and changes in stream channel morphology; the objectives are:

(i) Assess the change in riparian land use within the 100-yr floodplain of the S. F. Lac qui Parle River from 1967-2000.

(ii) Assess the change in crop diversity within the Lac qui Parle watershed from 1921-2000.

(iii) Develop a GIS database of the land improvements for a subset of the Lac qui Parle Watershed, and to use this database to analyze the amount and distribution of each land improvement within the subset of the Lac qui Parle watershed.

(iv) Analyze the precipitation and discharge record for the Lac qui Parle River and develop discharge/precipitation relationships.

(v) Determine the channel morphology of the S. F. Lac qui Parle River in 1965/66 and 2002/03.

(vi) Investigate the application of natural channel design to agricultural drainage ditches in the glacial tills of Western Minnesota.

Organization of Dissertation

This dissertation is written to conform with requirements of the Graduate School of the University of Minnesota for a doctoral project thesis and presented in the journal format (University of Minnesota, 2000). Chapter 1 consists of an introduction, literature review, justification, and objectives of the research. Chapters 2, 3, 4, and 5 are prepared for submission to a professional journal. Each contains an abstract, short literature review, and additional sections commonly found in journal publications. Chapter 2 describes the change in watershed conditions of the SF Lac qui Parle watershed. It details the land improvement history, cropping history, and riparian land use history of the SF Lac qui Parle River. Chapter 3 investigates the precipitation - dicharge relationship of the SF Lac qui Parle River. Chapter 4 describes the channel morphology of the SF Lac qui Parle River at two points in time, 1965/66 and 2002/03. Chapter 5 is a stand-alone document investigating the use of natural channel design for agricultural drainage ditches in Minnesota. Chapter 6 summarizes the findings in light of the hypothesis, draws conclusions and makes recommendations based on the findings from Chapters 2-5.

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Chapter 2: Watershed Conditions of the South Fork Lac qui Parle River, MN

Stream channels are an expression of the watershed characteristics such as slope, aspect, geology, and climate; and the land uses practices within the watershed. Stream channel morphology (geometry) is determined by the channel-forming (bankfull) discharge. Land uses practices determine the rainfall-runoff relationship of a watershed. Changes in the rainfall-runoff relationship can alter the magnitude of the channel forming discharge which can then alter channel geometry. Knowing the spatial and temporal distribution of land use changes in a watershed will provide information about changes to the channel forming discharge (i.e. changes in channel morphology). This research investigated land use changes in the Lac qui Parle (LqP) watershed from 1921 - 2006. The LqP watershed is dominated by agricultural land use (>75%). Specific land uses investigated in this research include: cropping history, riparian vegetation, and agricultural drainage. Spatial and temporal changes in the riparian corridor were analyzed with GIS software. The 100-year Federal Emergency Management Administration (FEMA) floodplain was used to define the limits of the riparian corridor in both years. Crop data were obtained from the National Agricultural Statistic Service (NASS). Results were complied and analyzed through a relational database. Spatial and temporal distribution of agricultural drainage were obtained from land alteration permits issued by the Lac qui Parle-Yellow Bank Watershed District (LQP-YB). Data were compiled in a relational database and merged with the Public Land Survey (PLS) database. The merged file was analyzed with GIS software.

Results indicate thirty-five (35) percent of the agricultural land within the nineteen-township study area are improved by agricultural drainage. Ninety-eight (98) percent of the agricultural acres within the SF LqP River watershed are dominated by a two-crop rotation of annual corn and soybean. The majority of the vegetative composition in the riparian corridor immediately adjacent to the SF LqP River in both the Upper and Middle watersheds is unchanged between 1967 and 2000. These results indicate the single largest land use change in the SF LqP watershed has been agricultural drainage. Furthermore, the amount of agricultural drainage has been grossly under-reported for the LqP watershed. Since agricultural drainage facilitates the movement of water off the landscape, the increase in agricultural drainage has the potential to impact the channel forming discharge and therefore, stream channel morphology (geometry). This has important implications for the success of restoration projects within the LqP watershed.

Introduction

The practice of improving agricultural lands via drainage has been carried out for centuries (Ritzema, 1994). Fraser and Fleming note that Greek and Egyptian civilizations relied on surface drainage to protect agricultural lands from flood waters (Fraser and Fleming, 2001); in the United States, land drainage greatly facilitated settlement in North America (USDA-ERS, 1987). Subsurface drainage improved land for agricultural production, and controlled diseases carried by mosquitoes and black flies. Today almost half the cropland in the US (45 million hectares) is improved by some form of drainage; 34% (15.3 million ha) is tile drained (Skaggs et al., 1994).

Agricultural drainage includes drainage ditches, sub-surface drainage tiles, and surface tile inlets. Augmenting these are dikes and/or levees that restrict and retain floodwaters to the immediate channel area and exclude flood waters from adjacent agricultural fields. Agricultural drainage has progressed at a fairly steady rate in the MRB (Wilson, 2000). Advances in technology saw this rate increase in the 1960s. By 1986 there were 4.5 million acres of land improved by agricultural drainage (USDA-ERS, 1987) in the MRB. In the fifteen-year period 1985 – 1998, the amount of agricultural land improved by drainage in Minnesota doubled (Zucker and Brown, 1998).

The Lac qui Parle watershed is one of twelve major watersheds in the Minnesota River Basin; located in west central Minnesota within Lac qui Parle, Lincoln, and Yellow Medicine counties (Figure 2.1). Agriculture is the predominant land use with approximately 554,674 acres (79-percent) utilized for grain production (corn and soybeans dominate). Of the land in agricultural productivity, 217,657 acres are classified as poorly drained. Approximately 7,021 acres (one percent), are improved by agricultural drainage (Mallawatantri, 1999). Cursory observations of surface tile inlets and drainage outfalls within the South Fork Lac qui Parle River (SF LqP) watershed suggest this value is under reported.

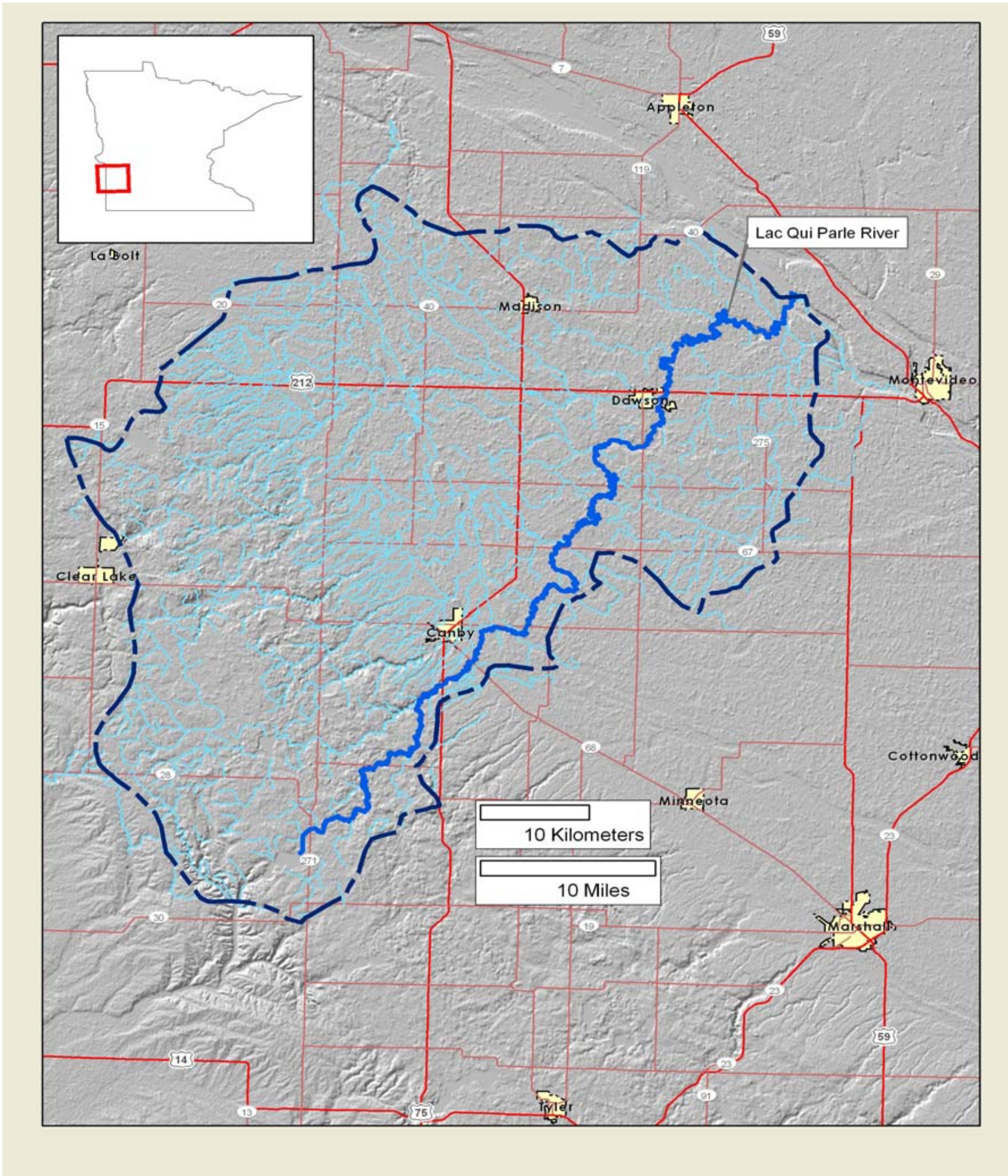

Figure 2.1. Location of the Lac qui Parle watershed with the South Fork of the Lac qui Parle River and tributary streams.

Agricultural drainage that removes excess water from a field is classified as a land improvement by the LQP-YB Watershed District. There are six common improvements (alterations) permitted by the LQP-YB Watershed District: subsurface tile drainage, surface tile inlets, channel clearing, ditch construction, dike construction, and grassed waterways. All but grassed waterways have the capacity to increase the efficiency by which water moves across fields into conveyance systems. Conveyance systems include both artificial and natural waterways. Natural streams and creeks include sections realigned to allow more arable land and to facilitate connection to surface and/or subsurface drainage systems. The impacts of these land uses on stream channel morphology are not well documented.

While agricultural drainage is the dominant land alteration applied in the Midwestern United States, the total amount of agricultural land improved by drainage is unknown. Since the dominant alteration made to agricultural lands is drainage; the amount of drainage applied to the landscape will influence the total volume and movement of water between the time it falls on fields until it makes its way into receiving waters.

Purpose

The goal of this work is: (1) establish baseline data for the spatial and temporal distribution in land alterations within the SF LqP watershed, (2) determine cropping history for the SF LqP watershed and (3) assess the changes in riparian vegetation width over a 33-year time frame.

A. Percent Agricultural Drainage

Methods

Four data locations were investigated for their ability to provide a spatial and temporal history of agricultural drainage in the SF LqP watershed. They include:

1. County Auditor's Office
2. County Environmental Office
3. Lac Qui Parle Soil and Water Conservation District (SWCD)

4. United States Department of Agriculture Natural Resources Conservation Service (USDA-NRCS)

Of these, only the Lac qui Parle County Environmental Office contained data on the spatial and temporal distribution of agricultural drainage because they issue the land alteration permits for the LQP -YB Watershed District. The permits contain information regarding six (6) commonly practiced land alterations (Figure 2.2):

1. surface drainage
2. subsurface drainage
3. new ditches
4. channel cleaning
5. grassed waterway
6. dikes.

LAC QUI PARLE-YELLOW BANK WATERSHED DISTRICT

APPLICATION FOR PERMIT

Number

Approval of permit necessary before work can start.

Name and address of applicant (s)

Telephone number

Township

County

Name and address of owner if other than applicant

Permit requested for:

seepage tile

Location where work will be done:

The work is necessary because:

seepage from hill area

Attach necessary maps, drawings, data, etc. to support proposal. Use additional paper if needed.

I hereby apply for a permit to proceed with the proposal described above.

Dated 11/2/04 Signed

Dated 11/2/04 Signed

Dated Signed

LAC QUI PARLE-YELLOW BANK WATERSHED DISTRICT

Permission is granted to do work in accordance with the purposes and overall plan of the district.

Comments:

Date Signed

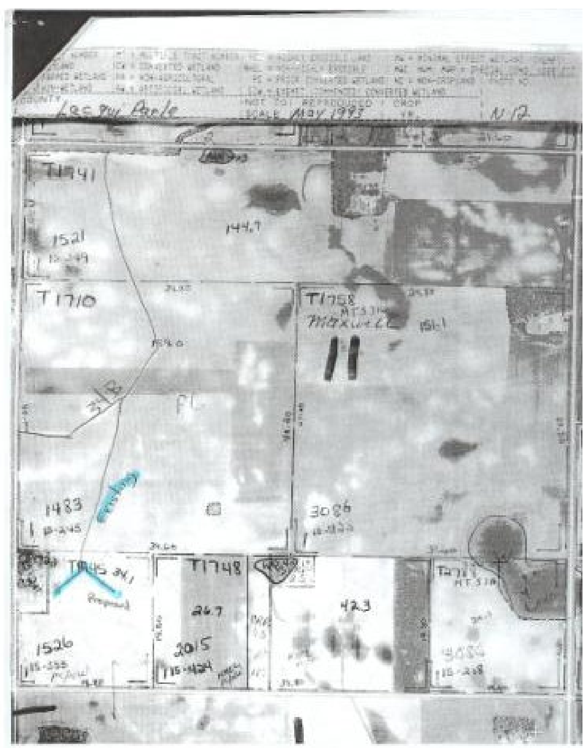

Figure 2.2. Example of a land improvement permit from Lac qui Parle County showing the information page and the location within the section.

The permits also contain the:

- name, address, and telephone number of the applicant
- county of the proposed land improvement
- township of the proposed land improvement
- type of proposed land improvement
- reason for the proposed land improvement
- date of the land improvement application
- land improvement permit application number, and
- location map of the proposed land improvement

Land improvement permits were photocopied, sorted by permit number, and catalogued by year then georeferenced to the existing public land surveys (PLS) for Lac qui Parle and Yellow Medicine Counties (MNDNR Data Deli). The Control Point Generated PLS layer contains line and polygon features to the 1/4 of 1/4 PLS section (approximately 40 acres) and government lot level. The layers were created using Government Land Office plat drawings and survey notes, official resurveys, and PLS control points from the DNR Control Point Inventory database. The database provides detailed PLS forty-level mapping at a scale of 1:24,000 of any information geo-referenced to the Public Land Survey System, especially land ownership and management. It can also be used as a general PLS reference map for any other data projected into UTM - meters, extended zone 15, or NAD83 (Appendix A).

The PLS system features described in this database are represented as attributed polygons, lines and label points. Lines have both a numeric code and a text field that indicate the PLS line type such as; township line, section line, meander line, etc. The following information is included for each polygon: county number, township number, range direction id, range number, section number, forty number, forty text (e.g. NENE), government lot number, and geocode fields that contain composite identifiers that uniquely defines a portion of land to the range, section, forty or government lot. Information from the land improvement permits were then entered into the database tables for Lac qui Parle and Yellow Medicine PLS. The database tables were augmented to include columns for each land improvement category (subsurface, surface, channel cleaning, new ditch, dike and grassed waterway). Database files were then generated for each county by year from 1972 through 2003 to create a spatial distribution of land improvements. An MS-Excel spreadsheet file provided a temporal distribution of each type of land improvement within Lac qui Parle and Yellow Medicine Counties.

An estimate of agricultural acres improved by drainage was obtained with a subset of the land improvement permits for the LqP watershed. Nineteen townships within Lac qui Parle and Yellow Medicine counties were identified for analysis (Figure 2.3). The land improvements permits from these nineteen townships (Table 2.1) were collected, catalogued, and analyzed.

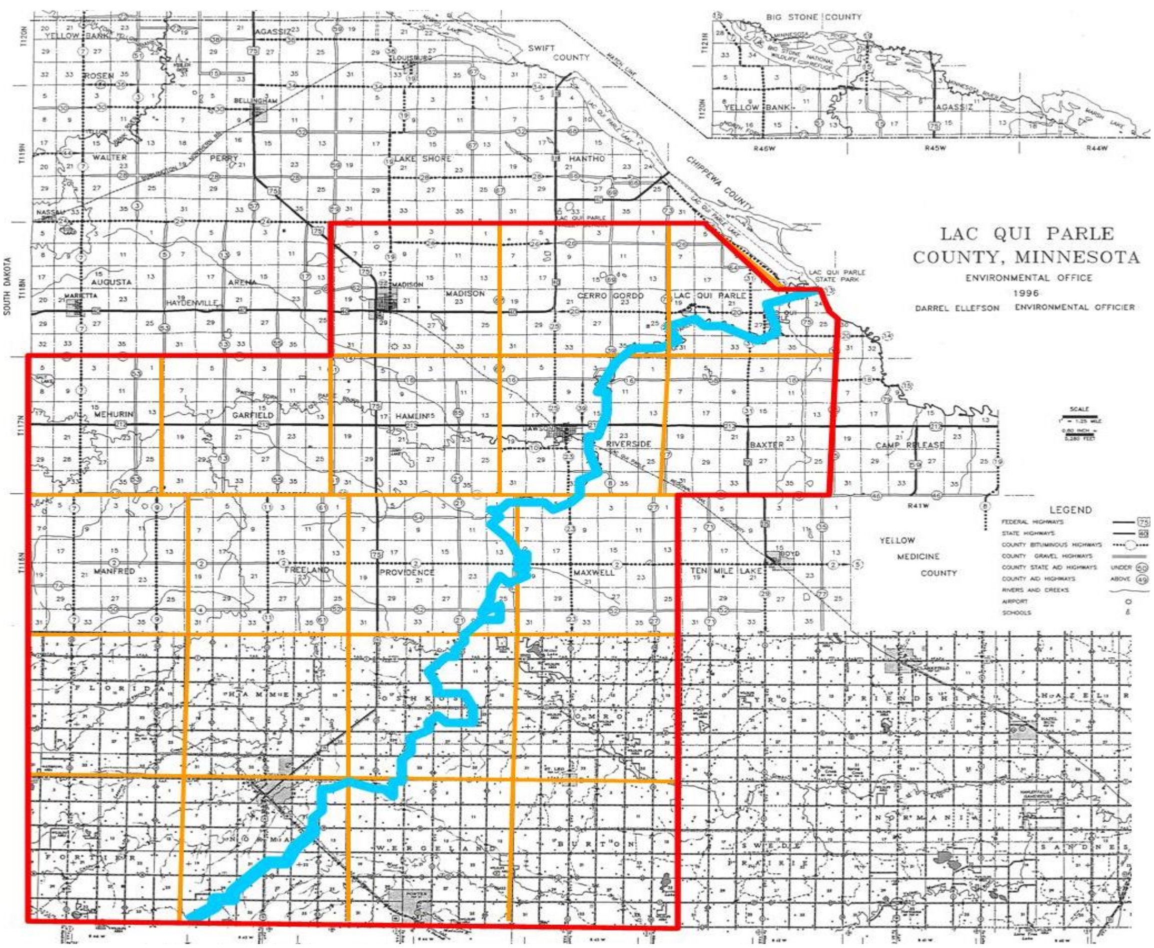

Figure 2.3. Public Land Survey (PLS) map of Lac qui Parle and Yellow Medicine counties, MN showing the twenty (20) townships for which permits were obtained and analyzed.

Table 2.1. Townships sampled within each county for land improvement data.

County	Townships
Lac qui Parle	Baxter, Cerro Gordo, Freeland, Garfield, Hamlin, Lac qui Parle, Madison, Manfred, Maxwell, Mehurin, Providence, Riverside
Yellow Medicine	Florida, Fortier, Hammer, Norman, Omor, Oshkosh, Wergeland

Results

Just over one third of the agricultural land within the LqP watershed is improved by tile drainage. The nineteen townships within the study area contain a total of 302,783 acres. Of this, 98,240 acres are drained by subsurface tiles with an additional 6,440 acres drained by surface tile inlets (Table 2.2); 35 percent of the sampled acreage and substantially greater than the 5.6% reported for the LqP watershed (Mallawatantri, 1999; MRBJPB, 2001). The LqP watershed includes portions of three (3) counties, Lac qui Parle (67.8%), Yellow Medicine (23.4 %), and Lincoln (8.8%). For purposes of this study, only LqP and Yellow Medicine counties were included in the analysis. According to the Minnesota River Basin Data Center, 4.4 percent and 1.2 percent of the agricultural land within LqP and Yellow Medicine counties respectively, are improved by tile drainage (Mallawatantri, 1999; MRBJPB, 2001). This equates to a total of 34,406 acres. Even if all 34,406 acres were contained within the 302,783 acres of the nineteen-township study area; it would only account for 32.9 percent of the 104,680 acres drained by tile in the study area.

Table 2.2. Amount and type of land improvement within the LqP River sub-watershed.

Land Improvement Type	Total Acres Improved	Percent of Sub-Watershed Area
Sub-surface Drainage	98,240	32.4
Surface Tile Inlets	6,440	2.2
Total Improved by Drainage	104,680	34.6
Channel Clearing	25,200	11.8
New Ditch	12,200	5.7
Dike	4,800	2.3
Grass Waterway	4,000	1.9
Total Acres Improved	150,880	49.8

Of the six land improvement types, subsurface tile drainage is the most common (Table 2.2). The current rate of subsurface tile drainage is 3,070 ac/yr.in the LqP watershed (Figure 2.4). By comparison, surface tile inlets have improved a total of 6,440 ac or 280 ac/yr (Figure 2.5). As illustrated in Figure 2.4, subsurface tile drainage is the most popular land improvement; far outdistancing channel clearing, the next most common land improvement. Since 1972 98,240 acres have been improved through subsurface tile drains (Figure 2.5). But as illustrated in Figure 2.6, some areas have had multiple land improvements.

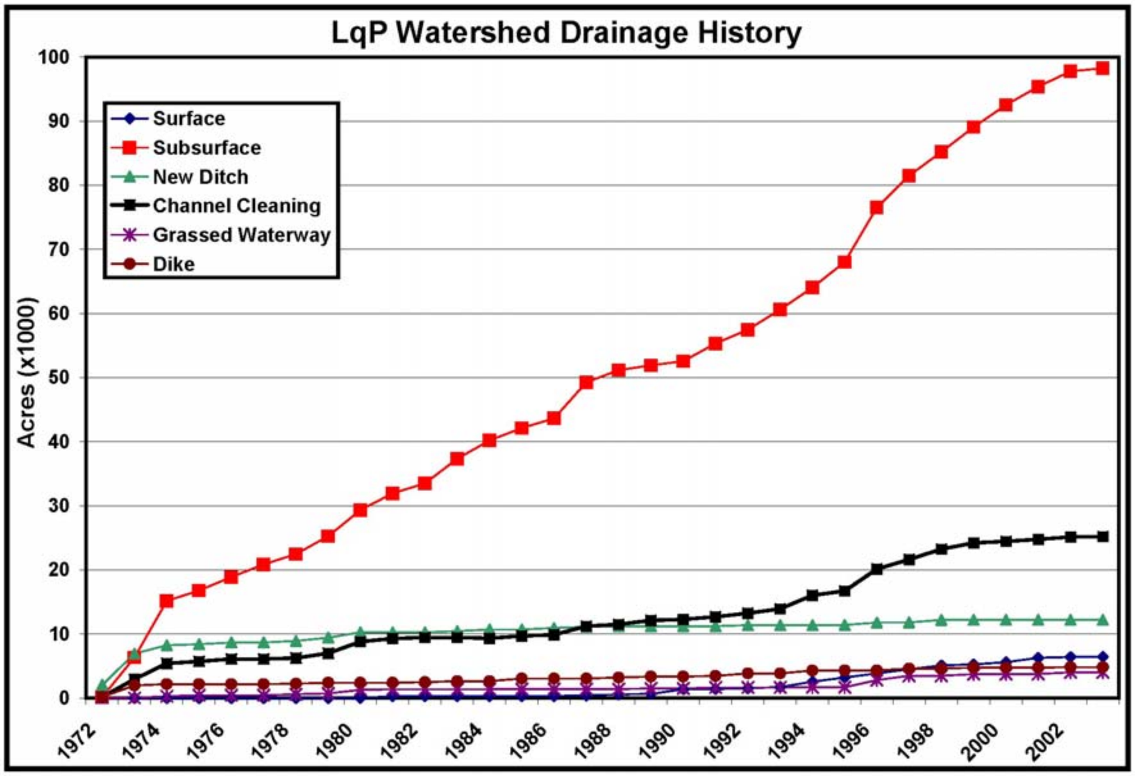

Figure 2.4. Type and amount of land improvements in the LqP watershed from 1972 – 2003 as reported on land improvement permits for Lac qui Parle County.

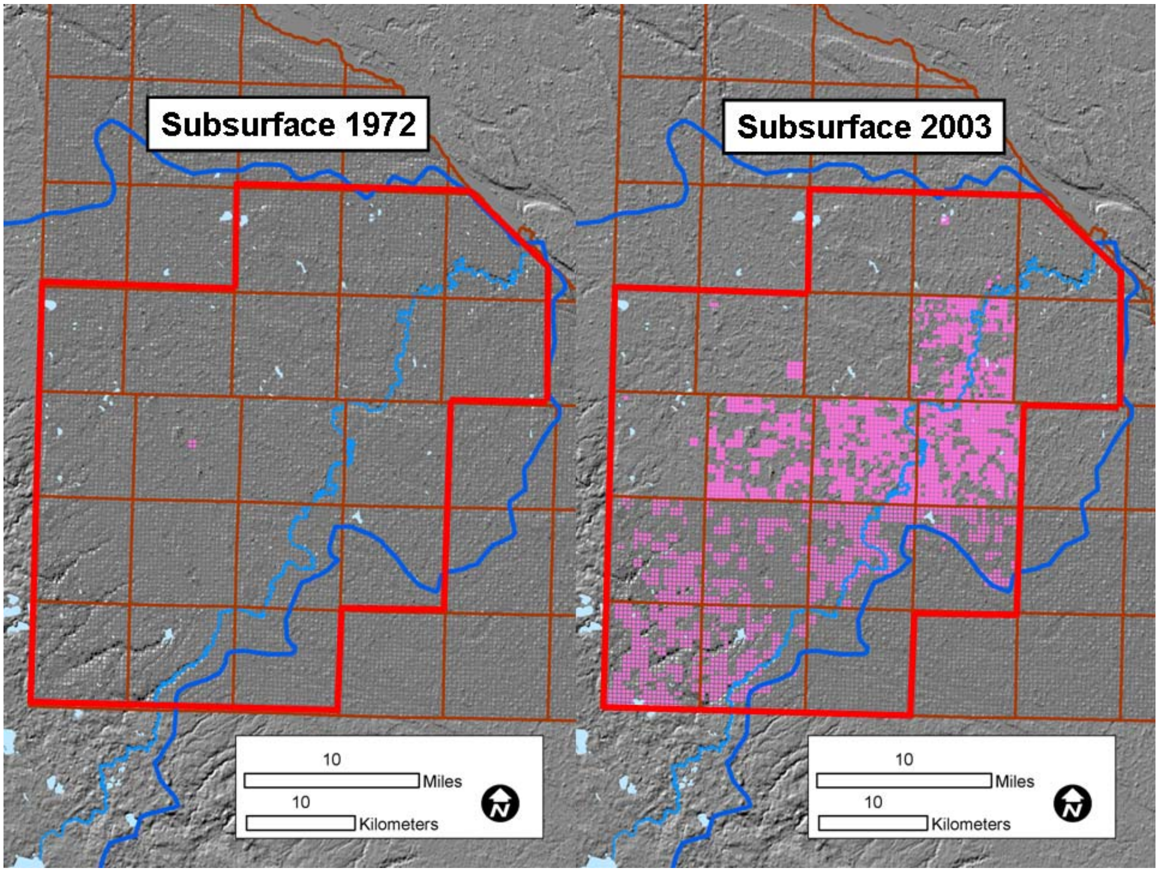

Figure 2.5. Change in subsurface tile drainage between 1972 and 2003. Each individual shaded square represents 40 acres.

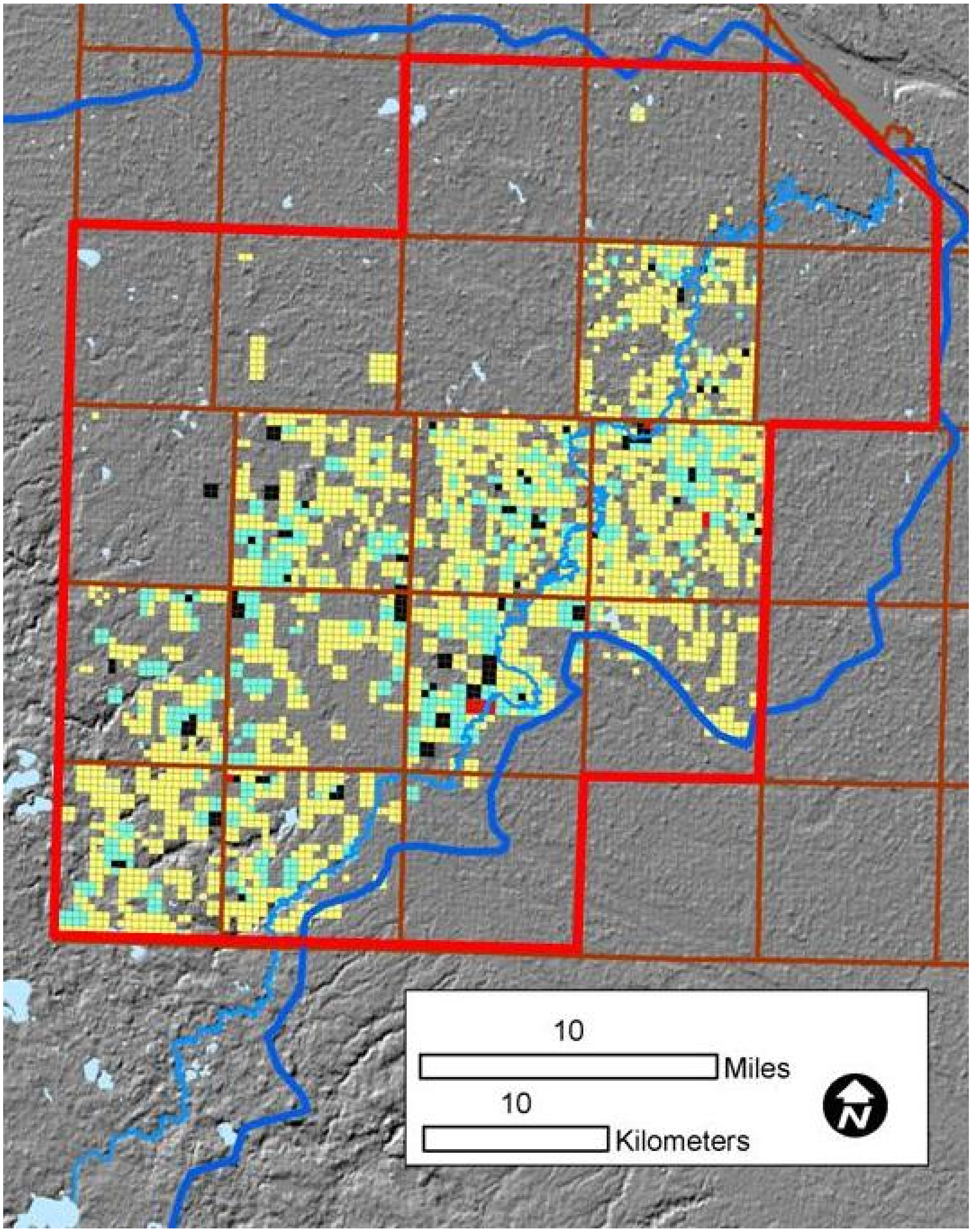

Figure 2.6. Number of land improvements per 40 acres for 19 township sub-survey on the SF LqP watershed. Yellow = 1, Blue = 2, Black = 3, Red ≥ 4

Since surface tile inlets are a relatively new land improvement, estimates for surface tile inlets are the most accurate of the six land improvements, while estimates for the remaining five land improvements are considered conservative given the extended history of land improvement for agricultural purposes within the Minnesota River Basin. Furthermore, land improvement permits for the LqP watershed cover barely one third of the last century, therefore the amount of agricultural land drained by subsurface tiles is greater than the values reported in this research. The recent increase in ethanol production within the United States will likely increase the use of marginal land (poorly drained) for crop production and add to the drainage within these watersheds.

B. Crop Diversity

The type (annual or perennial) and amount of crop grown provides insight into the water requirements, amount of vegetative cover provided to the soil, and length of growing season in the basin. The following excerpt describes the vegetative cover on the agricultural landscape as seen in 1916 Lac qui Parle County (Moyer and Dale, 1916).

"The prairies above the narrow valleys scooped out of the glacial clay by the streams contained neither tree nor bush, but were in the summer covered with a fine growth of native grasses. From the first of May until the first of September wild flowers were in blossom, one variety succeeding another as the season advanced. Numerous patches of plum and cherry trees bordered the streams. The deeper-lying bottom lands and the broken ground, sheltered by high banks or bayous from the prairie fires, were covered with heavy timber, maple, oak, basswood, elm, ash, boxelder, and hackberry. The cottonwood and the willow were the sentinels of these woodlands. They were the hardiest and most quick-growing. The timber lands usually had numerous gooseberry and raspberry bushes."

During the last century, the Lac qui Parle Watershed has undergone three major modifications to vegetation and land use within the watershed. The first change occurred during European settlement when perennial grasses were plowed under for cultivation of both perennial and annual cereal crops. Clearing of deciduous and coniferous forests (about 5% of the basin) also accompanied prairie conversion. The second change, in the early part of the twentieth century, was the replacement of perennial crops (clover and alfalfa) by annual corn and soybeans. The final major land use modification occurred over the last forty years with the introduction of plastic drainage tile. Plastic tile and trenching machines eased the installation and reduced the cost of subsurface drainage and surface tile inlets. With this additional tilling in wet soils marginal for crops, the vegetative community changed from perennial sedges and grasses to annual row crops; altering how water moves through the landscape (Isenhart et al., 1997; Miller et al., 2001).

Watershed-wide changes in plant water requirements and storm runoff have the potential to alter (increase) the amount of water reaching the river. Stream channels will adjust their morphology to accommodate the increase in runoff by altering their dimension, pattern, and/or profile. Understanding the spatial and temporal distribution of crop diversity provides insight into the possible changes in stream channel morphology within the Lac qui Parle watershed.

<u>Methods</u>

The LqP River watershed contains 702,119 acres. Crop data were obtained from the National Agricultural Statistic Service (NASS). Since greater than ninety percent of the LqP River watershed is contained within Lac qui Parle (67.8%) and Yellow Medicine (23.4%) counties, agricultural data were reviewed for only these two counties. Annual data (1921 – 2006) were compiled for total acres harvested for twelve (12) crops (barely, beans, corn, flaxseed, hay, potatoes, rye, soybeans, sugar beats, sunflower, and wheat).

<u>Results</u>

An average of 708,691 acres (+/- 11,436) have been in agricultural production in LqP and Yellow Medicine counties since 1921 (NASS, 2006). Over the next eighty-six years, crop diversity faded as the number of acres of perennial crops and cereal grains steadily declined (Figure 2.7). In 1921, the agricultural landscape was dominated by corn (31.2%), oats (25.4%) and wheat (21.8%), with minor contributions from barley

(4.0%), rye (2.2%) and flaxseed (1.8%). Crop diversity increased through 1940 with corn (26.8%), oats (21.2%), wheat (15.5%), flaxseed (12.7%), barley (11.7%), and alfalfa (10.5%) dominating the landscape. By 1950 the numbers began to shift. Today LqP and Yellow Medicine counties are dominated by a two crop rotation of corn and soybean. Gone from the farm are perennial crops such as clover, and alfalfa, and cereal grains such as wheat, rye, and oats (Figure 2.5).

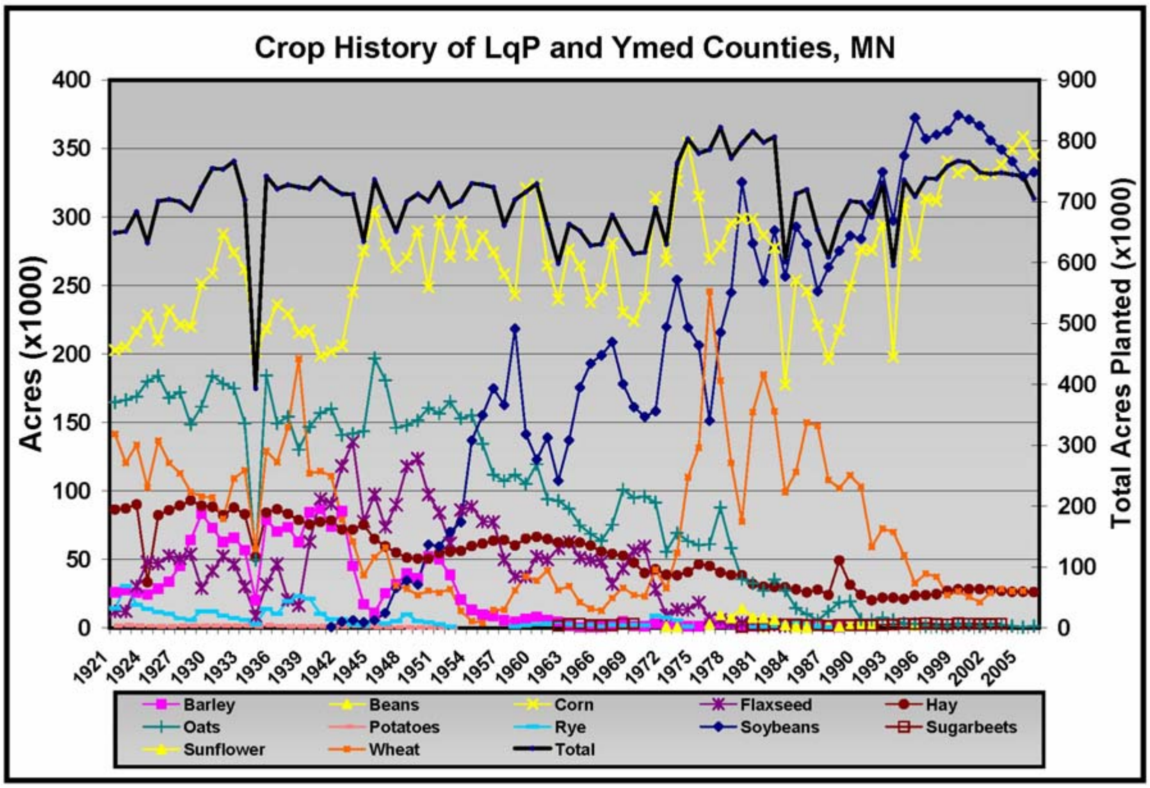

Figure 2.7 Crop history for LqP and Yellow Medicine counties (1921-2006) illustrating the number of acres (thousand) per crop in agricultural production per year, type of crop, and the total number of acres planted.

Soybeans comprised less than one percent of the total acres in production when they were first planted in 1941; by 1950 soybeans comprised 8.7% of the total acres planted, and was the fourth most popular crop. Soybean production continued to expand at a rate of 6,088 acres per year (r^2 = 0.91), and in 1979 it surpassed corn as the most popular crop (40.9% to 37.6% respectively). As the attractiveness of soybeans increased, other crops declined. Three crops dominated the landscape in 1979;

soybean, corn, and wheat (9.8%). These three continued to dominate through 1993 when a two-crop rotation of corn and soybeans combined to account for 89.1% of all the crop land planted. In 2006 these two crops account for 97.5% of the total acres planted.

Miller modeled the change in streamflow on the Little Cobb River, MN as a result of the conversion of land use from native prairie and forests to agriculture (Miller et al., 2001). Pre-settlement land use conditions assumed a vegetative cover of 95% pasture and 5% forest. Present-day land use, derived via digital and hard copy data analysis is 90% row crop, 5% pasture, 3% forest, and 2% homesteads. No distinction was made in the type of row crop, annual or perennial. Results from his work suggest the single most important reason for the increase in peak streamflow is loss of wetlands.

Wetlands provide internal storage within the watershed where water either evaporates or infiltrates and they are dominated by perennial vegetation adapted to inundated or saturated conditions (Mitsch and Gosselink, 2000). Perennial vegetation evapotranspires water for a longer time leaving greater available soil moisture storage and drier soil conditions through the full growing season. The switch to annual row crops increased antecedent soil moisture levels prior to crop development and after crop harvest. This reduced the infiltration capacity and increased the potential for surface runoff (Isenhart et al., 1997).

C. Riparian Buffer Assessment 1967 - 2000

Introduction

Riparian areas are generally defined as the zone along rivers between terrestrial and aquatic ecosystems (Gregory et al., 1991). They encompass the physical gradients of environmental factors, ecological processes, and plant communities. Riparian areas frequently flood but may be dry for a portion of the growing season (Mitsch and Gosselink, 2000). The benefits of natural riparian buffers are well documented in the literature (Basnyat et al., 2000; Castelle and Johnson, 2000; Correll et al., 1997; Dosskey et al., 1997a, b; Gregory et al., 1991; Lowrance, 1998; Naiman et al., 1988;

Naiman and Roberts, 1997; Schueler, 1995; Schultz et al., 2000; Wenger, 1999). These benefits include the trapping and removal of pollutants, stabilization of streambanks, reducing channel erosion, storage of flood waters, enhancing habitat for fish and other aquatic organisms, providing habitat for terrestrial organisms, moderating water temperatures, improving the aesthetics of stream corridors, and providing recreational and educational opportunities.

Natural riparian areas contribute important economical benefits both locally and regionally. Locally they provide erosion control by regulating sediment transport and distribution, enhancing water quality, and providing aquatic and wildlife habitat. Regionally, natural riparian areas are thought of as indicators of global environmental change because of their sensitivity to variations in the environment and hydrologic cycle (Odum, 1978). Although natural riparian areas typically encompass a very small proportion of the total landscape, they are extremely rich in plant and animal life, and provide essential habitat for many aquatic and terrestrial species. Finally, natural riparian areas are among the most diverse, dynamic, and complex biological systems on earth, contributing significantly to regional biodiversity (Naiman et al., 1993).

Natural riparian vegetation has different impacts on stream processes depending upon its position in the watershed. The type of riparian vegetation may also influence channel morphology (Davies-Colley, 1997; Friedman et al., 1996a, b; Hession et al., 2003; Hupp, 1999; Randolph and Senf, 2001; Trimble, 1997). Native riparian vegetation, while generally more expensive, is increasingly favored in stream restoration projects. Native species have evolved with the hydrological conditions in the watershed making them good candidates for long-term and sustainable revegetation practices that will most effectively achieve ecological and geomorphological project goals (Abernethy and Rutherfurd, 1998). Native riparian vegetation helps control the transport of sediment and chemicals to stream channels (Lowrance et al., 1984). This is especially important in agricultural settings where the application of fertilizers, pesticides, and herbicides can find their way into the stream. Retention in native riparian buffers reduces chemicals from agricultural runoff from entering a water system. Denitrification within native riparian buffers has the capacity to reduce the amount of nitrogen transported from farm fields into streams (Schnabel et al., 1997). However, much of the denitrification capacity in a properly functioning riparian buffer will go untapped when tile drains are installed on adjoining agricultural fields because tile drainage short-circuits natural drainage pathways. Drainage tiles reduce the amount of surface runoff that would flow through a healthy riparian buffer under normal conditions. This effectively negates the filtering benefits of a healthy and properly functioning riparian buffer.

Purpose

Te change in native riparian acreage between 1967 and 2000 along the Upper and Middle watersheds of the SF LqP River was determined using GIS technology. Changes in location and size of native riparian buffer areas can affect flooding, erosion rates, nutrient and sediment loading, and water temperature. A comparison of the native riparian buffer zones over this 33-year time frame may help determine future changes in the geomorphology and channel stability of the river, and assist land managers in identifying potential riparian restoration sites.

Methods

Seven aerial photographs taken in 1967 were scanned and converted to TIFF files (Tag Image File Format) with a preset minimum resolution of 600dpi suitable for differentiating vegetation cover. Scanned aerial photos and USGS Digital Orthoquads (DOQ's) with a three-meter resolution were orthorectified using ArcMap's Georeferencing feature (Appendix A). A minimum of five control points were utilized in the rectification process to ensure a root mean square error (RMSE) less than five (Appendix A).

Riparian zones were digitized from the 1967-orthorectified images. The 100-year FEMA floodplain was used to define the limits of the riparian zone in both years. Two land use types were differentiated within this zone: agricultural and non-agricultural (assumed native). The river surface is included with the riparian area in both years due to difficultly distinguishing vegetative cover from the water surface in the aerial photos.

Riparian shapefiles exist for the year 2000 and were obtained from the MN Department of Natural Resources (MNDNR). The 2000 riparian data was altered by adding riparian polygons immediately adjacent to the river surface. In addition, the water surface was added to the 2000 riparian shapefile for an accurate comparison to the 1967 digitization. Both 1967 and 2000 digitized riparian areas were assessed for changes in native riparian acreage within the 100-yr FEMA floodplain.

Results

The Upper watershed in the SF LqP River corridor gained 227 acres of native riparian land cover between 1967 and 2000. This total reflects 420 acres of previous riparian agricultural land converted to native riparian vegetation coupled with the conversion of 193 acres of previous native riparian vegetation to riparian agriculture. Total riparian area in the Middle watershed of the SF LqP River corridor increased by 80 acres between 1967 and 2000 (Table 2.3). This reflects a creation of 155 acres of new native riparian land coupled with the loss of 75 acres of former native riparian land converted to riparian crop land.

Table 2.3. Change in the native riparian area of the Upper and Middle watersheds of the South Fork LqP River.

	Middle Watershed		**Upper Watershed**	
	m^2	***Acres***	***m^2***	***Acres***
Total Native Riparian Area 1967	1,484,673	367	3,828,297	946
Total Native Riparian Area 2000	1,809,474	447	4,746,930	1173
Native Riparian Area Lost	304,254	75	781,034	193
Native Riparian Area Created	629,055	155	1,699,667	420
Net Change	+324,801	+80	+918,633	+227

The majority of the land use in the riparian corridor immediately adjacent to the river in both the Upper and Middle watersheds is unchanged over the 33-year period Although 268 acres of native riparian buffer were converted to agriculture (row crop) between 1967 and 2000, the riparian corridor benefited from the addition of 575 acres that were previously under agricultural land use. The majority of the new, native riparian buffer acres in the Middle watershed were added in a large wetland that was expanded near the central region of the watershed. While this area is not immediately adjacent to the SF LqP River, it does provide benefits associated with riparian buffers such as flood attenuation.

Since riparian buffers act as the right-of-way for a stream and function as an integral part of the stream ecosystem, the addition of 307 acres of native riparian land has the ability to positively impact the channel morphology of the Lac qui Parle River. Buffers also add to the quality of the stream and the community in many diverse ways. In many regions, these benefits are multiplied when the streamside zone is in a forested condition (Castelle and Johnson, 2000; Lowrance, 1998; Lowrance et al., 1984; Schultz et al., 2000). Although the majority of stream buffers alongside the SF LqP River are forested, those that have recently been converted back to function as riparian buffers lack the land stabilization and shading benefits provided by mature trees. These native riparian areas are in an early successional stage and will require time (years) before they achieve the added benefits of forested buffers.

Although the benefits of grassed riparian buffers are impressive, their capability to remove pollutants borne in urban stormwater is limited (Schueler, 1995). This is contrasted by the moderate to excellent sediment and nutrient removal reported for forested riparian buffers in rural areas (Basnyat et al., 2000; Lowrance, 1998; Lowrance et al., 1984). Much of the pollutant removal observed in rural and agricultural buffers is due to physical and chemical processes. Physical filtering is the trapping of pollutants such as sediment and plant debris within the buffer. The trapped material is then incorporated into the riparian corridor, decomposed and recycled. Chemical filtering involves chemical interactions between pollutants (sediment, nutrients, and contaminants) and the organic and inorganic compounds as water moves through the riparian corridor. Chemical filtering is enhanced by the relatively slow transport of pollutants across the buffer or through it in the vadoze zone (generally unsaturated zones above the water table). In both cases, the relatively slow movement of water across and through the buffer promotes greater removal of pollutants by soils, roots and microbes (Correll et al., 1997; Dosskey et al., 1997a, b; Schueler, 1995).

The ability of a particular buffer to provide benefits depends upon several, interacting variables: buffer width, slope, and vegetation. Castelle and Johnson investigated the ecological functions of riparian vegetation and the relationship between buffer width and effectiveness (Castelle and Johnson, 2000). They considered the effectiveness of six ecological functions: streambank stabilization, sediment reduction, chemical removal, production of large organic debris (LOD), and shade production to moderate stream temperature. They reported a buffer width between 5 – 25 m to be most effective for five of the six functions. Nieswand and others determined slope and width were the main factors influencing the effectiveness of buffers in trapping sediment and associated pollutants (Nieswand et al., 1990). They developed a formula for determining width based on slope and time of travel assuming the minimum width and slope was 15 m and zero percent slope. The research recommended a buffer width between 15 – 91 m to properly protect a New Jersey reservoir from sediment and pollutants. In contrast, research in the Bear-Evans Creek watershed, Washington suggested a buffer width of 15 m provided adequate protection on slopes up to 40 percent (Budd et al., 1987). While the riparian corridors along the Upper and Middle watershed on the SF LqP River are highly variable, the general geometry (width, slope) remained the same between 1967 and 2000. Therefore the ability of the riparian buffers to properly function has been limited in those areas where riparian land has been converted to agricultural land use.

Conclusions

Results indicate thirty-five (35) percent of the agricultural land within the nineteen-township study area are currently improved by subsurface tile drainage. Assuming these results reflect conditions throughout the watershed, this is considerably more than the one to five percent value currently reported for the LqP watershed and represents a conversion rate of 3,350 acres/year. It is unknown how many more acres of land within the SF LqP watershed will be drained; but assuming drainage tiles have been installed on 35-percent of the 217,657 agricultural acres classified as poorly drained, and applying the current installation rate of 3,350 (ac/yr) it would be 42 years before the remaining poorly drained soils have drainage tiles installed. This represents the potential for a significant amount of hydromodification within the SF LqP River in the near future.

The majority of the land use in the riparian corridor immediately adjacent to the river in both the Upper and Middle watersheds is unchanged over the 33-year period. Although 268 acres of native riparian buffer were converted to agriculture between 1967 and 2000, the riparian corridor benefited from the addition of 575 acres that were previously under agricultural land use. The majority of the new riparian buffer acres in the Middle watershed were added in a large wetland that was expanded near the central region of the watershed. While this area is not immediately adjacent to the SF LqP River, it does provide benefits associated with riparian buffers such as flood attenuation.

The addition of 575 acres has resulted in a 19-percent increase of perennial, riparian vegetation in the riparian corridor and is most likely due to governmental programs such as the: Conservation Reserve Program (CRP), Conservation Reserve Enhancement Program (CREP), Wetlands Reserve Program (WRP), Wildlife Habitat Incentives Program (WHIP), Grasslands Reserve Program (GRP) and others. While these programs have grown in popularity since 2000, the recent focus on ethanol as an alternative fuel source may make land inside the riparian corridor more economically viable for corn production (FWW et al., 2007). Conversion of native riparian lands to corn production may prove detrimental to the overall effectiveness of the riparian buffer and ultimately water quality (Basnyat et al., 2000; Schueler, 1995).

As noted earlier, modeling work on the Little Cobb River, MN indicates the single most important reason for the increase in peak streamflow is loss of wetlands. Wetlands provide internal storage within the watershed where water can either evaporate or infiltrate. They are also dominated by perennial vegetation adapted to inundated or saturated conditions (Mitsch and Gosselink, 2000). Since perennial vegetation evapotranspires more water throughout the year, less water is left in the soil profile. This translates to more soil moisture storage capacity which helps attenuate flood flows. The switch to annual row crops in the SF-LqP watershed raised antecedent soil moisture levels prior to crop maturity and following crop harvest. This in turn reduces a soil's infiltration capacity and increases surface runoff (Isenhart et al., 1997). The increased amount of drainage tile installed within the SF LqP watershed has reduced the filtering capacity of the riparian buffers and limits their buffering capacity to over-bank (flood) flows. An analysis of the change in channel morphology in areas where the native riparian buffer has been either converted to agricultural land use, or has decreased in width will provide further insight. Chapter 4 investigates the spatial and temporal changes in channel morphology and any associated connections to land use.

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Chapter 3: Precipitation - Discharge Assessment of the South Fork Lac qui Parle River Watershed, MN

The impacts of agricultural drainage on stream discharge are not well documented. Understanding the hydrologic impacts of agricultural drainage is key to developing successful restoration projects in watersheds dominated by agricultural drainage. Previous research suggests that increases in streamflow in agricultural watersheds are the result of vegetation conversion of native perennial forests and grasslands with annual row crops. However, contrasting research suggests increased stream flows are the result of a wetter climate. This research analyzed historic streamflow and precipitation data for the Lac qui Parle (LqP) watershed, MN. The watershed is dominated by agricultural land use (> 75%). Recent research suggests that half the agricultural land in the LqP watershed is artificially drained. Records from two precipitation gauges were analyzed to determine climatic changes. Results indicate no significant change in the precipitation regime of the LqP watershed from 1916 to present day. To evaluate land use impacts on streamflow the annual and peak discharge, and the precipitation-discharge relationship (Q/P ratio) pre-1960 and post-1960 were analyzed. Results indicate a 57-percent increase in the Q/P ratio post-1960 compared to pre-1960. Significant increases (95% CI) were also noted in annual stream flow values post-1960. While increases in peak discharge ($Q_{1.5} \rightarrow Q_{100}$) were noted post-1960, the increases were not significant at the 95% CI. These results indicate that land use changes in the LqP watershed post-1960 correspond with increased runoff generated from rainfall events compared to pre-1960. Since agricultural drainage is the dominate land use change in the LqP watershed post-1960, and has been installed on over 5 million acres in MN, these results have significant implications for future restoration projects in watersheds where agricultural drainage has been installed.

Key Words: Lac qui Parle River (LqP), agricultural drainage, vegetation conversion, climate change, peak discharge, annual discharge, annual precipitation, discharge/precipitation ratio (Q/P), riparian corridor, grazing,

Introduction

Understanding the effects of land use changes on streamflow discharge in the Minnesota River Basin (MRB) requires an assessment of the precipitation-discharge relationship in a watershed dominated by agricultural land use. While several researchers have investigated the hydrologic impacts of agricultural drainage, most research in this area has focused on the hydrologic impacts of agriculture since the early days of cultivation. Johnson and others investigated channel adjustments due to agricultural activities on a small stream in Oklahoma (Johnson et al., 1980). They modeled historical discharge based on soil type, vegetative cover, climate, slope, and drainage area and found storm flow volumes increased 60% and stream channel width increased two to threefold over a thirty-year period from 1871-1899. Additionally, the authors note that nearly all channels in the lower basin became entrenched due to an average of 3.5 feet of post-settlement alluvium (PSA). All impacts were attributed to land use change from native prairie and woodland to agriculture. In southwestern Wisconsin peak discharge from a two-hour duration storm increased 205% due to conversion of natural vegetation to agricultural land use (Knox, 1977). Similar trends were reported for North Fish Creek in Wisconsin (Fitzpatrick et al., 1999) where agricultural practices, preceded by clear-cut logging, significantly altered the hydrologic and geomorphic conditions in the watershed. Streambed erosion of up to three meters produced a doubling in channel capacity in the upper main stem of North Fish Creek. Deposition of PSA in the lower reaches were 4 - 6 times greater than pre-settlement rates. The authors concluded that current flood peaks may be double those expected under pre-settlement forest cover. Both studies document hydrologic changes due to changing land use practices since European settlement but do not document the impact of agricultural drainage.

A study by Magner and Steffen (2000) analyzed stream flow data from eleven tributaries to the Minnesota River over two time periods, 1936-1955 and 1979-1998. They report an average increase of 55% in the $Q_{1.01}$ from the 1936-1955 time-period to the 1979-1998 time period. Although the authors suggest the increased discharge was the result of wetland and prairie lake drainage, the result was inferred and not conclusive. A modeling study by Miller (1999) of the Little Cobb River, a tributary to the Minnesota

River, suggested storm flow volumes and peak flows associated with the 1.5-year to 2.0-year recurrence interval (RI) events have more than doubled as a result of wetland drainage and associated channel changes. Miller also compared pre-settlement conditions to current conditions and estimated bankfull discharge rates increased at least four times since European settlement due to wetland loss. However, others attribute the increased discharge solely to a wetter climate (Johnson et al., 2009; Mallawatantri et al., 1996). Recent discharge studies in Minnesota and Iowa suggest the increases are not due to a wetter clmate (Schilling et al., 2007). Furthermore, Raymond et al., (2008) found that streamflow volumes in the Mississippi River increased over the past 50 years due to changes in agricultural land use and not precipitation.

Approximately 79-percent of the South Fork LqP (SF LqP) watershed is in agricultural land use with about 49% drained (Christner, 2009). Drainage is meant to speed water flow from the basin into receiving waters and may alter channel size, channel position (incision) and increase channel erosion. Increases in precipitation (derived from climate change) may do the same. This research investigated the magnitude of a possible climatic change by examining the precipitation - runoff relationship from 1912 to 2002; and used the ratio of annual discharge to annual precipitation (Q/P) to investigate temporal changes. The pre-1960 period is compared to the post-1960 period to determine if the Q/P ratio changes correspond with changes in the installation rate of agricultural drainage.

Methods

Precipitation Regime

Precipitation data in the SF LqP watershed were collected from two sites; the Canby, MN rain gauge and LqP-Riverside, MN rain gauge (Figure 3.1). The Canby gauge is located in the upper watershed of the SF LqP River. Its precipitation data set runs from 1916-present day. The LqP-Riverside gauge is located in the lower watershed of the SF LqP River. Its precipitation record runs from 1889-present. Average monthly totals for the gauge records were computed for both data sets, plotted and reviewed. Monthly precipitation totals for both stations were then combined, averaged, plotted and reviewed. Mallawatantri (1996) and Johnson (2009) concluded that increases in discharge on the Minnesota River were due to a wetter climate since the 1960s. To investigate the hypothesis of a wetter climate since 1960, the average monthly totals were separated into pre- and post-1960. These data sets were then analyzed to determine differences in the precipitation regime for the SF LqP River watershed.

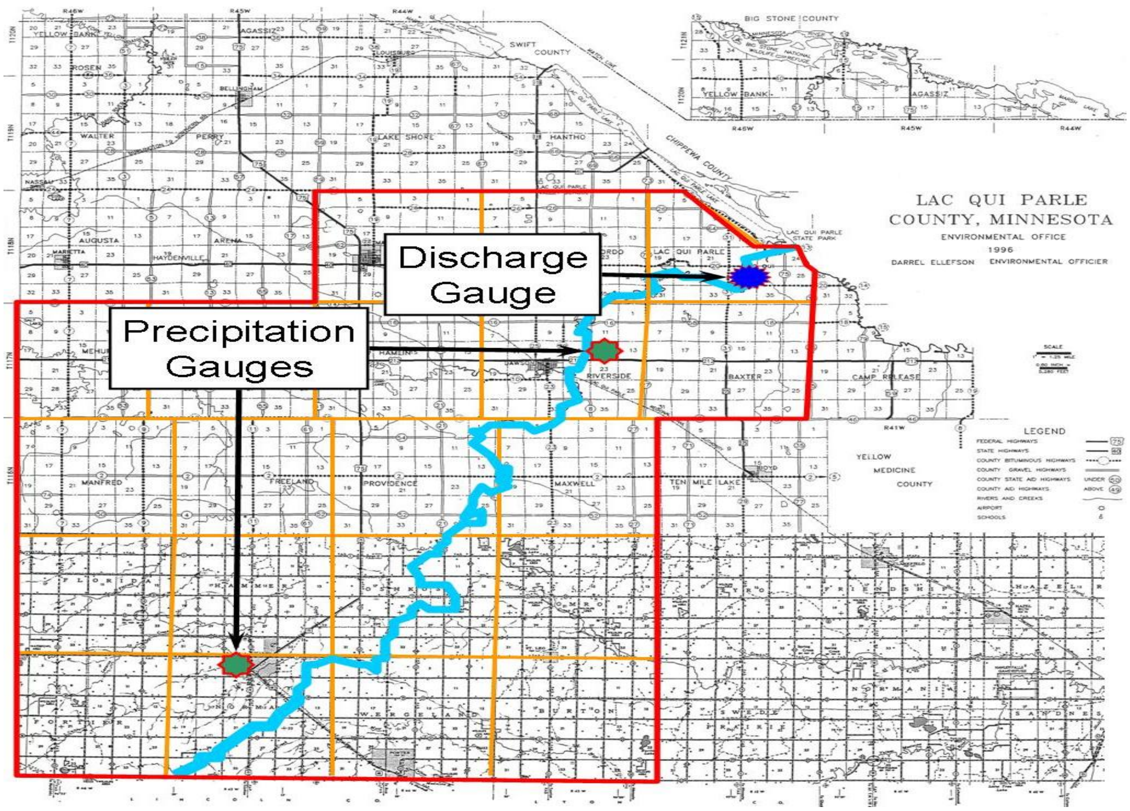

Figure 3.1. Location of Canby and LqP-Riverside precipitation gauges and the USGS discharge gauge 05300000 at LqP.

<u>Statistical Difference</u>

Temporal differences in precipitation and discharge were determined at the 95% confidence interval (CI) through a paired sample t-test of the means. The null hypothesis assumes the difference between the means of the two data sets (pre-1960 and post-1960) equals zero:

H_o = no significant difference between the means.

Discharge Regime

Discharge data were obtained from USGS gauge 05300000 on the LqP River near LqP, MN (Figure 3.1). The gauge yielded an 80-year record of data over two time frames, 1910-1914, and 1931-2007. The gauge was not recording data from 1915 through 1930. The analysis utilized the annual peak discharge data for the gauge. The data set was separated into two time frames; 1910-1960 and 1961-2007. Graphical frequency analysis was performed after methods described by Beard (Beard, 1962), and the analytical analysis uses the Log Pearson Type-III distribution outlined by the U.S. Water Resources Council (USWRC, 1976). Graphical analysis provides estimates from actual data plotted according to Beard's methods. This is a non-parametric method that makes no assumptions regarding distribution of the data. Therefore the frequency curves can be drawn without regard to any statistical distribution.

Graphical

The graphical approach computes plotting positions for annual peak discharge data and fits a hand-drawn curve to a plot of the data. The procedure involves the following steps:

- tabulate annual peak discharge data
- rank discharge data in order of magnitude
- calculate and assign plotting positions
- plot data on log-probability paper
- draw frequency curve

Plotting positions were calculated with the Median formula:

Median formula: $P = \frac{m}{(n+1)}$ where *P* is the plotting position for the extreme event in the series, *n* is the number of years in the record, and *m* is the rank of the event (Beard, 1962).

Analytical

The analytical approach utilizes the selection of a representative, but theoretical, frequency distribution for the data. For this study the Log Pearson Type III analytical method was used to evaluate the data per recommendations of the US Water Resources Council (USWRC, 1976). The data are transformed, statistics computed, and then adjusted to fit a frequency curve. The procedure involves the following steps:

- rank the discharge data, x
- take the log of the discharge data, Log x
- square the log of the discharge data, $[\log x]^2$
- sum the square of the log of the discharge data, 3 $[\log x]^2$
- compute the Log Pearson Type III skew coefficient (k) and plotting positions
- compute the mean ($\bar{x}$) and standard deviation (S) of the log discharge data
- compute the log Q from: $\log Q = [k*S] + \bar{x}$
- compute the discharge (Q) where $Q = 10^{(\log x)}$
- determine the adjusted exceedance frequency values (from table)
- compute the 95-percent confidence intervals

Discharge-Precipitation Ratio

Precipitation data from the Canby and LqP-Riverside rain gauges were analyzed in conjunction with the discharge data from the USGS gauge at LqP, MN. A total of sixty-six (66) years of concurrent precipitation and discharge data are available from these gauges for the analysis. Average yearly precipitation totals (inches) were computed by summing the yearly precipitation totals for each gauge and then calculating the yearly average. The average annual discharge data were obtained from the USGS LqP gauge #05300000. Volumetric data (cfs) were converted to depth (inches) of runoff. Only yearly values available from all three data sets were used in the analysis.

Results and Discussion

Precipitation Regime

The LqP-Yellow Bank Watershed Districts have participated in a cooperative effort with the State Office of Climatology and the Board of Water and Soil Resources to report and record climate data for the LqP watershed. According to these records the average annual precipitation in the LqP–Yellow Bank District is 22.5 (in). The monthly average maximum precipitation of 4.0 (in) falls in June, and the average minimum precipitation of 0.6 (in) falls in January (State of Minnesota, 2003). Data from the Canby and LqP-Riverside gauges indicate a similar precipitation distribution for the SF LqP River watershed (Figure 3.2). The maximum precipitation is recorded in June and the minimum in January for both gauges (Table 3.1). Mean yearly totals are 25.42 inches for Canby, MN and 23.89 inches for LqP, MN.

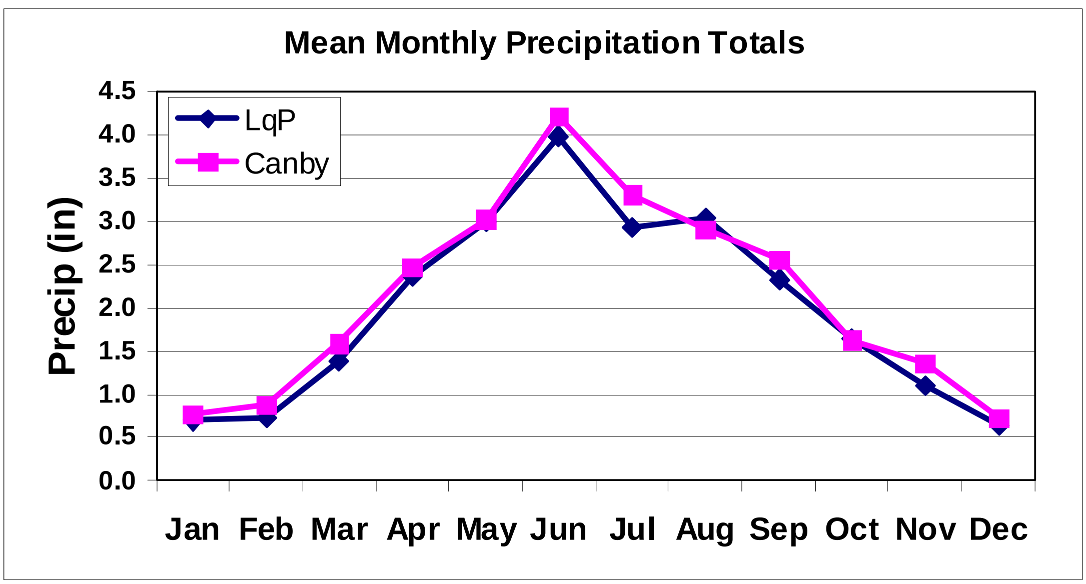

Figure 3.2. Mean monthly precipitation totals for the Canby (1916-2004) and LqP-Riverside (1889-2004) gauges.

Table 3.1. Mean monthly precipitation totals for Canby (1916-2004) and LqP-Riverside (1889-2004) gauges.

Month	Gauge	
	Canby	LqP
January	0.76	0.70
February	0.88	0.73
March	1.59	1.39
April	2.47	2.37
May	3.03	3.00
June	4.21	3.99
July	3.31	2.94
August	2.90	3.04
September	2.55	2.33
October	1.63	1.65
November	1.36	1.10
December	0.73	0.65

The majority of the precipitation occurs in the growing season between the months of April and September and accounts for 78% of the Canby total and 74% of the LqP-Riverside total. Mean monthly totals show little variation between the two gauges with no significant difference at the 95% confidence level.

Separating the data into pre- and post-1960 revealed minor variations in the average monthly totals (Figure 3.3). Prior to 1960, the months of May, June, August, September, and December were slightly wetter than post-1960. Post-1960, the months of January March, April, July, October, and November were slightly wetter (no difference in February totals). Statistical analysis of these results suggest there is no significant difference in the precipitation regime for the SF LqP River watershed between the periods 1890-1960 and 1961-2003 (P = 0.008). The precipitation post-1960 in the SF LqP River watershed is similar to the pre-1960 precipitation; contradicting the findings reported by Mallawatantri et al. (1996) who applied the Palmer Severity Drought Index to determine wet/dry months (Mallawatantri et al., 1996). Their research focused on the 1960-2000 time-period. This research is more comprehensive because it evaluates the complete records for two precipitation gauges within the watershed; one located in the upper reaches (Canby gauge) and one in the lower reaches (LqP-Riverside gauge).

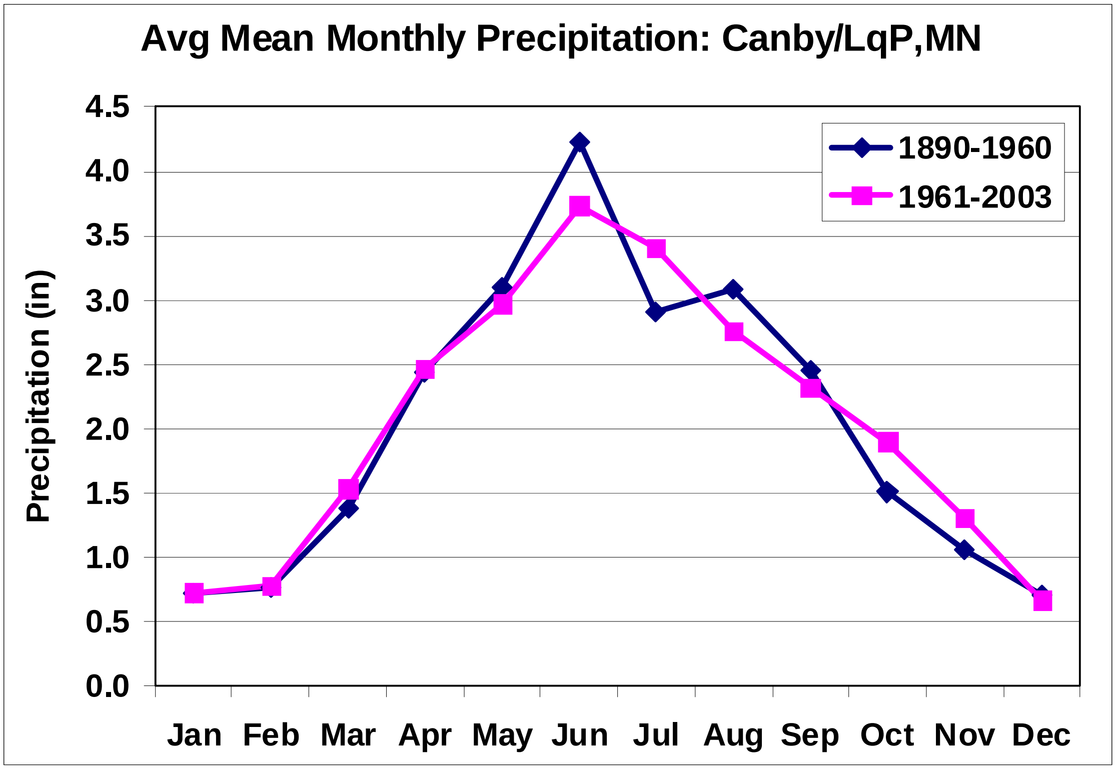

Figure 3.3. Average mean monthly precipitation totals for the LqP River watershed.

Discharge Regime

The flood discharge at a given recurrence interval is similar for both the graphical and analytical analyses (Table 3.2). The 100-yr flood (Q_{100}) computed by the graphical method is 16,800 cfs. The corresponding Q_{100} computed by the analytical method is 16,465 cfs, a 2-percent difference. The 2-yr flood (Q_2) is 1,660 for the graphical method and 1,636 cfs for the analytical method, a 1.5-percent difference. The Q_{50} flood is 12,850 cfs for the graphical and 12,723 cfs for the analytical method, a 1.0-percent difference.

Table 3.2. Flood discharge (Q_{peak}) for the LqP River based on complete record (1911-2007).

Recurrence Interval	Discharge (cfs)	
	Graphical	Analytical
2	1,660	1,636
5	3,600	3,876
10	5,750	6,008
25	9,300	9,509
50	12,850	12,723
100	16,800	16,465

When annual peak flows are separated into pre- and post-1960 periods, the graphical analysis shows post-1960 floods 35 to 43% higher than pre-1960 floods (Figure 3.4, Table 3.3).

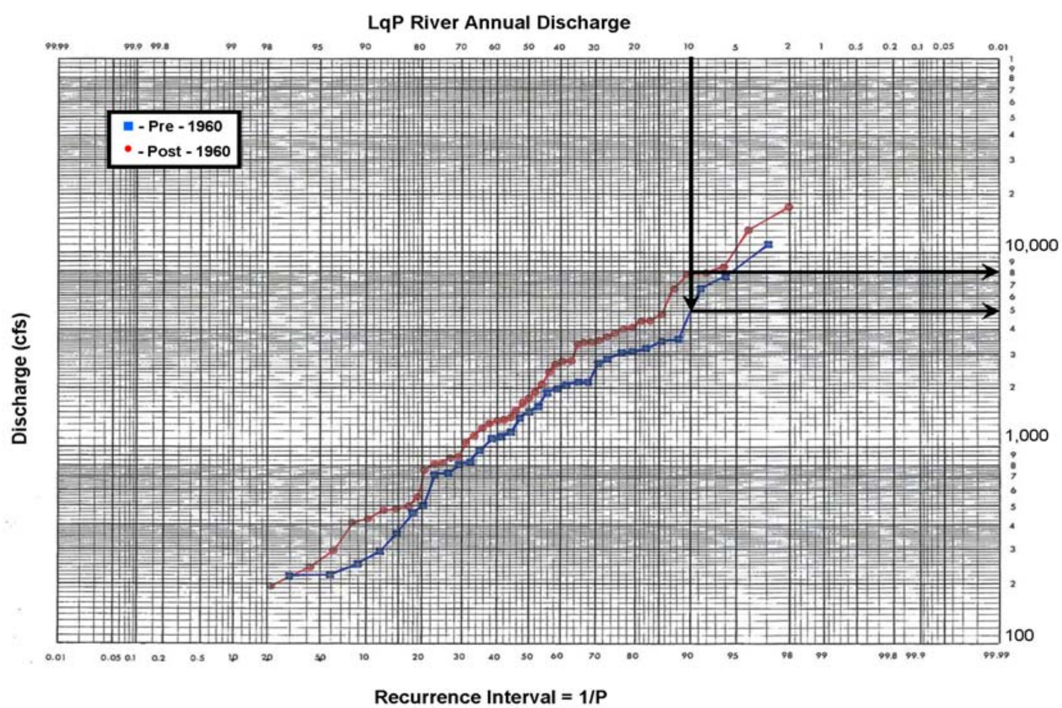

Figure 3.4. Graphical plot of annual peak discharge for the LqP River. Arrows indicate Q_{peak} for the 10-yr RI pre- and post-1960.

The analytical analysis also yields higher discharge values ranging 30 to 51% higher post-1960 than pre-1960. (Figure 3.5, Table 3.3). However, even though the results suggest a 30 – 51% increase in Q_{peak} post-1960, the increases are not statistically significant at the 95% level. Similarly, the mean annual peak discharge (mean Q_{peak}) increased 37% (Figure 3.6). Mean Q_{peak} post-1960 is 2,987 cfs, compared to 2174 cfs pre-1960, but this change is also not significant (alpha – 0.05).

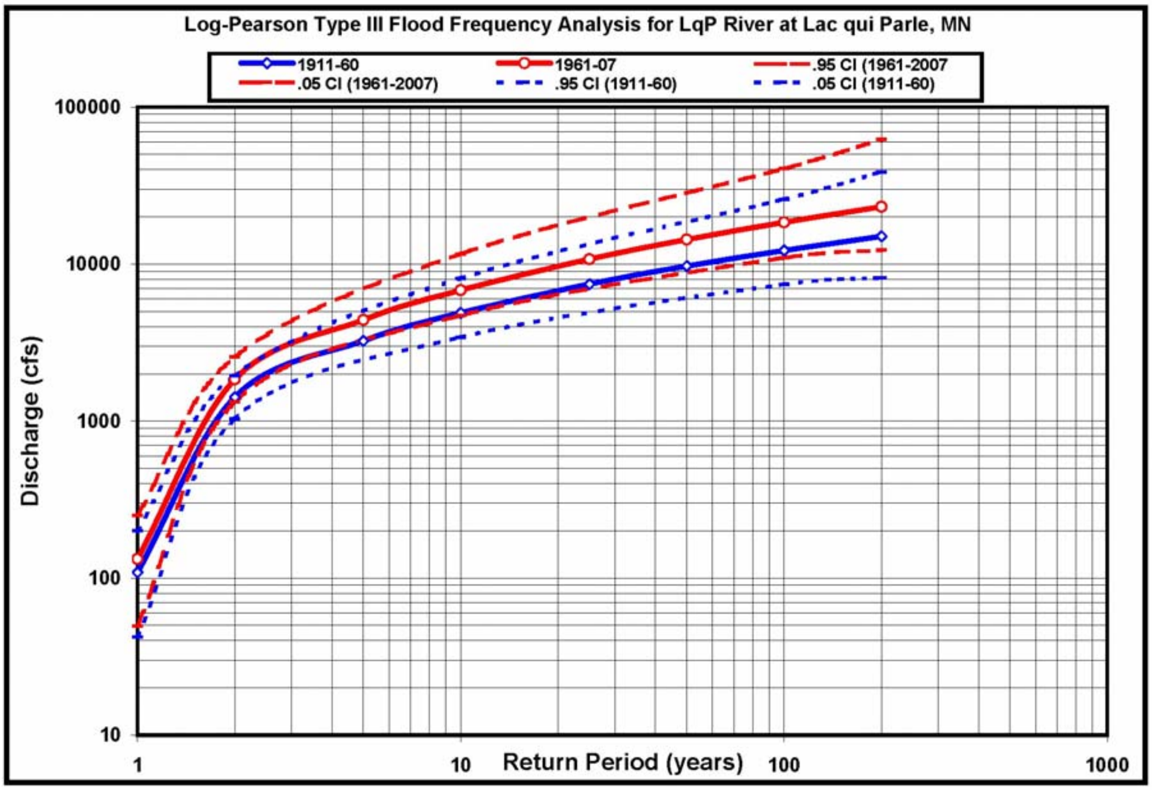

Figure 3.5. Log-Pearson Type III plot of annual peak discharge values for LqP River pre- and post-1960.

Table 3.3. Annual peak discharge (Q_{peak}) for the LqP River pre- and post-1960, as calculated through graphical and analytical methods.

Recurrence Interval	Discharge (cfs) Graphical Pre-1960	Discharge (cfs) Graphical Post-1960	Graphical % change	Discharge (cfs) Analytical Pre-1960	Discharge (cfs) Analytical Post-1960	Analytical % change
2	1,390	1,880	35	1419	1842	30
5	3,200	4,400	38	3241	4400	36
10	4,900	6,800	39	4883	6819	40
25	7,800	11,000	41	7446	10750	44
50	10,800	15,000	39	9694	14323	48
100	14,000	20,000	43	12216	18448	51

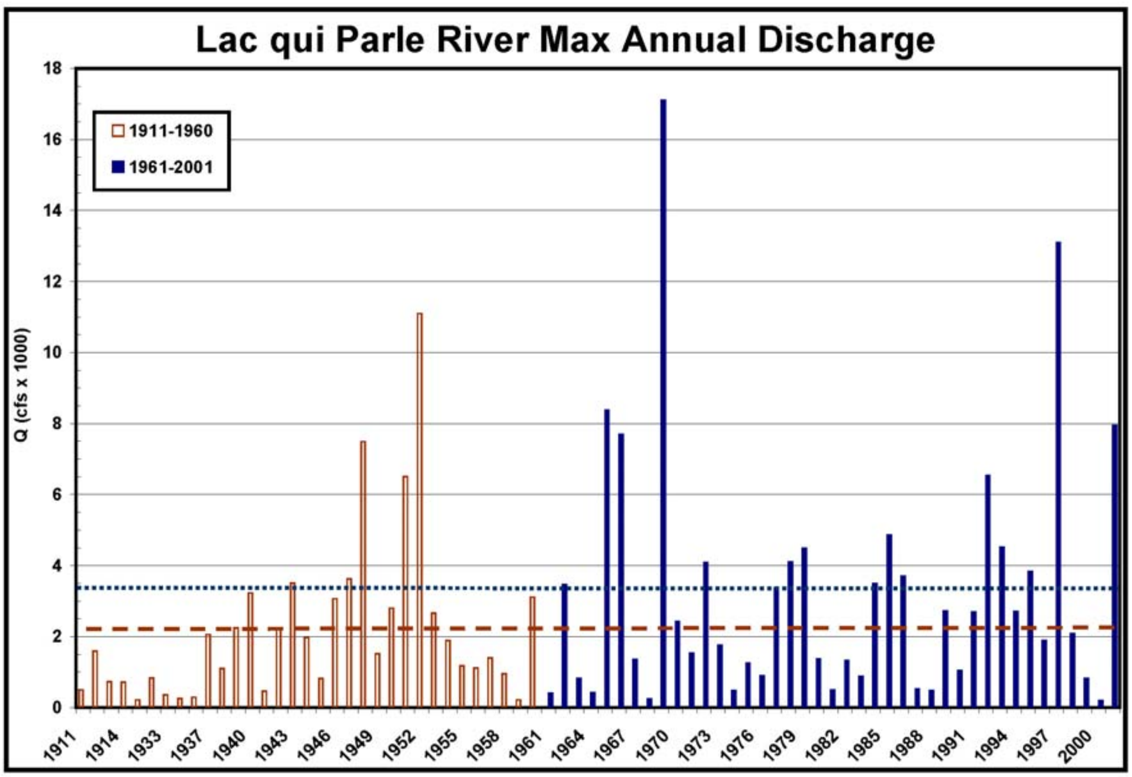

Figure 3.6. Annual peak discharges pre- and post-1960 with their respective mean discharge values (pre-1960 dashed line, post-1960 dotted line).

Discharge-Precipitation Ratio

To recap, these analyses have produced two results. First, the precipitation regime in the LqP watershed has remained consistent from 1890 through 2003. No significant change in precipitation was evident between the two time-periods (1890-1960 and 1961-2003). Second, graphical analysis of the annual peak discharge has shown a 37-percent increase post-1960. While the Log-Pearson results were not significant, results of the Graphical analysis, which does not rely on a statistical distribution, do indicate an increasing trend in the magnitude and frequency of peak flows post-1960 that is not supported by a corresponding increase in precipitation.

To investigate whether the trend of increasing discharge is due to something other than increasing precipitation, the discharge-precipitation ratio (Q/P) was calculated over the pre- and post-1960 periods. If discharge has indeed increased in the LqP watershed post-1960, it should be evident in the discharge-precipitation relationship.

As illustrated in Figure 3.7, the Q/P ratio for the LqP watershed exhibits multiple adjustments from 1912 through 2002. Linear regressions through the two data sets show a 27-percent increase in the slope post-1960 compared to pre-1960. The difference in slope is significant at the 95% confidence interval. This indicates more discharge is being generated from a similar amount of precipitation post-1960 than pre-1960.

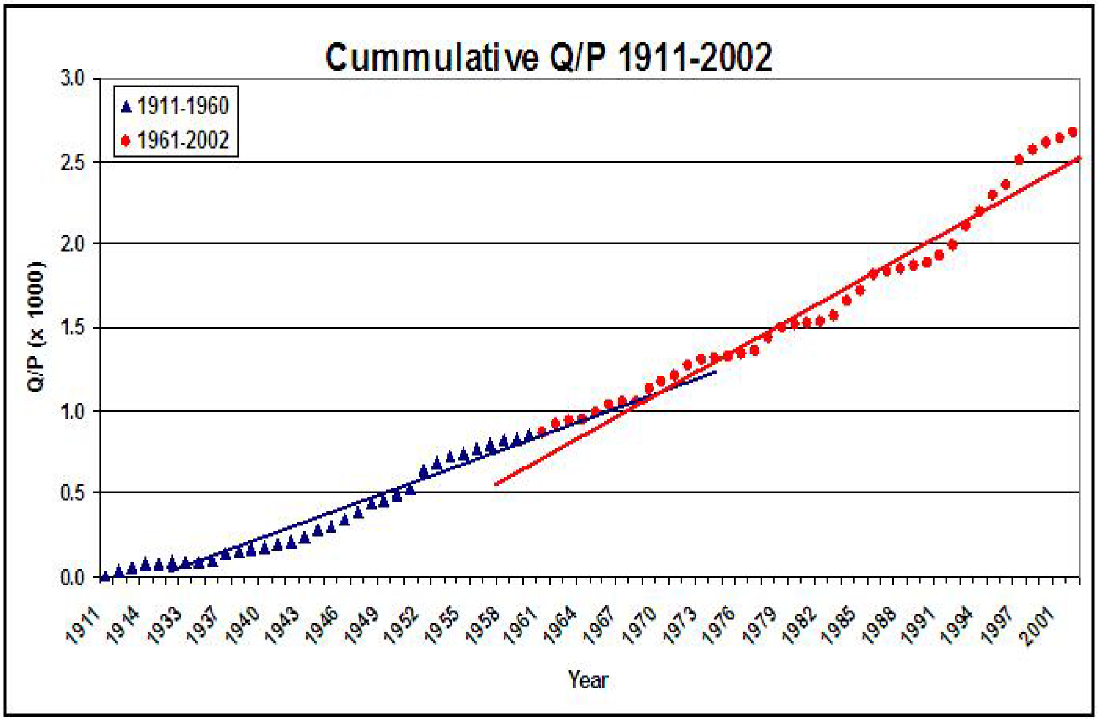

Figure 3.7. Cumulative annual Q/P values for the LqP watershed.

This trend is supported by a plot of discharge vs. precipitation for the two time-periods (Figure 3.8). The slope of the post-1960 Q versus P regression is almost double the pre-1960 slope and is significantly different at the 95% level of confidence. Linear regression analysis indicates a 125-percent increase in the slope post-1960 compared to pre-1960 and shows more discharge being generated from precipitation post-1960 than pre-1960. All but one of the pre-1960 annual precipitation totals (blue triangles) produce an annual discharge less than 4.0 (in), the annual precipitation total generated in 1952 of 5.2 (in). In fact, pre-1960 annual precipitation totals greater than 25 (in) produce annual discharge totals ranging from 0.78 – 3.60 (in). Similar annual precipitation totals post-1960 generate discharge values between 0.36 – 9.15 (in).

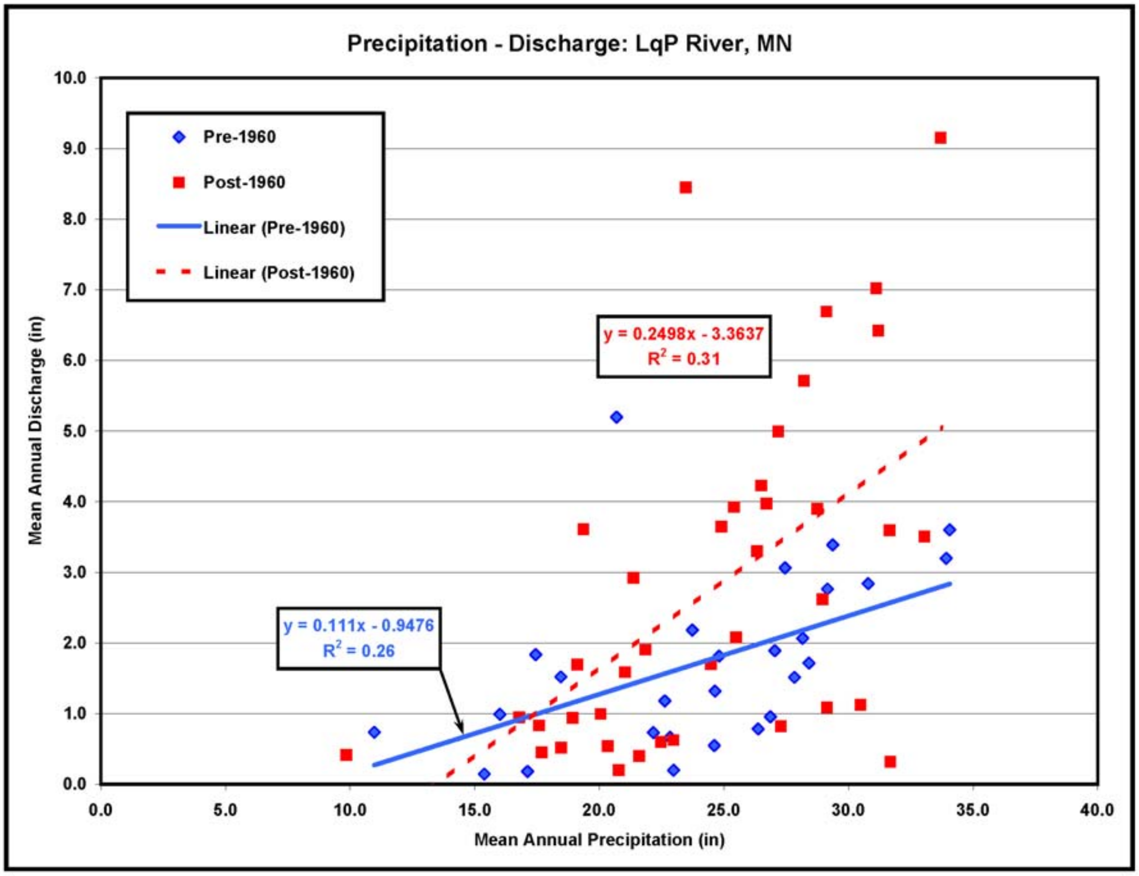

Figure 3.8. Annual discharge totals (Q) vs. annual precipitation totals 1912-1960 and 1961-2002. Discharge totals are from the LqP flow gauge. Precipitation totals are from the Canby and LqP-Riverside precipitation gauges.

This trend is also evident in a plot of annual Q/P values (Figure 3.9). All Q/P values pre-1960, except for 1952, are less then 0.125 (in). This is contrasted by fourteen (14) Q/P values post-1960 that exceed 0.125 (in).

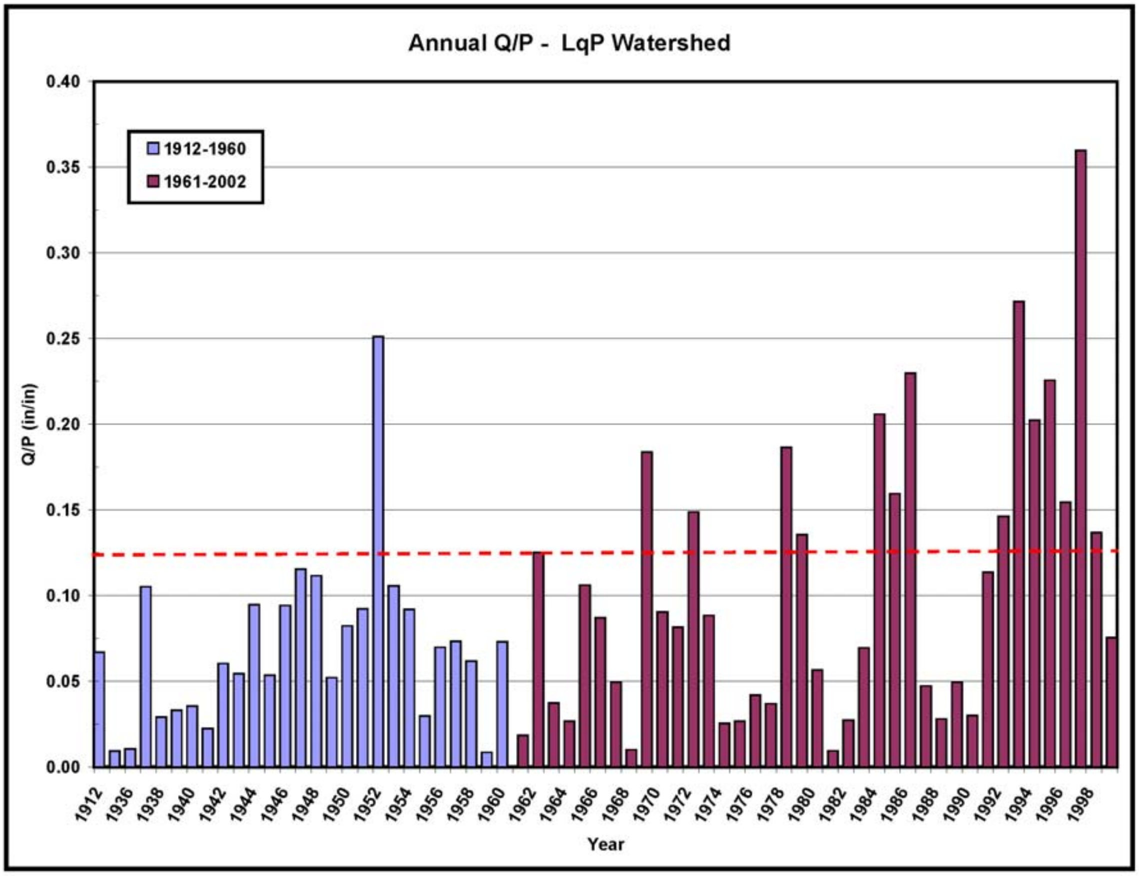

Figure 3.9. Annual Q/P ratio for LqP watershed 1912-1960 and 1961-2002. Note only one event exceeds 0.125 (dotted line) prior to 1961.

Indeed, the mean Q/P value post-1960 is significantly higher than pre-1960 (Figure 3.10). Prior to 1960, the mean Q/P is 0.07. Post-1960 the mean Q/P value jumps to 0.11. This is a 44-precent difference and represents a 57-precent increase in the Q/P value.

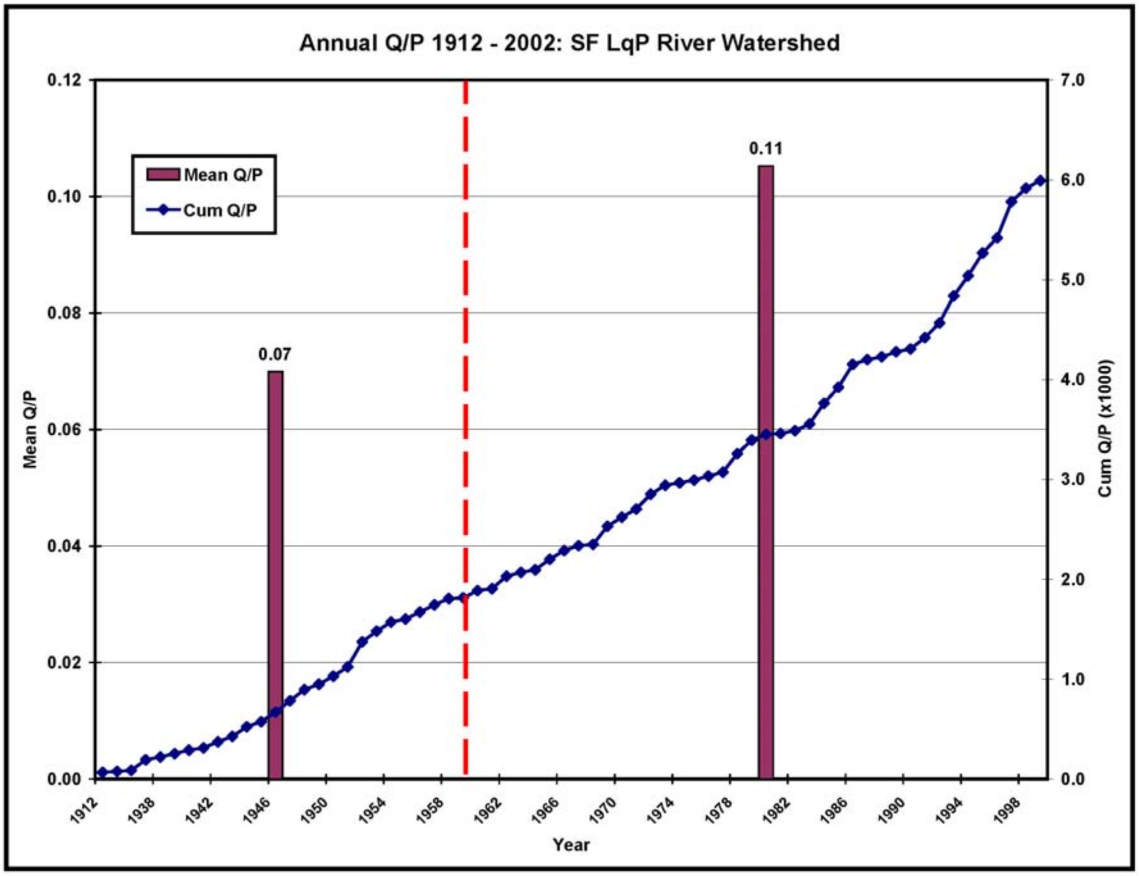

Figure 3.10. Cumulative Q/P 1912-2002 and mean annual Q/P for pre-1960 and post-1060 (dashed line).

Conclusions

Results from this research are consistent with those found by Magner and Steffan (2000) and Miller (1999). Three important conclusions can be derived from this research. First, annual peak discharge (Q_{peak}) for the LqP River has increased for the 1961-2002 time frame compared to the 1911-1960 time frame. While increases in annual peak discharges are not significant at the 95-% confidence interval utilizing the Log Pearson Type-III analysis; the Graphical analysis, which assumes no stastistical distribution shows an increase in all peak flows. Second, the increasing discharge is supported by significant increases in annual discharge post-1960 compared to pre-1960 for similar precipitation totals. Furthermore, the significant increase in the Q/P ratio also indicates higher discharges post-1960 compared to pre-1960. Third, and most importantly, no significant increase in monthly precipitation was detected for the LqP watershed from 1912-1960 to 1961-2002. Therefore, the increase in annual and peak discharge, and the Q/P ratio must be attributed to some mechanism that would facilitate the movement of water off the landscape and into receiving waters. This type of mechanism is consistent with the replacement of perennial vegetation by annual row crops and, the installation of surface tile inlets and subsurface tile drains.

The majority of the vegetative change from native prairie and wetlands to agricultural crops was accomplished prior to 1911, although from the mid 1950s to the early 1960s a major shift occurred from diversified cropping to the corn-soybean system with drainage. The combination of cropping changes and the increasing intensity of agricultural drainage coincides well with the noted increases in annual and peak discharge in the LqP watershed. Agricultural drainage (surface and subsurface) appears to have been a major factor that explains the 57-percent increase in Q/P post-1960 in the LqP watershed. The results of this analysis are consistent with findings by Schilling and others (2005, 2003). They researched the trends in annual streamflow records from 1903 to 2000 from 11 gauging stations in central Iowa. Their results indicate increases in annual baseflow for all stations. In some stations annual streamflow increased over time; in only one station was there a reduction in annual maximum flows (Schilling and Libra, 2003). The authors hypothesized that greater artificial drainage, increased stream channel incision, increasing row crop production, and improved conservation practices explained their results. During the period of 1980 to 2000, Schilling and Wolter (2005) conducted multiple regression analyses and found total streamflow was largely explained by rainfall, sand content, and row crop percentages of watersheds. Storm flow was largely explained by rainfall; however, baseflow was largely explained by the percentage of row crops in watersheds.

Human alterations to the landscape, including tile and ditch drainage, have also been shown to increase streamflow and accelerate streambank erosion in Central Iowa (Zaimes et al., 2006). The authors attributed this erosion to the reduction of water storage capacity on the landscape and a reduction in the time of concentration in watersheds and state: “Higher annual and peak discharges have increased stream scouring potential and sediment transport capacity, leading to extensive channel incision." Raymond et al. (2008), through analysis of a 100-year data set from the Mississippi River, found that over the past 50 years the "…increase in bicarbonate and water flux is caused mainly by an increase in discharge from agricultural watersheds that has not been balanced by a rise in precipitation…" The results of streamflow responses in the LqP watershed suggest similar channel responses may be present in the SF LqP watershed and led to the examination of channel morphology described in the following chapter.

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Chapter 4: Changes in Stream Channel Morphology over a 37-Year Time Frame on the South Fork Lac qui Parle River, MN.

This research investigates the change in stream channel morphology and the corresponding changes in land use over a 37-year time frame between 1965/66 and 2002/03. Historical data were obtained from a US Army Corps of Engineers (CoE) flood control study of the South Fork Lac qui Parle (SF LqP) River. Sixty-three cross-section sites were re-surveyed and evaluated to determine the change in channel form between 1965/66 and 2002/03. Current channel morphology was assessed through a second year of data collection. Thirty-five sites were chosen to characterize the present channel morphology based on a Level-II Rosgen Classification. Results indicate the SF LqP River has increased its cross-sectional area and slope through channel incision. The analysis has shown that channel morphology has changed between 1965/66 and 2002/03 on the SF LqP River.

Significant changes in channel cross-sectional area, mean depth, maximum depth, and W/D ratio were noted in the Middle and Upper watersheds. Mean depth increased 0.7-ft in the Middle watershed and 0.8-ft in the Upper watershed. W/D results indicate the channel down-cut between 1965/66 and 2002/03 in the Middle and Upper watersheds, although no change in channel width was noted, channel depth (mean and maximum) increased significantly. Overall, mean channel cross-sectional area increased 7-precent from 451.5 to 483.3 (ft^2) throughout the study reach. While changes in the Lower watershed were less than significant, mean channel cross-sectional area increased from 287.6 to 329.0 (ft^2) in the Middle watershed (P = 0.018) and from 112.0 to 145.6 (ft^2) in the Upper watershed (P = .0007) representing a 14 and 30-percent increase in the Middle and Upper watersheds and corresponding to a channel enlargement ratio (CER) of 1.02 – 1.30. Combined impacts from cultivation and drainage produce a CER of 2.32 – 2.6. Similar increases were noted for Q_{peak} (1.30 – 1.35). These CERs correspond to similar values developed for storm sewered streets (urbanization). All changes were significant at the 95-% confidence level (α = 0.05).

Results indicate agricultural drainage (surface and sub-surface) has the same impact on stream channel morphology as the installation of storm sewers associated with urbanization. The application of the channel evolution model (CEM) suggests the SF LqP River is unstable in the downstream portions of the Upper watershed, continuing into the Middle watershed. Land drainage was the major contributor with minor contributions from channel straightening and cattle grazing.

Key Words: channel morphology, Rosgen stream type, channel incision, bankfull, agricultural drainage, riparian corridor, grazing, channel evolution model (CEM), channel enlargement ratio (CER).

Introduction

Non-point source pollution (NPS) from the Upper Mississippi River Basin has been implicated as one of the principal causes for the expanding hypoxic zone that develops each spring and summer in the Gulf of Mexico (Rabalais et al., 1999). Agricultural practices in the upper Midwest have been cited as the major contributor to NPS pollution (Raymond et al., 2008; Schilling and Wolter, 2005; US-EPA, 1996). The Minnesota River Basin (MNRB) is the largest single contributor of sediment to the Mississippi River in the state of Minnesota. Row crop agriculture is the dominant land use within the MRB occurring on more than 90 percent of the landscape. Because most wetlands have been drained for agricultural purposes the number and amount of wetlands in the MRB have declined (Wilson, 2000). Greater than 80 % of the wetlands in the MRB have been drained since European settlement (Leach and Magner, 1992). Those that remain are either filling due to increased sedimentation rates, or have been adapted to function as modified retention basins by increasing their contributing area. The loss of wetlands, combined with the increase in agricultural drainage, has altered the hydrologic regime of the MRB resulting in unstable stream channels with active streambank erosion. Wetlands provide temporary storage of water on the landscape. Water is stored in a wetland and either slowly infiltrated to ground water resources, or evapotranspired back to the atmosphere. The drainage of wetlands, combined with the installation of agricultural tile, have short-circuited the hydrologic cycle.

The term agricultural drainage refers to both surface tile inlet and subsurface tile drainage. Subsurface tile drainage is a conduit (pipe) for removing excess water from within the soil profile (Fraser and Fleming, 2001). The pipe is made of fired clay, concrete, or more popularly, perforated corrugated plastic and is installed below the soil surface at predetermined depths and intervals based on a soil's physical properties. Surface tile inlets are drains installed at the soil surface and located in closed depressions (low spots) on the agricultural field where water generally ponds. The riser (drain) is connected directly to underground tile lines that drain to either a collection tank before discharging into receiving waters, or directly into receiving waters. The result is a quicker runoff response from precipitation events similar to those seen in urban and suburban landscapes due to hydromodification. Hydromodifications are activities that disturb natural flow patterns of surface water and groundwater and have been defined as "...activities which alter the geometry and physical characteristics of streams in such a way that flow patterns change" (US-EPA, 2006).

Knowledge of the hydromodifications from agricultural land use practices is essential to successful watershed restoration. Restoration of eroding stream channels is a component of a watershed-wide restoration plan and successful stream restoration depends upon a thorough understanding of the processes operating within the watershed to develop a stable channel design.

Several researchers have investigated the hydrologic impacts of agricultural drainage; however, most of this research has focused on the hydrologic impacts of agriculture since the early days of cultivation. Johnson and others (Johnson et al., 1980) investigated channel adjustments due to agricultural activities on a small stream in Oklahoma. They modeled historical discharge based on soil type, vegetative cover, climate, slope, and drainage area. They estimated peak runoff volumes increased 60% and stream channel width increased two to threefold over a thirty-year period from 1871–1899. Additionally, the authors note that nearly all channels in the lower basin were now entrenched due to an average of 3.5 feet of post-settlement alluvium (PSA). All impacts were attributed to land use changes from native prairies and woodlands to agriculture. Similar trends were reported for North Fish Creek in Wisconsin (Fitzpatrick et al., 1999) where agricultural practices, preceded by clear-cut logging, significantly altered the hydrologic and geomorphic conditions in the watershed. Streambed erosion of up to three meters produced a doubling in channel capacity in the upper main stem of

North Fish Creek. PSA depositional rates in the lower reaches are 4-6 times greater than pre-settlement rates. The authors concluded that current flood peaks might be double those expected under pre-settlement forest cover. Both studies document hydrologic changes due to changing land use practices (native vegetation to agriculture) since European settlement, but neither investigates the possible contributions due to agricultural drainage.

Most research investigating human induced changes to stream morphology has centered on the effects due to urbanization (Bledsoe and Watson, 2001; Booth, 1990, 1991; Brown, 1999; Caraco, 2000; Cianfrani et al., 2006a; Colosimo and Wilcock, 2007; Ebisemiju, 1989; Galster and Pazzaglia, 2007; Hammer, 1972; MacBride and Booth, 2005; Macrae and Rowney, 1992; May, 1998; Trimble, 1997). An investigation of the relationship between stream channel geometry and urbanization in the Maryland Piedmont indicates a direct correlation between the percent urbanization in a watershed and increased stream cross-sectional area, and stream depth (Brown, 1999). Watershed land use in the Brown study included agriculture, forest, urban, and golf courses. While he did collect stream cross-sectional data in a watershed dominated by agriculture, he did not investigate any relationships between specific agricultural land practices (drainage) and channel geometry.

Urbanization increases the amount of impervious surfaces within a watershed (Ferguson and Suckling, 1990; Hollis, 1975). The increased amount of impervious area coupled with the installation of a drainage network increases the amount of runoff generated from precipitation events and facilitates the movement of water off the landscape and into receiving waters. The quicker response to precipitation events increases peak flow magnitudes and reduces the time to concentration of the runoff event. This changes the streamflow regime for the watershed and results in increased peak flow magnitudes (Hammer, 1972; Hollis, 1975; Hollis and Luckett, 1976).

In their seminal work, Dunne and Leopold (1978) chronicled the effects of urbanization on channel morphology for a single stream over a seven-year period from 1967 to 1974. They surveyed monumented cross-sections on several arroyo channels in a small watershed prior to urban development and documented significant changes in stream morphology due to urbanization. Channel bed elevation dropped 1.8 feet and channel width narrowed 8–10 feet. Like Brown's research, Dunne and Leopold's work was carried out in a small watershed, less than 10 mi^2 in size and did not document the influence of any agricultural practice on channel geometry.

While most research within the MRB has focused on nutrient loading (Zucker and Brown, 1998), climate change (Magner and Steffen, 2000), and agricultural management practices (Anderson, 1998; Gupta et al., 2001; Mickelson, 2001; Taff, 1998; Zucker and Brown, 1998); three studies have investigated streambank and bluff erosion on the Blue Earth River, a main tributary to the MRB. The Blue Earth River and its tributaries are alluvial stream channels. Alluvial channels, by their nature, carry sediment. Their ability to carry sediment is termed their sediment load capacity and is determined by the delivery of sediment to the stream, the size and amount of the sediment particles, and the discharge of the stream (Leopold et al., 1964). Bauer used an erosion plot study to investigate streambank erosion and slumping along the Blue Earth River, MN (Bauer, 1998). Results were then combined with a digital elevation model (DEM) to estimate erosion rates. While Bauer's results were highly variable, he concluded that 36 to 84 percent of the suspended sediment in the Blue Earth River could be attributed to streambank and bluff erosion. A follow-up study by Sekely surveyed selected bluffs on the Blue Earth River to determine volumetric streambank erosion (Sekely et al., 2002). Results from the 3-year study were then analyzed to develop an annual erosion rate. Thoma (2005) utilized airborne laser altimetry to develop a digital elevation model of the Blue Earth River, its streambanks, and bluffs.

Both researchers concluded that streambank and bluff erosion accounted for a significant amount of the total suspended sediment load in the Blue Earth River. While these investigations have shown changes in streambank and bluff erosion, they failed to demonstrate a mechanism for the increased erosion. The studies are also limited in temporal data (3 years or less), and neither study investigated any relationship between the increased erosion rates and agricultural land use practices. If the sediment load of the Blue Earth River has increased, then a corresponding increase in stream power is required (Lane, 1955a, b; Leopold et al., 1964; Wolman and Miller, 1960). Furthermore, if the tributary is actively eroding its streambanks and bluffs, then the channel morphology of the Blue Earth River should show a corresponding adjustment (Booth, 1996; Montgomery and Buffington, 1998; Schumm, 1999; Smith and Smith, 1984; Thorne, 1999).

The use of drainage to improve agricultural land has steadily grown in the MRB. Advances in technology such as laser assisted installation and high quality plastic, saw this rate increase during the 1960s. In the thirteen year period between 1985 and 1998, the amount of agricultural land improved by drainage in the state of Minnesota doubled from twenty to forty percent (Zucker and Brown, 1998) or approximately 4.5 million acres of land (USDA-ERS, 1987). Of the 4.5 million acres, seventy-five percent (3.4 million acres) were drained for agricultural purposes.

Agriculture is the dominate land use in the Lac qui Parle (LqP) watershed, a tributary watershed to the Minnesota River, with over 79 percent of the watershed under cultivation (MRBJPB, 2001). A flood control survey was conducted by the U.S. Army Corp of Engineers (CoE) on the South Fork of the Lac qui Parle (SF LqP) River from 1965 through 1967. The study collected detailed data on the plan form, longitudinal profile, and cross-sectional geometry of the stream channel. The data from the CoE flood control survey, combined with the increased installation of agricultural drainage systems over the past forty years, provides the baseline data necessary to investigate the spatial and temporal changes in channel morphology in the SF LqP River watershed. Changes in channel morphology can then be compared to land use changes within the SF LqP watershed over the same time frame.

Previous chapters documented four key pre-existing conditions in the SF LqP watershed. First, portions of the riparian buffer have been converted from native, perennial vegetation to annual row crops. Second, the number of acres under cultivation has remained relatively steady since 1911. Third, the amount of land improved by drainage (surface and subsurface) has increased dramatically since 1972. And fourth, discharge generated from precipitation (Q/P ratio) has steadily increased since 1960 while precipitation has remained unchanged. If the amount of discharge generated from precipitation has indeed increased, then according to Lane's Balance (Figure 4.1), there should be a corresponding adjustment in channel morphology (Lane, 1955a, b). This research will investigate the spatial and temporal changes in channel morphology in the SF LqP River over a thirty-six year period between 1965 and 2002. Results will be compared to land use changes over the same time frame to infer a mechanism for the change. Land use changes investigated include: change in crop diversity, change in riparian vegetation within the 100-yr floodplain, installation of subsurface drainage, and the installation of surface tile inlets.

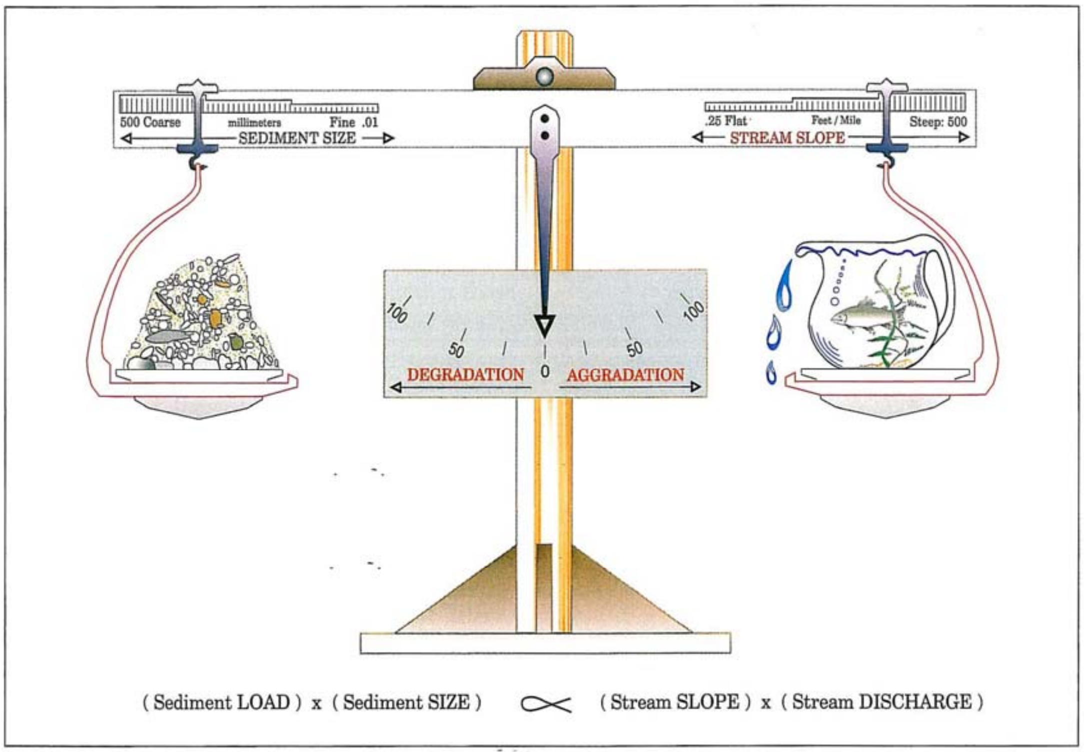

Figure 4.1. Lane's balance for alluvial channels illustrating influence of sediment load, sediment size, stream slope, and stream discharge on channel erosion (degradation) and deposition (aggradation) after Lane, 1955 (Rosgen and Silvey, 1996).

Objectives

The overall objective of this research is to determine changes in the channel morphology of the SF LqP River over a thirty-six year period. Specific objective are:

1. Determine the channel metrics for representative cross-sections on the SF LqP River from the 1965-67 CoE flood control survey.

2. Determine cross-section endpoint coordinates for the representative CoE cross-sections from the 1965-67 CoE flood control survey on the SF LqP River.
3. Determine the channel metrics for the re-surveyed CoE cross-sections
4. Determine spatial and temporal changes in channel geometry across a range of watershed sizes for the SF LqP River.
5. Identify relationships between channel morphology and land use within the SF LqP watershed.
6. Make suggestions for a sustainable watershed restoration plan for the SF LqP watershed that promotes channel stability, floodplain interaction, and healthy riparian zones.

Hypotheses

1. The entrenchment ratio of the SF LqP watershed has decreased over a thirty-six year period.
2. The width-to-depth ratio of the SF LqP River has decreased between 1965-67 to 2002 on the SF LqP River.
3. The channel cross-sectional area of the SF LqP River watershed has increased between 1965-67 and 2002.

Project Study Area

The Lac Qui Parle River watershed is one of the western-most tributary watersheds to the MRB (Figure 4.2). It is contained within Lac Qui Parle, Lincoln, and Yellow Medicine counties, Minnesota, and a small portion of northeastern South Dakota. Its watershed is approximately 614,398 acres (960 mi^2) in size, 487,336 of which are located in Minnesota. The watershed is subdivided into 78 minor watersheds that range in size from 2,844 acres to 32,090 (MRBJPB, 2001). Agriculture is the predominant land use within the watershed with seventy-nine percent under agricultural practices. Soils are derived from Blue Earth Tills (78 %) and the Ivanhoe-Worthington Coteau (22 %) with ninety-six percent located on slopes greater than 6 %. One third of these soils are classified as poorly drained. Annual precipitation across the basin ranges from 22 – 26 inches (Mallawatantri, 1999). The drainage network is defined by the Lac qui Parle

River and its tributaries, public and private drainage systems, lakes, and wetlands. The Lac qui Parle River flows to its confluence with the Minnesota River above Lac Qui Parle Dam in Lac qui Parle County. The total distance of the stream network within Minnesota is 1,434 miles of which 1,052 miles are intermittent streams and 382 miles are perennial streams.

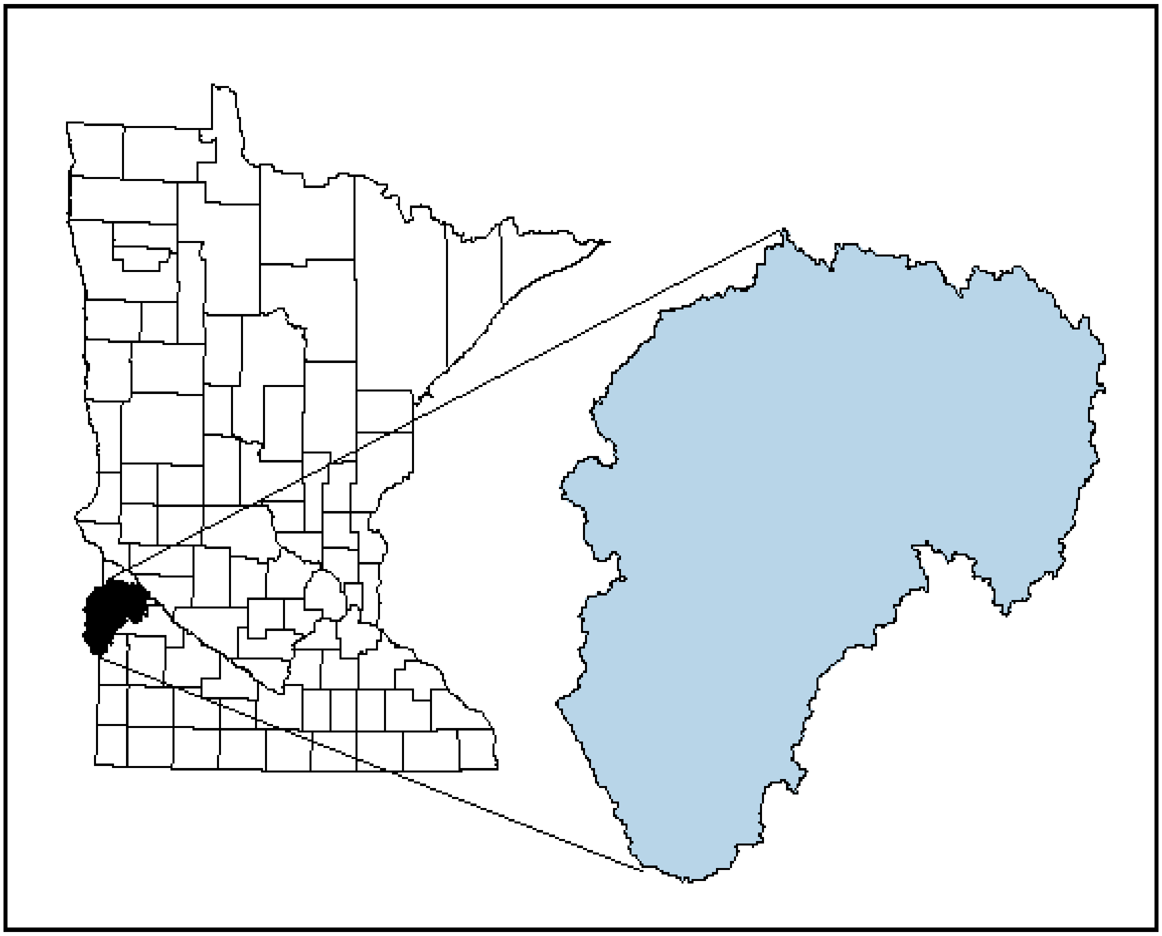

Figure 4.2. Location of Lac qui Parle Watershed, MN.

Field Site Location

Historic CoE cross-section locations were delineated on the CoE flood control alignment maps with a line drawn across the stream, perpendicular to stream flow, and labeled with the corresponding CoE cross-section number (Figure 4.3). Flood control cross-section drawings locate each cross-section by river mile. Elevations were delineated in feet above sea level. The width of each cross-section line on the map represents an actual distance on the surface of the earth. A sampling of 10 CoE cross-section lines produced an average line width equal to 13.3 m (43.6 ft) in real-world distance. Field location for each cross-section was determined by delineating an area defined by four coordinates, two each on the right and left streambanks:

- one at the upstream intersection of the cross-section line and streambank line
- one at the downstream intersection of the cross-section line and the streambank line

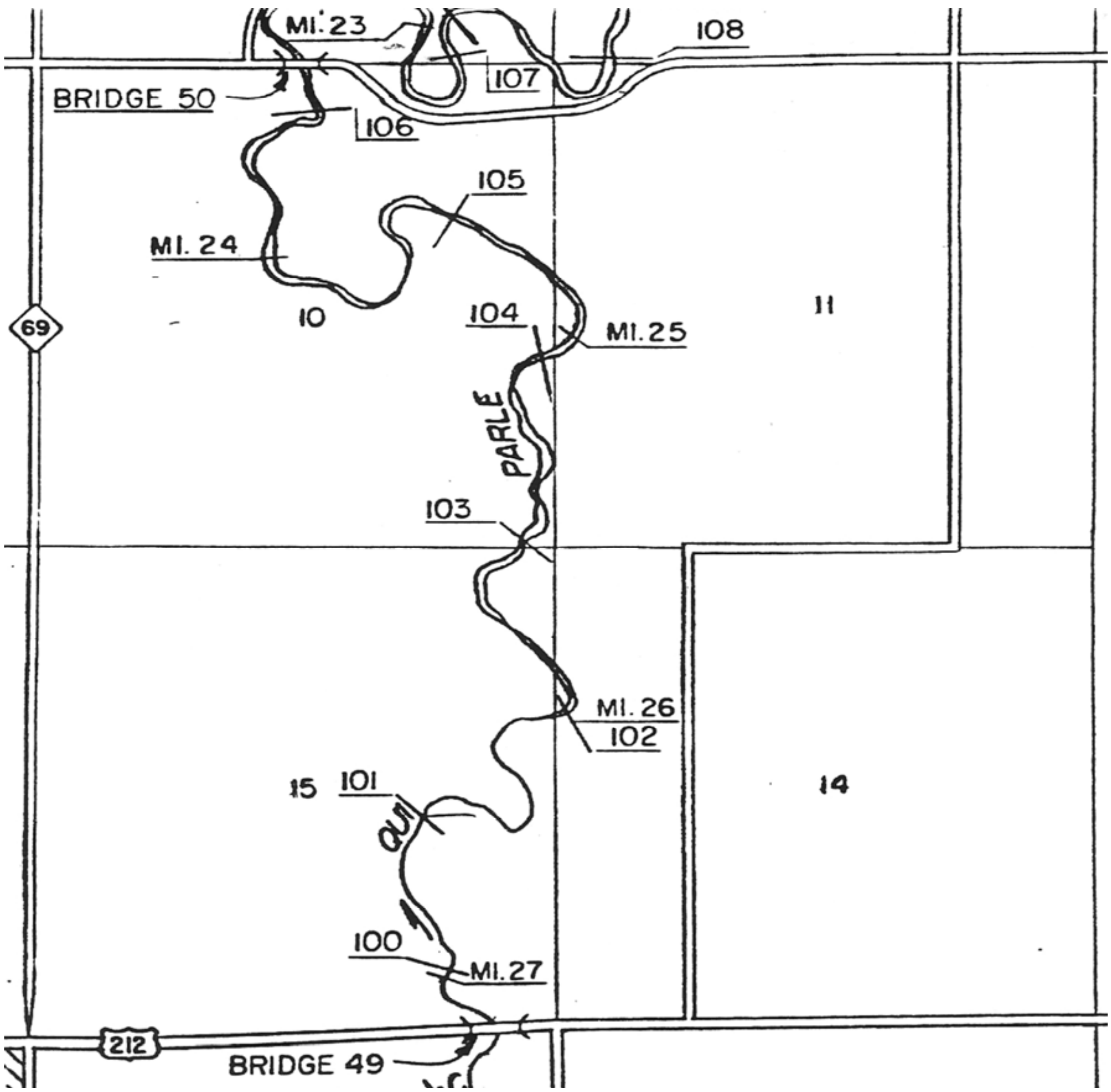

Figure 4.3. Historical CoE flood control map for SF LqP River illustrating the river mile location and delineation of cross-sections 100 – 108.

The coordinates were then marked (staked) along the streambank at the corresponding field site. From this “window” the cross-section location was determined based on:

1. Accessibility
2. Presence and location of a riffle morphology
3. A straight segment between the limits of the coordinates.

Methods

Sample Size

Two separate analyses were performed in this study. The first analysis investigated the change in channel geometry between 1965/66 and 2002/03 at specific CoE cross-section sites. The second analysis investigated the current morphological condition of the SF LqP River. Each analysis utilized a different data set and sample size. In each analysis the SF LqP data set was stratified according to drainage area. Three natural breaks in drainage area exist within the watershed (Table 4.1). Sixty-three cross-sections were evaluated to determine changes in channel geometry from 1965/66 to 2002/03. Thirty-five cross-sections were surveyed to determine the current morphological condition on the SF LqP River.

Table 4.1. Sample size distribution based on three natural breaks in drainage area.

Cross-Sections	Drainage Area (mi^2)	Sample Size (n) 1965/66 Re-survey	Sample Size (n) Current Morphology	Sub-Watershed
1 – 48	156.1 – 318.6	23	13	Upper
49 – 97	318.6 – 871.9	22	13	Middle
98 – 136	871.9 – 960.4	18	9	Lower

Image Rectification

Historic CoE flood control maps were constructed from previous CoE maps and aerial photographs. These maps express locations in the Township/Range (T/R) coordinate system. In order to re-occupy historical CoE cross-sections it was necessary to establish real world coordinates for the CoE flood control maps. The procedure involved the following steps:

1. Image (flood control map) was scanned and imported into ArcView™.
2. Once imported the image was rectified through use of the ArcView™ "align" tool. This tool matched scanned CoE map images with corresponding images from a geo-referenced digital orthoquandrangle (DOQ) and assigned coordinates to the CoE flood control maps.
3. Coordinates for each CoE cross-section were then obtained for each cross-section on the CoE flood control maps.

Channel Metrics

Historic Conditions of the LqP River from 1965/66 CoE Cross-Sections

Evaluation of historical stream channel morphology was completed through an analysis of the 1965/66 CoE flood control study. Data regarding the dimension, pattern, and profile (channel cross-section, sinuosity, and longitudinal profile) for surveyed cross-sections were catalogued into a relational data set (spreadsheet). Rosgen stream type morphologies were delineated for each surveyed cross-section based on the slope, channel materials, width/depth ratio, sinuosity, and entrenchment ratio (Rosgen, 1994). This level of data collection describes the existing morphology (dimension, pattern, profile, and materials) of the channel at each cross-section. This level of description however, may not necessarily represent a stable form or describe the potential of the stream (Rosgen, 1996).

Historic CoE cross-sections were collected on both straight and curved (bends) reaches along the SF LqP River. Stream bends represent areas of outer bank erosion and inner bank deposition and therefore were not included in the sample data set. After inventorying the 1965/66 CoE alignment drawings, 63 cross-sections were identified as representing possible locations of relatively straight reaches on the SF LqP River. Each site was then field verified to determine suitability as a cross-section survey site. Data for each cross-section were compiled in the spreadsheet program "RiverMorph Stream Restoration Software©, V3.1" (Athanasakes, 2004) and the "Reference Reach Spreadsheet©, V1.3" (Mecklenburg, 1999). These programs have pre-defined forms (macros) which compile, and evaluate, stream channel data. Program output includes a suite of data such as: width/depth ratio (W/D), entrenchment ratio (ER), bankfull cross-sectional area ($Area_{bkf}$), bankfull width (W_{bkf}), average depth (d_{mean}), maximum depth (d_{max}), flood prone width (W_{fp}), wetted perimeter (WP), and hydraulic radius (HR). These values were used to determine the Level-II Rosgen stream classification for each cross-section.

Present-Day Conditions of CoE Cross-Sections

Present-day morphologic conditions were determined by re-surveying historic CoE cross-sections and collecting the appropriate field data. Channel measurements were made with a TOPCON RL-H self-leveling, rotating laser with audio receiving rod after methods described by Harrelson (Harrelson et al., 1994). Particle size distributions were determined at each cross-section according to procedures outlined by Bevenger and King (Bevenger and King, 1995). Cross-section coordinates were collected with a Garmin, hand-held GPS unit. Elevation coordinates for each cross-section were determined with a survey-grade GPS using a Trimble Real-Time Kinematic (RTK) Global Positioning System (GPS) capable of achieving sub-centimeter results horizontally with a vertical component half as accurate.

Assessment of Change from 1965/66 to 2002/03

Historic CoE cross-section data are expressed in real-world elevations as feet above sea level (fasl). The survey grade GPS provided real-world elevation coordinates necessary to investigate changes in stream cross-sectional area. Before and after data sets were developed for channel cross-sectional area, channel width, mean channel depth, maximum channel depth, and W/D. Absolute change in cross-sectional area was calculated by matching channel bank features from the 1965/66 CoE cross-section survey with those from the 2002/03 survey (Figure 4.4). Results were statistically analyzed to determine any significant change in channel metrics. Differences between 1965/66 and 2002/03 were calculated and assessed to quantify the direction and magnitude of change over time. Negative values indicate a decrease in channel area or W/D from 1965/66 to 2002/03; positive values indicate an increase.

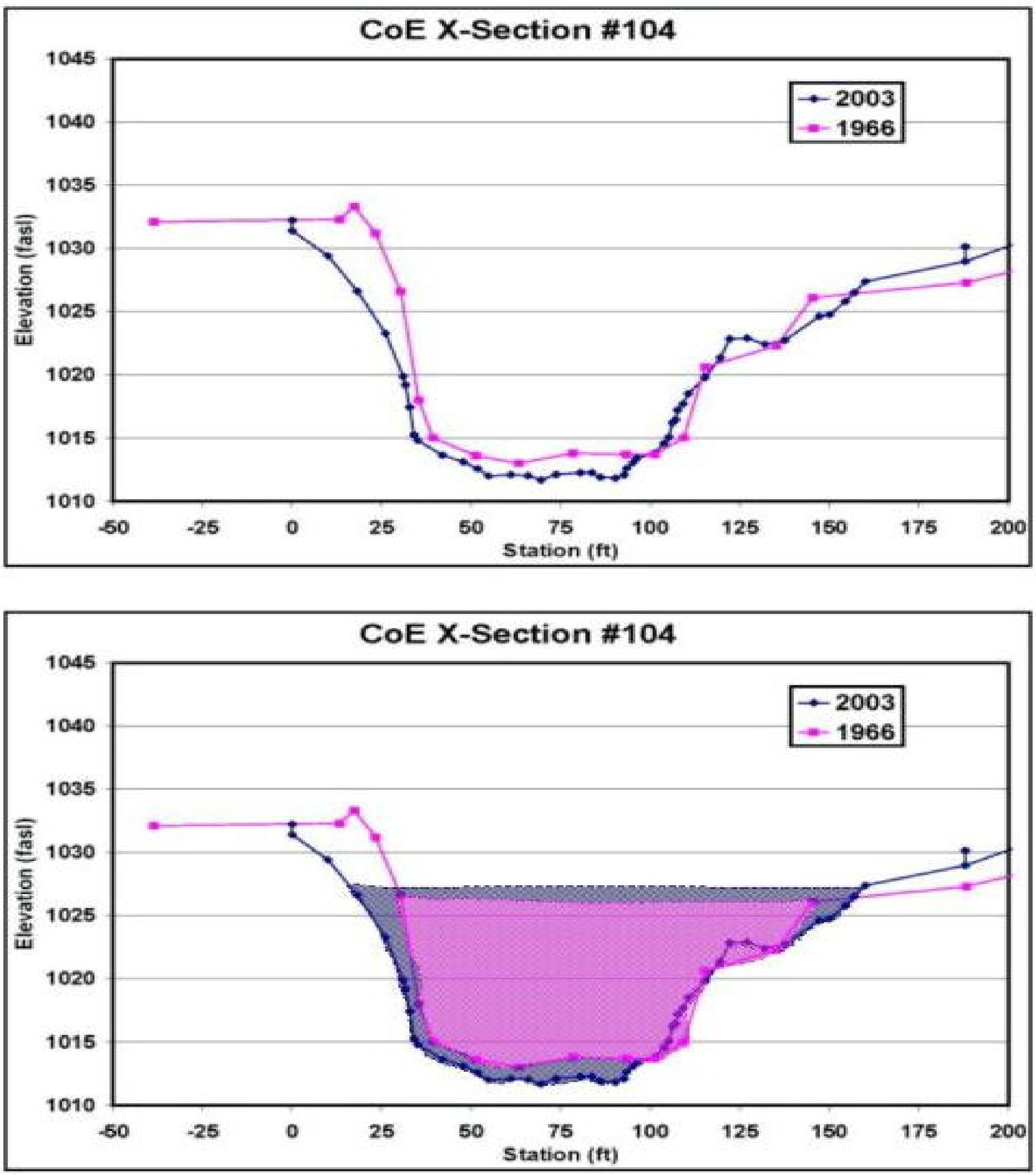

Figure 4.4. CoE cross-section #104 illustrating changes in channel area from 1966 (pink squares) to 2003 (blue diamonds).

Statistical Difference

Temporal differences in channel metrics were determined at the 95% confidence interval (CI) through a paired sample t-test of the means. The null hypothesis assumes the average difference between the means of the two data sets (1965/66 and 2002/3) equals zero:

H_o = no significant difference between the means.

Current Channel Morphology and Relative Equilibrium

Present-day channel morphology was assessed through an evaluation of representative cross-sections from each watershed (Upper, Middle and Lower). Because streams are dynamic systems, changes in channel morphology are best determined at the location of stable channel morphologies. Riffle morphology has been shown to be the most stable channel morphology over time (Clinton et al., 1999; Harrelson et al., 1994; Leopold et al., 1964; Rosgen, 1996). Because the location of the 1965/66 CoE cross-sections was random, they corresponded to a variety of channel morphologies (pools, riffle, runs). Seven (7) of the original 1965/66 CoE cross-sections correspond with riffle channel morphology. Of these, three are located in the lower watershed and two each in the Middle and Upper watersheds. Twenty-nine (29) additional riffle cross-section sites were identified during data collection in the first year of survey work. This resulted in a total of thirty-five (35) representative riffle cross-sections (13-Upper, 13-Middle, and 9-Lower) to evaluate the current morphological conditions on the SF LqP River. Each new site was identified by the nearest CoE cross-section along with a designation of its relative location to the nearest CoE cross-section (u = upstream, d = downstream). For example, a representative riffle site immediately downstream of the 1965/66 CoE cross-section #72 would be identified as XS-72d. Each reference cross-section site was evaluated to determine the channel cross-sectional geometry, longitudinal profile, and particle size distribution (Rosgen Level-II evaluation).

Results

<u>Assessment of Change from 1965/66 to 2002/03 – Resurvey of CoE Cross-Sections</u>

Analysis of 63 cross-sections indicates a significant change in channel morphology over the 37-year time frame between the 1965/66 CoE survey and the 2002/03 re-survey. The majority of the morphological changes occurred in the Middle and Upper sub-watersheds with minor changes occurring in the Lower sub-watershed.

<u>Cross-Sectional Area</u>

Overall, mean channel cross-sectional area increased 7-precent from 451.5 to 483.3 (ft^2) throughout the study reach. Channel cross-sectional area increased at 43 sites and decreased at 20 sites. The overall increase in mean channel cross-sectional area is significant at the 95% CI (P = 0.047). While these increases are significant, results from sub-watersheds varied. No significant change was noted in the Lower watershed, although mean channel cross-sectional area appeared to increase from 1085.2 to 1103.2 (ft^2). While changes in the Lower watershed were less than significant, increases in mean channel cross-sectional area were significantly different in the Middle and Upper watersheds (Table 4.2). Mean cross-sectional area increased from 287.6 to 329.0 (ft^2) in the Middle watershed (P = 0.018) and from 112.0 to 145.6 (ft^2) in the Upper watershed (P = .0007).

Table 4.2. Number, direction of change, and mean channel cross-sectional area for each sub-watershed on the SF LqP River. Percent change values in bold are significant at the 95% level of confidence.

Sub-Watershed	Number Increased	Number Decreased	Area 1965/66 (ft^2)	Area 2002/03 (ft^2)	% change
Upper	18	5	112.0	145.6	**30**
Middle	16	6	287.6	329.0	**14**
Lower	9	9	1085.2	1103.2	2
Total	43	20			
Overall			451.5	483.3	

While analysis of channel cross-sectional area indicates an increasing trend from 1965/66 to 2002/03, the results do not indicate whether the increase is in width, depth or both. Analysis of the W/D over this time period may provide further insight.

Width-Depth Ratio (W/D)

The width/depth (W/D) ratio represents the relationship between overall channel width and the mean channel depth. It describes the shape of the channel cross-section, can provide insight into channel stability (Rosgen and Silvey, 1996), and is the most commonly used index of channel shape (Knighton, 1998). Analysis of the mean W/D at the 63 sites (Table 4.3) indicates the overall W/D declined an average 11.4 percent from 16.7 to 14.9 (P = .054). Thirty-eight sites experienced a decrease while twenty-five sites increased their W/D. The Upper watershed W/D declined from 18.0 to 14.6. While this result was not significant at the 95-% CI it was at the 90-% CI (P = .056). The W/D in the Middle watershed declined from 15.6 to 13.0 (P = .011). The Lower watershed actually experienced an increase in the mean W/D from 16.0 to 17.6 (P = 0.054 @ 95-% CI).

Table 4.3. Number, direction of change, and mean W/D for each sub-watershed on the SF LqP River.

Sub-Watershed	Number Increased	Number Decreased	W/D 1965/66	W/D 2002/03
Upper	9	14	18.0	14.6
Middle	5	17	15.6	13.0
Lower	11	7	16.0	17.6
Total	25	38		
Overall			16.6	14.9

Direction of change in the W/D ratios indicates that channel width is narrowing and channel depth is increasing in the Middle and Upper watersheds while the Lower watershed is experiencing the opposite trend. Because the W/D ratio is a proportion that describes the relative relationship between channel width and channel depth, it is possible that the channel width and depth actually increased between 1965/66 and 2002/03. A separate analysis of channel width and depth is required in order to determine the absolute change in channel geometry. This analysis may provide insight into the direction and magnitude of change in both metrics.

Channel Width (W)

While more sites experienced an increase than a decrease in mean channel width, there was no significant change in mean channel width throughout the study reach. Mean channel width increased 0.7 ft from 75.5 to 76.2 ft between 1965/66 and 2002/03 (Table 4.4) but the changes were not significant (P = .745). Sub-watershed values were similar with increases of 2.4 and 0.3 ft in the Lower and Upper watersheds respectively, and a 1.7 decrease in mean channel width on the Middle watershed. While the number of increases in mean channel width was greater than the number of decreases by 10-percent, the increase in mean channel width essentially equaled the decrease in mean channel width (+14.0 ft to -14.8 ft respectively), therefore mean channel width was essentially unchanged.

Table 4.4. Number, direction of change, and mean channel width (W) for each sub-watershed on the SF LqP River.

Sub-Watershed	Number Increased	Number Decreased	Width 1965/66 (ft)	Width 2002/03 (ft)
Upper	12	11	43.8	44.1
Middle	11	11	65.9	64.2
Lower	10	8	127.6	132.0
Total	34	29		
Overall			75.5	76.2

These results suggest the increases in channel cross-sectional area and decreases in W/D are the result of an increase in channel depth.

Mean Channel Depth (D_{mean})

Mean channel depth was significantly greater at 77-percent of the sites throughout the study reach. Mean channel depth increased at 43 sites and decreased at 19 sites. From 1965/66 to 2002/03, overall mean channel depth increased from 4.8 to 5.3 ft ($P = .0004$). Similar outcomes were seen in the sub-watersheds but the results were mixed. There was virtually no change in the D_{mean} in the Lower watershed from 1965-66 to 2002/03 ($P = .926$). Additionally, the number of increases equaled the number of decreases (Table 4.5) and the D_{mean} remained unchanged at 8.2 ft. Results were more noticeable in the Middle and Upper watersheds where 73-precent of the sites in the Middle and 86-precent of the sites in the Upper experienced an increase in the D_{mean}. Mean depth increased 0.8 ft ($P = .0004$) in the Middle watershed and 0.7 ft ($P = .0002$) in the Upper watershed.

Table 4.5. Number, direction of change, and mean channel depth (D_{mean}) for each sub-watershed on the SF LqP River.

Sub-Watershed	Number Increased	Number Decreased	D_{mean} 1965/66 (ft)	D_{mean} 2002/03 (ft)
Upper	19	3	2.6	3.3
Middle	16	6	4.2	5.0
Lower	8	10	8.2	8.2
Total	45	17		
Overall			4.8	5.3

Maximum Channel Depth (D_{max})

Similar trends were evident in the maximum channel depth with 69-precent of all sites experiencing an increase (Table 4.6). The overall mean D_{max} increased 0.5 ft from 7.4 ft to 7.9 ft ($P = .006$) between 1965/66 to 2002/03. Sub-watershed increases were comparable with 61-percent in the Lower, 67-precent in the Middle, and 77-percent in the Upper. However, while all three sub-watersheds experienced increases, only the Middle and Upper increases were significant with P-values of .019 and .002 respectively.

Table 4.6. Number, direction of change, and maximum channel depth (D_{max}) for each sub-watershed on the SF LqP River.

Sub-Watershed	Number Increased	Number Decreased	D_{max} 1965/66 (ft)	D_{max} 2002/03 (ft)
Upper	17	5	4.6	5.4
Middle	14	7	6.6	7.4
Lower	11	7	11.8	11.7
Total	42	19		
Overall			7.4	7.9

Collectively these results reveal a channel-deepening trend in the Middle and Upper watersheds and no significant change in channel geometry in the Lower watershed. This trend is illustrated in Figure 4.5 with a plot of the Δ channel width and Δ D_{max} throughout the study reach.

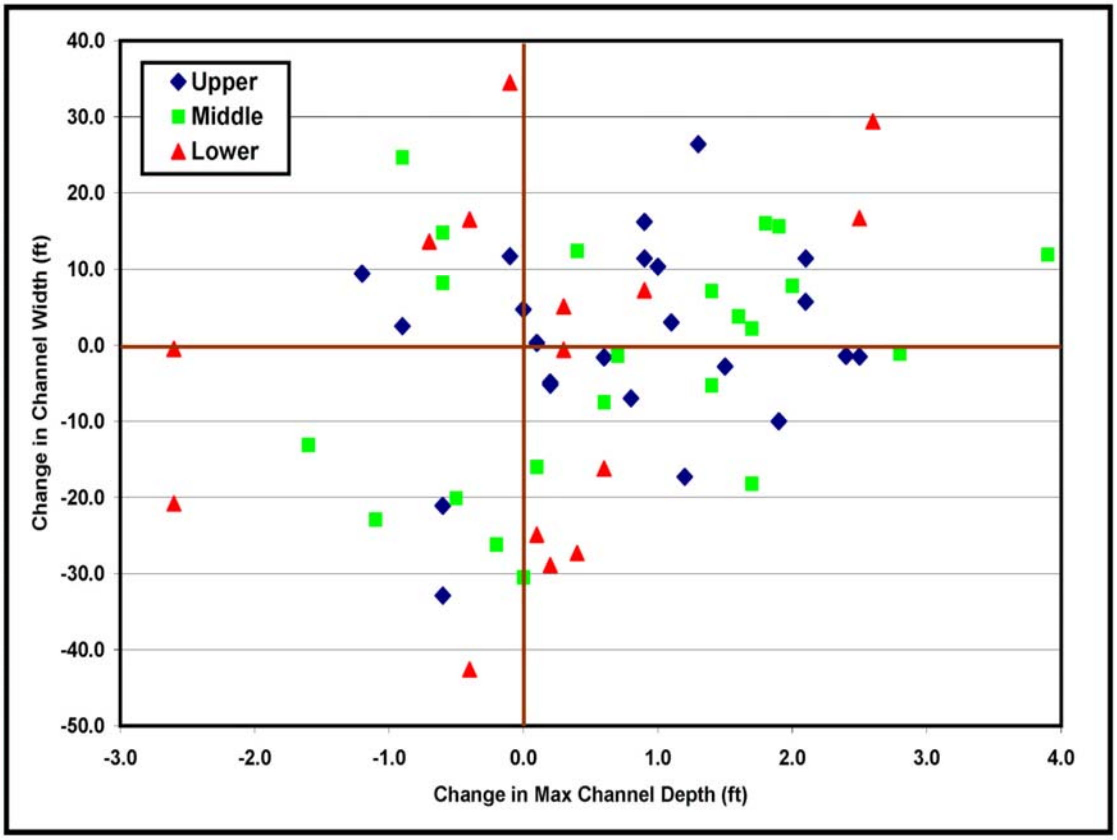

Figure 4.5. Change in channel width and maximum channel depth (D_{max}) from 1965/66 to 2002/03 along the SF Lac qui Parle River.

The plot clearly suggests a channel-deepening trend with 42 sites experiencing an increase in mean channel depth and only 19 declining. Sites experiencing channel widening are nearly offset by those experiencing channel narrowing with 33 and 30 occurrences respectively. Some of the larger increases in maximum channel depth were measured at cross-sections #40 and #66 with increases of 2.5-ft and 3.9-ft respectively.

Overall, the SF LqP River experienced increases in the mean channel cross-sectional area, D_{mean}, and D_{max}; and a decrease in the W/D (Table 4.7). While the Lower watershed did experience similar trends, only changes measured in the Middle and Upper watersheds were significant.

Table 4.7. Amount of significant change in channel morphology measured throughout the study reach and within individual sub-watersheds. Crosshatched areas indicate changes were not significant at the 95% confidence interval.

Sub-Watershed	Area (ft^2)	W/D	Width (ft)	D_{mean} (ft)	D_{max} (ft)
Lower					
Middle	+41.4	-2.6		+0.8	+0.8
Upper	+33.6	-3.4		+0.7	+0.8
Overall	+31.9			+0.5	+0.5

Current Channel Morphology and Relative Equilibrium – 2003 Survey

Channel geometry was assessed at 35 sites during the summer of 2003. Results indicate the SF LqP River exhibits the expected trends in channel morphology but with differing degrees of variability (σ) (Figures 4.6 – 4.8). As expected, channel cross-sectional area ($Area_{bkf}$) increases in a downstream direction due to larger discharge associated with increased watershed size (Dunne and Leopold, 1978; Knighton, 1998; Schumm, 1977; Wolman and Miller, 1960). Bankfull cross-sectional area increases at a moderate rate of 1.6 (ft^2/mi) in the Upper watershed with values ranging from 44 up to 106 ft^2. This rate increases to 6.2 and 6.0 (ft^2/mi) in the Middle and Lower watersheds respectively (Table 4.8). While the rate of cross-sectional area increased 4.6 (ft^2/mi), σ jumped from 17 ft^2 in the Upper Watershed to 71 ft^2 in the Middle and Lower watersheds. The trend is slightly different for bankfull width.

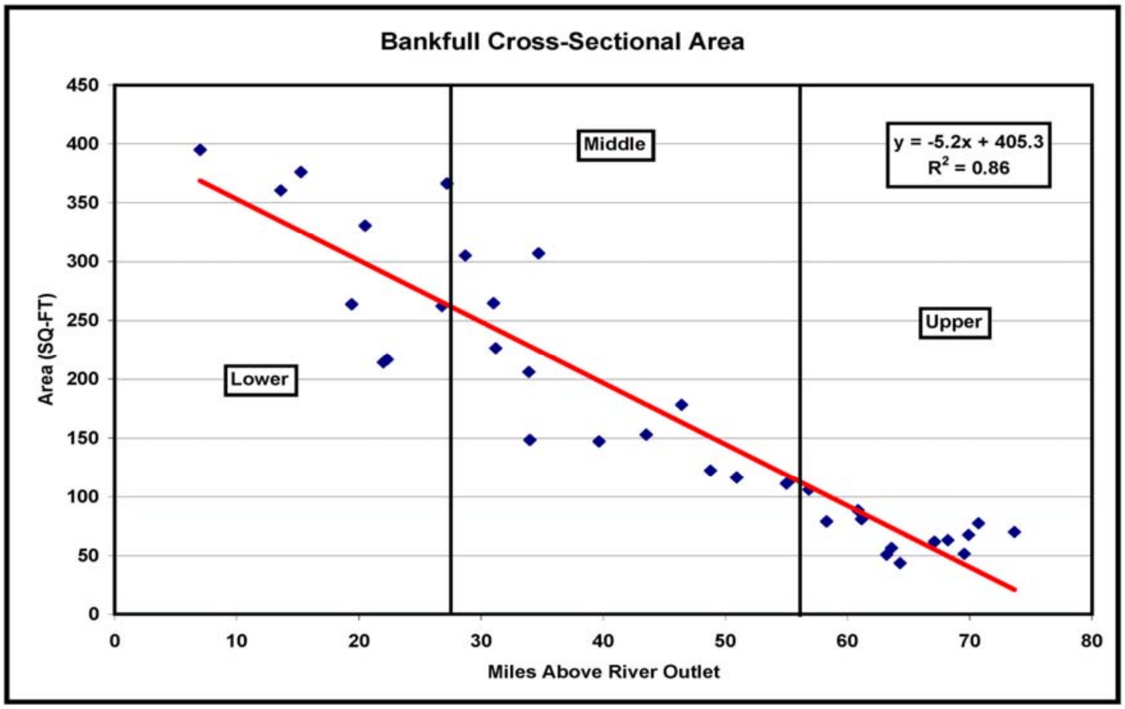

Figure 4.6. Plot illustrating the trend and variability in the cross-sectional area at bankfull stage on the SF LqP River from the channel mouth to 80 miles upstream.

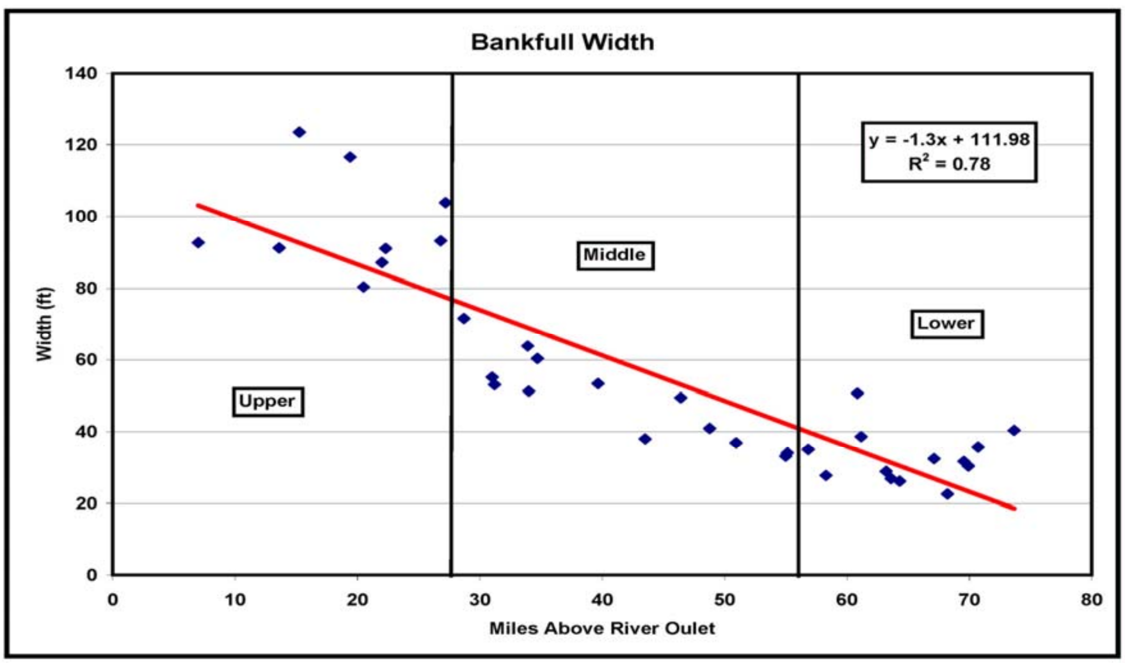

Figure 4.7. Plot illustrating the trend and variability in the channel width at bankfull stage on the SF LqP River from the channel mouth to 80 miles upstream.

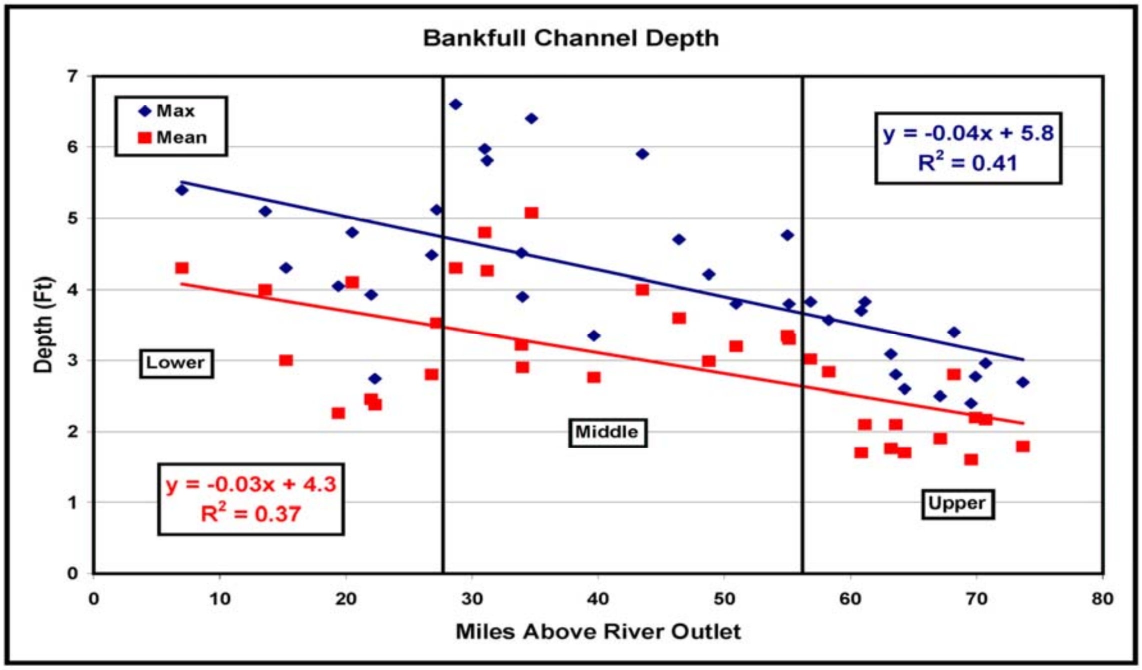

Figure 4.8. Plot illustrating the trend and variability in the mean and maximum channel depth at bankfull stage on the SF LqP River from the channel mouth to 80 miles upstream.

Table 4.8. Mean values, rate of change, and variability for channel metrics on the Upper, Middle and Lower sections of the SF LqP River.

Sub-Watershed	$Area_{bkf}$			W_{bkf}			D_{max}			D_{mean}		
	Mean (ft^2)	Rate (ft^2/mi)	σ (ft^2)	Mean (ft)	Rate (ft/mi)	σ (ft)	Mean (ft)	Rate (ft/mi)	σ (ft)	Mean (ft)	Rate (ft/mi)	σ (ft)
Upper	68.9	1.6	17.3	32.9	0.1	14.1	3.1	0.1	0.5	2.1	0.04	0.5
Middle	184.4	6.2	71.0	49.3	1.1	12.1	4.9	0.1	1.1	3.7	0.04	0.7
Lower	309.5	6.0	71.0	97.7	0.2	7.4	4.4	0.1	0.8	3.2	0.06	0.8

The plot of bankfull width (Figure 4.7) indicates the Middle watershed experiences the greatest rate of increase per stream mile while the Upper and Lower watersheds experience relatively lower rates of increase. The rate of increase in bankfull width for the Middle watershed is 1.1 (ft/mi) with σ = 12.1 (ft/mi). This is contrasted by rates of 0.1 and 0.2 (ft/mi) in the Upper and Lower watersheds, and σ of 14.1 (ft/mi) and 7.4 (ft/mi) respectively. As illustrated in Figure 4.7, channel width is quite variable in the Upper watershed, and then again in the downstream portion of the Middle watershed that carries over into the Lower watershed. The rapid increase in channel width in the downstream portion of the Middle watershed is most probably the result of the increased watershed size associated with the confluence of the West and South Forks of the Lac qui Parle River at Dawson, MN, that marks the boundary between the Middle and Lower watersheds.

Overall, channel depth increases with increasing distance downstream (Figure 4.8), but sub-watershed values suggest a different pattern. Mean depth (D_{mean}) varies from 2.1-ft in the Upper watershed to 3.7-ft in the Middle watershed. However, the Lower watershed value of 3.1-ft is 0.6-ft less than the Middle watershed value. Variability increases downstream in the three watersheds with σ equal to 0.5, 0.7, and 0.8 for Upper, Middle and Lower watersheds respectively. Results for the maximum depth (D_{max}) are similar with values of 3.1-ft, 4.9-ft, and 4.1-ft for the Upper, Middle and Lower watersheds respectively. Variability is greatest in the Middle watershed with σ equal to 1.1-ft followed by σ values of 0.5 and 0.8 for the Upper and Lower watersheds respectively.

<u>Particle Size Distribution</u>

While particle data indicates an overall pattern of increasing particle size in a downstream direction; the Upper and a portion of the Middle watersheds are characterized by fines (Figure 4.9). Cross-sections 9 thru 63 have d_{50} and d_{84} values less than 10 mm. This is contrasted by a mean d_{50} of 11.1 mm and mean d_{84} of 35.2 mm for cross-sections 66 thru 136.

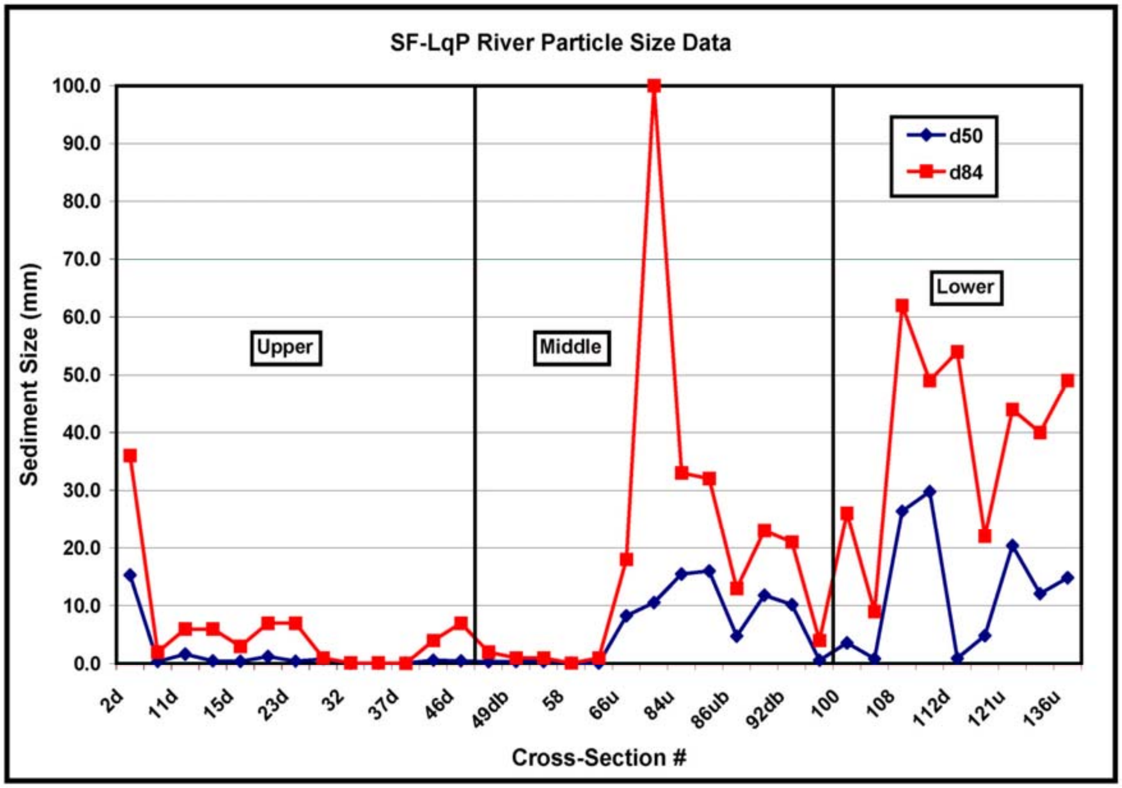

Figure 4.9 Plot of the d_{50} and d_{84} for all cross-sections on the SF LqP River.

Upper Watershed

Channel morphology in the Upper watershed is dominated by B and C channel types with a few E and F channels (Figure 4.10). B channels are moderately entrenched with width-to-depth (W/D) ratios > 12, and channel slopes between 2 - 4% (Rosgen, 1996). C channels are slightly entrenched with W/D ratios > 12, and channel slopes < 0.02-percent. E channels are characterized by very low entrenchment (ER > 2.2), low W/D ratios, and channel slopes < 0.02-percent. F channels are deeply entrenched (ER < 1.4) with W/D > 12, and channel slopes < 0.02. Channel entrenchment indicates the degree of vertical containment of a river. The entrenchment ratio (ER) is defined as the floodprone width divided by the bankfull width (W_{fp}/W_{bkf}). The flood prone width is measured at an elevation equal to twice the maximum bankfull channel depth. Streams with ER > 2.2 have well developed floodplains and are able to convey flood flows (Rosgen, 1994). Channels with ER ≤ 2.2 are vertically constrained (entrenched) and the flood prone width more closely resembles the bankfull width.

Basin	*n*	*n*	XS#	River Mile From MNR (mi)	Cross-Sectional Area (ft^2)	W_{bkf} (ft)	d_{max} (ft)	d_{mean} (ft)	W_{fp} (ft)	ER	W/D	Sinuosity (k)	Slope %	d_{50} (mm)	d_{84} (mm)	Rosgen Stream Type
Upper	1	1	2 d	73.7	70.0	40.4	2.7	1.8	182.3	4.5	22.6	1.5	0.08	15.30	36.00	C4c
	2	2	9 d	70.7	77.5	35.7	3.0	2.2	200.0	5.6	16.5	1.2	0.11	0.37	2.00	C5
	3	3	11 d	69.9	67.6	30.4	2.8	2.2	350.0	11.5	13.8	0.8	0.08	1.64	6.00	C5c-
	4	4	12 u	69.6	51.5	31.7	2.4	1.6	95.1	3.0	19.8	1.4	0.01	0.49	6.00	C5c
	5	5	15 d	68.2	63.0	22.6	3.4	2.8	44.2	2.0	8.1	1.5	0.04	0.41	3.00	B5c
	6	6	17 d	67.1	61.7	32.5	2.5	1.9	37.5	1.2	17.1	1.5	0.08	1.25	7.00	F5
	7	7	23 d	64.3	43.7	26.2	2.6	1.7	40.4	1.5	15.4	1.6	0.08	0.43	7.00	B5c
	8	8	24 d	63.6	56.4	26.9	2.8	2.1	55.7	2.1	12.8	1.8	0.16	0.80	1.00	B5c
	9	9	32	63.2	50.8	28.9	3.1	1.8	65.0	2.2	16.4	2.0	0.05	0.06	0.11	C6c-
	10	10	36	61.2	81.0	38.6	3.8	2.1	73.0	1.9	18.4	1.7	0.06	0.06	0.11	C6c-
	11	11	37 d	60.9	88.3	50.7	3.7	1.7	152.1	3.0	29.8	1.3	0.02	0.10	0.06	C6c-
	12	12	44 u	58.3	78.9	27.8	3.6	2.8	100.0	3.6	9.8	1.5	0.06	0.60	4.00	E5
	13	13	46 d	56.8	105.9	35.1	3.8	3.0	191.4	5.5	11.6	1.5	0.18	0.49	7.00	E5
Middle	14	1	49 da	55.0	111.3	33.2	4.8	3.4	73.2	2.2	9.9	1.8	0.16	0.33	2.00	E5
	15	2	49 db	55.1	112.3	34.1	3.8	3.3	246.3	7.2	10.3	1.8	0.13	0.36	1.00	E5
	16	3	55 d	50.9	116.5	36.9	3.8	3.2	46.7	1.3	11.5	1.8	0.03	0.36	1.00	G5c
	17	4	58	48.8	122.4	41.0	4.2	3.0	127.9	3.1	13.7	1.5	0.04	0.12	0.00	C5c-
	18	5	63	46.4	178.1	49.5	4.7	3.6	250.0	5.1	13.8	1.9	0.09	0.09	1.00	C5c-
	19	6	66 u	43.5	152.8	38.0	5.9	4.0	200.0	5.3	9.5	2.0	0.07	8.28	18.00	E4
	20	7	72 d	39.7	147.2	53.4	3.4	2.8	135.7	2.5	19.4	1.6	1.08	10.57	100.00	C4
	21	8	84 u	34.7	306.8	60.4	6.4	5.1	250.0	4.1	11.9	1.5	0.11	15.48	33.00	E4
	22	9	86 ua	33.9	206.0	63.9	4.5	3.2	395.6	6.2	19.8	1.6	0.21	16.00	32.00	C4
	23	10	86 ub	34.0	148.3	51.3	3.9	2.9	172.2	3.4	17.7	1.6	0.21	4.76	13.00	C4
	24	11	92 da	31.2	226.4	53.1	5.8	4.3	200.0	3.8	12.5	1.7	0.25	11.82	23.00	C4
	25	12	92 db	31.0	264.7	55.2	6.0	4.8	200.0	3.6	11.5	1.7	0.25	10.20	21.00	E4
	26	13	97 d	28.7	305.0	71.6	6.6	4.3	115.8	1.6	16.7	1.8	0.02	0.60	4.00	B5c
Lower	27	1	100	27.2	366.4	103.9	5.1	3.5	173.8	1.7	29.4	1.8	0.05	3.60	26.00	B4c
	28	2	101	26.8	262.2	93.2	4.5	2.8	103.5	1.1	33.3	1.7	0.28	0.88	9.00	F5
	29	3	108	22.3	216.6	91.1	2.7	2.4	132.0	1.4	38.3	1.6	0.14	26.36	62.00	B4c
	30	4	109 d	22.0	214.2	87.2	3.9	2.5	165.8	1.9	35.4	1.9	0.53	29.76	49.00	B4c
	31	5	112 d	20.5	330.7	80.4	4.8	4.1	127.0	1.6	19.6	1.7	0.21	0.95	54.00	B5c
	32	6	113 a	19.4	263.6	116.5	4.1	2.3	146.9	1.3	51.5	1.2	0.03	4.85	22.00	F4
	33	7	121 u	15.3	376.2	123.5	4.3	3.0	132.5	1.1	41.2	1.8	0.12	20.40	44.00	F4
	34	8	123 u	13.6	360.6	91.2	5.1	4.0	208.0	2.3	22.8	2.2	0.21	12.08	40.00	C4
	35	9	136 u	7.0	395.0	92.7	5.4	4.3	155.2	1.7	21.6	2.2	0.11	14.83	49.00	B4c

Figure 4.10. Channel metric and stream typing values for 35 reference sites along the SF LqP River collected in 2003.

Entrenchment values in the Upper reaches range from 1.2 at XS-17d, to 11.5 at XS-11d. Width-to-depth ratios also exhibit high variability ranging from 9.8 at XS-44u, to 29.8 at XS-37d. Spatial patterns indicate a series of four C channels in the upper reaches and three C channels in the lower reaches. Middle reaches are defined by three B channel reaches and one F channel reach, with two E channel reaches defining the bottom segment.. Stability analysis indicates a possible evolutionary tendency at four sites where slight changes in the entrenchment and/or W/D ratio will shift channel morphology into a different stream type (Table 4.9).

Table 4.9. Channel stability and direction of shift at four sites in the Upper watershed.

Cross-Section	Metric	Direction of Shift	Change in Classification
XS-11d	W/D	+ 1.8	C5c- to E5
XS-23d	ER	- 0.2	B5c to F5
XS-24d	ER	+ 0.2	B5c to C5
XS-32	ER	- 0.1	C6c- to B6c
XS-46d	W/D	+ 0.4	E5 to C5

Middle Watershed

Channel morphology in the Middle watershed exhibits similar diversity but with increased instability. While the Upper watershed was dominated by B and C channels, morphology in the Middle watershed is dominated by C and E channels with a single occurrence of B and G channel types (Figure 4.10). G channels (gully) are highly entrenched (ER < 1.4) channels with low W/D ratios (W/D < 12), and low – moderate sinuosity. The shift in channel morphology to E channels is a continuation from a process begun in the lower reaches of the Upper watershed. Two E-type channels precede the transition from the Upper to the Middle watershed. This trend continues in the Middle watershed with E and G channels defining the upper three reaches of the Middle Watershed.

Entrenchment values in the Middle reaches range from 1.3 at XS-55d, to 7.2 at XS-49db. Width-to-depth ratios also exhibit less variability ranging from 9.5 at XS-66u, to

19.8 at XS-86ua. Spatial patterns indicate an E→E→G→C→C→E→C→E→C→C→ C→E→B channel pattern distribution. Channel stability analysis indicates that slight changes in the W/D ratio would shift the channel type to one dominated by E channels such as: E→E→F→E→E→E→C→E→C→ C→E→ E→B.

As illustrated in Table 4.10, the majority of changes to channel morphology are achieved through changes in the W/D. The W/D ratio is defined as the bankfull width divided by the mean channel depth [W_{bkf}/D_{mean}]. E channels will increase their bankfull width as they erode their streambanks. This in-turn will decrease the mean bankfull depth resulting in a higher W/D. This process alone would account for the shift of three E channels to C channels.

Table 4.10. Channel stability and direction of shift at eight sites in the Middle watershed.

Cross-Section	Metric	Direction of Shift	Change in Classification
XS-49da	ER	+ 0.1	E5 to B5c
XS-49db	W/D	+ 1.7	E5 to C5
XS-55d	ER	+ 0.2	G5c to B5c
	W/D	+ 0.4	G5c to F5
XS-58	W/D	- 1.7	C5c- to E5
XS-63	W/D	- 1.8	C5c- to E5
XS-84u	W/D	+ 0.2	E4 to C4
XS- 92da	W/D	- 0.5	C4 to E4
XS-92db	W/D	+ 0.6	E4 to C4

Lower Watershed

The Lower watershed is characterized by high and steep bluffs throughout most of the reach. These high bluffs are actively failing (sloughing) due to erosion at the bluff-stream interface (Figure 4.11). Channel morphology in the Lower watershed exhibits the lowest diversity and moderate channel instability. While the Middle and Upper watersheds are characterized by four stream types each, the Lower watershed is characterized by three: B, C, and F (Figure 4.10). B channels dominate (57-percent) the morphology in the Lower watershed, followed by F channels (33-percent) and C channels (11-percent). Entrenchment values in the lower watershed range from 1.1 to 2.3 and exhibit the lowest variability (σ = 0.4) of the three sub-watersheds. Spatial analysis indicates a B→F→B→B →B→F→ F→C→B channel pattern. Stability analysis suggests four of these sites are sensitive to changes in the ER: XS-108, XS-112d, XS-113A, and XS-123u (Table 4.11). Changes in the ER would result in either a B or an F channel indicating the channel morphology in the Lower watershed is more typically a B channel with moderate entrenchment and W/D ratios. Changes in the ER at XS-113A and XS-123u would result in two more B-type channels and produce a B→F→B→B→B→B→F→B→B spatial distribution of channel morphology.

Figure 4.11. Downstream view at XS-128 illustrating the steep bluffs found along the SF LqP River in the Lower watershed. Soil material is actively eroding into the SF LqP River due to erosion at the toe-of-slope. Vegetated area in foreground is a remnant slope failure.

Table 4.11. Channel stability and direction of shift at four sites in the Lower watershed.

Cross-Section	Metric	Direction of Shift	Change in Classification
XS-108	ER	- 0.1	B4c to F4
XS-112d	ER	- 0.2	B5c to F5
XS-113A	ER	+ 0.2	F4 to B4c
XS-123u	ER	- 0.1	C4- to B4c

Land Use Impacts

Grazing

Thirteen of the original CoE cross-sections sites were identified as actively grazed sites in 2003 and include cross-sections: 6, 7, 13, 15, 17, 19, 20, 26, 47, 48, 58, 74, and 121. The majority of these sites (77-percent) are located in the Upper watershed (XS #s 6 thru 48). Of the remaining three sites, two are located in the Middle watershed (XS # 58 and 74) and one in the Lower watershed (XS # 121). Five channel metrics were evaluated for significance of change between the 1965/66 CoE survey and 2002/03 re-survey: cross-sectional area, channel width, mean depth, maximum depth, and W/D. Only results for channel width were not significant (P = 0.768). Channel cross-sectional area increased at 11 of the 13 grazed sites (85-percent) between 1965/66 and 2002/03. Differences between years was significant at the 95 percent CI (P = 0.03). Mean channel depth increased at all sites ranging from 0.2-ft at XS-07, up to 2.0-ft at XS-121 (P = 0.0000). Maximum channel depth increased at 12 of 13 sites (92-percent) ranging from 0.2-ft at XS-07, up 2.1-ft at XS-19 (P = 0.002). While changes in channel width were not significant with six sites narrowing and seven sites widening; changes in the W/D values were (P = 0.006). W/D ratios decreased at 10 of 13 sites (77-percent). The general trend seen at grazed sites is similar to the overall trend described previously. Increases in channel cross-sectional area were noted at 77-percent of the sites; but while cross-sectional area increased, channel width remained essentially unchanged. Increases in channel cross-sectional area were driven by increases in channel depth noted at all grazed sites.

Five of the 35 stream reference sites surveyed in 2003 occur in grazed sites, three in the Upper watershed (XSs 15d, 17d, and 46d) and one each in the Middle (XS-58) and Lower watersheds (XS-121u). Only XS-58 is a stream reference site that corresponds with the 1965/66 CoE cross-section site.

Riparian Buffer

A review of the riparian buffer data indicates that all channel cross-section sites occur in areas where no significant change in the size of the riparian buffer were noted. Riparian buffer changes were investigated in the Upper and Middle watersheds. The majority of change in the riparian buffer width in the Upper watershed occurred at two locations; 1) the reaches above Canby, MN and, 2) at XS-39 and XS-40. The reaches above Canby, MN were not included in the 1965/66 CoE flood control study and were therefore excluded in this analysis. Cross-sections 39 and 40 were heavily modified during the construction of the by-pass channel. Any impact due to the change in riparian buffer width is thought to be insignificant compared to the impacts caused by the construction of the by-pass channel.

Discussion

The data suggest there has been a change in the channel geometry between the time of the 1965/66 CoE flood control survey, and the 2002/03 re-survey. Results from the re-survey of CoE cross-sections indicate an increase in channel cross-sectional area driven by channel deepening with no appreciable change in channel width (Table 4.4). Further analysis of the data reveals specific activities in and around the channel responsible for these processes.

By-Pass Channel Construction

Channel shortening is a process where the physical length of the stream channel is shortened by the construction of a by-pass channel of shorter length. This physical alteration of the stream channel is analogous to the more natural meander-cutoff where channel length is shortened when a whole meander bend is cut off by erosion of the channel banks on the outside meander bends immediately upstream and downstream of the cutoff meander.

Channel length was shortened at four sites in the Upper Watershed on the SF LqP River:

1. at river mile 70.2 between cross-sections 21-22,
2. at river mile 60.5 between cross-sections 41-42,
3. at river mile 59.0 between cross-sections 42-44, and
4. between river-mile 61.6 and 65.9, cross-sections 29-39.

The most dramatic of these modifications occurred between river-mile 61.6 and 65.9 (cross-sections 29-39) that removed 4.3 miles of the original stream channel and replaced it with 1.34 miles of by-pass channel (Figure 4.12). The effects of this modification are illustrated in cross-section #40 (Figure 4.13). Channel deepening at cross-section #40 is attributed to head-cut migration initiated by the construction of the by-pass channel. The by-pass channel increased channel slope (gradient) by shortening the length of stream channel. Loss of channel length increased stream power (ω), which initiated channel incision as seen at cross-section #40. Stream power is defined as:

$$\omega = \gamma QS,$$ where:

γ = specific weight of water
Q = stream discharge
S = water surface slope

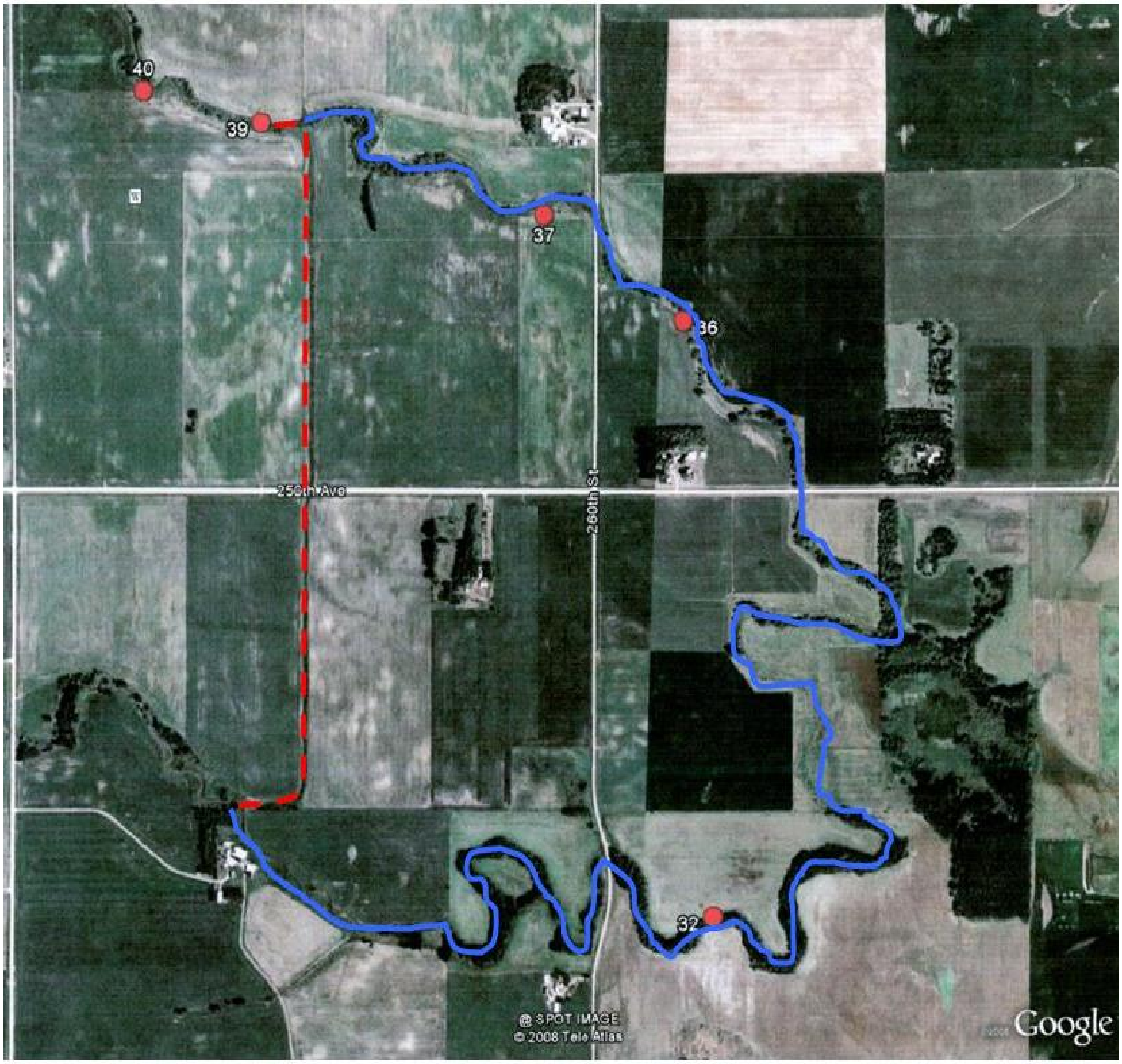

Figure 4.12. Plan view of SF LqP River 10.5 miles southwest of Dawson, MN illustrating the loss in channel length (solid line) due to construction of a by-pass channel (dashed line) that resulted in a net loss of 2.96 miles (15,628.8 ft) of stream channel. Red dots signify CoE cross-section locations.

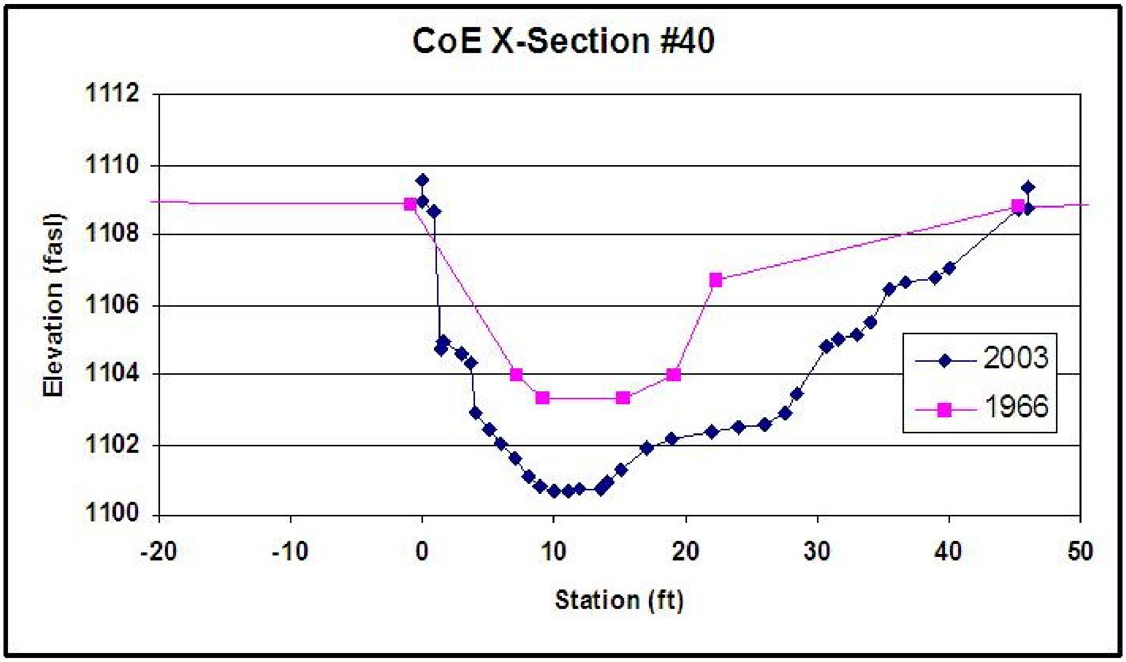

Figure 4.13. CoE cross-section #40 illustrating the channel erosion initiated by the construction of a by-pass channel between river-mile 61.6 and 65.9.

Increasing stream power increases the sediment transport capacity of the channel as illustrated by Lane's Balance (Figure 4.2). The channel adjusted its bedform geometry by increasing its channel width and depth (cross-sectional area) until the sediment load and size were in equilibrium with stream slope and discharge. Cross-sectional area increased 87-percent, maximum channel depth increased 46-percent, mean depth increased 92-percent, and channel width remained virtually unchanged with a 3-percent decrease (Table 4.12).

Table 4.12. Channel metrics surveyed at CoE cross-section #40 in 1965/66 and 2002.

	Area	**Width**	**D_{max}**	**D_{mean}**
	(ft^2)	**(ft)**	**(ft)**	**(ft)**
1965/66	117.4	45.8	5.5	2.6
2002/03	219.8	44.3	8.0	5.0
%-Change	87.2	-3.3	45.5	92.3
%-Difference	60.7	-3.3	37.0	63.2

Equilibrium was never achieved between river-mile 61.6 and 65.9 (cross-sections 29-39). Channel erosion was so severe following construction of the by-pass channel that it necessitated the installation of a grade control structure (Figure 4.14) at the upstream end of the newly constructed by-pass channel. The interlocking steel panels driven into the channel bed represent a drastic solution (hard armoring) to arrest the channel bed erosion initiated by the construction of the by-pass channel. Channel erosion continued after the installation of the steel panels and necessitated the installation of two rip-rap grade control structures along the north-south section of by-pass channel.

Figure 4.14. Installation of inter-locking steel panels to arrest channel erosion initiated by the construction of the by-pass channel between river miles 61.6 and 65.9.

The loss of 15,629 feet of stream channel due to the construction of the by-pass channel, coupled with the increased depth due to channel erosion, combined to increase channel slope 72-percent from 0.0005 to 0.0018 (ft/ft). Stream power increased from 0.003 to 0.054 (lb/ft/sec). Shear velocity increased from 0.20 to 0.50 (fps). Instream velocities increased from 1.9 (fps) to 5.0 (fps), resulting in a six-fold increase in the threshold grain size from 5 mm in 1965/66, up to 29 mm in 2002/03. The grade control structures also served as energy dissipaters and helped keep stream power in-check and control erosion.

Channel shortening at river miles 59.0 and 70.2 removed 7233.6 feet (1.37 mi), and 1531.2 feet (0.29 mi) of channel length respectively. Both sites appear to be the result of erosional processes due to channel shortening activities that cut-off meander bends. Channel shortening at river mile 60.5 removed 2221.0 feet of channel and replaced it with 628.6 feet of channel for a net loss of 1592.4 feet (0.30 mi). The channel shortening at this location appears to be associated with the replacement of county bridge #33.

Channel shortening at all four sites resulted in a net loss of 25,978 feet (4.9 mi) of channel length. The product of these reductions in channel length is illustrated in Figure 4.15. While overall channel gradient was increased, the effects were not propagated throughout upstream reaches. Grade control structures in the form of box culverts served to localize the impacts of the channel shortening activities.

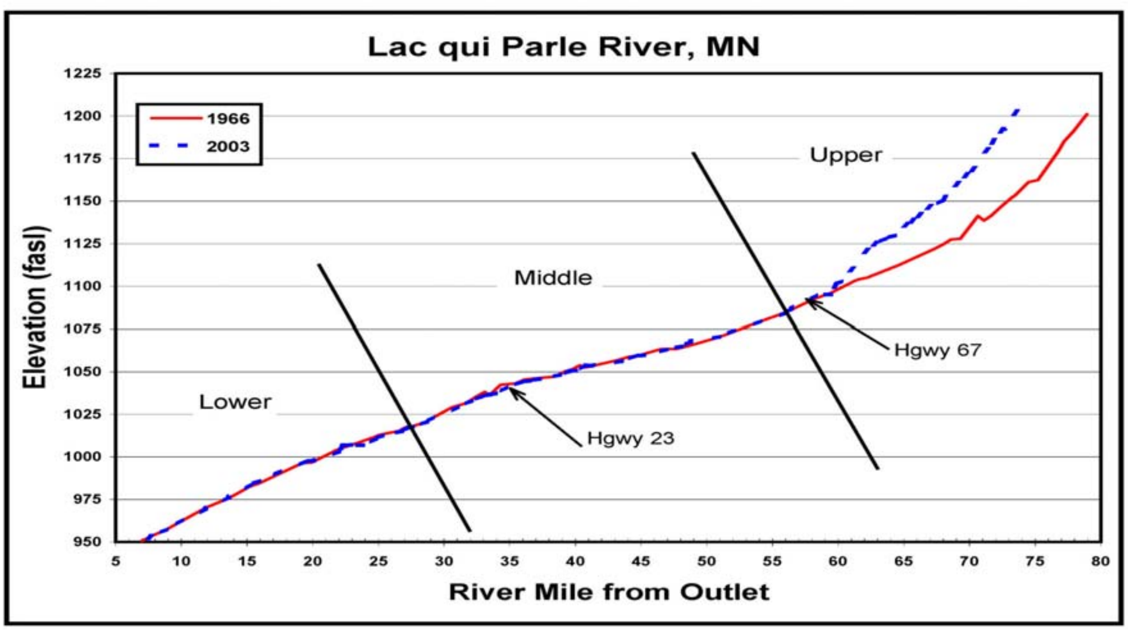

Figure 4.15. Channel slope of SF LqP River from river outlet to 80 miles upstream. Solid red line indicates 1965/66 slope; dashed blue line indicates 2002/03 slope.

While it is important to note the location and cause of channel degradation, it is equally important, and interesting, to note the lack of channel degradation seen at cross-section #32. Cross-section #32 is located at river mile 64.6, on the stretch of river removed by the construction of the by-pass channel (Figure 4.12). It is 3.0 miles upstream from the start of the by-pass channel. Data collected during the 2002/03 re-survey indicate little, if any, change in channel geometry between 1965/66 and 2002/03 (Figure 4.16). Although construction of the by-pass channel resulted in a net loss of 2.96 miles of stream channel, or 69-percent of the original channel length; the original stream channel geometry remained undisturbed. Today the original stream channel is utilized only during times of high flow and to convey drainage discharge from sub-surface tile drains (Figure 4.17).

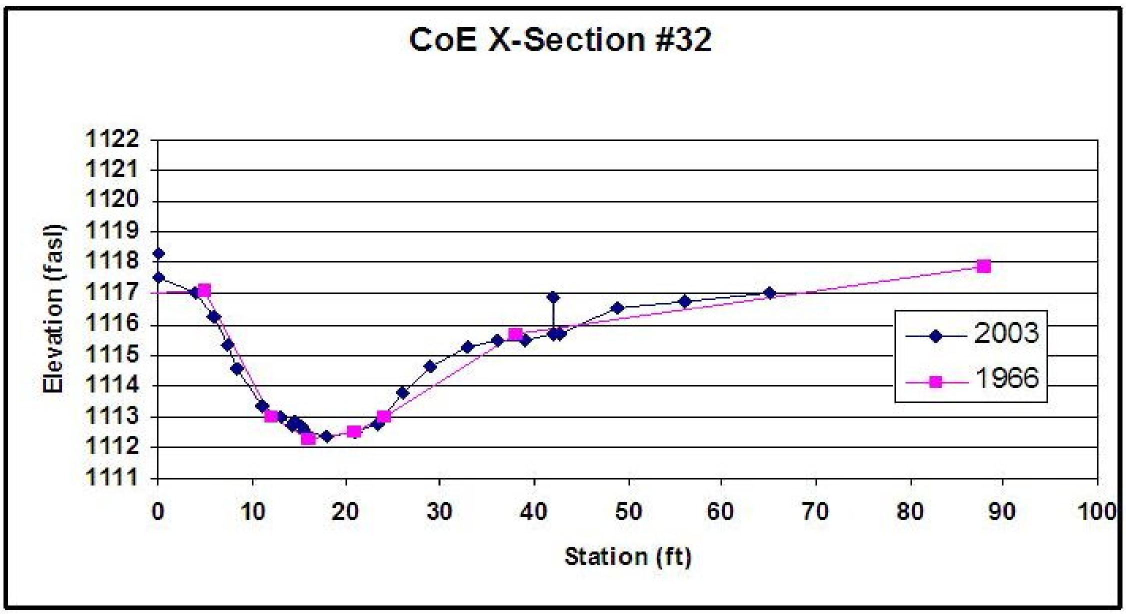

Figure 4.16. CoE cross-section #32 illustrating the lack of change in channel geometry from 1965/66 (pink squares) to 2002/03 (blue diamonds).

Figure 4.17. Discharge from sub-surface drainage collection tank near CoE cross-section #32 into SF LqP River.

Changes to channel morphology due to impacts from the by-pass channel may skew the data analysis by “artificially” increasing the number of sites with negative impacts. Analysis of the data after removal of the cross-sections impacted by construction of by-pass channels, indicates changes in channel depth are still significant at the 99-percent confidence level (P = 0.002).

Field Leveling

As noted earlier, increases in channel cross-sectional area were driven by increases in channel depth. Analysis of the 1965/66 and 2002/03 cross-sections indicates the increase in channel depth at three (3) sites were the result of construction activities in and around the channel that altered the channel bank height. Grading activities in agricultural fields immediately adjacent to the stream channel sometimes increased the overall channel bank height. The net result of the added material was to confine and concentrate in-stream flows. Field grading activities were noted at XS-24 in the Upper watershed and XS-62, and XS-66 in the Middle watershed.

The addition of new material to both banks at CoE XS-24 raised the channel banks 2.2-ft on the left and right channel banks (Figure 4.18). The addition of material was the result of field leveling activities on both sides of the channel. While this increased mean channel depth 0.9-ft, maximum channel depth 2.1-ft, and cross-sectional area 60.2-ft^2; channel width decreased 2.1-ft (Table 4.13). While the decrease in channel width, combined with the increased channel bank height, further confined and concentrated instream flows, overall channel bed elevation decreased just 0.1-ft from 1965/66 to 2002/03.

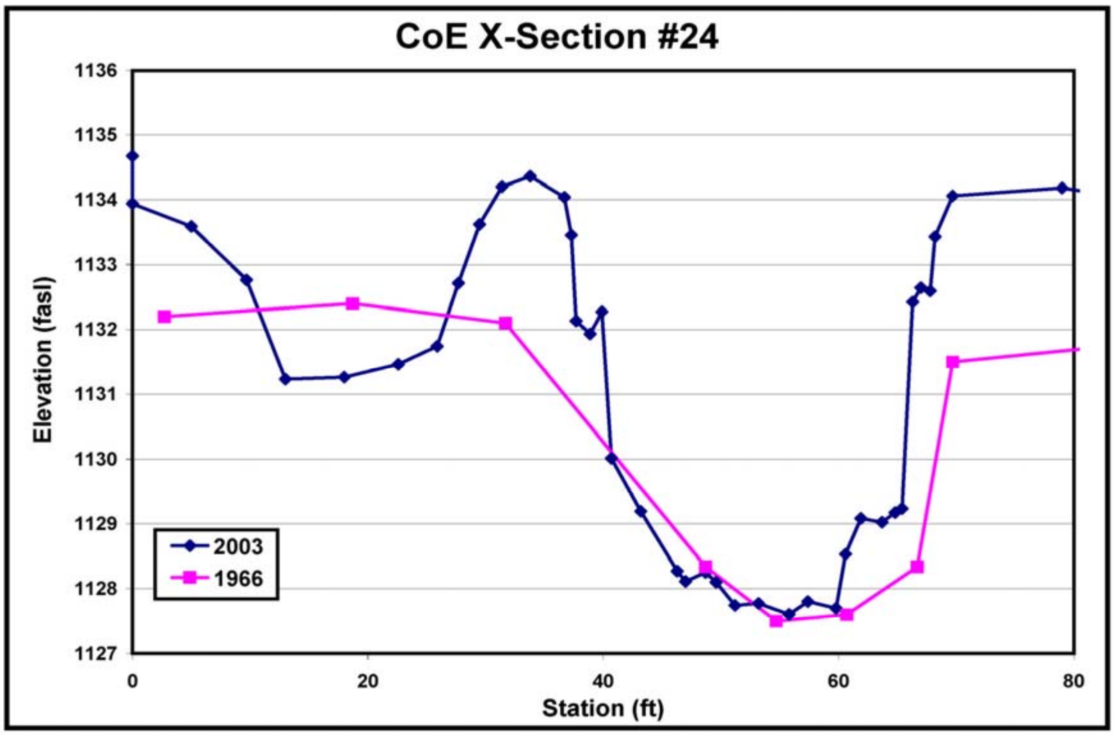

Figure 4.18. CoE XS-24 illustrating the increase in channel bank height due to field leveling activities in the adjacent agricultural fields.

Table 4.13. Channel metrics for COE cross-sections XS-24, XS-62, and XS-66 based on the 1965/66 CoE survey, the 2002/03 re-survey and a top of bank reference point.

COE XS	Year	Area (ft^2)	W (ft)	D_{max} (ft)	D_{mean} (ft)	W/D
XS-24	1965/66	93.7	35.3	4.0	2.7	13
	2002/03	153.9	33.2	6.5	4.6	7
	% Change	64%	-6%	63%	70%	-46%
XS-62	1965/66	353.0	85.8	7.4	4.1	21
	2002/03	306.6	59.6	7.3	5.1	12
	% Change	13%	31%	1%	20%	67%
XS-66	1965/66	114.8	32.8	5.2	3.5	9.4
	2002/03	230.2	41.9	8.3	5.5	7.6
	% Change	101%	28%	60%	57%	-19%

Increases in bank height due to grading activities were also evident at cross-sections XS-62 and XS-66 in the Middle watershed (Table 4.13). Changes to channel geometry at XS-62 were minimal. Total cross-sectional area decreased 46.4-ft^2 (13%) from 1965/66 to 2002/03, while channel width experienced the greatest change decreasing 26.2-ft (31%) from 85.8-ft in 1965/66 to 59.6-ft in 2002/03. Channel depth values were mixed. While maximum depth decreased 0.2-ft, mean depth increased 1.0-ft. The loss of channel width resulted in a 44-percent decrease in the W/D.

Grading activities along the channel banks at CoE XS-66 had a more pronounced effect. Re-working of the channel banks due to re-grading of adjacent agricultural fields produced a 3.1-ft increase in maximum channel depth. While overall channel depth increased 3.1-ft, absolute channel bank height increased 3.0-ft. These changes further confined channel flows and produced a 0.3-ft decrease in the channel bottom elevation from 1056.7 feet above sea level (fasl) in 1965/66 to 1056.4 (fasl) in 2002/03.

Changes to channel morphology due to impacts from construction activities in and around the channel that altered the channel bank height may also skew the data analysis by “artificially” increasing the number of sites with negative impacts. Analysis of the data after removal of CoE cross-sections XS–24, XS-62, and XS-66 indicates changes in channel depth are still significant at the 99-percent confidence level for the Upper (P = 0.004) and Middle watersheds (P = 0.002).

Grazing

Significant increases in cross-sectional area and mean depth were noted at 13 grazed sites. All of the sites noted in this study were being actively grazed when the 2002/03 data were collected; yet only XS-121 in the Lower watershed exhibited any sign of channel widening. As illustrated in Figure 4.19, channel cross-sectional area at CoE cross-section #121 has increased substantially due to the erosion of a large portion of the right bank since the 1965/66 CoE survey. Yet, while the 2.0-foot increase in mean depth was the most for all grazed sites, maximum depth and channel width, based on a top-of-bank reference, remained relatively unchanged (Table 4.14). Changing the reference point to the bankfull elevation of 992.8-fasl, as identified in 2003, shows channel width increased 28-percent from 103-ft to 131-ft (Table 4.15). This is accompanied by a 2-percent decrease in cross-sectional area, a 23-percent decrease in mean channel depth, and a 67-precent increase in the W/D.

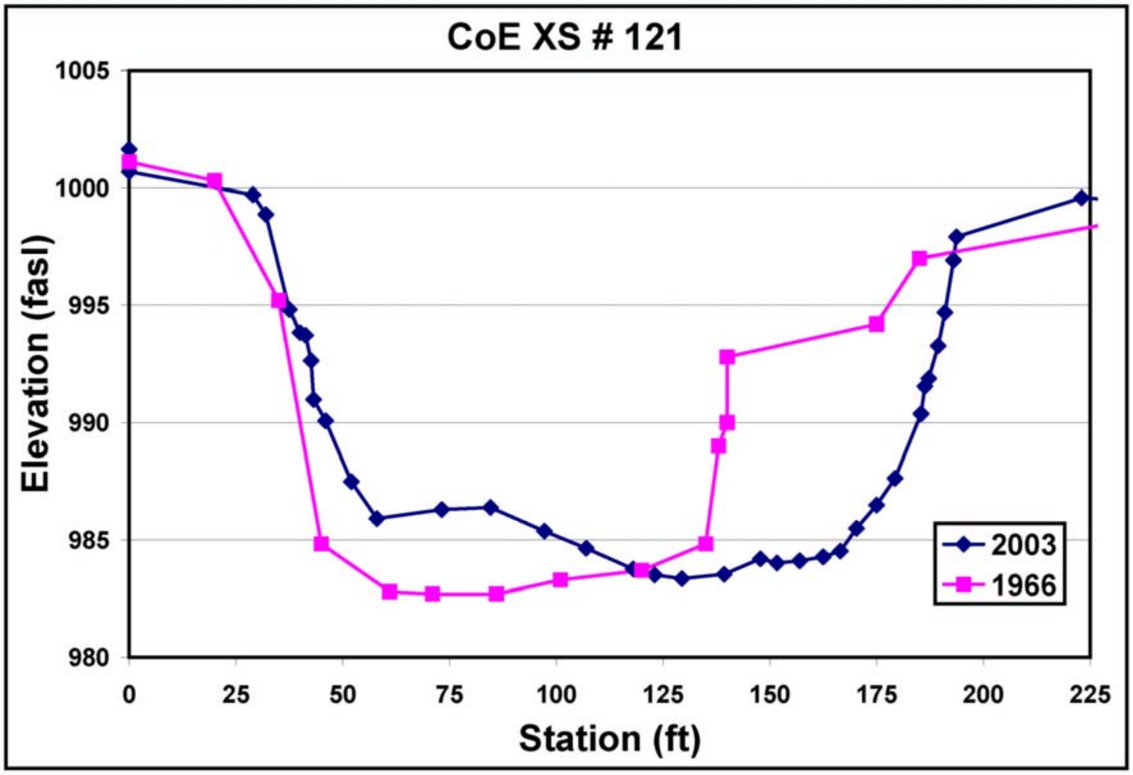

Figure 4.19 CoE cross-section #121 illustrating the change in channel geometry from 1965/66 (pink squares) to 2002/03 (blue diamonds).

Table 4.14. Channel metrics for XS-121 based on the 1965/66 CoE survey, the 2002/03 re-survey, and a top of bank reference point.

Year	Area (ft^2)	W (ft)	D_{max} (ft)	D_{mean} (ft)	% Slope	Sinuosity	ER	W/D
1965/66	1481.7	155.3	14.3	9.5	0.04	1.5	3.2	16.3
2002/03	1838.4	160.4	14.6	11.5	0.04	1.5	2.9	13.9
% Change	24%	3%	2%	21%	NA	NA	9%	-16%

Table 4.15. Channel metrics for XS-121 based on the 1965/66 CoE survey, the 2002/03 re-survey, and an estimated bankfull elevation reference point.

Year	$Area_{bkf}$ (ft^2)	W_{bkf} (ft)	D_{max} (ft)	D_{mean} (ft)	% Slope	Sinuosity	ER	W/D
1965/66	902.2	102.7	10.1	8.8	0.04	1.5	3.2	12
2002/03	887.9	131.4	8.3	6.8	0.04	1.5	1.4	20
% Change	-2%	28%	-18%	-23%	NA	NA	56%	67%

Channel widening due to cattle grazing is a well-documented impact to channel morphology (Kondolf, 1993; Magilligan and McDowell, 1997; Trimble and Mendel, 1995) and appears to have caused the impacts noted at XS-121. Additionally, the landowner commented that the channel was much narrower and deeper back in the 1960s. He also indicated his children use to swing on a rope from a tree along the bank, into a large pool that was no longer present because the channel had become so wide and shallow (Schueller, 2003). The loss of pool morphology is an impact associated with cattle grazing (Magilligan and McDowell, 1997). When asked if he thought cattle grazing had any impact on the channel widening seen at this site the landowner responded quite confidently "No."

While significant changes in channel morphology were noted at grazed sites, cattle grazing alone does not explain the channel deepening process documented at each site. Research on the impacts of cattle grazing on stream channel morphology (geometry) has demonstrated cattle grazing causes channel widening, not deepening (Kondolf, 1993; Magilligan and McDowell, 1997; McLean, 1994; Naiman et al., 1993; Naiman and Roberts, 1997; Trimble and Mendel, 1995). Furthermore, channel widening impacts from cattle grazing have been shown to last for several decades (Kondolf, 1993; Magilligan and McDowell, 1997). The channel deepening trend documented in this research is contradictory to the channel-widening trend reported in the literature, and implies the channel deepening process noted in this study is the result of other, not yet considered, land use changes/activities within the watershed.

Cultivation

Land use in the SF-LqP watershed has been dominated by agricultural cultivation since the latter part of the 19th century (Van Alstine, 1998). Seventy-nine percent of the watershed is under agricultural practices (Mallawatantri, 1999). Since streams are an expression of the activities practiced on the landscape within their respective watershed, agriculture has played an important role in the processes shaping the morphology of the SF LqP River. Indeed, cultivation has been shown to enlarge channel cross-sectional area compared to natural, unaltered conditions (Hammer, 1972). Data collected in this research suggests similar processes may be operating within the SF LqP watershed.

Overall, mean channel cross-sectional area increased 7-precent from 451.5 to 483.3 (ft^2) throughout the SF LqP River. Channel cross-sectional area increased at 43 sites and decreased at 20 sites. While changes in the Lower watershed were less than significant, increases in mean channel cross-sectional area were significantly different in the Middle and Upper watersheds (Table 4.2). Mean channel cross-sectional area increased 14-percent from 287.6 to 329.0 (ft^2) in the Middle watershed ($P = 0.018$) and 30-percent from 112.0 to 145.6 (ft^2) in the Upper watershed ($P = .0007$). The increase in channel cross-sectional area is similar to channel enlargement ratio (CER) values associated with the effects due to urbanization (Hammer, 1972; Leopold, 1968).

Hammer (1972) reported a CER of 1.3 due to effects of cultivation when compared to a natural, unaltered, channel. An analysis of the CER from 1965/66 to 2002/03 on the SF LqP watershed indicates the CER is 1.3 for the Upper watershed, 1.14 for the Middle watershed, and 1.02 for the Lower watershed. While the research noted a CER of 1.02 - 1.3, the time required for these impacts to manifest themselves in the watershed is unclear.

Leopold documented changes on Watts Branch over a 20-yr period. A more focused research by MacRae et al. (1992), reported that it required several decades for stream channels to achieve a new equilibrium following urbanization. Although MacRae suggested the impacts may require several decades to equilibrate, the impacts were generally noted within one decade (Macrae and Rowney, 1992). While the time required for these land use changes to manifest themselves in channel morphology on the SF LqP River is unknown; the CERs reported by Hammer due to cultivation suggest stream channel cross-sectional area increases with time up to approximately 30 years, at which time a new equilibrium is achieved. The SF LqP watershed has been dominated by agricultural land use (cultivation) for over one-hundred years (Christner, 2009). If cultivation alone was responsible for the changes in channel morphology, these effects should have manifested themselves by now and the channel should have established a new dynamic equilibrium. However, the increase in stream channel cross-sectional area documented in this research suggests the channel is currently in a state of disequilibrium. Furthermore, the 1.02 – 1.3 CER noted in this research, has occurred over a 37-year period between 1965/66 – 2002/03. If cultivation alone causes a CER of 1.3, and the SF LqP watershed has been under cultivation for over 100-years; then another, as yet unconsidered process, must be the cause for the more recent 1.02 – 1.3 increase in the CER documented in this research.

Agricultural drainage (surface and sub-surface) is the only notable land use change within the SF LqP watershed over this time frame. This research documented a 35-percent increase in the amount of land "improved" by surface tile inlets and subsurface tile drainage between 1972 and 2003. It was the single largest land use change noted within the watershed and affected almost 35-percent of the area. Additionally, when added together the 1.3 CER due to cultivation and the 1.02 – 1.3 CER noted in this research, equal a CER of 2.36 – 2.6. This CER is greater than the 2.2 CER noted for houses > 4-yrs old on sewered streets (Hammer, 1972). The CERs developed by Hammer were found to be strongly correlated to urbanization and ranged from 0.7 to 3.8 with the majority of the CER values lying between 1.0 and 2.0. Impervious cover associated with a 2.2 CER ranges from 26 to 50-percent. This suggests that agricultural drainage (surface and sub-surface) has the same impact on stream channel morphology as the installation of storm sewers associated with urbanization and 26 to 50-percent impervious cover.

In addition to the physical changes to channel cross-sectional area documented by Hammer, Leopold suggested the amount of channel enlargement would approximately equal the increase in flow associated with the 1.5-year recurrence interval (Leopold, 1968). Hollis (1975) expanded this work to include impacts from various amounts of impervious surfaces on a range of flood flows. Analysis of the stream discharge record at the Lac qui Parle gage at Lac qui Parle, MN indicates a 1.35 to 1.43 increase in the $Q_{1.5}$ pre-1960 compared to post-1960 (Table 4.16). This increase in flow is consistent with the results reported by Leopold due to the impacts of urbanization. The process of urbanization tends to increase peak flow magnitudes through the spread of impervious surfaces. This increases the volume of runoff through the installation of storm sewers which facilitate the movement of water off the landscape and into receiving waters.

Table 4.16. Comparison of pre- and post-1960 1.5-year recurrence interval flow data from the Lac qui Parle gauge at Lac qui Parle, MN.

Flow Record	Peak Flow (cfs)	
	Graphical Method	**Analytical Method**
Pre-1960	850	700
Post-1960	1150	1000
Ratio	1.35	1.43

Impacts of Farm Bill Legislation

The Wetland Conservation provision in the 1985 Farm Bill was designed to give farmers incentive to protect existing wetlands on their farm. The provision denied certain government benefits to anyone who converted a wetland for agricultural use after December 23, 1985. This included participation in: the price-support loan program, farm storage loans, Federal crop insurance, disaster payments, new loans made by Farmers Home Administration if the loan would contribute to the conversion of the wetland, and CCC payments for storage (Hartman and Golstein, 1994).

The term “wetland” was defined in the 1985 Farm Bill as “land that has a predominance of hydric soils and that is inundated or saturated by surface or groundwater at a frequency and duration sufficient to support and that under normal circumstances does support, a prevalence of hydrophytic vegetation typically adapted for life in saturated soil conditions.” In anticipation of this new provision, many farmers began converting marginal, “wet” areas on their farm to tillable land through the installation of tile drains (surface and subsurface). While the purpose of the 1985 Farm Bill was to promote wetland conservation, the unintended result was that wet areas of land were drained prior to the enactment of the 1985 Farm Bill to avoid the pending restrictions of the new provision (Hayden, 1990). A review of the cumulative precipitation – discharge record for the LqP Watershed suggests this may have been the case in Western Minnesota. As previously mentioned, Figure 3.7 exhibits multiple adjustments in the Q/P ratio for the LqP watershed from 1912 through 2002. Figure 4.20, indicates the cumulative Q/P ratio has a noticeable increase in the annual Q/P rate post-1984 compared to pre-1984. Further support for this trend is seen in a separate plot of the discharge vs. precipitation for the two time-periods, 1912-1983 and 1984-2002 (Figure 4.21).

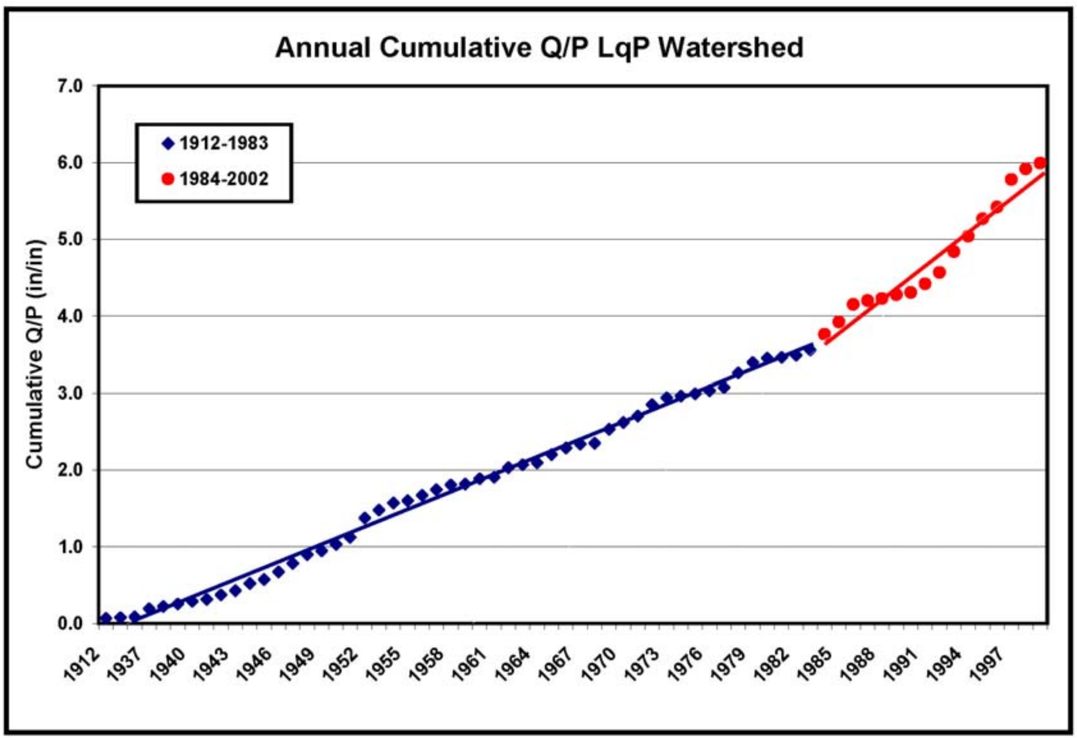

Figure 4.20. Cumulative annual Q/P values for the LqP watershed 1912-1983 (blue triangles/line) and 1984-2002 (red circles/line).

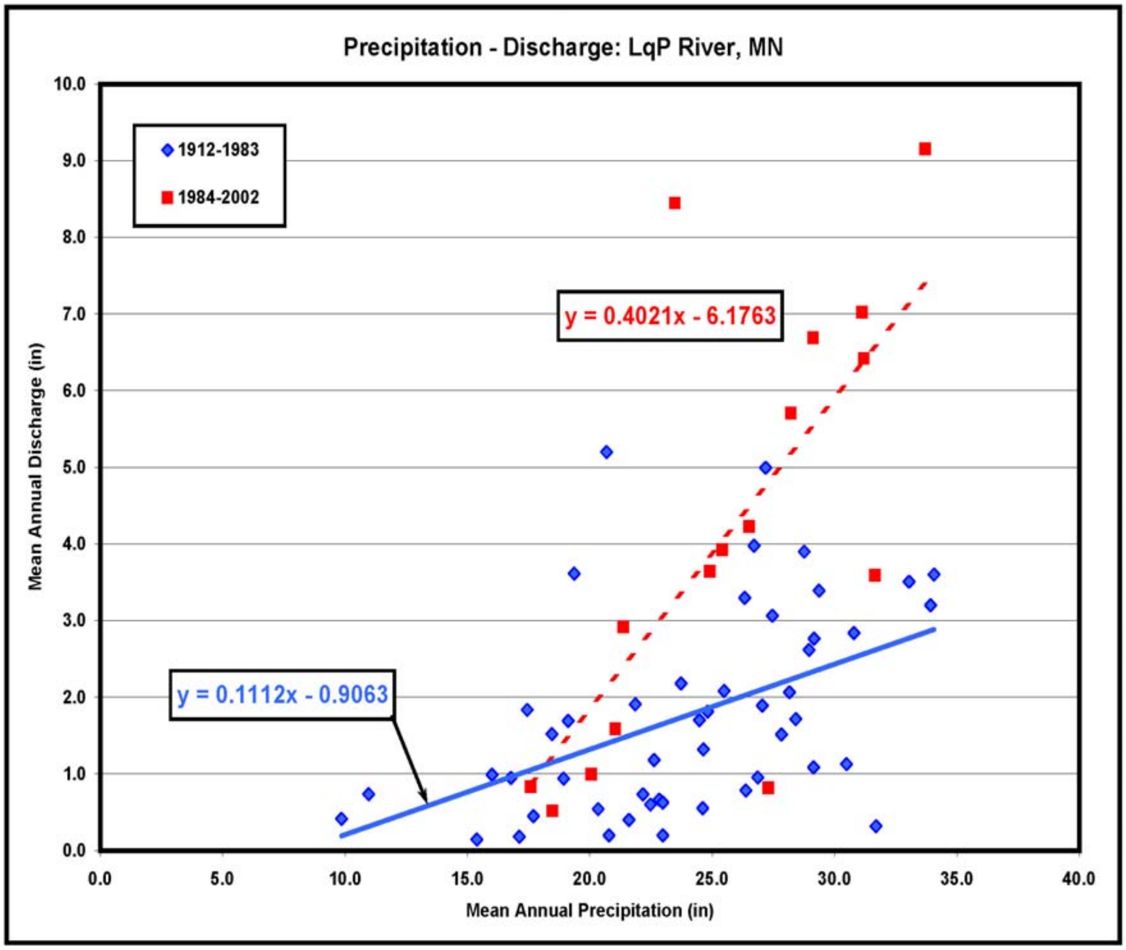

Figure 4.21. Annual discharge totals (Q) vs. annual precipitation totals 1912-1983 (solid line) and 1984-2002 (dashed line). Discharge totals are from the LqP flow gauge. Precipitation totals are from the Canby and LqP-Riverside precipitation gauges.

The slope of the 1984-2002 Q versus P regression is 3.6x greater than that of the 1912-1983 slope and is significantly different at the 99% confidence level. Linear regression analysis indicates a 212-percent increase in the slope post-1984 compared to pre-1984 and shows more discharge being generated from precipitation post-1984 than pre-1984. Analysis of the annual peak discharge record suggests similar increases in annual peak flow post-1984 compared to pre-1984.

Graphical frequency analysis of annual peak flow data for the two time periods indicates an increase in the peak flows associated with the 1.25-yr – 2.70-yr recurrence intervals (RI) (Figure 4.22). This increasing trend in the channel-forming discharge range is contrasted by the peak flow analysis of the 1912-1960 and 1961-2002 time periods. As illustrated in Figure 3.4, the greatest increases in peak flow discharge post-1960 are seen in the 1.04-yr to 1.14-yr RI flows, and the 2.70-yr to10.00-yr RI flows. Increases to the channel forming discharge have the capacity to alter channel geometry (form). The significance of the channel forming discharge (a.k.a. channel maintaining discharge, and the bankfull discharge) is well documented (Leopold et al., 1964; Hammer, 1972; Williams, 1978; Ferguson and Suckling,1990). The more frequent flows associated with the channel forming discharge carry more sediment and convey more water over time compared to the less frequent flows associated with higher discharge events. The increase noted post-1984 suggests a mechanism to modify channel geometry in the SF-LqP River as noted in this research.

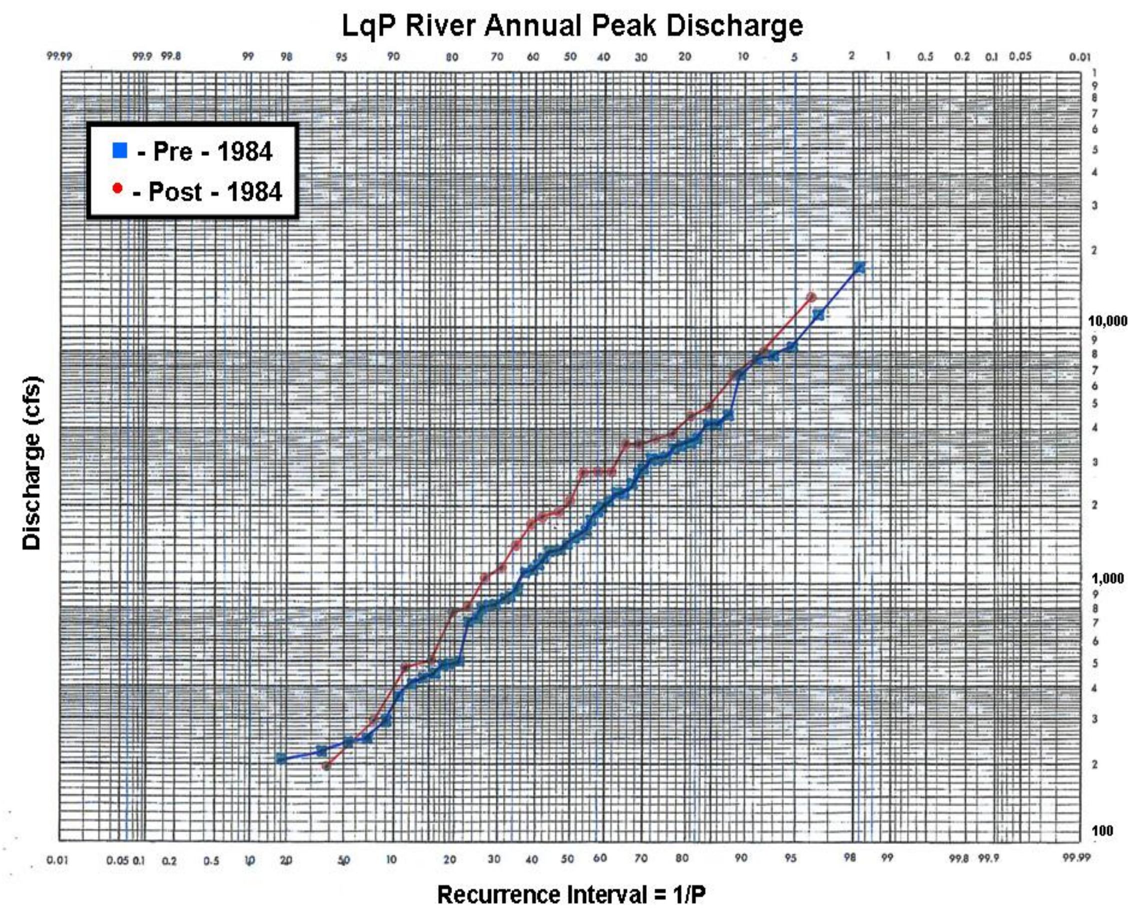

Figure 4.22. Graphical plot of annual peak discharge for the LqP River for two time frames; 1912-1983 and 1984-2008.

Table 4.17. Comparison of pre- and post-1984 channel forming flows from the Lac qui Parle gauge at Lac qui Parle, MN.

Return Interval	1.25	1.5	2.0	2.5
Post-1984 Discharge (cfs)	800	1425	2125	2700
Pre-1984 Discharge (cfs)	500	925	1480	2025
Percent Increase	42.9	54.1	43.6	33.3
Ratio [$Q_{post-84}/Q_{pre-84}$]	1.6	1.5	1.4	1.3

Current Channel Morphology and Relative Equilibrium – 2003 Survey

Results from the channel survey during the summer of 2003 indicate the SF LqP River exhibits varying stages of channel degradation. As noted earlier, mean cross-sectional area in the Upper watershed increased from 112.0 to 145.6 (ft^2) and in the Middle watershed from 287.6 to 329.0 (ft^2) (Table 4.2). The increase in cross-sectional area was driven by an increase in channel depth (Tables 4.5 and 4.6, Figure 4.5). This channel deepening process is described as the "Degradation Stage" in the channel evolution model (CEM), and is characterized by rapid erosion of the channel bed (Schumm et al., 1984; Simon and Hupp, 1986). The 5-stage CEM, developed by Schumm and others, was expanded to six stages by Simon and Hupp (1986). The "Degradation Stage corresponds to Type-II reaches as described by Schumm et al., and Type-III as described by Simon and Hupp. Since Simon and Rupp's 6-stage CEM contains all stages from the 5-stage CEM, it will be used for purposes of reference in this discussion. Type-III stages in the CEM are characterized by:

1. a sediment transport capacity that exceeds sediment supply,
2. a bank height that is less than the critical bank height
3. little or no bed sediment deposits,
4. a lower bed slope than a Type-I reach, and
5. a lower width-depth ratio value than the Type-I reach (Simon and Hupp, 1986).

W/D ratios decrease in Type-III reaches because channel depth increases while channel width remains relatively unchanged due to lack of streambank failure. This trend is seen in the Upper and Middle watersheds where the W/D decreased at 14 of 23 sites (61%)

and 17 of 22 sites (77%) respectively (Figure 4.23). Average W/D declined from 18.0 to 14.6 in the Upper watershed and from 15.6 to 13.0 in the Middle watershed (Table 4.3). Land use changes and channel modifications that removed and shortened portions of the SF LqP River have facilitated some of these changes in channel morphology of the SF LqP River.

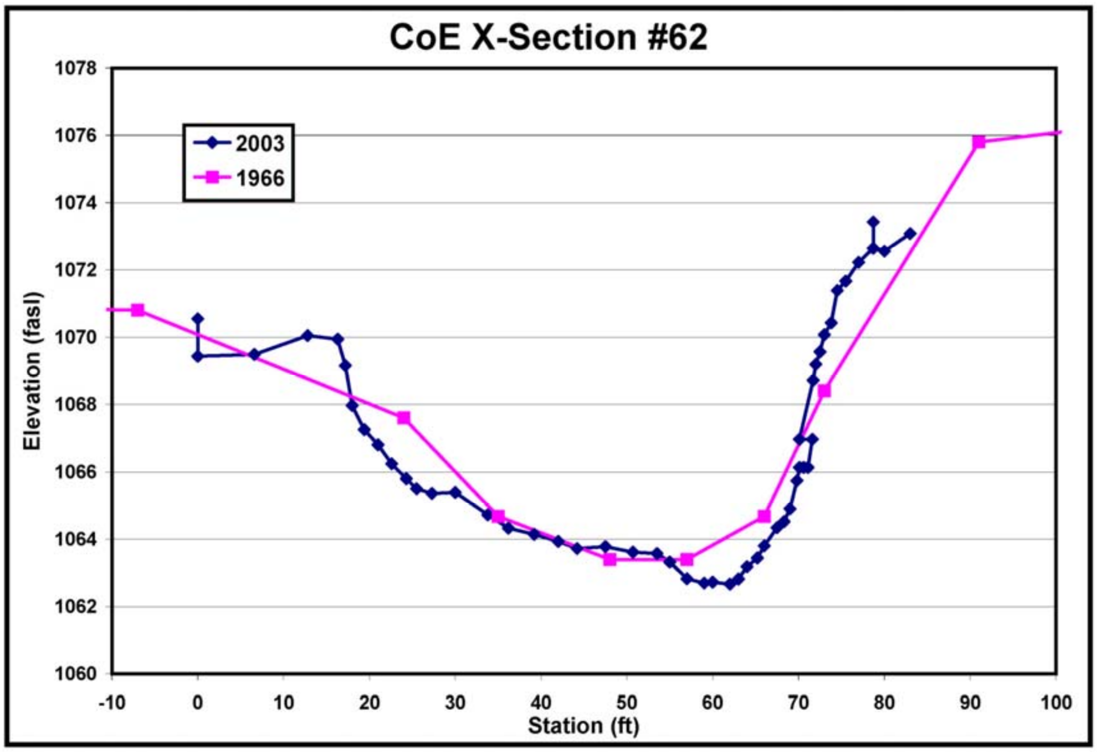

Figure 4.23. CoE XS-62 illustrating erosion of the channel bed typical of Stage-III degradation. Note the under-cut bank on the right of the 2003 cross-section.

While all three sub-watersheds exhibit signs of degradation, the data illustrate that Type-IV and V reaches are also present throughout the SF LqP River. This indicates that while some sections of these sub-watersheds are experiencing degradation, other sections are in the latter stages of the evolutionary process. Whereas Type-III reaches are characterized as the “degradation stage”, Type-IV reaches mark the exceedance of a threshold in the erosional process due to the combined erosion of the channel bottom along with the channel banks (Figure 4.24). This process produces a deeper and wider channel. Active channel widening occurs through erosion of the previously slumped channel bank material that failed in Stage-III. Bank failure is the result of erosion that undercuts banks causing them to fail (Bledsoe et al., 2002). This is seen in several sites on the Upper and Middle watersheds (Table 4.18). However, channel widening by itself was not a statistically significant process throughout the SF LqP watershed.

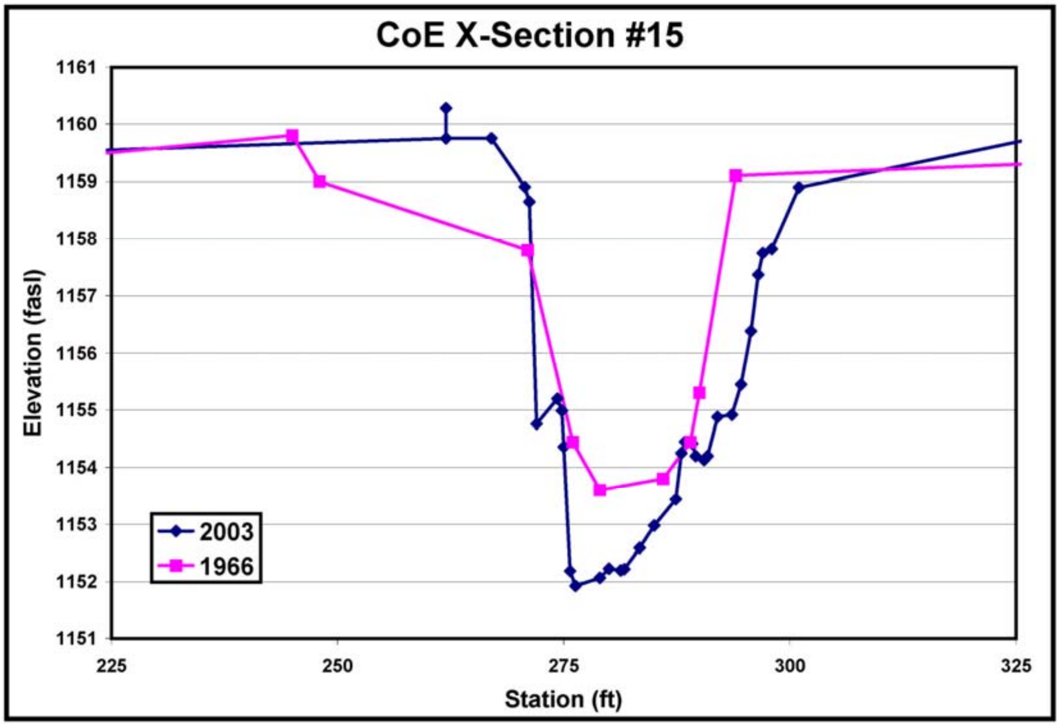

Figure 4.24. CoE XS-15 illustrating down-cutting and widening typical of Stage-IV reaches. Note the recently slumped streambank material at the base of both banks.

Table 4.18. Cross-section #, channel evolutionary stage, and sub-watershed location for 27 sites on the SF LqP River.

XS #	CEM Stage	Watershed	XS #	CEM Stage	Watershed
13	IV	Upper	88	IV	Middle
15	III → IV	Upper	90	V	Middle
19	V	Upper	92	IV → V	Middle
26	III → IV	Upper	97	IV → V	Middle
48	IV	Upper	99	V	Lower
62	III	Middle	100	IV	Lower
66	IV	Middle	101	IV → V	Lower
69	IV	Middle	104	III → IV	Lower
71	III	Middle	105	III → IV	Lower
72	III → IV	Middle	106	III → IV	Lower
74	V	Middle	107	III	Lower
81	IV → V	Middle	109	III	Lower
86	III → IV	Middle	113a	V	Lower
			121	III → IV	Lower

In addition to the presence of Stage-III and IV reaches, four (4) reaches appear to have progressed to Stage-V development; XS-74, XS-81, XS-92, and XS-97. Stage-V reaches are characterized by the aggradation of material on the channel bed (Simon and Hupp, 1986). Upon bank failure in Stage-IV, a new source of sediment has been introduced into the reach. The reach moves from a sediment starved system to a system that now exceeds its ability to transport sediment. This results in channel aggradation and produces Stage-V reaches with a nearly trapezoidal cross-section shape, and a width-depth ratio higher than the Stage-III reaches. While all four of these sites exhibit evidence of aggradation, only XS-90 appears to have clearly evolved past the threshold stage into the aggradation stage (Figure 4.25).

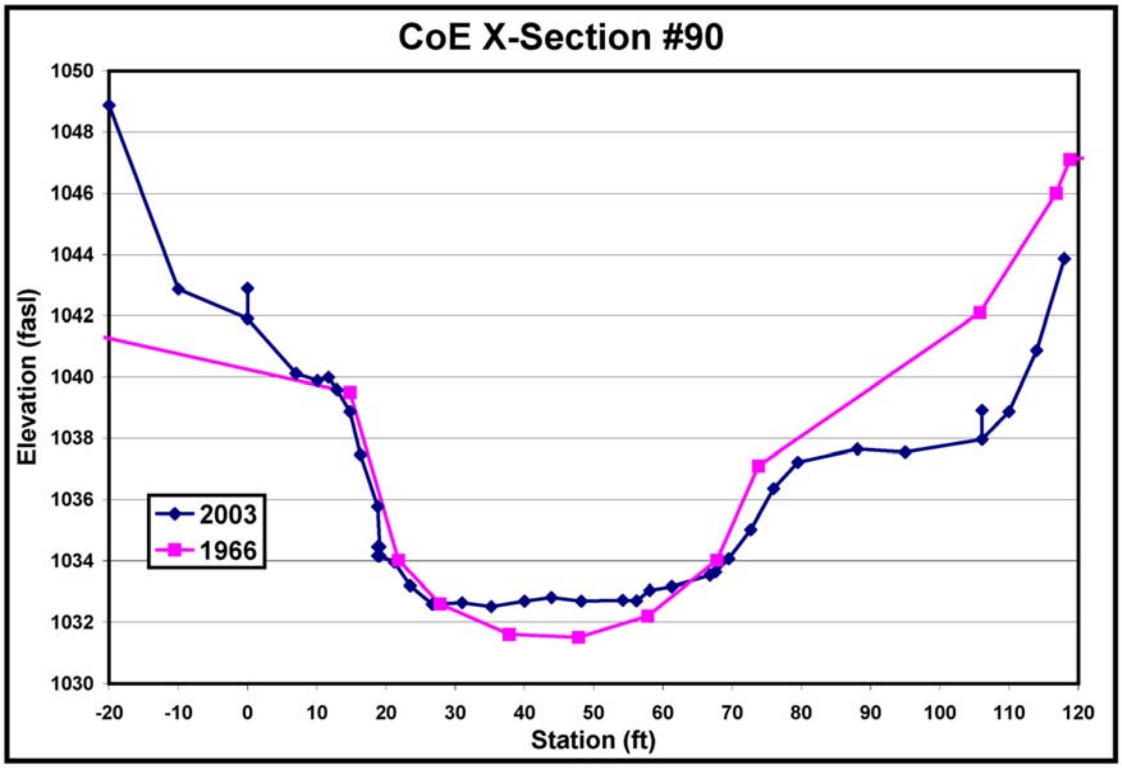

Figure 4.25. CoE XS-90 illustration the accumulation of new material on the channel bed since the 1965/66 survey.

Furthermore, the results from this research document changes in channel morphology since the 1965/66 CoE survey. This suggests that another process is responsible for enlarging channel cross-sectional area 1.3x over the 37-yr time frame. Additionally, if channel cross-sectional area is 1.3x greater today than 1965/66, and cultivation alone is responsible for a 1.3x increase in cross-sectional area, than today's channel cross-sectional area is at least 2.6x to 2.8x larger now compared to pre-settlement conditions.

Conclusions

The analysis has shown that channel morphology has changed between 1965/66 and 2002/03 on the SF LqP River. Significant changes in channel cross-sectional area, mean depth, maximum depth, and W/D ratio were noted in the Middle and Upper watersheds. W/D results indicate the channel down-cut between 1965/66 and 2002/03 in the Middle and Upper watersheds. These results were supported by the analysis of the channel width, mean depth and maximum depth. No significant change in channel width was noted throughout the SF LqP watershed. However, channel depth, both mean and maximum, showed significant increases in both the Middle and Upper watersheds. Mean depth increased 0.7-ft in the Middle watershed and 0.8-ft in the Upper watershed. All changes were significant at the 95-% confidence level.

Land use changes between 1965/66 and 2002/03 may explain some of the impacts. Alterations to channel morphology from the construction of a by-pass channel were noted at two sites, XS-39 and XS-40. Minor channel straightening was also noted at river mile 70.2 between cross-sections 21-22, at river mile 60.5 between cross-sections 41-42, and at river mile 59.0 between cross-sections 42-44. River cutoffs shorten channel length and increase channel slope. This may reduce the time to concentration and increase the peak discharge for a storm event of the same magnitude. While channel loss at these locations may explain changes to the channel morphology at XS-21 and XS-43, impacts to channel morphology were still significant at the 99 % confidence level after removal of these sites from the analysis.

Although significant changes in channel morphology were noted at grazed sites, cattle grazing alone does not explain the impacts noted to channel morphology at grazed sites. Research has shown cattle grazing causes channel widening, not deepening (Knox, 2001; Kondolf, 1993; McLean, 1994; Naiman et al., 1993; Naiman and Roberts, 1997; Trimble and Mendel, 1995). Furthermore, channel widening impacts have been shown to last for several decades (Kondolf, 1993; Magilligan and McDowell, 1997). The channel deepening trend documented in this research is contradictory to the channel widening trend reported in the literature, and implies the channel deepening noted in this study are the result of other land use changes/activities within the SF LqP watershed.

Changes in the width of the riparian corridor were shown to have significant impacts at one site, XS-62. All other cross-sections sites occurred where no significant changes in the width of the riparian corridor were noted.

Changes in channel morphology indicate the SF LqP River is in a state of disequilibrium with various stages of the CEM present throughout the Lower, Middle and Upper watersheds. The random distribution of CEM stages suggests the impacts to channel morphology are the result of multiple disturbances/impacts within the SF LqP watershed. Analysis of the CER indicates the degree of channel enlargement within the SF LqP watershed is caused by other land use changes besides cultivation. CER values reported for this study are similar to those reported for urbanized areas with sewers. Agricultural drainage in a rural landscape appears to impact stream channel morphology in a manner similar to sewers on an urbanized landscape. Additionally, increases in the peak flow associated with the 1.5-year recurrence interval correspond with increases reported by Leopold due to the impacts of urbanization. Increases in the Q/P ratio of 30 percent corresponds to a 30 and 14 percent increase noted in the channel cross-sectional area of the Upper and Middle watersheds respectively. Additional analysis also suggests that pending changes in the 1985 Farm Bill may have had unintended consequences and resulted in more wetlands being drained to avoid impacts of the legislation. The 1.3x to 1.6x increase in the channel forming discharge post-1984 corresponds well with the 1.3x increases described by Leopold. Higher discharge has caused a change in the channel morphology of the SF LqP River resulting in an unstable channel. These results suggest that agricultural drainage has impacted the stream channel morphology of the SF LqP River, but the temporal changes have yet to be determined.

Stream channels exist in a state of dynamic equilibrium. They respond to changes within their watershed that impact the timing and amount of precipitation making its way into receiving waters (Cianfrani et al., 2006b; Dunne and Leopold, 1978; Fitzpatrick et al., 1999; Harvey and Watson, 1986; Magilligan and McDowell, 1997; Magner and Steffen, 2000; Schumm et al., 1984; Williams, 1978). The use of agricultural drainage, both surface and sub-surface have been shown to change the timing and amount of precipitation making its way into receiving waters (DeLaney, 1995; Fraser and Fleming, 2001; Manguerra and Garcia, 1997). This research has shown significant increases in the mean channel depth, maximum channel depth, and cross-sectional area of the SF LqP River, MN from 1965/66 to 2002/03. Analysis of land use impacts over this same time frame indicate that the 35-percent increase in surface tile inlets and subsurface tile drainage is the most likely cause for the these changes in channel morphology on the SF LqP River.

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Chapter 5: Natural Channel Design for Agricultural Ditches in SW Minnesota

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Agricultural drainage ditches are a common occurrence throughout the Minnesota River Valley. Current ditch construction utilizes a trapezoidal form engineered to contain both small and large volume flows. However, following high flows, sediment accumulation in the channel bottom necessitates periodic channel cleaning. This (inefficient) design results in annual costs to local governments and private citizens. Joint research by the University of Minnesota (UMN) and Minnesota Pollution Control Agency (MPCA) investigated the use of a "compound" channel design to reduce and/or eliminate the need for periodic ditch maintenance. Compound channels incorporate smaller, self-maintained, "natural" channels within the larger flood channel geometry. An 800-m section of Judicial Ditch #8 (JD #8) in Swift County, MN was over-widened during routine cleanout maintenance. The over-widening allowed a smaller, low-flow channel with an active floodplain to establish within the larger flood channel. Measurements indicate a naturally stable B4 channel has developed within the larger flood channel. The smaller, stable channel allows for higher velocities during low flow conditions that efficiently move water and sediment. The ability of this channel design to transport sediment represents a potential savings in periodic clean-out maintenance. Additional benefits include enhanced fish and lowland bird habitat.

Introduction

The use of natural channel design for the restoration of degraded stream channels is based on an understanding of the fluvial geomorphic processes operating within a watershed. While extensive work has been performed on natural channels, less thought has been extended to its application on agricultural ditches. Agricultural ditches are man-made structures designed to move water through a watershed where natural drainage features are lacking. Typical drainage ditch design incorporates a trapezoidal channel shape (Figures 5.1 and 5.2) devoid of any natural stream channel morphology. This criteria is contrary to those established for natural channel design and creates a dysfunctional water and sediment transport system.

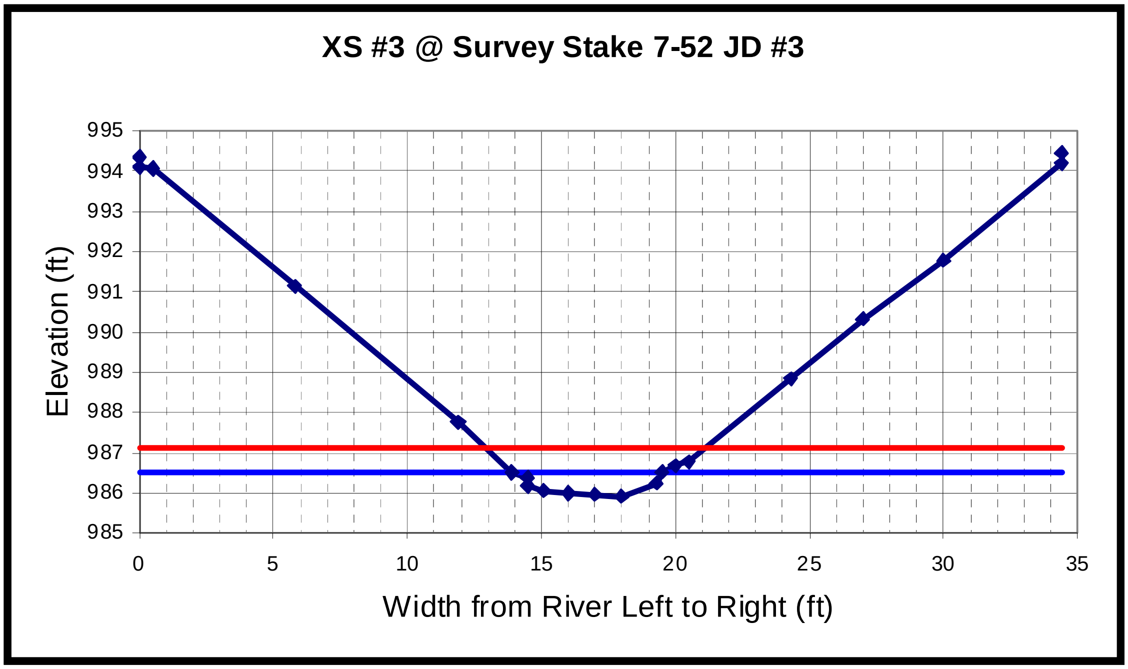


Figure 5.1. Cross-section of typical trapezoidal channel design. Judicial Ditch #3 (JD #3), Murray County, MN.

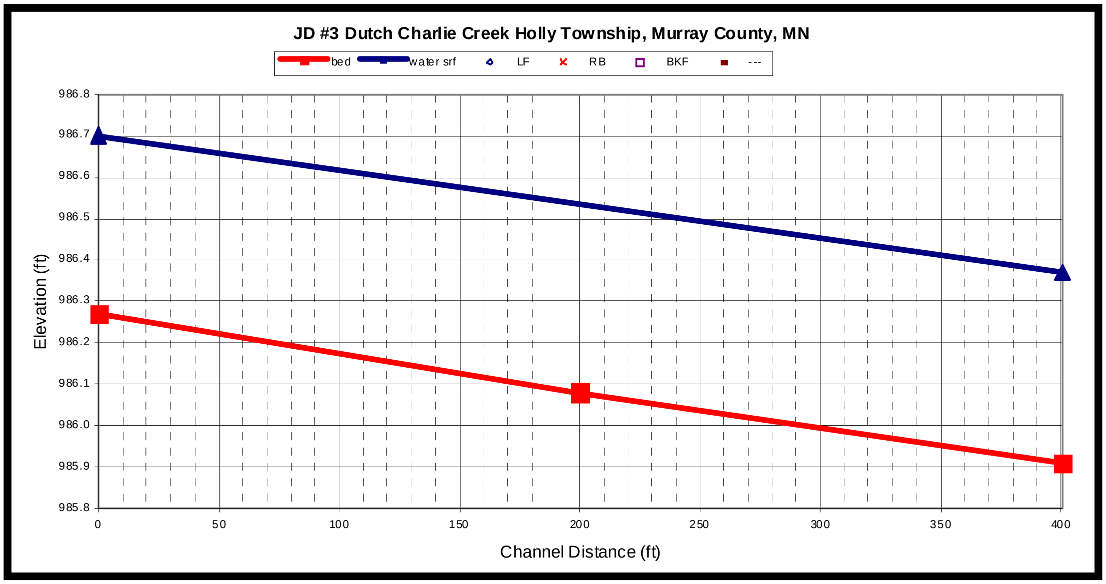


Figure 5.2. Longitudinal profile of typical drainage ditch design, JD #3 Murray County, MN.

Natural channel design is based on the fundamental concept that stable stream channel morphology is determined by the channel forming or bankfull discharge (Q_{bkf}). This discharge is associated with a more frequent return interval, generally between 1 to 2 years (Leopold et al., 1964). Agricultural ditch construction does not consider this design criterion. Agricultural drainage ditches are designed; "…to carry the maximum anticipated flow when filled to 80% of their depth" (Troeh et al., 1991). Return intervals associated with these discharge values occur less frequently and are typically greater than 50 years. Consequently, agricultural ditches require periodic clean-out maintenance to remove sediment that accumulates due to improper channel design (Figure 5.3). Chippewa County, MN estimates average annual ditch maintenance costs between $65-$115 per linear foot (Magner, 2001). Ditch cleaning is a common land improvement practice performed in SW Minnesota (Figure 5.3).

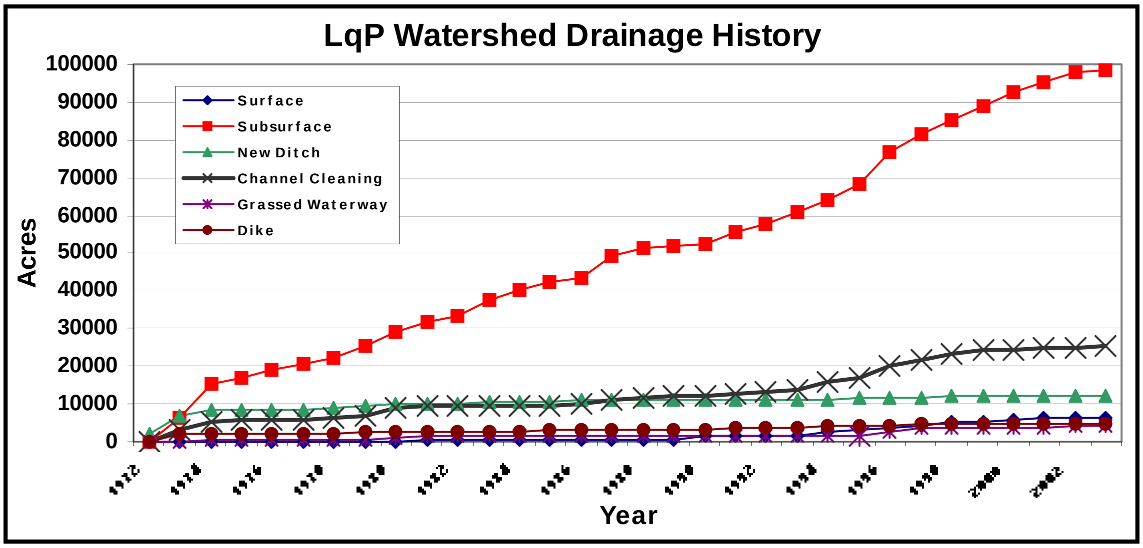


Figure 5.3. Six most common land improvement practices performed in the South Fork Lac qui Parle watershed between 1972-2003 and the number of affected acres.

Methods

In order to apply natural channel design principles to agricultural ditches, a suitable reference reach must exist. This reference reach provides design data on channel dimensions such as: width, depth, slope, velocity, particle size distribution, sediment load, and discharge necessary to maintain a stable channel or, in this situation, ditch. Since agricultural ditches are man-made structures, no "natural" ditches exist. This makes collecting the required reference data problematic. A solution to this problem was inadvertently constructed in Swift County, MN. A 0.8 km section of Judicial Ditch #8 (JD #8), was over-widened during routine clean-out maintenance. The over-widening produced a wider, U-shaped channel. The new and wider channel allowed the low-flow channel in JD #8 room to meander and establish its own dimension, pattern, and profile along with an active floodplain.

A Topcon self-leveling laser was used to collect longitudinal and cross-sectional data during the summer of 2001. Channel metrics were collected for the natural section of JD #8 and two trapezoidal sections, one immediately upstream, and the other a tributary to

JD #8 henceforth referred to as the Middle Fork Trapezoidal. A total of seven (7) cross-sections and three longitudinal profiles were surveyed after methods described by Harrelson and others (Harrelson et al., 1994). Each cross-section was classified to determine the presence of a natural channel design (Rosgen, 1996). Particle size distribution for each cross-section was determined after methods described by Wolman, (Wolman, 1954). Meander geometry data (Figure 5.4) were directly measured in the field. Radius of curvature values were determined according to equation 5.0.

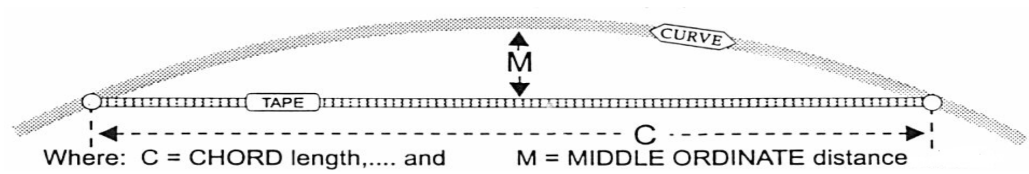


Figure 5.4. Radius of curvature measurements (after Rosgen, 2001).

Equation 5.0 $$Rc = \left(C^2 / 8M\right) + \left(M / 2\right)$$

Where: R_c equals the radius of curvature

C equals the chord length

M equals middle ordinate length

Results and Discussion

Data collected from the cross-sectional and longitudinal surveys confirm the over-widened section of JD #8 has shifted from a trapezoidal channel design to a channel that exhibits natural facets. The channel morphology established in this 0.8 km reach is a direct result of the hydrologic conditions operating within the watershed. Data collected in the natural reach of JD #8 confirm the development of a moderately entrenched B4 channel type (Figure 5.5) with low sinuosity (Rosgen, 1994). This natural channel is contrasted by an entrenched trapezoidal channel type, with no sinuosity immediately upstream (Rosgen and Silvey, 1996). Four reaches were classified to determine channel morphology: cross-sections 2, 4, and 6 on the natural reach, and the trapezoidal cross-section (Table 5.1). Differences in channel morphology between the natural and trapezoidal reaches are related to differences in the width of the floodplain (W_{fpa}), channel depth (d_{max}), and sinuosity (Table 5.1). The natural and trapezoidal reaches are similar only in their bankfull cross-sectional areas (A_{bkf}). All other channel forming variables are distinctly different due to the over-widening of JD #8 that resulted in a larger floodplain. Consequently, the natural reach is less entrenched than the trapezoidal reach with an entrenchment ratio (ER) of 2.5, 2.1, and 2.2 compared to an ER of 1.2 for the trapezoidal reach. The entrenchment ratio is defined as the vertical containment of a stream (Kellerhals et al., 1972). The ER indicates the degree to which a stream is incised in the valley floor and its ability to access the floodplain. Entrenched streams have limited access to their floodplains. Because of its lack of entrenchment the natural channel on JD #8 has created a low-flow channel able to access its floodplain through a greater range of flows. Additionally, the low-flow channel produces higher velocities during base flow conditions than the wider trapezoidal channel. Higher base flow velocities result in better sediment transport. The wider trapezoidal channel design produces lower velocities at base flow, which reduces its ability to transport sediment. This results in sediment deposition and leads to periodic cleanout maintenance. Sediment deposition also has implications for the quality of aquatic habitat.

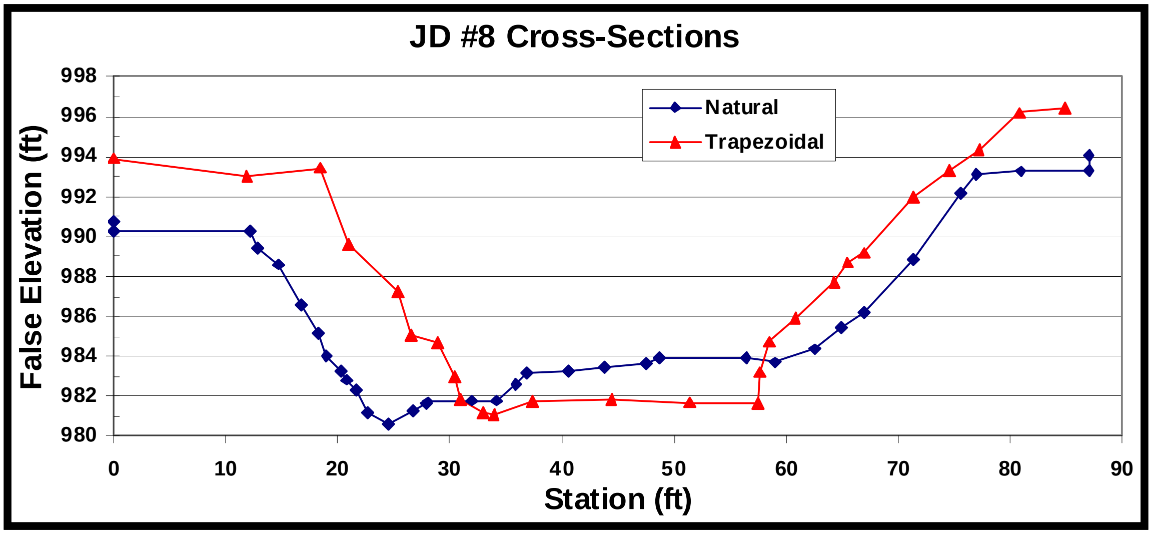


Figure 5.5. Cross-sections on JD #8 illustrating the differences in channel area of the natural and trapezoidal reaches.

Table 5.1. Channel metrics for JD #8 (All measurements in feet or square feet).

Location	A_{bkf} (ft^2)	W_{bkf} (ft)	W_{fpa} (ft)	d_{max} (ft)	d_0 (ft)	***Sinuosity***	W/D	ER	Rosgen Stream Type
JD#8 Trapezoidal	41.1	27.5	33.0	2.2	1.7	1.0	18	1.2	F5
JD#8 New #1	41.4	24.6	61.0	3.3	1.7	1.2	14	2.5	C4
JD#8 New #2	43.8	29.6	53.0	3.4	1.5	1.2	20	1.8	B4
JD#8 New #3	45.1	25.1	53.5	3.3	1.8	1.2	14	2.1	B4
JD#8 New #4	43.9	31.6	45.0	2.4	1.4	1.2	23	1.4	B4
JD#8 New #5	43.9	25.8	56.0	3.3	1.7	1.2	15	2.2	B4
JD#8 New #6	54.1	32.8	47.4	2.9	1.6	1.2	21	1.4	B4

In addition to the differences in channel dimension and profile, the natural channel exhibits greater sinuosity than the trapezoidal channel with sinuosity values of 1.2 and 1.0 respectively. The meander geometry associated with this sinuosity supports the presence of a stable B4 channel on JD #8. Table 5.2 contains radius of curvature values collected at 9 meander bends on JD #8. Figure 5.6 illustrates the relationship between channel pattern (radius of curvature) and channel dimension (bankfull: depth, width, and cross-sectional area). The mean radius of curvature (R_c) value plotted in Figure 5.6 agrees with the established relationships, indicating a stable channel design for JD #8. Mean bankfull depth for JD #8 equals 0.5m (1.6 ft), mean bankfull width equals 8.6m (28.2 ft), and mean bankfull cross-sectional area equals 4.4 m^2 (47.4 ft^2).

Table 5.2. Radius of curvature values for JD #8.

Site	R_c	
	(m)	(ft)
1	11.1	36.4
2	13.2	43.3
3	16.5	54.1
4	18.1	59.4
5	15.8	51.8
6	14.0	45.9
7	16.8	55.1
8	19.3	63.3
9	26.1	85.6
Average	16.8	55.1

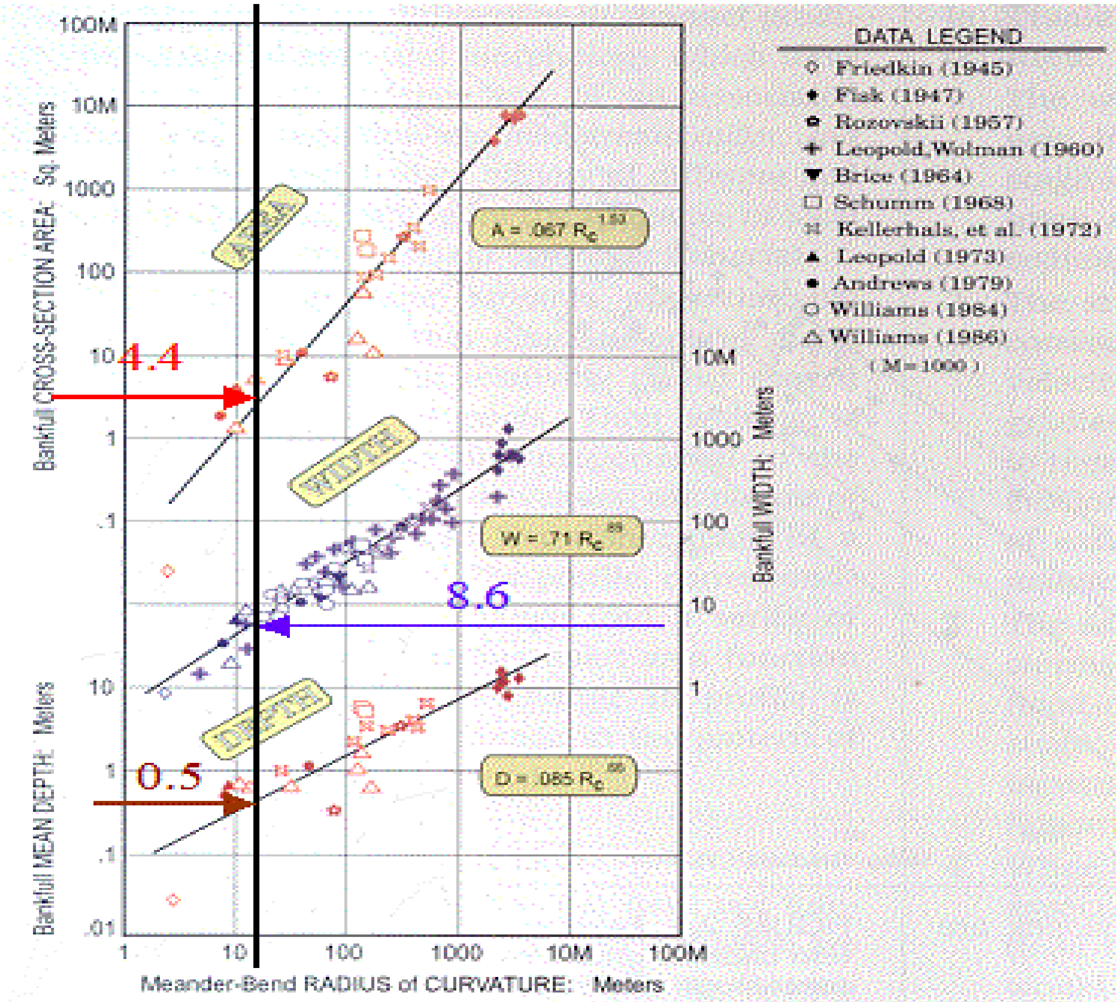
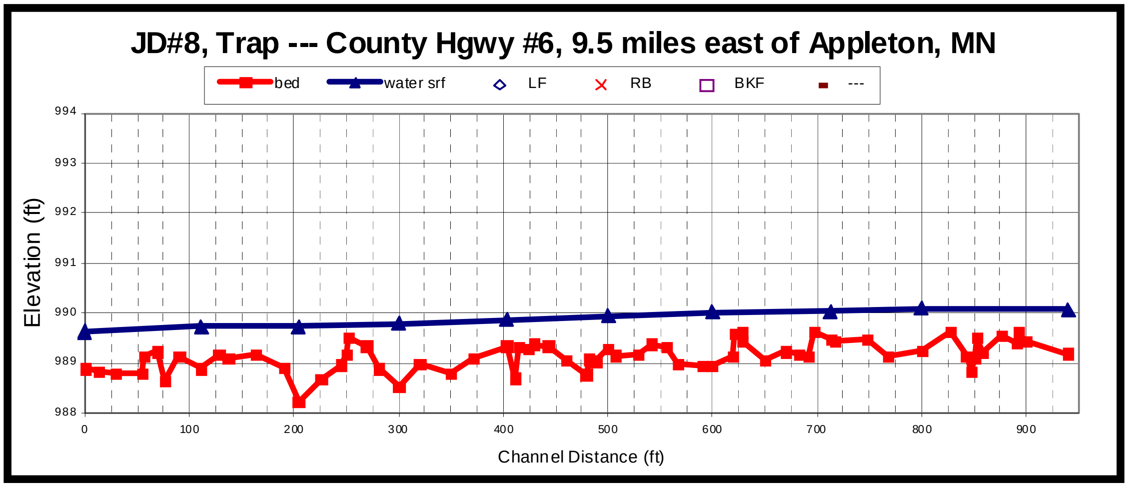


Figure 5.6. Relation of radius of curvature to channel dimensions for JD #8 (In Rosgen 1996, after Williams 1986).

All six cross-sections in the new reach of JD #8 have similar bankfull channel areas. However, while average depth of the trapezoidal and natural reaches are similar with values of 1.7 feet and 1.6 feet respectively, the maximum depth (d_{max}) of the trapezoidal channel is 2.2 feet, an increase of 23 %. This is contrasted by a 53 % increase in the depth of the natural reach with a maximum depth of 3.4 feet. The longitudinal profile in Figure 5.7 illustrates the difference in channel bottom variability and residual pool depth.



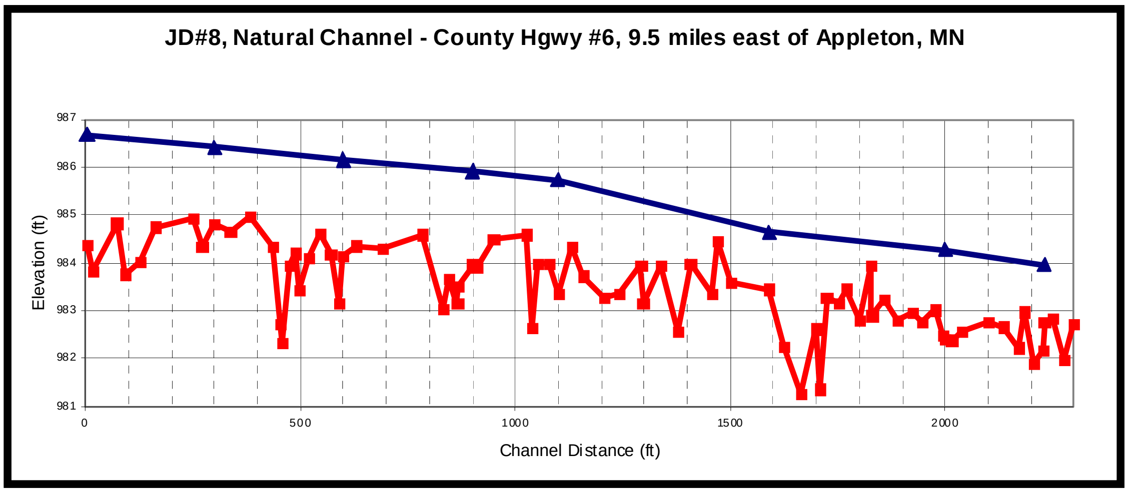


Figure 5.7. Longitudinal profile of the trapezoidal (upper) and natural (lower) reaches on JD #8. Note the greater channel variability in the natural reach.

Residual pool depth is the difference in streambed elevation from the pool top to the pool bottom, and indicates the aquatic habitat available to fish. Streams with greater variability (i.e. deeper pools) provide better habitat and buffer in-stream temperature changes (Harper and Everard, 1998; Shields et al., 2000).

The natural reach on JD #8 offers the best overall fish habitat with the highest mean residual pool depth of 1.2 feet, and greatest residual pool depth variability of 0.21 feet (Table 5.3). Mean residual pool depth for the trapezoidal reach varies from 0.6 feet in the Middle Fork, to 0.8 feet in the Main Fork. Low residual pool depth limits the ability of a trapezoidal channel to provide aquatic habitat and buffer changes in water temperature which may result in fish mortality (Kohler and Hubert, 1999).

Table 5.3. Comparison of residual pool depth data for trapezoidal and natural sections of JD #8 (All measurements in feet).

Feature	Middle Fork Trapezoidal	Main Fork Natural	Main Fork Trapezoidal
Count	20	18	10
Minimum	0.3	0.5	0.2
Maximum	1.5	2.0	0.8
Mean	0.8	1.2	0.6
Variance	0.13	0.21	0.04

Another indicator of aquatic habitat is channel substrate size. Figure 5.8 illustrates the difference in channel substrate between the natural and trapezoidal reaches on JD #8. Seventy-two percent of the sediment in the trapezoidal reach is 1.0 mm in size or less. The same particle size accounts for only thirty-seven percent in the natural reach. Additionally, the D_{90} particle in the trapezoidal reach is 2 mm, compared to 32 mm in the natural reach. Greater channel substrate variability results in better aquatic habitat (i.e. better riffle quality where quality refers to well-aerated riffle w/o fines clogging interstitial spaces). It also indicates the natural channel is actively transporting finer sediment. This is important from a maintenance perspective. Self-maintaining channels do not require periodic cleanout maintenance. This can translate into substantial savings in county monies.

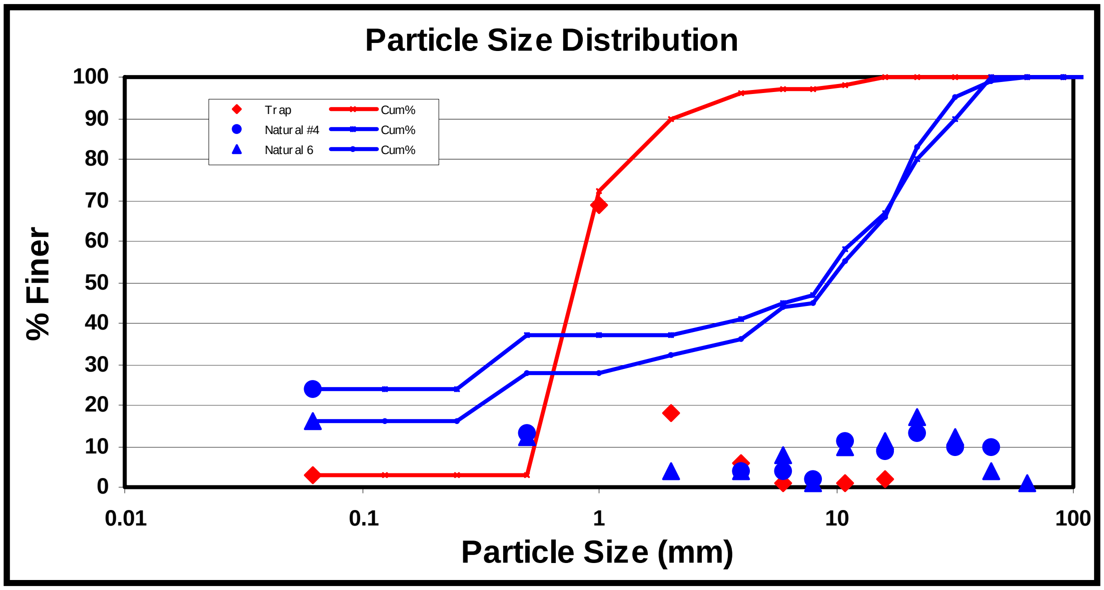


Figure 5.8. Particle size distribution for JD #8.

One of the main drawbacks of agricultural ditches, from a landowner's perspective, is the amount of land they remove from production (Troeh et al., 1991). Any proposed change in ditch design must address the amount of land required to maintain the design. Meander belt width (W_{belt}) describes the lateral extent of river meander, or the amount of land required to maintain the channel design. The average meander belt width of the natural channel on JD #8 is 52.7 ft. with a maximum value of 61.0 ft. (Table 5.4). The meander width ratio (MW_r) is the ratio of the meander belt width to the bankfull channel width (W_{bkf}) and describes the degree of lateral channel containment. The average meander width ratio for JD #8 is 1.9 with a maximum value of 2.5. This indicates the natural channel on JD #8 requires 53.8–70.8 ft to maintain the channel belt width. Current meander belt width of the trapezoidal channel on JD #8 varies between 68.0-80.0 ft. This is 9.2 ft more the required meander belt width of the natural channel design. This indicates that at this watershed scale natural channel design can be accomplished without removing any more land from production.

Table 5.4. Meander width ratio data for JD #8 (All measurements in feet.).

Site #	W_{bkf}	W_{belt}	MW_r
1	24.6	61.0	2.5
2	29.6	53.0	1.8
3	25.1	53.5	2.1
4	31.6	45.0	1.4
5	25.8	56.0	2.2
6	32.8	47.4	1.4
Average	28.3	52.7	1.9

Conclusions

The natural section of JD #8 displays a large variance in channel width and depth throughout the reach indicating the existence of a variety of channel morphology and aquatic habitat. The meandering, natural channel represents a stable channel design or dynamic equilibrium in the morphology of JD #8. Since stable channels develop as a result of the current hydrologic conditions operating within a watershed they are able to efficiently transport the water and sediment delivered to the stream, through the watershed, without aggrading or degrading (Rosgen and Silvey, 1996). The ability to transport sediment represents a potential savings in public and private monies spent on ditch clean-out maintenance.

There are more than 27,000 miles of open agricultural ditches in Minnesota (Taff, 1998). Chippewa County, MN spends an average of $65-$115/ft on annual ditch maintenance (Magner, 2001). Application of natural channel design to agricultural ditches in Minnesota has the potential to offer substantial savings to public and private entities through reduced ditch maintenance costs without the need to remove any additional land from production.

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Chapter 6: Conclusion and Recommendations for the South Fork Lac qui Parle River and Its Watershed

Conclusions

This research investigated the relationship between land-use changes in the SF LqP watershed and corresponding changes in stream channel morphology. Land use results show significant changes in cropping practices and agricultural land improvement (drainage); but only slight changes in the amount of non-agricultural land use within the riparian corridor.

Native vegetation in the riparian corridors of the Middle and Upper SF LqP watersheds have both increased 13-percent from 1967 to 2000. The Upper watershed added 227 acres while the Middle watershed added 80 acres. Crop diversity has steadily declined from a 13-crop mix dominated by corn from 1911 thru the 1940s, to the present-day 2-crop rotation dominated by corn and soybeans. As crop diversity declined, the amount of agricultural drainage (surface and sub-surface) installed within the SF LqP watershed has steadily increased. A total of 104,680 acres (49-percent) of the watershed have had agricultural drain tile installed. Current rates indicate that sub-surface tiles are installed on 3,088 acres every year.

A second aspect of this research investigated the precipitation and discharge records for the SF LqP watershed. Results from this analysis indicate that average monthly precipitation from 1911-1960 is not significantly different from the average monthly precipitation from 1961-2003. A parallel analysis of the discharge record on the SF LqP River indicates stream flow associated with the 2-yr event has increased between 30 to 51-precent post-1960 compared to pre-1960. A combined analysis of the discharge generated from similar precipitation totals (Q/P ratio) indicates there has been an 18-precent increase post-1960 compared to pre-1960. These results suggest that while the riparian corridor increased in size, stream flow generated from similar precipitation totals increased, and is counterintuitive to the established theory that increasing the size of the riparian floodplain and re-establishing native riparian vegetation helps reduce the peak flows associated with more frequent flows (Auble et al., 1994; Lowrance et al., 1984;

Parsons et al., 1998; Scott et al., 2000; Zaimes et al., 2006), and indicates that some mechanism has facilitated the movement of precipitation off the landscape post-1960 and by-passed the riparian buffer.

Land-use analysis showed an increase of 49-percent in the amount of agricultural drainage installed since 1972, the first year records were logged. Since the Q/P ratio increased 18-percent post-1960, and agricultural drainage increased 49-percent while crop diversity declined; it is reasonable to conclude that these land use activities appear to contribute to the movement of water off the landscape into receiving waters. The purpose of agricultural drainage is to remove water from the landscape in order to farm/work the land (Anderson, 2001; DeLaney, 1995; Fraser and Fleming, 2001). Previous research has demonstrated how agricultural drainage increases stream flow (Anderson, 2001; Anderson, 1998; Bengston et al., 1995; Fraser and Fleming, 2001; Isenhart et al., 1997; Mickelson, 2001). Surface tile inlets and subsurface tile drains remove water from the soil surface and soil profile respectively, and transport it to receiving waters. Since surface tile inlets and subsurface tile drainage facilitate the movement of water off the landscape and into receiving waters, and the amount of drainage (surface tile inlets plus subsurface tiles) in the SF LqP watershed has increased 35-percent since 1972, it seems logical to conclude that surface tile inlets and subsurface tile drainage contributed to (caused) the increase in the Q/P ratio of the SF LqP watershed. The increase in surface tile inlets and subsurface tile drainage is the only notable change to occur within the SF LqP watershed that would facilitate, and expedite, the movement of water off the landscape and cause the noted increases in discharge documented in this research.

While the 30 to 51-percent increase in post-1960 flow for the 2-yr event has the capacity to alter the channel morphology of the SF LqP River, post-1984 flow increases were greater (33 to 54-percent) and concentrated in the more frequent flows (1.25-yr through the 2.5-yr event). The 2-yr flow corresponds to the return interval associated with the bankfull discharge (Griffin, 1996; Olsen et al., 1997; Rosgen, 1996; Wolman and Miller, 1960). Bankfull discharge, also known as the channel forming discharge, is the discharge that, over time, carries the most sediment and performs the majority of the channel maintenance work (Austin and Gracie, 1996; Griffin, 1996; Leopold, 1997;

Leopold et al., 1964; Walling and Webb, 1998; Williams, 1978; Wolman and Miller, 1960). The increases noted in the channel forming discharge post-1984 correspond well with the enactment of the 1985 Farm Bill and may indicate increased wetland drainage activity in response to the enactment of the 1985 Farm Bill.

Streams exist in a state of dynamic equilibrium. They respond to changes within their watersheds through adjustments in their dimension, pattern and profile (channel morphology). Analysis of the channel morphology of the SF LqP River in 2002/03 indicates several changes to channel morphology have occurred since the CoE flood control survey in 1965/66. These changes include:

- Increase in cross-sectional area
- Increase in channel depth, (both mean and maximum) and,
- Decrease in the width-to-depth (W/D) ratio

These results are significant at the 95% CI and support the theory that changes in stream channel morphology of the SF LqP River are the result of increased runoff due to the installation of surface tile inlets and sub-surface tile drainage in the SF LqP watershed.

Recommendations

1. Create a GIS database for the watershed that shows the location of all the drainage. The old adage "you don't know what you don't know" applies here. You can't begin to address problems within the watershed until you have all the data. The data exist; they just need to be gathered from the land improvement permits in the County Environmental office.
2. Determine when the channel shortening activities took place in the SF-LqP River. Knowing when the channel segments were shortened would provide insight into the total impact these activities had on channel morphology.
3. Focus restoration efforts on the Middle watershed first. The Middle watershed has the highest variability in channel morphology and stability. Restoration efforts will realize more "bang for the buck" implementing projects in the middle watershed because it is more disturbed. The channel is also more entrenched in

the Middle watershed. Reducing and/or eliminating channel entrenchment will provide multiple benefits (see #3 below).

4. Incorporate the compound channel design in restoration designs. This design will provide a floodplain for the channel. Floodplains provide numerous benefits such as physical and chemical filtering. Chemical filtering will provide nutrient attenuation, which is especially important in an agricultural watershed. The compound design will also reduce channel entrenchment and the erosive velocities associated with entrenched streams. This will eliminate undercut banks and reduce sediment load contributions from channel bank material.
5. Eliminate cattle grazing within the stream channel. Giving cattle access to the stream channel is poor land management. Cattle destroy streambanks by hoof-shear action (Figure 6.1). Continued grazing leads to over-widened channels. Provide alternative water sources away from the stream channel and fence them out via exclusions if needed. If they are given access to the channel area it needs to be limited. Proper grazing management needs to be practiced with the correct amount of rest-rotation.

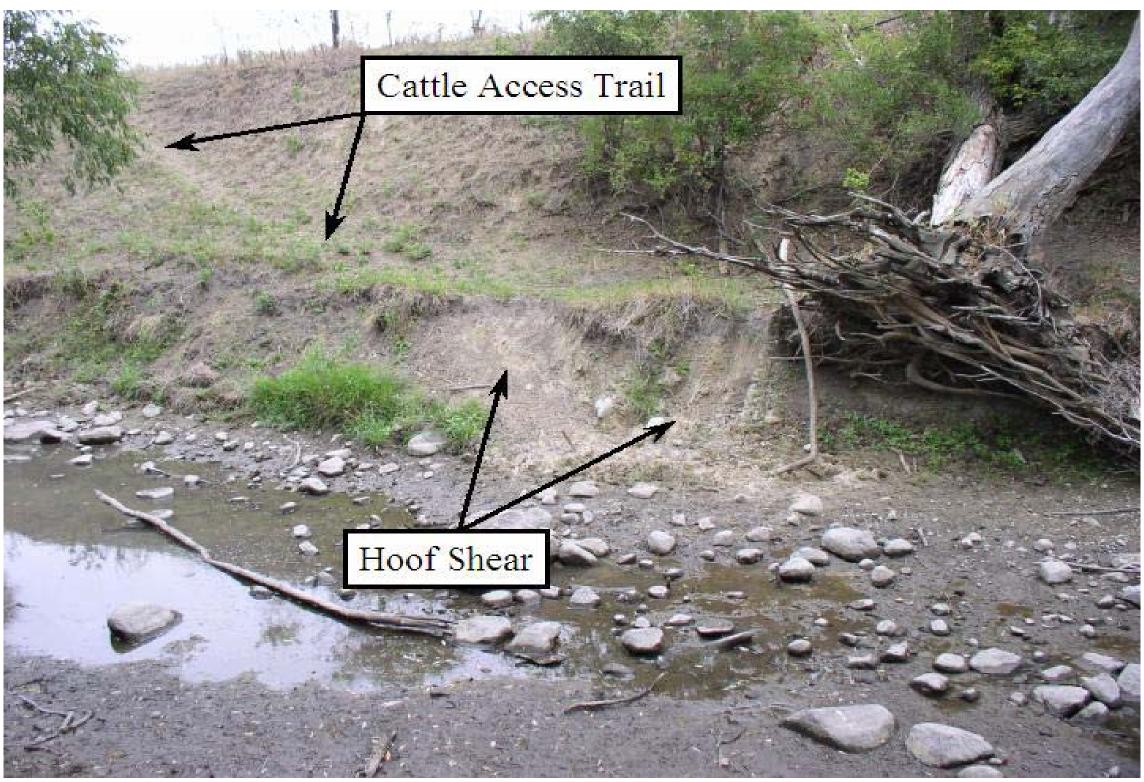

Figure 6.1. Stream channel impacts at XS-74 after one season of cattle grazing.

6. Properly size box culverts at road crossings. I noted at least four (4) box culverts within the Upper watershed that were oversized for the channel. A 3-section box culvert is 60-ft wide. Channel widths in the upper reaches of the Upper watershed are 30 to 40-ft wide. Installation of 3-box systems over-widens the channel. This reduces the competence and capacity of the channel to carry sediment and results in sediment deposition (aggradation). Several box culverts were half-filled with sediment; some were actively being cleaned out because they were viewed as being “plugged” (Figure 6.2).

Figure 6.2. Sediment accumulation in a box culvert at U.S. Army Corp of Engineer’s bridge #23 in the Upper watershed of the South Fork Lac qui Parle River.

7. Promote increased crop diversity. Currently the watershed is dominated by a 2-crop rotation of corn-soybeans. This mono-cultural has been show to have negative impacts on soil quality, soil fertility, crop yields, weed control, plant vigor, and water use efficiency (Anderson, 2006; Tanaka et al., 2005). This will require outreach education, marketing, and possible financial incentives.

8. Step-up the outreach education in the watershed. Numbers 4, 5 and 6 above are good examples of how outreach education can help. Cleaning out a “plugged” culvert may seem like a good idea, but it will only fill again with more sediment. Cattle grazing in the stream channel is not a good land management practice. And promoting crop diversity can be a win-win situation. Landowners need to be educated and they need financial assistance to institute alternative practices.

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APPENDIX A

Control Point Survey

Control Point Generated Public Land Survey (PLS) lines, Minnesota Department of Natural Resources (MNDNR) Data Deli

Full Description
- **Identification Information**
- **Data Quality Information**
- **Spatial Data Organization Information**
- **Spatial Reference Information**
- **Entity and Attribute Information**
- **Distribution Information**
- **Metadata Reference Information**

Brief Description
Attributes
Sample
Data Use Contact
Distribution Contact
Process to Transfer Land Improvement Permit Data into Public Land Survey File

Lac qui Parle County Totals

Yellow Medicine County Totals

Lac qui Parle Watershed Totals

Control Point Generated PLS – lines

Full Description

Home | Data Catalog | Download Data | Data Status | Web Services | About | FAQ | Contact Us

SECTION 1: Identification Information

Originator:	Minnesota DNR -Land and Minerals Division
Title:	Control Point Generated PLS - polygons
Metadata Product ID:	23000001
Abstract:	The Control Point Generated PLS layer contains line and polygon features to the 1/4 of 1/4 PLS section (approximately 40 acres) and government lot level. The layer was created using the most accurate information available at the time, including Government Land Office plat drawings and survey notes, official resurveys, and PLS control points from the DNR's Control Point Inventory database.
Purpose:	Detailed PLS forty level mapping at a 1:24,000 scale of any information geo-referenced to the Public Land Survey System, especially land ownership and management. It can also be used as a general PLS reference map for any other data projected into UTM - meters, extended zone 15, NAD83.
Usage Tips:	The most accurate comprehensive PLS source at the DNR. The positional accuracy of the data varies greatly, and ranges from 40 feet to sub-meter accuracy in some areas.
Time Period of Content:	1991
Currentness Reference:	Data is derived from sources dating continuously from mid-nineteenth century survey notes to results from current modern surveys.
Progress:	in work
Maintenance Frequency:	Eventually
Spatial Extent of Data:	Minnesota
Bounding Coordinates:	E = -89 W = -97.5 N = 49.5

	S = 43
Place Keywords:	Minnesota
Theme Keywords:	PLS, Public Land Survey, Townships, Sections, Forties, Government Lots, planningCadastre
Theme Keyword Thesaurus:	None
Access Constraints:	None
Use Constraints:	Use of the data are constrained only by the DNR GIS Data License Agreement
Data Use Contact:	Contact
Sample Graphic:	Data Sample

SECTION 2: Data Quality Information

Attribute Accuracy:	*pls_fortypy3.pat:* Polygon attribute information is independently verified several times throughout the process of creating this data from the Control Point Inventory (CPI) database..
Logical Consistency:	Data are topologically correct using ARC/INFO 7.0.3. All polygons are closed and lines intersect where intended.
Completeness:	All available Government Land Office Land Survey notes, plats and resurvey information was used in the creation of this data set. Since the meander line data is being derived from the Government Land Office PLS survey notes, margins around meandered water bodies tend to have a coarse representation and may not accurately reflect the current shape of these features on the ground. Meander lines are NOT land ownership boundaries. The Public Land Survey process was conducted, in part, to inventory the rough acreage of land for the purposes of selling it for agriculture, timber, railroads, etc. Meander lines were used to determine how many acres of land were available for sale at the time, whereas the beds of navigable water bodies are held in ownership by the state. Depending upon when the survey was conducted, surveyors followed different guidelines for what was to be meandered. 'In subdividing any one township, you are to meander as hereinafter directed, any lake or lakes, pond or ponds, lying entirely within the boundaries thereof, of the area of [twenty five to] forty acres and upwards, and which cannot be drained and are not likely to fill up, or from any cause to become dry.' (A Collection of Original Instructions to Surveyors of the Public Lands, 1815 - 1881, Roy Minnick, Landmark Enterprises)
Horizontal Positional	Variable. At its least accurate, the data is based upon points derived from manual digitizing of PLS section corners from 1:24,000 scale

Accuracy: paper media (GISMO and SECTIC-24K points). At its most accurate, the data is based upon points collected using GPS units operating at a sub-meter level of accuracy. Refer to the ACCURACY and METHOD fields in the related PLS Control Point layer (cornrpt3), for specific information.

Vertical Positional Accuracy: Not Applicable

Lineage: Attribute Lineage:

pls_fortypy3.pat: PLS attribute information is added to this data-set after the area features have been built for each township.

Cartographic Lineage:

PLS 40 Areas: The Control Point Generated PLS and PLS Control Points are a subset of the Control Point Inventory (CPI), a database maintained by the DNR, Bureau of Engineering, Survey Section. A majority of the points in CPI came from the GISMO or SECTIC-24K control point data sets. Refer to the metadata for the PLS Control Point layer (cornrpt3) for further information. PLS corner data is extracted from CPI, one township at a time, in State Plane - feet and is used as a starting point for the Control Point Generated PLS layer. The data is then processed , in conjunction with bearings and distances captured from the Government Land Office plats and survey notes, in Cadastral Measurement Management (CMM) software from the Bureau of Land Management. The two procedures used in CMM are AUTOPROP and DXFLSA. AUTOPROP is designed to automatically proportion and subdivide a township down to the level of center of quarter sections. (Cadastral Survey Measurement Management System-Version 1.0 Documentation, March 1991, U.S. Bureau of Land Management.) DXFLSA generates an AutoCAD DXF file that allows the points and lines to be processed using Arc/INFO and Arc/COGO (coordinate geometry). Data files are projected, using a UTM projection, units are meters, extended zone 15, NAD 83. Meander lines are added from the bearings and distances from the original survey notes using Arc/COGO. The township is then further processed to add the necessary PLS attribute information. Individual township coverages are combined into county coverages using the Arc/INFO command mapjoin.

PLS 40 Lines: The TRSQ dataset was developed from a series of client projects conducted at LMIC. The initial effort began in 1990 when the Department of Natural Resources Engineering Division contracted with LMIC to help map federal, state and county lands in Minnesota. This effort, funded by a grant recommended by the Legislative Commission on Minnesota Resources, resulted in the publication of maps identifying public recreational lands. These Public Recreation Inventory Maps (PRIM) used U.S. Geological Survey 1:100,000-scale separations containing information about roads, railroads, rivers and lakes, as well as the basic network of land survey lines. The survey lines consisted of state, county, township, range and section boundaries but not quarter-quarter sections. To prepare a public ownership layer that took advantage of digital information available from DNR and LMIC, LMIC constructed a quarter-quarter section map base that complemented the USGS separations. This was done between 1990 and 1992 for 16 of the 71 quadrangles that cover Minnesota . LMIC used the following procedure: 1. Digitized section lines from USGS 1:100,000 paper maps for the 16 requested 30-by-60-minute quadrangles, 2. Added section corner tics at the intersections of the digitized section lines, 3. Created quarter sections and quarter-quarter sections using the LMIC-developed program GEN40 (undocumented). GEN40 used two sources of information: (a). the section corner coordinates, and (b). a list of the number of government lots within a quarter-quarter section (GLOT List). This undocumented list had been compiled at LMIC in the late 1980s from a 1936 series of annotated maps produced by the Minnesota Department of Transportation and various other sources. If the coordinates indicted that a section was regularly shaped (its section lines were 1,308 feet long) and if the GLOT List did not indicate the presence of government lots, GEN40 evenly bisected the lines connecting the corner coordinates to create quarter-

quarter sections. Otherwise, GEN40 used a default distance of 1308 feet to create as many quarter-quarter sections as possible. 4. Check plots were made and any areas in which the program had extended lines too far or not far enough were noted (this could occur at lake boundaries or at the state boundary). In these cases, lines were manually digitized or clipped to ensure that the survey line network was complete. Government lot boundaries and meander lines around lakes were not digitized. 5. Color check plots at a scale of 1:48,000 were produced in order to compare the features visually with the Minnesota Department of Transportation's 1936 county highway map series (MNDOT Map), which contained information on government lots (see Attribute Lineage for more information). In 1993 and 1994, an additional 38 quadrangles were completed with funding provided by the U.S. Department of Justice, DNR and LMIC. Seven quadrangles were created at the request of the Metropolitan Council. Work began in August 1995 to complete the remaining 10, with funding provided by the Board of Water and Soil Resources, and was completed in 1996. The process for these 56 quadrangles (see Section 1 - Time Period of Content; process = PLSS) was the same as the PRIM process outlined above except that the section lines were digitized from stable base mylar separations instead of paper maps. Following standardization, the data were placed into an ARC LIBRARIAN library using the 100K tiling scheme.

Source Scale Denominator:	24000

SECTION 3: Spatial Data Organization Information

Native Data Set Environment:	ARC/INFO 7.0.3
Geographic Reference for Tabular Data:	Not Applicable
Tiling Scheme:	county
Spatial Object Type:	polygon

Vendor Specific Object Types:	polygon

SECTION 4: Spatial Reference Information

Horizontal Coordinate Scheme:	UTM
Ellipsoid:	GRS1980
Horizontal Datum:	NAD83
Horizontal Units:	meters
Altitude Datum:	Not Applicable
Altitude Units:	Not Applicable
Depth Datum:	Not Applicable
Depth Units:	Not Applicable
Cell Width:	0
Cell Height:	0
Latitude Resolution:	0
Longitude Resolution:	0
UTM Zone Number:	15
SPCS Zone Identifier:	null
County Coordinate Zone Identifier:	null
Coordinate Offsets or Adjustments:	Not Applicable
Map Projection Name:	Transverse Mercator
Map Projection Parameters:	Not Applicable
Other Coordinate System Definition:	Not Applicable

SECTION 5: Entity and Attribute Information

Entity and Attribute Overview: The Public Land Survey System features described in this database are represented as attributed polygons, lines and label points. Lines have both a numeric code and a text field that indicate the PLS line type such as, township line, section line, meander line, etc. The following information is included for each polygon: county number, township number, range direction id, range number, section number, forty number, forty text (e.g. NENE), government lot number and geocode fields that contain composite identifiers that uniquely defines a portion of land to the range, section, forty or government lot. GEOGLOT is one of the commonly used geocode fields. It contains a 14 digit number consisting of county, township, range direction, range, section, forty and government lot. GEOGLOT is used to link to DNR Land Records data. Because different methods have been used over time to assign a forty value to government lots, often GEOGLOT is not the quickest field to link on because mismatches may occur (e.g., Government Lot 1 might cover part of the NENE (forty code = 11) and part of the NWNE (forty code = 12).) In the Control Point Generated PLS for Aitkin county (county code = 1), Township 46 N, Range 26 W, section 5, GEOGLOT will be 1046026051201. A forty value of 12 was assigned because most of the government lot covers the area of the NWNE of the section. In the DNR Land Records database, GEOGLOT will be 1046026051101. A forty value of 11 was assigned because forty 11 is the first forty (lowest forty value) the government lot covers. To get around this mismatch, the DNR has established a temporary standard, using a geocode field called GEOMATCH. For every Control Point Generated PLS and DNR Land Record that has a government lot value, the FORT part of the geocoded field is zeroed out. Using the example above, GEOMATCH for either the PLS record or the land record, would be 1046026050001. The last four digits of this field contain two digits for the zeroed out FORT code and a two digit GLOT code. It is a quick and dirty method for matching PLS geocoded information until the DNR gets all of it's PLS related data into the same coding scheme. This method will be discontinued following completion of data cleansing and code matching on the DNR Land Records.

Entity and Attribute Citation:

Attribute Tables: Data Table

SECTION 6: Distribution Information

Publisher: Minnesota DNR - Division of Lands & Minerals

Publication Date:	6/1/1995
Distribution Contact	Contact
Distributor Data Set Identifier:	pls_fortypy3
Distribution Liability:	The Minnesota Department of Natural Resources makes no representation or warranties, express or implied, with respect to the reuse of data provided herewith, regardless of its format or the means of its transmission. There is no guarantee or representation to the user as to the accuracy, currency, suitability, or reliability of this data for any purpose. The user accepts the data 'as is', and assumes all risks associated with its use. By accepting this data, the user agrees not to transmit this data or provide access to it or any part of it to another party unless the user shall include with the data a copy of this disclaimer. The Minnesota Department of Natural Resources assumes no responsibility for actual or consequential damage incurred as a result of any user's reliance on this data.
Transfer Format Name:	Shapefile
Transfer Format Version:	Not Applicable
Ordering Instructions:	Visit the DNR Data Deli at the link provided.
Online Linkage:	http://deli.dnr.state.mn.us

SECTION 7: Metadata Reference Information

Metadata Content Contact:	Contact
Metadata Standard Name:	Minnesota Geographic Metadata Guidelines
Metadata Standard Date:	4/4/2001
Metadata Standard Version:	1.2
Metadata Standard Online Linkage:	http://www.gis.state.mn.us/stds/metadata.htm

report type: full | brief | attributes | data sample | contact information

Questions or comments should be sent to: GISDataDeli@dnr.state.mn.us.

Last site update: Mon Sep 3 06:15:02 CDT 2007

Brief Description

Metadata Product ID:	23000001
Layer Name:	pls_fortypy3
Long Name:	Control Point Generated PLS - polygons
Abstract:	The Control Point Generated PLS layer contains line and polygon features to the 1/4 of 1/4 PLS section (approximately 40 acres) and government lot level. The layer was created using the most accurate information available at the time, including Government Land Office plat drawings and survey notes, official resurveys, and PLS control points from the DNR's Control Point Inventory database.
Intended Application:	Detailed PLS forty level mapping at a 1:24,000 scale of any information geo-referenced to the Public Land Survey System, especially land ownership and management. It can also be used as a general PLS reference map for any other data projected into UTM - meters, extended zone 15, NAD83.
Usage Tips:	The most accurate comprehensive PLS source at the DNR. The positional accuracy of the data varies greatly, and ranges from 40 feet to sub-meter accuracy in some areas.
Spatial Extent:	Minnesota

Attributes

The DNR Data Deli

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Table Name	Field Name	Begin Column	Definition	Valid Values	Description
PLS_FORTYPY3.PAT					
	COUN	1	2,null,Integer Number		County number (from 1 to 87). (COUNTY.CODE - alias in ArcGIS)
	TOWN	2	3,null,Integer Number		PLS township number. (TOWNSHIP - alias in ArcGIS)
	RDIR	3	1,null,Integer Number		PLS range direction as a number (0, 1, or 2) rather than as a direction (West, East, West - half township or half range). (RANGE.DIRECTION - alias in ArcGIS)
	RANG	4	2,null,Integer Number		PLS range number. (RANGE - alias in ArcGIS)
	SECT	5	2,null,Integer Number		PLS section number. (SECTION - alias in ArcGIS)
	FORT	6	2,null,Integer Number		PLS forty number (that is, the quarter-quarter section), rather than a text description such as NWNE. (FORT is based on the MLMIS40 codes that have been used in the state for many years.) (FORTY.CODE - alias in ArcGIS)
	GLOT	7	2,null,Integer		PLS government lot

			Number		number. (GOVERNMENT.LOT - alias in ArcGIS)
	PARC	8	2,null,Integer Number		Parcel number - currently not used. The original intent of this field was to use this code in relation to the forty or government lot to identify unique parcels. (PARCEL.CODE - alias in ArcGIS)
	FORT_DESC	9	40,null,Text		PLS forty description using text. The descriptions should be red n the following way: NWNE is the Northwest 1/4 of the Northeast 1/4. This IS NOT necessarily the legal description for the parcel, particularly in the case of government lots, where the FORT and FORT_DESC are for locational reference only.
	GEOMATCH	10	14,null,Integer Number		The geocoding field used to match the Land Records to the PLS40 base layer. The format of this field is as follows: CCTTTDRRSSFFGG, where CC is COUN, TTT is TOWN, D is RDIR, RR is RANG, SS is SECT, FF is FORT or "0") (see following not), and GG is GLOT. Note: if the GLOT is greater than 0, such as government

					lot 1, the FF part of GLOTMATCH is set to 00.
	GEOPARC	11	16,null,Integer Number		In an Arc/INFO coverage, one can redefine items found in the attribute table. In this case, GEOPARC includes COUN, TOWN, RDIR, RANG, SECT, FORT, GLOT, PARC. Currently not used for any specific purpose. (GEOCODE - alias in ArcGIS)
	GEOGLOT	12	14,null,Integer Number		In an Arc/INFO coverage, one can redefine items found in the attribute table. In this case, GEOGLOT includes COUN, TOWN, RDIR, RANG, SECT, FORT, GLOT.
	GEOFORT	13	12,null,Integer Number		In an Arc/INFO coverage, one can redefine items found in the attribute table. In this case, GEOFORT includes COUN, TOWN, RDIR, RANG, SECT, FORT.
	GEOSECT	14	10,null,Integer Number		In an Arc/INFO coverage, one can redefine items found in the attribute table. In this case, GEOSECT includes COUN, TOWN, RDIR, RANG, SECT.
	GEORANG	15	8,null,Integer Number		In an Arc/INFO coverage, one can redefine items found in the attribute table. In

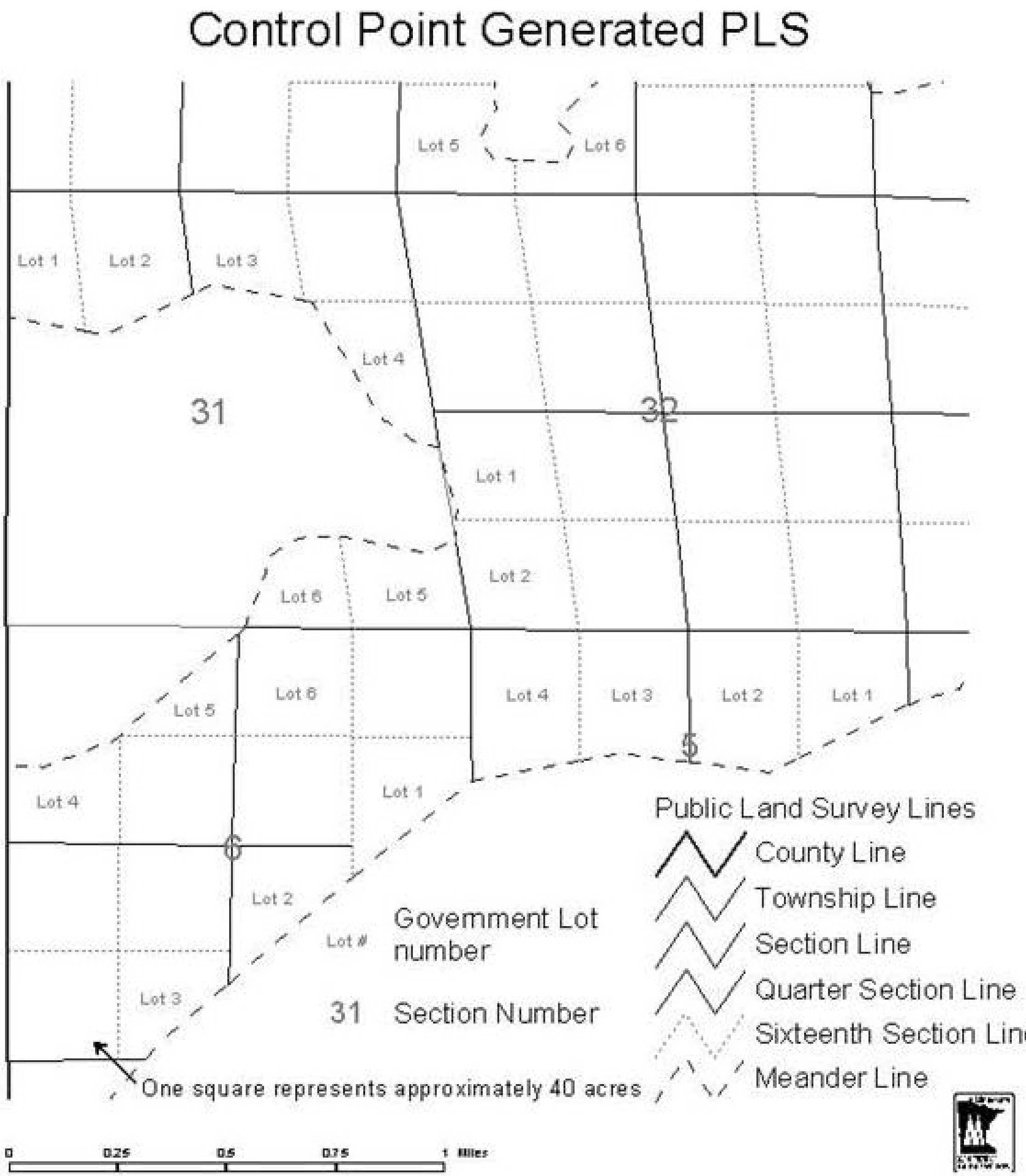
					this case, GEORANG includes COUN, TOWN, RDIR, RANG.

report type: full | brief | attributes | data sample | contact information

Questions or comments should be sent to: GISDataDeli@dnr.state.mn.us.

Last site update: Mon Sep 3 06:15:02 CDT 2007

Sample


Control Point Generated PLS
Lot 5
Lot 6
Lot 1
Lot 2
Lot 3
Lot 4
31
32
Lot 1
Lot 6
Lot 5
Lot 2
Lot 5
Lot 6
Lot 4
Lot 3
Lot 2
Lot 1
5
Lot 4
Lot 1
6
Lot 2
Lot 3
Public Land Survey Lines
County Line
Township Line
Section Line
Quarter Section Line
Sixteenth Section Line
Meander Line
Lot #
Government Lot number
31
Section Number
One square represents approximately 40 acres
0
0.25
0.5
0.75
1 Miles

Data Use Contact:

Name: Renee Johnson
Organization: DNR-Lands and Minerals
Title: ITS 3
Address: 500 Lafayette Road - Box 45
City, State, Zip: St. Paul, MN 55155
Phone: (651) 259-5396
Fax: (651) 296-5939
Email: renee.johnson@dnr.state.mn.us

Distribution Contact:

Name: Hal Watson
Organization: DNR-MIS
Title: GIS Database Coordinator
Address: 500 Lafayette Road, Box 11
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Phone: (651) 259-5508
Fax: (651) 297-4946
Email: hal.watson@dnr.state.mn.us

Metadata Content Contact:

Name: Renee Johnson
Organization: DNR-Lands and Minerals
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Phone: (651) 259-5396
Fax: (651) 296-5939
Email: renee.johnson@dnr.state.mn.us

Process to Transfer Land Improvement Permit Data into Public Land Survey File

Public Land Survey Information for Lac qui Parle and Yellow Medicine Counties, MN

Information is sorted by township name;

- Yellow Medicine County

Township Name	**Worksheet Cell #**
Burton	4000
Wergeland	4577
Norman	5153
Fortier	5729
Omor	8620
Oshkosh	9196
Hammer	9772
Florida	10348

- Lac qui Parle County

Township Name	**Worksheet Cell #**
Maxwell	580
Providence	1300
Freeland	1800
Manfred	2340
Baxter	3400
Riverside	3870
Hamlin	4570
Garfield	5050
Mehurin	5610
Lac qui Parle	6200
Cerro Gordo	6690
Madison	7125

Enter data according to description on the permit under “Permit requested for:”
Determine the amount of section area covered by the work by:

1. The description under “location where work will be done:”
2. Any drawing and/or air-photo provided
    a. If no drawing/air-photo is provided, check the location with the county plat book.
    b. If you cannot determine what portion of a section has been modified then credit the whole section.
3. Enter the year the work was performed under DATE
4. Enter the file # under LQP_FILE_#
    a. If there is an existing file, then enter both file #s.

Tile drain = SUBSURFACE
Tile inlets = SURFACE
Channel and/or ditch cleaning or straightening = CHNL_CLNG
NEW_DITCH =
DIKE =
GRASSED_WTRW

Lac qui Parle County Totals

Lac qui Parle: 40 acre parcels

Year	Year	Surface (parcels)	Subsurface (parcels)	New Ditch (parcels)	Channel Cleaning (parcels)	Grassed Waterway (parcels)	Dike (parcels)
1972	72	0	4	0	0	0	0
1973	72 - 73	0	56	36	39	0	8
1974	72 - 74	0	162	40	67	4	12
1975	72 - 75	0	186	40	67	4	12
1976	72 - 76	0	206	46	72	4	12
1977	72 - 77	0	234	46	72	4	12
1978	72 - 78	0	261	48	76	4	14
1979	72 - 79	0	317	58	88	4	18
1980	72 - 80	0	375	59	120	14	18
1981	72 - 81	7	408	59	120	14	18
1982	72 - 82	7	427	59	124	14	18
1983	72 - 83	7	470	59	124	14	22
1984	72 - 84	8	485	61	121	14	22
1985	72 - 85	8	495	61	130	14	30
1986	72 - 86	8	515	67	134	14	30
1987	72 - 87	10	641	68	148	14	30
1988	72 - 88	14	673	70	155	14	34
1989	72 - 89	16	691	70	171	14	34
1990	72 - 90	34	702	70	167	14	34
1991	72 - 91	35	718	70	177	14	34
1992	72 - 92	38	738	74	191	14	36
1993	72 - 93	43	773	74	208	14	36
1994	72 - 94	64	836	74	230	14	47
1995	72 - 95	79	891	75	239	14	48
1996	72 - 96	91	979	80	263	14	48
1997	72 - 97	107	1044	81	284	14	54
1998	72 - 98	122	1095	86	287	14	54
1999	72 - 99	126	1140	87	291	14	54
2000	72 - 00	130	1203	87	297	14	54
2001	72 - 01	131	1243	87	301	14	54
2002	72 - 02	134	1271	87	307	14	55
2003	72 - 03	135	1276	87	308	14	55

Lac qui Parle: Total Acres

Year	Year	Surface (acres)	Subsurface (acres)	New Ditch (acres)	Channel Cleaning (acres)	Grassed Waterway (acres)	Dike (acres)
1972	72	0	160	0	0	0	0
1973	72 - 73	0	2240	1440	1560	0	320
1974	72 - 74	0	6480	1600	2680	160	480
1975	72 - 75	0	7440	1600	2680	160	480
1976	72 - 76	0	8240	1840	2880	160	480
1977	72 - 77	0	9360	1840	2880	160	480
1978	72 - 78	0	10440	1920	3040	160	560
1979	72 - 79	0	12680	2320	3520	160	720
1980	72 - 80	0	15000	2360	4800	560	720
1981	72 - 81	280	16320	2360	4800	560	720
1982	72 - 82	280	17080	2360	4960	560	720
1983	72 - 83	280	18800	2360	4960	560	880
1984	72 - 84	320	19400	2440	4840	560	880
1985	72 - 85	320	19800	2440	5200	560	1200
1986	72 - 86	320	20600	2680	5360	560	1200
1987	72 - 87	400	25640	2720	5920	560	1200
1988	72 - 88	560	26920	2800	6200	560	1360
1989	72 - 89	640	27640	2800	6840	560	1360
1990	72 - 90	1360	28080	2800	6680	560	1360
1991	72 - 91	1400	28720	2800	7080	560	1360
1992	72 - 92	1520	29520	2960	7640	560	1440
1993	72 - 93	1720	30920	2960	8320	560	1440
1994	72 - 94	2560	33440	2960	9200	560	1880
1995	72 - 95	3160	35640	3000	9560	560	1920
1996	72 - 96	3640	39160	3200	10520	560	1920
1997	72 - 97	4280	41760	3240	11360	560	2160
1998	72 - 98	4880	43800	3440	11480	560	2160
1999	72 - 99	5040	45600	3480	11640	560	2160
2000	72 - 00	5200	48120	3480	11880	560	2160
2001	72 - 01	5240	49720	3480	12040	560	2160
2002	72 - 02	5360	50840	3480	12280	560	2200
2003	72 - 03	5400	51040	3480	12320	560	2200

Yellow Medicine County Totals

Yellow Medicine : 40 acre parcels

Year	Year	Surface (parcels)	Subsurface (parcels)	New Ditch (parcels)	Channel Cleaning (parcels)	Grassed Waterway (parcels)	Dike (parcels)
1972	72	0	0	51	4	0	5
1973	72 - 73	0	102	137	35	0	41
1974	72 - 74	0	217	166	68	3	42
1975	72 - 75	0	233	170	76	7	42
1976	72 - 76	0	266	171	80	7	42
1977	72 - 77	0	287	171	80	7	42
1978	72 - 78	0	300	175	80	11	42
1979	72 - 79	0	314	177	87	14	42
1980	72 - 80	0	358	197	100	18	42
1981	72 - 81	0	390	197	112	20	42
1982	72 - 82	0	410	197	112	20	44
1983	72 - 83	0	463	202	112	20	44
1984	72 - 84	0	520	206	112	20	44
1985	72 - 85	0	558	206	112	21	46
1986	72 - 86	0	576	206	113	21	46
1987	72 - 87	0	590	210	132	21	46
1988	72 - 88	0	606	210	132	21	46
1989	72 - 89	0	606	210	132	23	50
1990	72 - 90	0	612	210	140	23	50
1991	72 - 91	0	665	210	140	27	52
1992	72 - 92	0	698	210	140	27	60
1993	72 - 93	0	742	210	140	27	60
1994	72 - 94	0	765	210	171	28	60
1995	72 - 95	1	809	210	179	28	60
1996	72 - 96	5	934	214	240	56	60
1997	72 - 97	5	993	214	256	73	61
1998	72 - 98	5	1035	218	294	73	61
1999	72 - 99	5	1087	218	314	79	65
2000	72 - 00	10	1110	218	314	79	65
2001	72 - 01	26	1141	218	318	80	65
2002	72 - 02	26	1173	218	321	86	65
2003	72 - 03	26	1180	218	322	86	65

Yellow Medicine: Total Acres

Year	Year	Surface (acres)	Subsurface (acres)	New Ditch (acres)	Channel Cleaning (acres)	Grassed Waterway (acres)	Dike (acres)
1972	72	0	0	2040	160	0	200
1973	72 - 73	0	4080	5480	1400	0	1640
1974	72 - 74	0	8680	6640	2720	120	1680
1975	72 - 75	0	9320	6800	3040	280	1680
1976	72 - 76	0	10640	6840	3200	280	1680
1977	72 - 77	0	11480	6840	3200	280	1680
1978	72 - 78	0	12000	7000	3200	440	1680
1979	72 - 79	0	12560	7080	3480	560	1680
1980	72 - 80	0	14320	7880	4000	720	1680
1981	72 - 81	0	15600	7880	4480	800	1680
1982	72 - 82	0	16400	7880	4480	800	1760
1983	72 - 83	0	18520	8080	4480	800	1760
1984	72 - 84	0	20800	8240	4480	800	1760
1985	72 - 85	0	22320	8240	4480	840	1840
1986	72 - 86	0	23040	8240	4520	840	1840
1987	72 - 87	0	23600	8400	5280	840	1840
1988	72 - 88	0	24240	8400	5280	840	1840
1989	72 - 89	0	24240	8400	5280	920	2000
1990	72 - 90	0	24480	8400	5600	920	2000
1991	72 - 91	0	26600	8400	5600	1080	2080
1992	72 - 92	0	27920	8400	5600	1080	2400
1993	72 - 93	0	29680	8400	5600	1080	2400
1994	72 - 94	0	30600	8400	6840	1120	2400
1995	72 - 95	40	32360	8400	7160	1120	2400
1996	72 - 96	200	37360	8560	9600	2240	2400
1997	72 - 97	200	39720	8560	10240	2920	2440
1998	72 - 98	200	41400	8720	11760	2920	2440
1999	72 - 99	200	43480	8720	12560	3160	2600
2000	72 - 00	400	44400	8720	12560	3160	2600
2001	72 - 01	1040	45640	8720	12720	3200	2600
2002	72 - 02	1040	46920	8720	12840	3440	2600
2003	72 - 03	1040	47200	8720	12880	3440	2600

Lac qui Parle Watershed Totals

LqP Watershed Totals

Year	Year	Surface (acres)	Subsurface (acres)	New Ditch (acres)	Channel Cleaning (acres)	Grassed Waterway (acres)	Dike (acres)
1972	72	0	4	51	4	0	5
1973	72 - 73	0	158	173	74	0	49
1974	72 - 74	0	379	206	135	7	54
1975	72 - 75	0	419	210	143	11	54
1976	72 - 76	0	472	217	152	11	54
1977	72 - 77	0	521	217	152	11	54
1978	72 - 78	0	561	223	156	15	56
1979	72 - 79	0	631	235	175	18	60
1980	72 - 80	0	733	256	220	32	60
1981	72 - 81	7	798	256	232	34	60
1982	72 - 82	7	837	256	236	34	62
1983	72 - 83	7	933	261	236	34	66
1984	72 - 84	8	1005	267	233	34	66
1985	72 - 85	8	1053	267	242	35	76
1986	72 - 86	8	1091	273	247	35	76
1987	72 - 87	10	1231	278	280	35	76
1988	72 - 88	14	1279	280	287	35	80
1989	72 - 89	16	1297	280	303	37	84
1990	72 - 90	34	1314	280	307	37	84
1991	72 - 91	35	1383	280	317	41	86
1992	72 - 92	38	1436	284	331	41	96
1993	72 - 93	43	1515	284	348	41	96
1994	72 - 94	64	1601	284	401	42	107
1995	72 - 95	80	1700	285	418	42	108
1996	72 - 96	96	1913	294	503	70	108
1997	72 - 97	112	2037	295	540	87	115
1998	72 - 98	127	2130	304	581	87	115
1999	72 - 99	131	2227	305	605	93	119
2000	72 - 00	140	2313	305	611	93	119
2001	72 - 01	157	2384	305	619	94	119
2002	72 - 02	160	2444	305	628	100	120
2003	72 - 03	161	2456	305	630	100	120

LqP Watershed Totals

Year	Year	Surface (acres)	Subsurface (acres)	New Ditch (acres)	Channel Cleaning (acres)	Grassed Waterway (acres)	Dike (acres)
1972	72	0	160	2040	160	0	200
1973	72 - 73	0	6320	6920	2960	0	1960
1974	72 - 74	0	15160	8240	5400	280	2160
1975	72 - 75	0	16760	8400	5720	440	2160
1976	72 - 76	0	18880	8680	6080	440	2160
1977	72 - 77	0	20840	8680	6080	440	2160
1978	72 - 78	0	22440	8920	6240	600	2240
1979	72 - 79	0	25240	9400	7000	720	2400
1980	72 - 80	0	29320	10240	8800	1280	2400
1981	72 - 81	280	31920	10240	9280	1360	2400
1982	72 - 82	280	33480	10240	9440	1360	2480
1983	72 - 83	280	37320	10440	9440	1360	2640
1984	72 - 84	320	40200	10680	9320	1360	2640
1985	72 - 85	320	42120	10680	9680	1400	3040
1986	72 - 86	320	43640	10920	9880	1400	3040
1987	72 - 87	400	49240	11120	11200	1400	3040
1988	72 - 88	560	51160	11200	11480	1400	3200
1989	72 - 89	640	51880	11200	12120	1480	3360
1990	72 - 90	1360	52560	11200	12280	1480	3360
1991	72 - 91	1400	55320	11200	12680	1640	3440
1992	72 - 92	1520	57440	11360	13240	1640	3840
1993	72 - 93	1720	60600	11360	13920	1640	3840
1994	72 - 94	2560	64040	11360	16040	1680	4280
1995	72 - 95	3200	68000	11400	16720	1680	4320
1996	72 - 96	3840	76520	11760	20120	2800	4320
1997	72 - 97	4480	81480	11800	21600	3480	4600
1998	72 - 98	5080	85200	12160	23240	3480	4600
1999	72 - 99	5240	89080	12200	24200	3720	4760
2000	72 - 00	5600	92520	12200	24440	3720	4760
2001	72 - 01	6280	95360	12200	24760	3760	4760
2002	72 - 02	6400	97760	12200	25120	4000	4800
2003	72 - 03	6440	98240	12200	25200	4000	4800