2009 Project Abstract
For the Period Ending June 30, 2012

Project Title: Intensified Tile Drainage Evaluation
Project Manager: Shawn Schottler
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St. Croix Watershed Research Station
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Funding Source: Environment and Natural Resources Trust Fund
Legal Citation: M.L. 2009, Chp. 143, Sec. 2, Subd. 5d

Overall Project Outcome and Results

Agricultural rivers throughout Minnesota are impaired by excess sediment, a significant portion of which comes from non-field, near-channel sources, suggesting that rivers have become more erosive over time. In the upper Mississippi basin, crop conversions have lead to an intensification of artificial drainage, which is now a critical component of modern agriculture. Coincident with the expansion of drainage networks were increases in annual rainfall. To disentangle the effects of climate and land-use we compared changes in flow, runoff ratio, precipitation, crop conversions, and extent of drained depressional areas in 21 watersheds over the past 70 years. Major finding from this study are:

- flow and runoff ratio have increased by than more 50% in about half of the watersheds.
- increases in rainfall generally account for less than half of the increases in flow.
- the largest increases in flow are correlated to the largest conversions to soybeans and extent of artificial drainage.
- using a water budget, calibrated to the first 35 years of record, we calculate that artificial drainage accounts for the majority of the statistically significant increases in flow.
- artificial drainage of depressional areas reduces water residence time on the landscape, consequently; a significant portion of annual rainfall that was once returned to the atmosphere via evapo-transpiration, is now routed to the rivers.
- loss of depressional areas and wetlands are strongly correlated to increases in excess flow in the 21 watersheds, thus supporting the proposed linkage between facilitated drainage of depressional areas and increases in river flow.
- rivers with increased river flow have experienced channel widening of 10-40%.
- climate, crop conversion and artificial drainage have combined to create more erosive rivers, with drainage as the largest driver of this change.

Project Results Use and Dissemination

Results of this study have been submitted for publication to the journal Hydrological Processes and have been accepted pending final review. Summaries and findings and implications of this study have been presented at more than 30 technical meetings in

Minnesota and nationally. Many of these presentations have been in conjunction with local watershed groups, and have an audience of County Commissioners, farmers, SWCD staff, and agricultural consultants. These meetings have been highly successful at delivering the findings of this study to people who are directly involved in watershed management but are less likely to attend scientific meetings or read scientific journals.

Trust Fund 2009 Work Program

Date of Report: September 15, 2012
Final Report
Program Approval: 6/16/2009
Project Completion Date: July 1, 2012

I. PROJECT TITLE: Intensified Tile Drainage Evaluation

Project Manager:	Shawn Schottler
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Location: Study will evaluate 24 watersheds throughout Minnesota contributing to Lake Pepin. See map in appended research addendum.

Total Trust Fund Project Budget:	**Trust Fund Appropriation**	**$ 300,000**
	Minus Amount Spent:	**$ 300,000**
	Equal Balance:	**$ 0**

Legal Citation: M.L. 2009, Chp. 143, Sec. 2, Subd. 5d

Appropriation Language:
$300,000 is from the trust fund to the Science Museum of Minnesota for the St. Croix watershed research station to conduct a comparative assessment of hydrologic changes in watersheds with and without intensive tile drainage to determine the effects of climate and tile drainage on river erosion. This appropriation is available until June 30, 2012, at which time the project must be completed and final products delivered, unless an earlier date is specified in the work program.

II. and III. FINAL PROJECT SUMMARY:

Agricultural rivers throughout Minnesota are impaired by excess sediment, a significant portion of which comes from non-field, near-channel sources, suggesting that rivers have become more erosive over time. In the upper Mississippi basin, crop conversions have lead to an intensification of artificial drainage, which is now a critical component of modern agriculture. Coincident with the expansion of drainage networks were increases in annual rainfall. To disentangle the effects of climate and land-use we compared changes in flow, runoff ratio, precipitation, crop conversions, and extent of drained depressional areas in 21 watersheds over the past 70 years. Major finding from this study are:

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IV. OUTLINE OF PROJECT RESULTS*:*

Introduction

Rivers in intensively row-cropped watersheds are often impaired by high sediment turbidity (Belmont *et al*., 2011; Engstrom *et al*., 2009; Schottler *et al*., 2010; Thoma *et al*., 2005), which degrades their habitat and recreational value and negatively impacts downstream surface waters. In the latter half of the 20th century, cropping patterns in the USA and especially the midwestern corn belt underwent major changes (USDA, 2011). One of the most dramatic shifts was the conversion of small grains and forage crops to soybeans (see Result 1 below). Over this same period both river flows and sediment loading from agricultural watersheds increased markedly (Engstrom *et al*., 2009; Lenhart *et al*., 2011; Novotny and Stefan, 2007; Raymond *et al*., 2008; Schilling *et al*., 2008; Zhang and Schilling, 2006). Although it is tempting to assume that conversion to row crops resulted in increased erosion from fields, several studies have shown large contributions from non-field, near-channel sources such as streambanks, bluffs, and ravines (Belmont *et al*., 2011; Schottler *et al*., 2010; Sekely *et al*., 2002; Thoma *et al*., 2005). This observation and the need to target effective management strategies raises the question, have rivers in agricultural watersheds become more erosive, and if so, why?

Understanding increases in river flows and non-field suspended sediment loads over the latter half of the 20th century is confounded by multiple possible causes. Higher flows have been related to increased precipitation (Johnson *et al*., 2009; Nangia *et al*., 2010; Novotny and Stefan, 2007) however, other critical factors are coincident and cannot be neglected. In particular, the 20th century crop conversions are relevant to watershed hydrology, not only because they can induce significant changes in seasonal evapotranspiration (ET) potential from the landscape (Schilling *et al*., 2008; Zhang and Schilling, 2006), but also because the conversion is often accompanied by an increase in artificial drainage(Blan *et al*., 2009; Schilling and Helmers, 2008; Sugg, 2007). However, the specific effects of artificial drainage as contributors to increased streamflow are not well known. Given the extent of past wetland drainage and current intensification of subsurface drainage (Blann *et al*., 2009; Sugg, 2007), artificial drainage networks in total have the potential to alter water budgets and river flows on a watershed scale and must be quantified before management strategies can be fully developed.

The central hypothesis examined in this study was: ***Has artificial drainage created more erosive rivers****?* In Result 1 of this study we estimate the current and historical extent of artificial drainage and changes in cropping patterns for 21 watersheds with long-term data sets of climate and flow. In Result 2 we quantify the changes in flow for these watersheds, and construct a water balance to apportion the change in flow due to changes in rainfall, crop conversion and increases in artificial drainage. Rivers in about half of the watersheds were found to have significant increases in flow. Artificial drainage was a major driver of this increase, exceeding the effects of precipitation and crop conversion. Rivers with altered hydrology were also shown to exhibit channel widening since the mid-20th century, supporting the hypothesis that agricultural land-use changes have created more erosive rivers.

RESULT 1: QUANTIFICATION OF TEMPORAL AND SPATIAL EXTENT OF ARTIFICIAL DRAINAGE

Result 1 was conducted by the Water Resources Center at Minnesota State University, Mankato. The principal investigator for this work was Richard Moore.

Deliverable	Completion Date
1. Estimation of present day artificial drainage.	July 2011
2. Historical trends of installation of artificial drainage	July 2012

Summary Budget Information for Result 1: **Trust Fund Budget: $ 150,000**
Amount Spent: $ 150,000
Balance: $ 0

Deliverable	Completion Date	Budget	Status
1. Estimation of present day artificial drainage.	July 2011	$ 75,000	100%
2. Historical trends of installation of drainage	July 2012	$ 75,000	100%

Final Report Summary

Artificial Drainage

Artificial drainage is any physical alteration to the landscape that changes the natural flow pattern and rate of removal of water. These hydrologic alternations are often done for the explicit purpose of improving agricultural productivity, but can have unintended consequences on river hydrology. Currently, most common purpose of artificial drainage is to remove excess water from the soil profile in order to enhance crop production. Subsurface drainage removes excess water from the soil profile, usually through a network of subsurface tile or pipes which eventually drain into surface drainage systems. The most common form of tile is corrugated plastic tubing. The plastic tubing is placed about 3 – 4 feet under the surface and have a general spacing of 40 – 80 feet between the tile lines. The water infiltrates through the soil until it reaches the tile and then is transported through the tile. This in essence lowers the water table to a level that is beneficial to plant growth. Surface drainage is the removal of water that collects on the land surface. Many fields have low spots or depression where water ponds, either seasonally or perennially. Surface drainage techniques such as constructing surface inlets to subsurface drains and the construction of shallow ditches or waterways can allow the water to leave the field rather than causing prolonged wet areas.

As shown in Figure 1, an artificial drainage system consists of many different components. The main component of this system is the drainage ditch, also called surface drainage. The drainage ditches were initially created to drain overland flow and connect low areas together so as to remove the water from the lowest areas of the land. Further up the system are tile mains. Tile mains are subsurface drainage that connect smaller areas of low depressions as well as act as conduits for pattern tiling. Pattern tiling is the tiling of fields in equally spaced rows of tile that are connected together by the main lines which eventually lead to the drainage ditch. Surface inlets are tile that is brought to the surface to improve the drainage of low areas that hold water for an extended period of time. The direct connection to the surface by these tiles removes the water quickly but also can act as an efficient conduit for sediment and nutrients through the system. In combination, the various forms of artificial drainage not only remove surplus water from the soil profile, but also allow for drain surface water from wetland and shallow depressional areas. Before artificial drainage, these depressional areas could have held water in them for a short period of time (ephemeral ponds) or perennially (wetlands) depending on the soil type and geomorphology of the depression. Under natural conditions water would leave these depressions through a combination of infiltration and evapotranspiration (ET). A significant portion of infiltrated water would have been routed to the river as shallow groundwater, while ET would have returned the water to the atmosphere and remove it from the watershed. After drainage has been introduced, a greater proportion of the water is removed quickly and routed to the rivers. The cumulative result of drainage is the increased connectivity between storage areas (wetlands/depressions) and natural flow paths (streams/rivers). This reduces water residence time on the landscape (i.e. quickly dries a field for planting) and increases the watershed area that directly contributes to river flow.

Figure 1. Aerial photography from the Beauford sub-watershed (Blue Earth River watershed) showing different components of an artificial drainage system and the density of installation.

In the comparative assessment of our study watersheds, we analyzed data that could help us identify the amount of each of these artificial drainage features in the 21 watersheds. Some of the data can be readily mapped or may have existing datasets that could be analyzed, however some of these features are sub-surface and cannot be easily seen through aerial photographs. Through multiple methods, we have attempted to estimate the extent of the different forms of artificial drainage and their importance relative to changes in long-term water budgets.

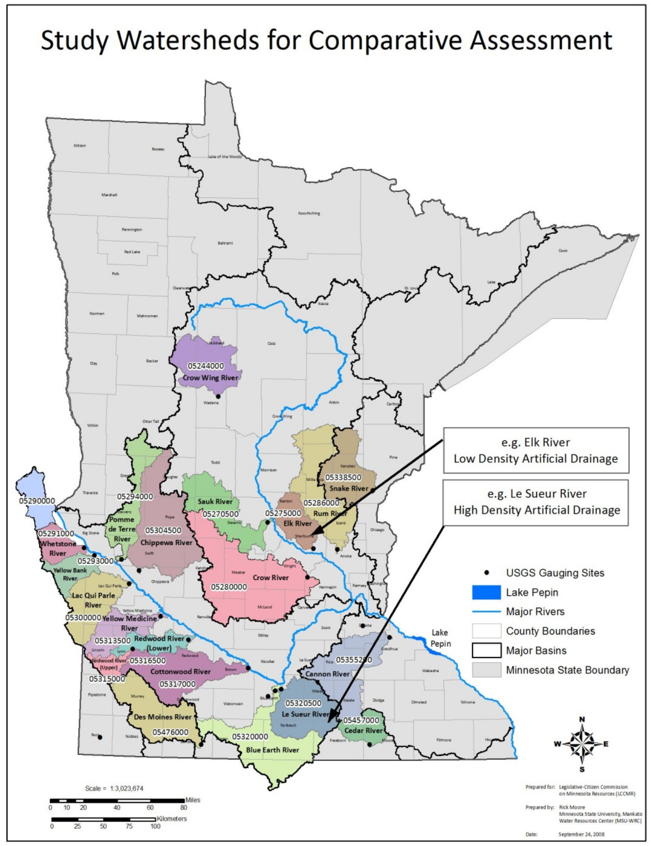


Figure 2. Map depicting the 21 study watersheds.

Study Watersheds

The 21 watersheds in our study occur throughout Minnesota as well as a small part of Iowa and South Dakota as shown in Figure 2. For the most part, watersheds are located in the southern half of Minnesota with Crow Wing Watershed being the furthest north. All the watersheds ultimately flow into the Mississippi. Landuse in the most of the watersheds is dominated by row crops, mainly corn and soybeans. The amount of land in row crops varies across the 21 watersheds with the Snake River watershed having only 4.2% and the Blue Earth River Watershed having the most at 82.5% based on the Crop Data Layer from the National Agricultural Statistics Service (NASS). The dominant soil materials of the different watersheds range from mainly silty glacial sediments in the southern two-thirds of our study area along with some sand and gravel textures along the riverine systems. Near the Blue Earth and Le Sueur River watersheds, they have a dominant soil material of clay and silt. In the northern watersheds such as Crow Wing, Elk, Snake and Rum, their dominant soil material is a combination of sandy glacial sediments varying from sandy loam to gravel. There has been a large change in cropping patterns across the basin mainly from corn and small grain crops in the 1940 to mainly corn and soybeans in 2010.

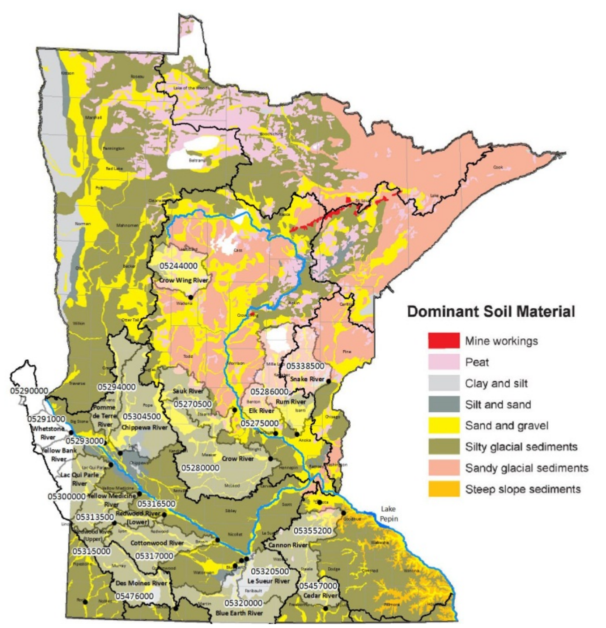


Figure 3. Dominant soil material in Minnesota and the study watersheds.

Result 1: Deliverable 1.

ESTIMATION OF PRESENT DAY ARTIFICAL DRAINAGE

Note: The original workplan included 23 watersheds for assessment. After reviewing available data for all watersheds, it was determined that the flow records in two watersheds had more than 15 years of missing data, and could not be reliably used.

1.1.1 POORLY DRAINED SOILS AND POTENTIAL FOR DRAINAGE.

The potential for drainage is a difficult feature to map. Surface drainage is easily seen through aerial photography, however, subsurface drainage is below ground and not easily mapped through aerial photography. A surrogate for mapping drainage or the potential for drainage is through the analysis of soil types. Soil types classified by the Soil Survey Geographic database (SSURGO) as poorly drained are soils that would benefit from tile drainage. Using the SSURGO soils database for each county in our study area, we can query certain attributes that reflect this description of poorly drained soils. Numerous soil properties and interpretations within this database can be used to indicate the need for drainage. Examples include the land capability class modifier “water”, soil drainage class information such as poorly drained, and the hydrologic class modifier “D”. Across the 21 watersheds, soil types vary considerably yielding different amounts of areas that would benefit from artificial drainage—thus providing a surrogate to compare differences in expected drainage density between the 21 watersheds.

Methods

The extent and distribution of poorly drained soils were determined using the SSURGO database. Seven classes of natural soil drainage are recognized in SSURGO: excessively drained, somewhat excessively drained, well drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained. We extracted the poorly drained and very poorly drained classes to reflect the soils that would benefit from artificial drainage. The polygon input layers were clipped to the 21 watersheds using GIS software and converted to raster format at a 56-m^2 pixel size. A 56-m^2 resolution was selected for identification because of the size of the study area in this project as well as for consistency with the resolution of the NASS crop data layer. Current cultivated land and crop type were determined from data compiled by the National Agricultural Statistics Service (NASS), which used a 2008 Landsat satellite image with 56-m^2 resolution. The NASS produces a GIS raster layer called the Cropland Data Layer (CDL) going back multiple years for the states in our study area. The CDL can be considered a “Census by Satellite”, as it is a comprehensive land-use classification covering an entire state and uses ortho-rectified imagery to accurately locate and identify field crops. We then computed the area of poorly drained soils by multiplying the cell count by 56 m^2. The representative slope from the SSURGO data was also used to stratify the data; taking into account that subsurface drainage occurs on lands with minimal slopes. The areas of cultivated crops were intersected with the poorly drained soils (see section 1.1.6) and then combined with the slopes layer to yield a final product predicting those areas that should have sub-surface artificial drainage.

Findings

The percentage of area for each watershed meeting the soil and land cover criteria are summarized in Figure 4. While there are no absolute criteria to compare these estimates against, work done by Jayne and James (2008) in “The Extent of Farm Drainage in the United States” show a correlation by area that matches our analysis. The majority of the soils that would benefit from drainage occur in the watersheds in the Minnesota River Basin. The Blue Earth, Le Sueur, and Cottonwood watersheds show the greatest need for drainage based on soil types, while the watersheds in the northern part of the study, Crow Wing, Snake, Elk and Rum, have better drained soils. Physiographically, the area in southern Minnesota lies within the northern portion of the western young drifts section of the central lowland province. The final phase of the "Wisconsin glaciation" covered much of southern Minnesota and northern Iowa. The ice lobe which extended as far south as Des Moines, Iowa is known as the Mankato Lobe. Characteristic features of the landscape within the Mankato Lobe are large areas of level plain of outwash, lacustrine and drift origin, interspersed with low, indistinct recessional moraines, which often impart a gently rolling appearance to the landscape.

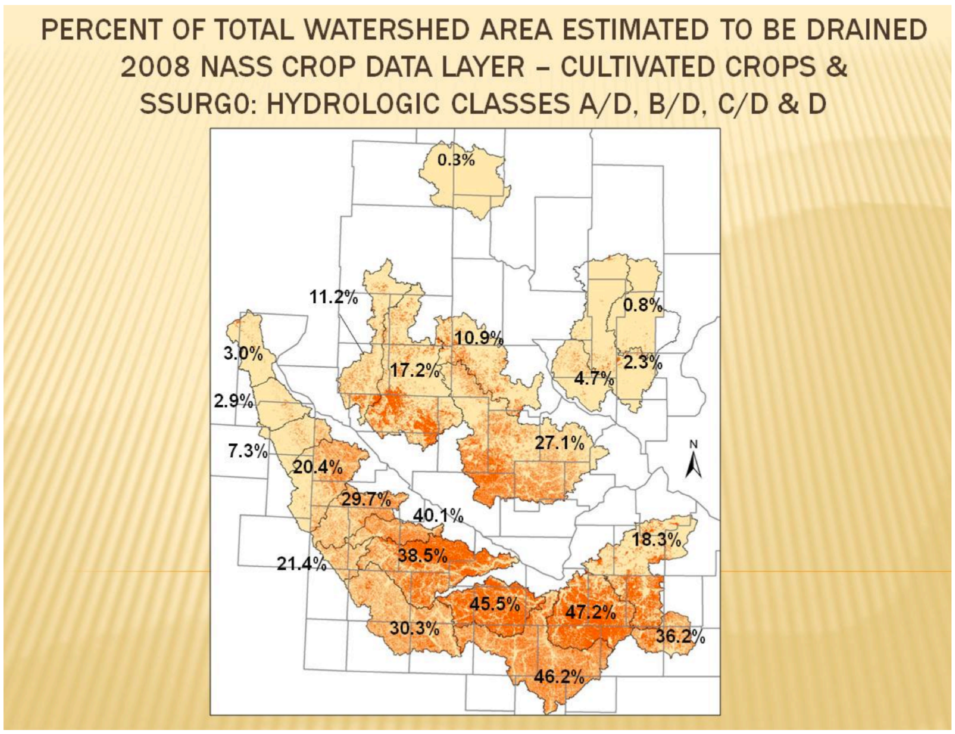


Figure 4. Estimation of drainage in each watershed based on soil types and land use. Both the National Land Cover Dataset (NLCD) and the Crop Data Layer from NASS were used for land use. The SSURGO soils database was used for the soil analysis.

In these watersheds, the level nature of the topography and heavy textured soils have caused a lack of natural drainage which is reflected by numerous shallow lakes, marshes, meadowland and wet prairie areas. Under such conditions, native vegetation ranged from mesic and wet prairie interspersed with cattail/sedge wetlands. This vegetation and soil types contributed to the development of the poorly drained Webster series of prairie soils which cover much of the central and southern portions of the Mankato Lobe. The higher upland areas of the Minnesota River Basin tend to have a more rolling landscape and a greater relief change. In the southwestern portion of the Minnesota River Basin, the prairie coteau has a relief change from the uplands to the Minnesota River of 1000 feet in some areas.

The areas adjacent to the Minnesota River and the low flat landscape of the southern part of the Minnesota River basin, combined with the soil types in this area, make this a prime area in need of drainage to accommodate farming of the land. Our estimates predict that one-third to one-half of all cultivated land in these watershed has been modified with tile drainage. In contrast, the western watersheds which are drier, and the northern study watersheds which have better natural drainage are estimated to have generally less than 10% of the cultivated lands modified by tile drainage.

1.1.2 Survey of Surface Inlets

Surface water inlets, or vertical drains, are used to allow ponded water to flow directly into the sub-surface tile networks without seeping through the soil. For this reason, they are of great value in poorly drained depressions where water collects and would drown the plants if not removed. Surface inlets work much like a bath-tub drain to quickly remove surface ponded water. Examples of surface inlets are shown in Figure 5. They are seldom necessary in well drained soils or sloping lands with natural outlets. An inventory of surface risers was completed for all 21 watersheds in June of 2011. The survey quantified the density of surface risers in 40 locations throughout each of the watersheds and used this to predict the total number and density of surface inlets for the watersheds. This inventory provides an indication of the amount of tiling in an area and ability of that watershed to quickly route water to the rivers.

Methods

The inventory consisted of 40 random point locations within the cultivated areas of the watersheds. The strategy for efficiently completing the inventory utilized the public road network. Road segments consisting of a one mile straight stretch of road were selected from the larger datasets. Each road segment was then converted to its center point by doing a polyline to point transformation. One mile straight road segments were chosen to allow the selection of risers within a one mile stretch and be able to compare similar stretches throughout each watershed. The second dataset used in the inventory was the 2008 NASS Crop Data Layer. The raster image for the 21 watersheds was converted to a vector shapefile and all areas/fields that contained cultivated crops were selected. The areas of these polygons were then calculated. A selection of cultivated polygons that were within 100 feet of the road segment point and

Figure 5. Examples of surface risers observed in the survey

had an area of 160 acres were selected. Of the remaining road segments, each segment was given a random number through a random number generator. The first forty points from the lowest random number to the highest were selected. A layer of 40 points was created for each watershed and network analysis created a route for the points to be surveyed.

The field inventory occurred over two seasons from early May until middle June in 2010 and 2011. When conducting the survey, the surveyors drove from one end of the line segment to the other and recorded the location of the surface risers. Both sides of the roads and at a distance of ¼ mile from the road segment were surveyed. The point locations of the risers were mapped using ESRI ArcPad and given a location on the map. The type of riser was also included in the attributes such as Higgenbottom, flag, rock inlet, etc.

Findings

The number of risers is highest in the Chippewa, Crow, Cottonwood, and Redwood watersheds. Not surprisingly, fewer risers are seen in the naturally well-drained watersheds of Snake, Crow Wing, Elk, Rum and the upper watersheds of the Minnesota River Basin (Figure 6). However, the poorly drained, but flat watersheds in the middle Minnesota basin (Blue Earth, LeSueur, Cottonwood, Cedar) also had fewer surface inlets. The amount of small, shallow closed basins in a rolling landscape (e.g. Crow) versus a flat landscape (Cedar) is a likely reason for the differences in surface inlet density. We compared the distribution of elevation differences measured for our point locations to the total number of surface risers occurring in a one mile by one mile square area. The analysis (Figure 7) shows a correlation between the range in elevations and the number of surface risers occurring. There are very few risers in areas with relatively uniform elevation (net difference in elevation = 0 to 20 meters, i.e. flat areas), and many more risers where elevations vary by 20 to 45 meters (rolling terrain). In agricultural watersheds that have a flat landscape, the use of pattern tiling may help drain a field better than having a surface inlet within the field. In a rolling landscape, deep, concentrated low areas may need to be connected by tile and the surface risers can drain the water from these depressions in a quicker manner than pattern tiling.

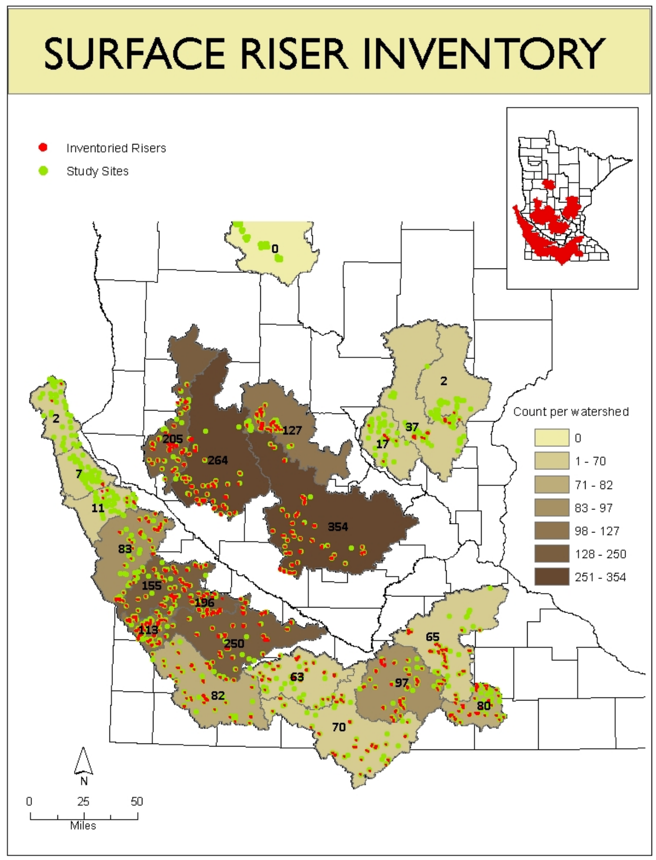


Figure 6. Map of the surface riser locations and density in each of the watersheds.

Also pattern tiling may not work in these rolling landscapes depending on the amount of relief and the slope characteristics.

1.1.3 Drainage Ditch Density and Length

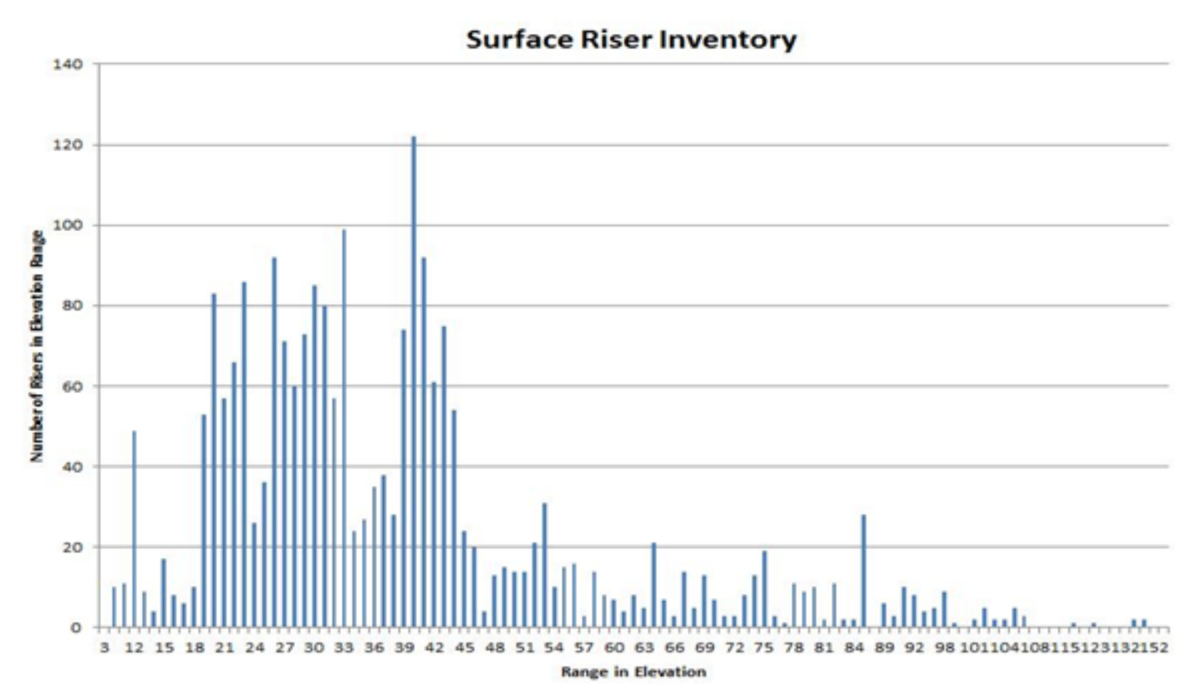


Figure 7. This chart shows ranges in elevation for points surveyed and the number of points that fall within those elevation ranges.

Drainage ditches are open trenches and serve as the main arteries to convey water in a drainage network. Typically, shallow ditches draining individual fields flow into deeper collection ditches that ultimately discharge into streams and other surface waters. Water enters both shallow and deeper ditches via surface and subsurface pathways. In areas with high water tables, drainage ditches effectively lower the water table to allow farm machinery to operate at critical times, such as planting. Drainage ditches act as direct conduits between agricultural fields and surface waters. In determining drainage ditch density, no pre-existing dataset that encompasses the broad region of our study area was available. The most detailed information for each watershed comes from the counties that fall within those watersheds as

Figure 8. Example drainage ditch in the Minnesota River Basin during harvest time.

well as any watershed districts that work within those watersheds. Availability of data varies between counties, with some counties in the forefront having their ditch systems digitized and attributed in detail. Other counties still may be using paper maps but that is slowly changing. Other ditch inventories have been conducted at larger scales such as the 13 county ditch dataset created by the Water Resources Center at Minnesota State University. The information comes from data retrieved from the counties in the early 1990's. This dataset only contains the ditch systems and not the natural systems. Also, the extent of the 13 county layer would cover only about 5 or 6 of the watersheds in our study.

The National Hydrography Dataset (NHD) is a vector dataset used by GIS systems. The NHD contains features such as lakes, ponds, streams, rivers, canals, dams and stream gages. These data are designed to be used in general mapping and in the analysis of surface water systems. NHD flowlines are important features in the NHD because they contain flow direction and form a network. We used the NHD for our analysis of drainage ditch density and length.

Methods

The NHD flowline dataset attributes a line feature as either a river/stream or main channel. This is the most basic attribute and is the basis for the natural hydrology flow path. Also contained in the attributes of the database is a connector definition. A connector is a flow path through a lake or large waterbody that connects back to rivers, streams or ditches. In order to do flow analysis with this dataset, the flow of water through a lake needs to have that connection. The final attribute that shows up in our study area is the canal/ditch. A canal/ditch is a flow path that has been altered to convey water across the landscape. The canal/ditch flowline is our delineation for altered hydrology.

The NHD is a living database, meaning new data is always being added to it or information is being updated. This is noted because five of our watersheds did not contain any attributes defining flow paths as ditches or canals, even though past research shows that these watersheds do contain ditch systems. Information from the Chippewa, Pomme de Terre, Little Minnesota, Whetstone, and Yellow Bank watersheds has not been integrated into the database and were removed from the analysis.

To determine the

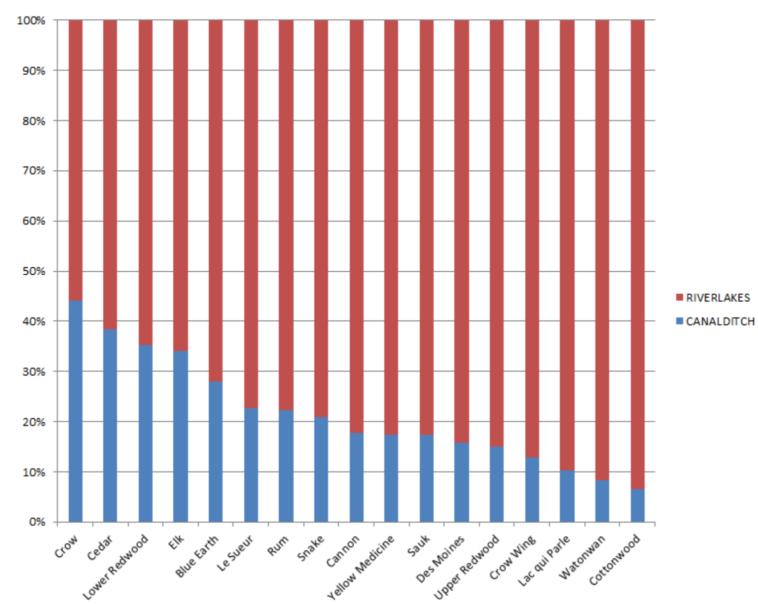


Figure 9. Percentage of the total surface flow paths that are altered (ditch/canal) and unaltered (river/lake) in each watershed. Blue bars are altered flow paths (ditches) and red bars are natural flow paths.

amount of natural versus altered hydrology contained in each watershed, we combined all NHD layers for different basins into one larger database that was then clipped to our 16 watersheds. The lengths of the streams/rivers, the connectors, and the main channel/artificial path were calculated and the resulting values were combined for their watershed and displayed in Figure 9.

In order to compare the amount of natural hydrology systems to altered hydrology systems, we needed to analyze them at a smaller scale within each watershed. Using the Watershed Hydrography Dataset from the Minnesota Department of Natural Resources, we intersected the National Hydrography Dataset layer with it. This assigned a watershed code to each stretch in the NHD dataset. We then recalculated the length of each stretch so that the line segments had the correct length assigned to it. The next step was to analyze the amount of the natural systems and altered systems in each smaller watershed, and then join those values back to the MNDNR Watershed Hydrography Dataset. This information could then be mapped to show the percentage of altered versus natural networks in each of the watersheds. The information was then mapped as shown in Figure 10.

Findings

Figures 9 and 10 show total percentages and distribution of natural hydrology compared to altered hydrology for each watershed. The findings from this analysis show that the Crow River watershed has the highest percentage of flow systems devoted to ditches or altered hydology. Watersheds such as the Blue Earth and Le Sueur are near the top of the grouping of watersheds but their percentages fall between 20% and 30%. If we take topography into account as we look at Figure 9, watersheds with a high elevation change in their upper reaches, such as the Lac qui Parle and Yellow Medicine, have fewer ditches (alter flow paths) because the high relief creates natural channels for water to flow off the landscape.

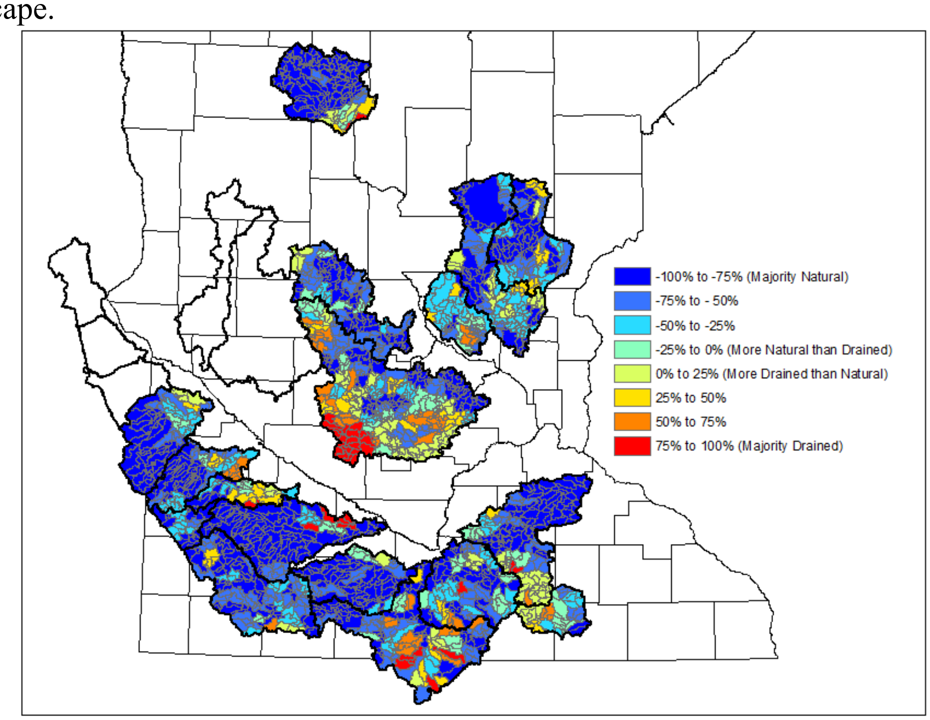


Figure 10 – Distribution of natural versus altered surface hydrology in watersheds with available data from the MN DNR Hydrology Dataset**.**

Flat watersheds need ditch systems to move water across their landscape. This effect can be seen in Figure 10 where the greatest density of artificial drainage occurs in the flatter regions of the watersheds, such as the lower reaches of the western Minnesota River basin watersheds or the upper reaches of the Blue Earth and Le Sueur watersheds. Natural or unaltered systems tend to dominate in areas that have a higher elevation difference, such as the prairie coteau of the the western Minnesota River Basin or the lower reaches of the Cannon River near the Mississippi River. Many altered systems connect directly to natural systems over short distances and this may not be reflected in Figure 10. Overall this analysis provides a comparative assessment of the watersheds and an estimate of how much altered hydrology exists in each of the watersheds.

1.1.4 Drained Depressional Areas

Wetlands are typically defined by the presence of saturated soils and vegetation which is specifically suited to wet conditions. Wetlands typically occur in topographical low areas where rainwater collects or where groundwater reaches the surface. Depressional areas and prairie potholes are the result of glacier activity. The decaying ice sheet left behind depressions formed by the uneven deposition of till in ground moraines. These depressions can fill with water, creating seasonal wetlands. Depressional areas and wetlands, historically, drained either by infiltration or by evapotranspiration. Wetlands, prairie potholes and seasonally inundated depressions were common features on the natural landscape in our 21 study watersheds (Figure 11). These were often described as wet-prairie in the original land surveyor notes from the mid 1800's, and comprised a significant portion of the pre-European land classification.

Figure 11. Aerial photograph of the prairie pothole region of the Minnesota River Basin.

In order to quantify how many wetlands or depressional areas with ponded water were originally on the landscape we used the Restorable Wetlands Inventory (RWI). This inventory covered most of our study area and was beneficial to the discussion of water residence time and water storage capability discussed in Result 2. The RWI along with the National Wetlands Inventory (NWI) allow us to show the landscape as it may have originally looked prior to settlement. Using this dataset, we can make comparisons between the different watersheds and how much loss of depressional areas has occurred.

Methods

Depressional areas were calculated based on the data from the Minnesota Restorable Wetlands Inventory (RWI) created by the Restorable Wetlands Working Group (USFWS 2011), as well as data from the National Wetlands Inventory (USFWSb, 2011) (Figure 12). These inventories used National Aerial Photography Program (1:40,000 scale) color infrared photographs viewed in stereo pairs at 5X magnification to delineate and digitize existing and drained depressional areas. Drained depressional wetlands were delineated on mylar and then digitized to a polygon shapefile dataset. The RWI consulted collateral data during the delineation process to validate the results. These data consisted of published county soil-surveys and descriptions of hydric soils, USDA Farm Service Agency compliance slides (aerial 35 mm slides) acquired in 1993 (immediately after a period of intense precipitation), USGS 7.5 min topographic maps, and National Wetlands Inventory (NWI) maps.

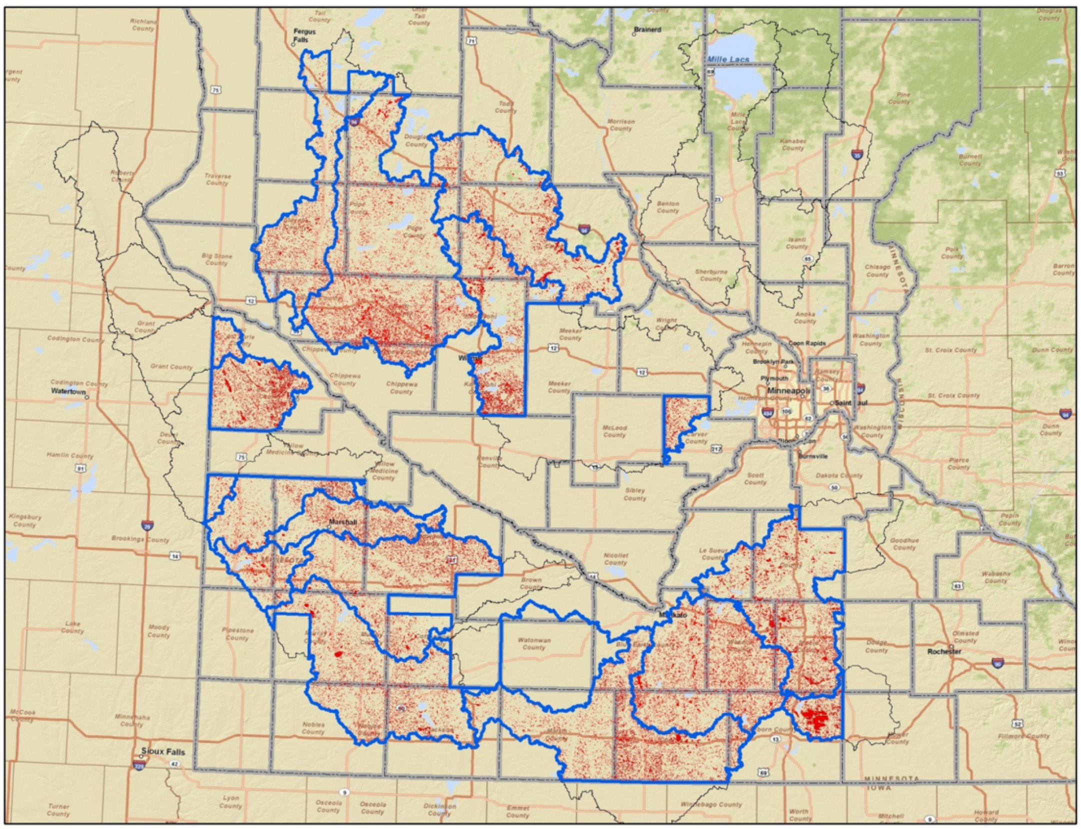


Figure 12. Restorable Wetlands Inventory – The red polygons show the areas of restorable wetlands in our study watersheds per the restorable wetlands inventory where data is available.

The data were downloaded from the Ducks Unlimited website (USFWSa 2011), reviewed and found to contain duplicate data within certain files for some counties. Staff at the Water Resources Center at MSU-Mankato manually removed the duplicate polygons to create a clean dataset. The county data were then clipped to each watershed in the study area and then each partial county was aggregated into the corresponding watershed (Figure 13).

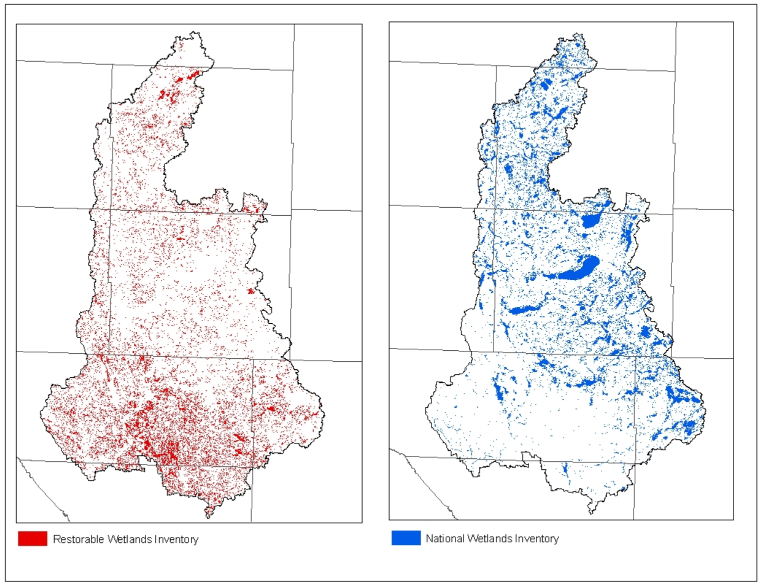


Figure 13. Restorable Wetlands Inventory and National Wetlands Inventory for Chippewa River Watershed

The RWI data and analysis of drained depressional areas only encompassed about 60% of the total area in our 21 watersheds. To estimate the total loss of depressional area for an entire watershed, we calibrated the relationship between drained depressional areas and poorly drained cultivated soils in the watersheds with RWI data to predict the amount of drained depressional areas in watersheds without RWI data (Figure 14).

A.

B.

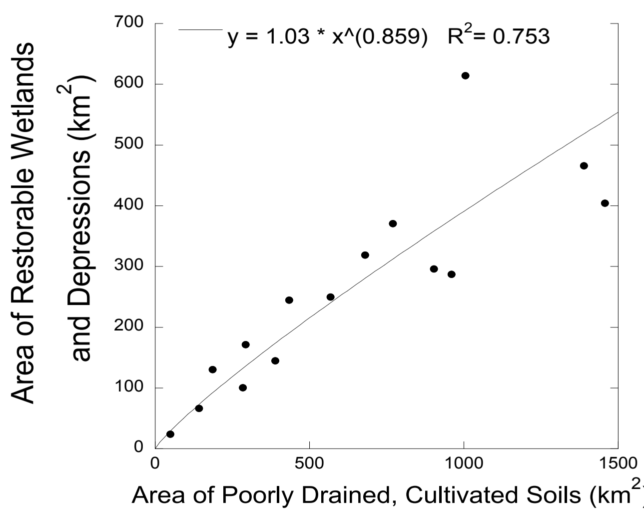


Figure 14. (A)Example of RWI data showing drained depressional areas, soil type and cultivated lands. (B) Predictive relationship between drained depressions and poorly drained cultivated soils

The extent and distribution of poorly drained soils were determined using the Soil Survey Geographic (SSURGO) database (see Result 1.1.1) We extracted the poorly drained and very poorly drained classes, which reflect the soils that would benefit from artificial drainage, and intersected these with cultivated lands to determine the amount of poorly-drained, cultivated soils in each watershed. The county data were then clipped to each watershed in the study area and then each partial county was aggregated into the corresponding watershed and the area of poorly drained, cultivated soil was regressed against the amount of drained depressions as determined from the RWI. This regression (r^2= 0.75) and the total amount of poorly drained cultivated soils in each watershed was used to estimate the total depressional area lost in each of the 21 watersheds (Figure 14).

Findings

Our estimates for the loss of depressional areas using the Restorable Wetlands Inventory dataset show that watersheds with poorly drained soils and a high percentage of cultivated land have high losses of depressional areas. In these watersheds nearly all of the natural wetlands and depressional areas have been altered by drainage, representing a

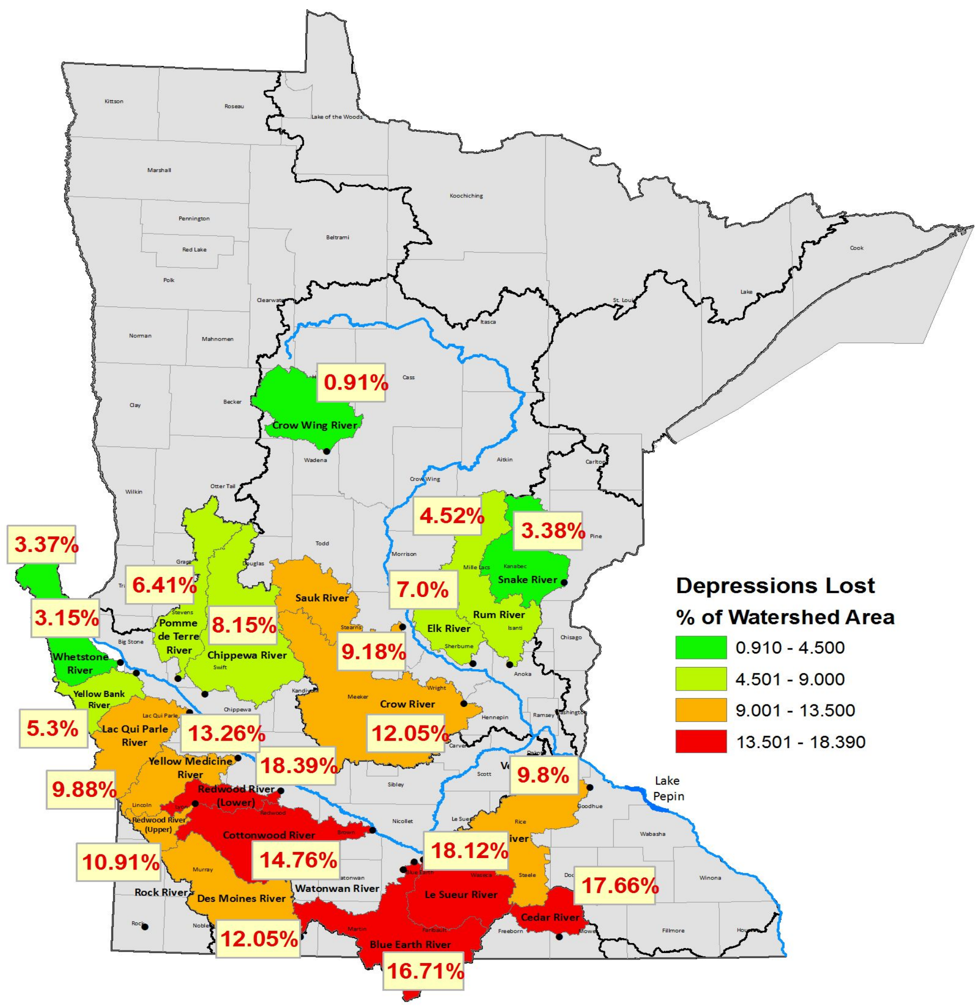


Figure 15. Drained depressional area as a percentage of total watershed area.

profound hydrological modification of up to 20% of the total watershed area (Figure 15).

The loss of these depressional areas translates into a reduced water residence time of ponded water and thus a reduction in ET with less water routed back to the atmosphere—and presumably more water routed to rivers. These depressions range from former wetlands with significant residence times to extensive ephemeral ponded water in fields. In all cases artificial drainage reduces the amount of time that water is on the landscape that can be lost to ET. In watersheds where drained depressional areas represent 10 to18% of the total watershed area this represents a major alteration to the hydrologic cycle.

The RWI inventories offer a good starting point for assessing changes to ET and the routing of water through a watershed. In result 2 below, the loss of depressional areas provides a quantitative way to compare hydrologic changes among watersheds and offers an important mechanistic correlation to changes in water budgets. However, these inventories do not give detailed temporal trends that can be compared to long term flow records and are an incomplete surrogate for estimating changes in ET. The RWI and NWI inventories likely do not capture very shallow depressions with short residences times. This type of ponded water continues to be drained with intensive, close-spaced pattern tiling. It is possible that the pattern tiling under small but extensive depressions is continuing to reduce water residence time on the landscape, and that this form of artificial drainage remains an important alteration to the water budget and stream flow.

1.1.5 Changes in Cropping Patterns

Quantifying changes in cropping patterns was not an initial objective of this study, but given the potential effect of crop conversions on water budgets and ultimately river flow, it was added to the study. The role of crop conversions as a driver of changes to river flow is discussed in Result 2 below. An analysis of annual crop acreage from 1940 to 2009 was completed using the NASS historical data of crop production for all counties in the study watersheds. The National Agricultural Statistics Service (USDA, 2010) has a database of crops grown by county from roughly 1920 until the present. This type of data is valuable because it not only gives us a historical account of how land cover has changed and the temporal relationship to trends in river flow, but can also be used to estimate changes in crop evapotranspiration (see result 2)

Methods

An analysis of crops harvested annually since the 1920's was completed using the National Agricultural Statistics Service (USDA 2010) with data of crop production for Minnesota, South Dakota and Iowa downloaded from their Quick Stats site. County data was intersected with the 21 watershed and aggregated to calculate the acres harvested of each crop type for the give watershed. Acreages of corn, soybeans, small grains, hay, alfalfa, pasture, and non-crop land were determined for each year. Median acreages for the two 35-year time periods (1940-1974 and 1975-2009) were used to assess and compare crop conversion in the different watersheds watersheds.

Findings

The cropping patterns analysis yields an interesting and important picture of the evolution of cropping patterns within our study area and is representative of the Midwest as a whole. In the heavily agriculture area of the Minnesota River Basin, soybeans only started to be grown in the 1940's and their importance as crop increased steadily for the next 70 years. In many of the watersheds, soybeans now constitute nearly half of the row-cropped acreage, with corn comprising the remainder. This increase in soybeans is mirrored by a decrease in acreage of small grains and hay. Interestingly over the 90-year time span of NASS crop records, the total acreage in row-crop does not change much, and there were nearly as many acres of corn planted in 1940 as there was in 2009. A few watersheds, such as the Blue Earth and Le Sueur showed minor increases (less than 10%) in the total amount of land used for row-crops, principally from an increase in corn acreage. The conversion from a diverse set of row-

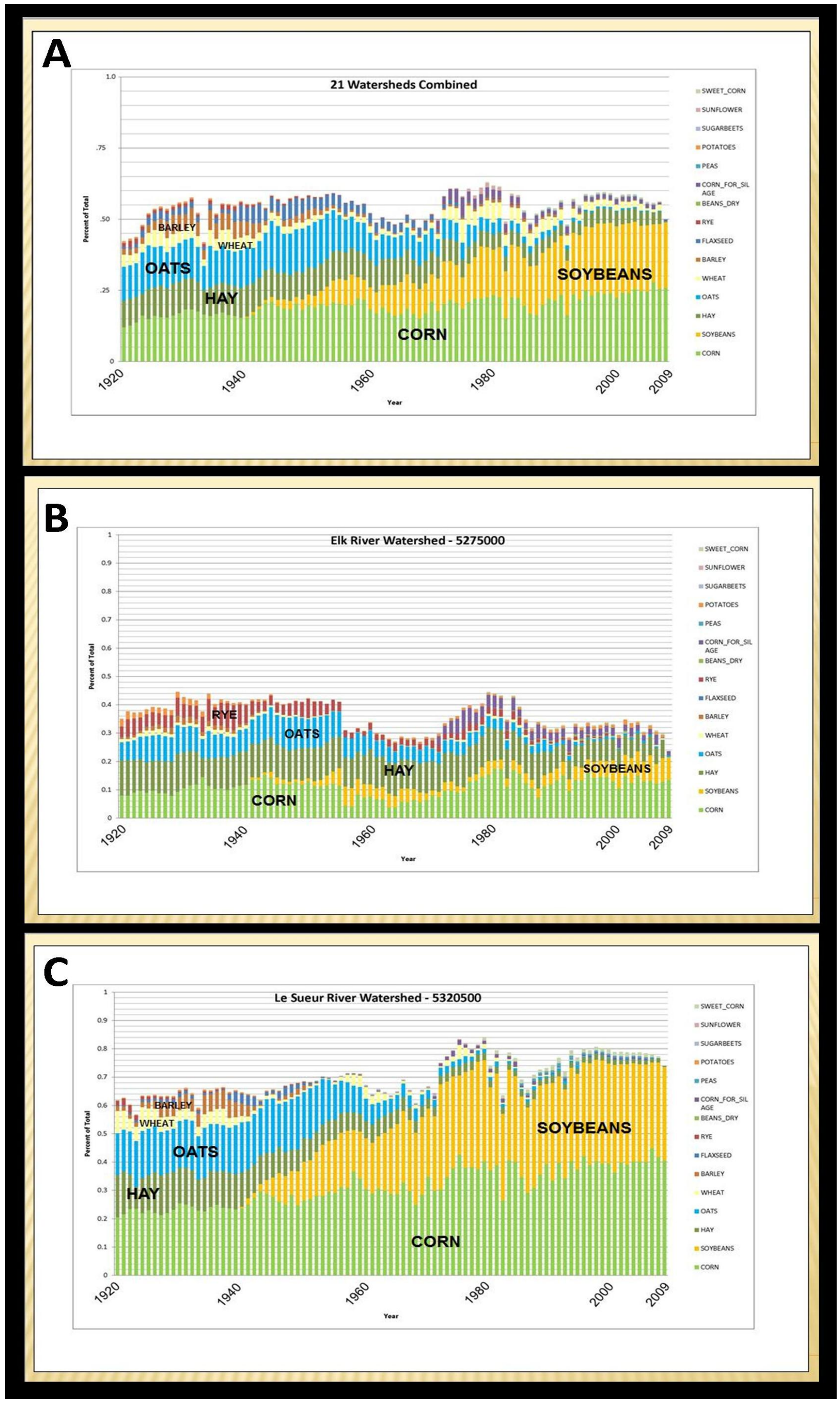


Figure 16. Changes in cropping patterns from 1920 to 2009. Percent of harvested acres of each crop for (A) all watersheds, (B) Elk River watershed and (C) Le Sueur River.

crops to a soybean and corn monoculture is most pronounced in the Minnesota River Basin in the watersheds of Le Sueur, Blue Earth, Cedar, Cottonwood, and Redwood. The smallest changes in increase or the amount of land in corn/soybean production occur in the watersheds in the northern part of our study.

Table 1. Change in cropping patterns for the 21 study watersheds. "Ag" is the percentage of the total watershed that is cultivated for any crop. Percentages are the fraction of the total watershed used for a particular crop. Values represent the mean for a 35 year time period. The increase in soybeans is simply the difference between the two periods. The increase in soybeans is mirrored by a decrease in hay and small grains. In most watersheds, the total amount of land in cultivation and the percentage used for corn changes by less than 10% over the 70 year record.

	% of Watershed Area 1940 - 1974				% of Watershed Area 1975 - 2009					
Watershed	Ag	Soy	Corn	Hay, , Small Grains	Ag	Soy	Corn	Hay, Small Grains	Increase in Soy: percent of total watershed	Decrease in Hay, Small Grains
Blue Earth	68%	18%	34%	16%	82%	37%	42%	3%	19%	-12%
Cannon	57%	8%	22%	27%	62%	21%	31%	10%	13%	-17%
Cedar	66%	14%	27%	25%	77%	31%	38%	8%	17%	-17%
Chippewa	57%	7%	17%	34%	57%	18%	23%	17%	12%	-17%
Cottonwood	72%	14%	31%	27%	79%	35%	36%	7%	21%	-19%
Crow	56%	7%	20%	29%	59%	19%	26%	14%	12%	-15%
Crow Wing	16%	0%	2%	13%	15%	2%	3%	11%	2%	-2%
Des Moines	72%	12%	33%	27%	78%	35%	37%	5%	23%	-21%
Elk	36%	3%	10%	23%	35%	5%	16%	13%	2%	-9%
Lac qui Parle	65%	7%	22%	36%	63%	24%	24%	15%	16%	-21%
Le Sueur	68%	17%	29%	21%	77%	33%	39%	5%	16%	-16%
Little Minnesota	55%	2%	10%	44%	46%	13%	11%	22%	11%	-22%
Lower Redwood	72%	11%	32%	29%	78%	34%	36%	8%	23%	-21%
Pomme de Terre	60%	5%	16%	39%	64%	20%	21%	22%	15%	-16%
Rum	20%	1%	5%	14%	20%	3%	8%	9%	2%	-5%
Sauk	46%	1%	12%	33%	47%	6%	20%	21%	5%	-12%
Snake	14%	0%	3%	12%	15%	1%	4%	10%	1%	-2%
Upper Redwood	68%	5%	28%	36%	68%	25%	30%	12%	20%	-23%
Whetstone	57%	2%	11%	44%	49%	15%	13%	21%	13%	-23%
Yellow Bank	59%	3%	14%	42%	53%	17%	17%	19%	14%	-24%
Yellow Medicine	69%	7%	28%	34%	71%	28%	31%	12%	20%	-22%

1.1.6 Estimation of Tile Density from Aerial Photography and Landowner Survey

Quantifying the amount and distribution of subsurface tile networks is difficult. Records for tile currently being installed are limited and even less is documented for tile networks installed in earlier decades. Until recently, maps of tile lines may have not been created or saved after the installation of the tile lines. Many of the maps currently being produced are submitted to the permitting agency and privacy issues do not allow the data to be viewed by the public. Methods used to map tile lines are through aerial photography or landowner surveys of their property. Both of these techniques have limitations.

Landowner surveys can be beneficial if the land owner has kept good records of their installation of tile and have mapped the tile at time of installation. However, many landowners have not kept good records of the installation, usually relying on their memory of the installation. Another problem with landowner surveys is the participation rate of the landowners within a watershed to share their information on the location of their tile lines. Participation rates can affect any type of analysis if data is missing for parts of the watershed.

An alternative method for mapping tile lines is through aerial photography (see figure 17 for example). The resolution of aerial photography allows us to pick out the details of a feature that could only encompass a couple of meters wide. As the tiling removes the moisture from the ground, the soil above the tile dries at a quicker rate than the soil between the tile lines, making the tile patterns visible. This type of regular aerial photography has its limitation in that the identification of tile lines is by visual examination of the photo and requires the correct season and soil conditions to make the networks visible. Different sensors can be integrated into the aerial imagery such as color infrared or thermal imaging, but these additional sensors increase the cost of the imagery and are not always done. Freely available imagery from the USDA Farm Service Agency (FSA) does contain color infrared layers but the imagery is usually acquired in the summer months. The resulting imagery does not produce the necessary signature due to the vegetation cover. Spring leaf off imagery can produce the signature but the timing needs to done at the right time when the soils are drying at different rates due to the presence of tiling underneath the ground.

Methods

At the beginning of this project, the Blue Earth County LiDAR aerial photography was known to show tile lines for a majority of the county. The LiDAR was flown in early April of 2005 at the time that the soils were warming up and the moisture in the soil was starting to flow through the tile lines. Research from previous studies on locating tile lines has shown that flying aerial photography 2–3 days after a one inch rainfall can produce effects similar to Blue Earthy County aerial photography (Naz and Bowling, 2008). The digitizing of the Blue Earth County tile lines was completed in December 2010 by visually identifying the tile lines from the aerial photo and creating line features in a GIS shapefile. At that point, we were trying to determine the amount of tile and the length of the tile that we could identify using this aerial photography (Figure 17).

A subset of the data from Blue Earth County was used to analyze the relationship between the soil type (i.e. poorly drain and well drained, See Section 1.1.1) to the total length of sub-surface tile. Using 19 sub-basins within the Le Sueur watershed (Figure 18), we delineated the areas of poorly drained and well drained cultivated land and then, using the aerial photography, estimated the length of sub-surface tile in each of the watersheds (see

Figure 17 for example). This provides a current estimate of sub-surface tile density (total length per acre) for poorly drained and well drained cultivated lands in the watershed.

In a separate project, the Minnesota River Assessment Project (MRAP) surveyed 32 small watersheds (< 25 mi^2) back in 1991 for the extent of tile in those watersheds. This data was recorded through aerial photographs and surveys. In 2010, five of the watersheds were resurveyed and updated based on available information. The Beauford Ditch was inventoried for tile back in 1991 under MRAP and a reinventory was completed in 2010 using landowner interviews and the additional aerial photography from 1991 and 2005 (Blue Earth LiDAR photography). Additional data from the MRAP Tile Re-inventory project was used to improve the data for the Beauford Ditch watershed. The other four minor watersheds in Kandiyohi, Cottonwood, Redwood counties were reinventoried as well, and one additional in Blue Earth County was added. Tile density (length of tile per cultivated area) for each of these watersheds was estimated and the data is available but due to privacy issues with landowner surveys, we have not included this data in this report. However, relationships from these four watersheds are similar to the Blue Earth and Beauford watershed.

Figure 17. Blue Earth county LiDAR aerial photograph overlaid with linework showing the locations of tile lines as digitized from the aerial photograph.

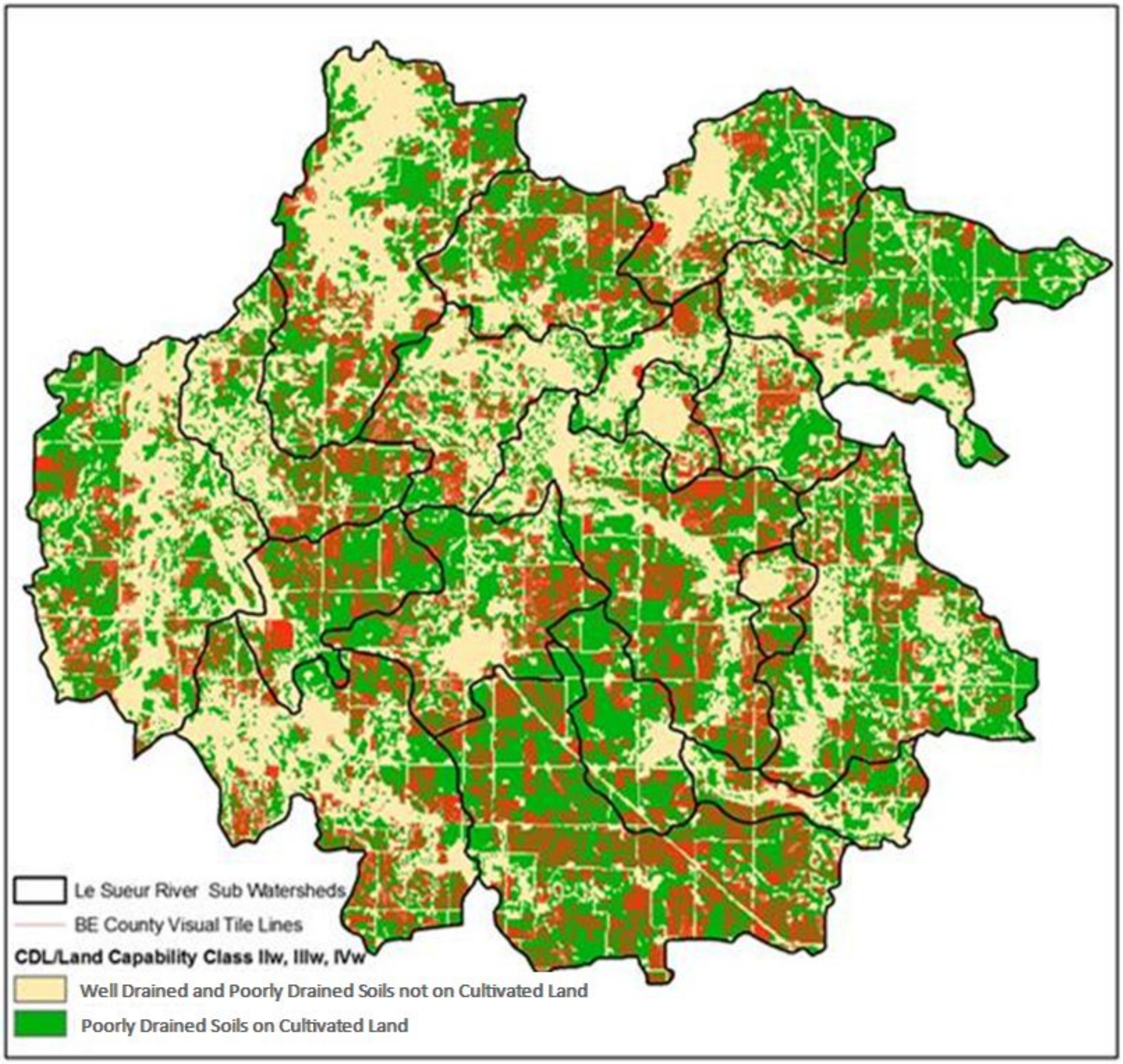


Figure 18. Blue Earth county LiDAR derived tile lines and SSURGO derived poor and very poorly drained soils on cultivated land for 19 sub-basins within the Blue Earth and Le Sueur watersheds

Findings

In general, the density of pattern tiling is associated with cultivated soils that are specified as poorly drained and very poorly drained (Figure 18). Correlation of soil type to the length of tile for 19 sub-basins in the Le Sueur watershed demonstrates this relationship and provides an estimation of the overall density of tile on poorly drained and well drained soils (Figure 19). For the 19 sub-basins combined, 71% of the cultivated land is classified as poorly drained and has an average of 141 meters of sub-surface tile per hectare of row-cropped land. As expected the poorly drained soils have a higher density of tile but it is only about double that of the well drained soils (164 v. 94 m/ha respectively, Figure 19). The strong correlation shown in Figure 19 indicates that the density of tile on cultivated land is similar throughout the watershed and can be reasonably predicted from soil type and landuse.

The two regressions shown in figure 19 provide a method to estimate tile density that is applicable to watersheds with similar soils, farming practices, climate and topography, but further analysis on other watersheds is necessary to define the regional applicability of the regression.

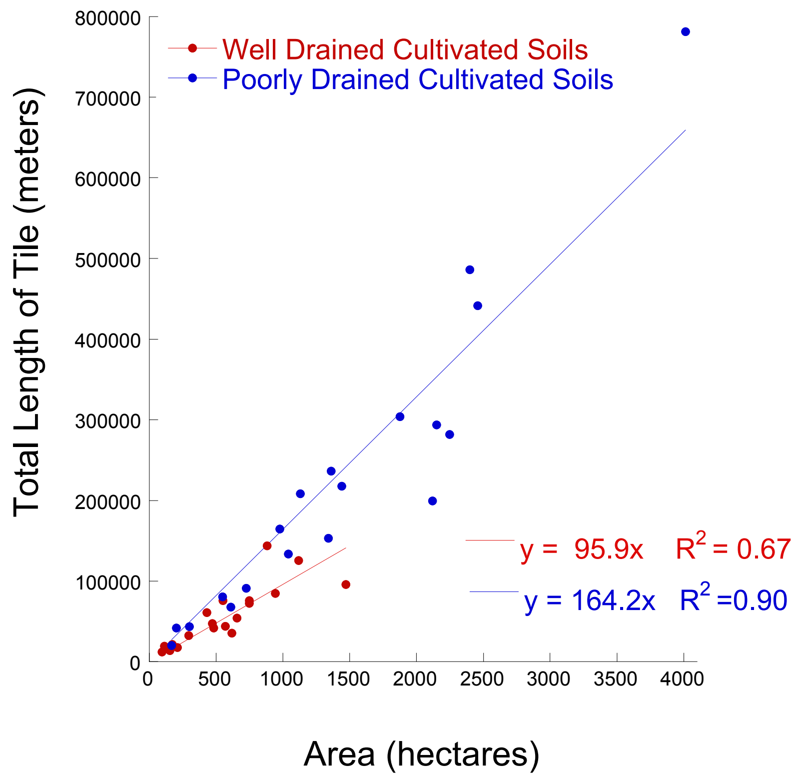


Figure 19. Relationship of length of tile per area of cultivated land for 19 sub-basins in the Le Sueur watershed (eastern Blue Earth county). The slope of the regression predicts the overall density (meters/ha) of tile on poorly drained and well drained cultivated soils.

1.1.7 Changes in Urbanization

Increases in impervious surface could contribute to increases in river flow. We used changes in population or urbanization as a surrogate for changes in the amount impervious surface area. Presumably as population increases, and agricultural lands are urbanized, there is proportional increase in impervious surface. The first step to toward examining this change is to quantify the change in population upstream of the flow monitoring site in each watershed.

Methods

An analysis of the population trends within the 21 watersheds was completed in October of 2010. Using historical census data for township, villages, and cities within the 21 watersheds, we created a detailed analysis of the actual population that resided in the portions of the watersheds upstream of where rive flow was measured. Aggregating data to a watershed level from county level data can be misleading due to the fact that population is not consistent across the county, and that many of the larger urban areas are below our monitored flow site. For example, the city of Mankato is downstream of the gauging stations on the Le Sueur and Blue Earth rivers, thus changes in Mankato impervious surface area have no effect on the flow trends in these two rivers. By using the township and city data, we can more accurately reflect the population trends in the watersheds as relate these to any observed trends in river flow.

Using the 1990 census population layer as our base layer of townships and cities/towns, we used the census population publications from 1930 – 1980 and inputted the population for these areas into a spreadsheet accordingly. The 1990 and 2000 census populations were already in shapefile format from the census bureau and other sources. Upon creating layers for each census year from 1930 to 2000, we clipped the layers by the 21 watersheds. Townships and cities along the boundary of the watersheds were clipped along the boundary. The areas of the two clipped polygons were calculated and the percentage of the two clipped polygons was calculated based on the original area of the full polygon. This percent and the population of the full polygon were multiplied to determine a population of the clipped polygons. Finally, all polygons within each watershed were aggregated into their corresponding watershed to determine the population of the watershed

Findings

Several ways to view changes in population are shown in Figures 20-22: Census population by watershed (Figure 20), Acres per person (Figure 21) and Persons per Acre (Figure 22). Both the Population Census (Figure 20) and the Persons per Acre (Figure 22), show that many watersheds in the Minnesota River Basin actually have decline in population from 1930 until the present. The Redwood River watershed which encompasses Marshall and Redwood Falls is an exception. The Le Sueur River watershed shows a consistent persons per acre over the 70 year time span. The Le Sueur River watershed is located just south of Mankato and certain growth areas of Mankato fall into this watershed. The Sauk, Elm, Crow and Rum River Watersheds showed an increase in population over the time period. These watersheds are located north and west of the Minneapolis-St. Paul Twin Cities Metropolitan Statistical Area. Their proximity to the ever expanding Twin Cities have seen population growth consistent with the urban expansion. Other watersheds seeing increased growth in persons per acre are the Cannon, Cedar and Snake River. These watersheds have a major city or cities that have seen a growth in both size and population.

In result 2 below, we show that many of the agricultural watersheds in the Minnesota River basin have had large and significant increases in river flow. These same watersheds have had minmal population changes, and several have actually decreased. <u>Based on this data, it is reasonable to conclude that for these study watersheds, urbanization is not be an important driver of changes to hydrology.</u>

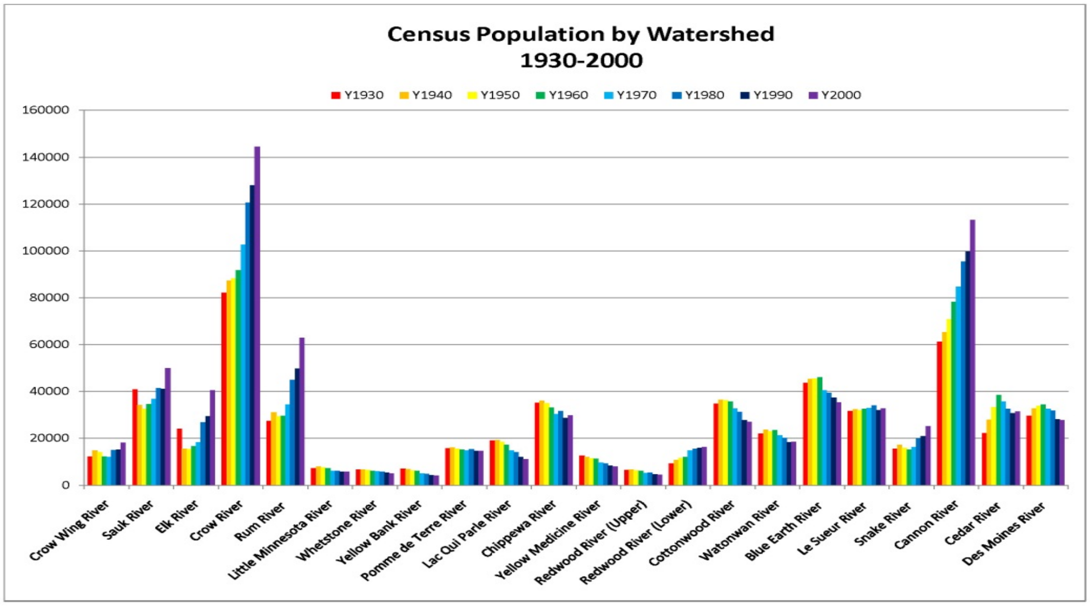


Figure 20. Census population by watershed for the years 1930 -2000. The population estimates were aggregated by the smallest township and city units available for those years.

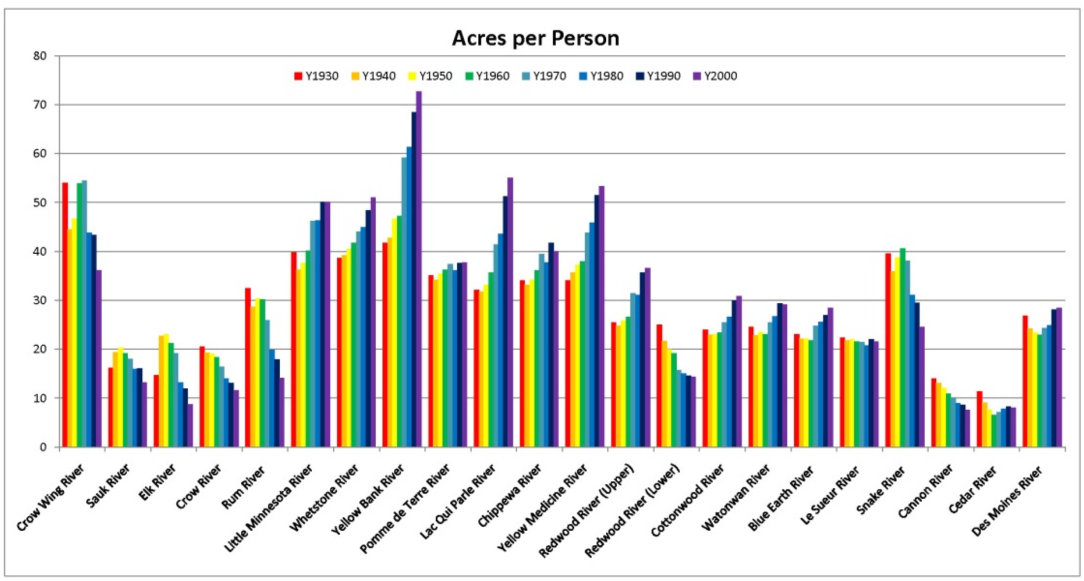


Figure 21. Acres per Person by watershed for the years 1930 -2000. The population estimates were aggregated by the smallest township and city units available for those years.

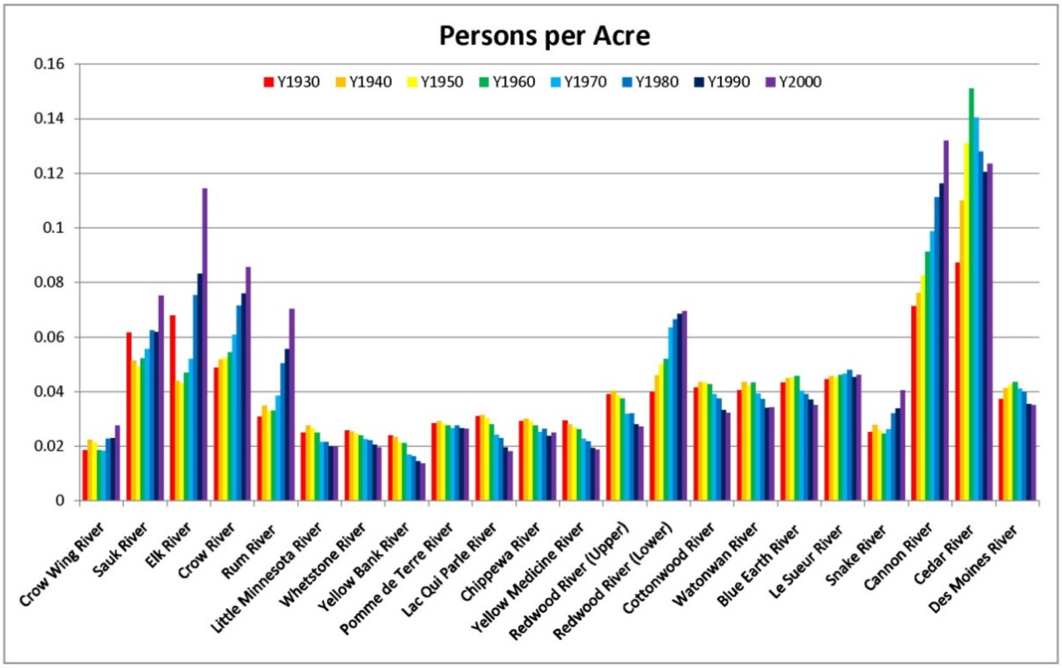


Figure 22. Persons per Acre by watershed for the years 1930 -2000. The population estimates were aggregated by the smallest township and city units available for those years.

Result 1: Deliverable 2.

HISTORICAL TRENDS IN INSTALLATION OF DRAINAGE

1.2.1 SUMMARY OF EXISTING DATA: SEVEN MILE CREEK

The Seven Mile Creek Watershed completed a study called, "An Historical Perspective on Hydrologic Changes in Seven Mile Creek Watershed" which documented hydrologic changes, but more specifically wetland losses, in the Seven Mile Creek Watershed. (http://mrbdc.mnsu.edu/sites/mrbdc.mnsu.edu/files/public/org/bnc/pdf/smc_airphoto.pdf)
The analysis completed by Kevin Kuehner on the Seven Mile Creek Watershed mirrored many of the methods we used in our study and was thus a good comparison study area to compare to our analysis. Seven Mile creek does not have a long-term flow record, thus temporal trends in river flow could not be compared to the trends in drainage installation. Nonetheless, the drainage history in the Seven Mile creek watersheds offers a useful surrogate for the drainage trends in the agricultural watersheds of Minnesota.

Methods

The 95.3 km^2 (36.8 mi^2) study area is a small, agricultural watershed located in south-central Minnesota. Historical aerial photos along with a Geographic Information System (GIS) were used to assess changes in water resource features of the watershed. More than 130 aerial photographs from seven different periods dating back to 1938 were scanned and rectified for use in a GIS database. Wetland areas converted to cropland were delineated and digitized. In addition, other land use changes, such as surface and sub-surface drainage modifications and cropping system shifts, were mapped and documented.

Findings

Results from the study indicate significant hydrologic changes have occurred in the watershed. Analysis of pre-settlement maps and survey notes indicate that about 50% of the watershed was once covered by wetlands. Of those wetlands, it is estimated that 88% of the natural wetlands have been converted to cropland. About 47% of those losses occurred from early settlement (late 1800's) to 1938. From 1938 to 1985, an additional 41% of the wetlands were drained and converted to cropland. This translates to an average annual net wetland loss of 40 hectares (100 ac.) per year.

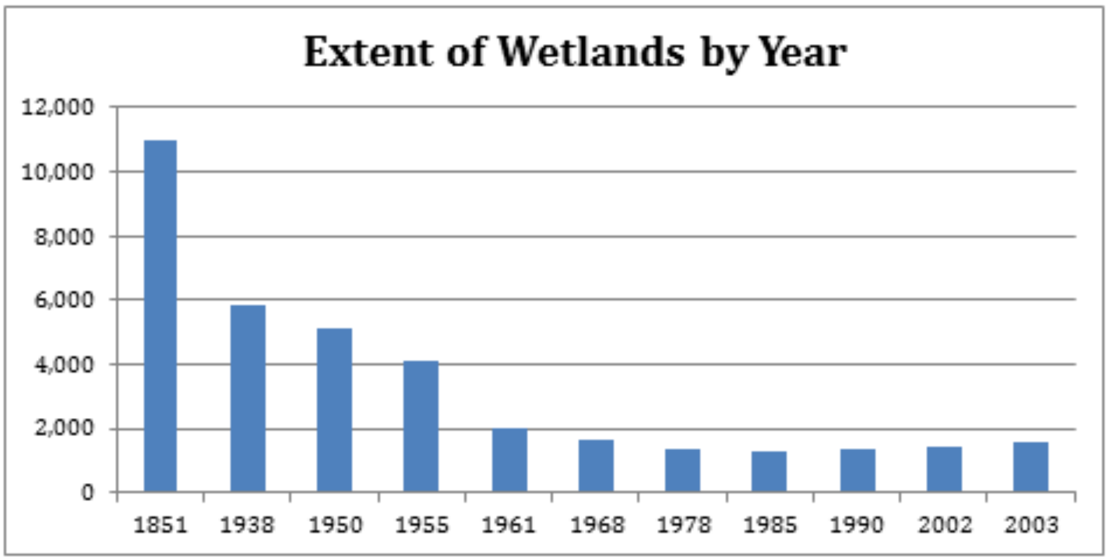


Figure 23. Extent of wetlands by year in the Seven Mile Creek Watershed.

During this same period (1938- 1985), 40 km (25 mi.) of drainage ditches were constructed, more than 966 km (600 mi.) of public and private sub-surface drainage systems were installed, and it is estimated that total corn and soybean acreage increased from 30% to 96% within the watershed. The most rapid percent change, a 50% wetland decrease, occurred between 1955 and 1961. The construction of two county drainage ditch systems in 1955 accounts for this change. After 1985 the rate of wetland lost decreased. Wetland increases are a direct result of conservation programs combined with grants from private and state water resource protection programs. Figure 23 shows the change in acres of wetland area in Seven Mile Creek Watershed.

Using the original land survey records and pre-settlement maps for the almost 11,000 acres were originally considered wet areas1800's (Figure 24). By 1938, surface drainage systems had already connected many of these wet areas to the natural hydrology and thus the outlet to the watershed. Areas that originally held water on the landscape for a long period of time (wetlands) were now altered to route this water directly to the creeks, ditches or river, thus allowing these areas to be used for pasture or cultivation. This landscape alteration is documented in detail for the period 1938 to 1985. Starting in 1985, wetland complexes were being constructed to benefit water quality, and the loss of wetlands has stabilized. Nonetheless, nearly all wetlands in the Seven Mile creek watershed have been drained. While the time trend of wetland loss cannot be documented as well in our study watersheds, the extent and magnitude of wetland loss observed in Seven Mile creek is representative of watersheds in the Minnesota River basin.

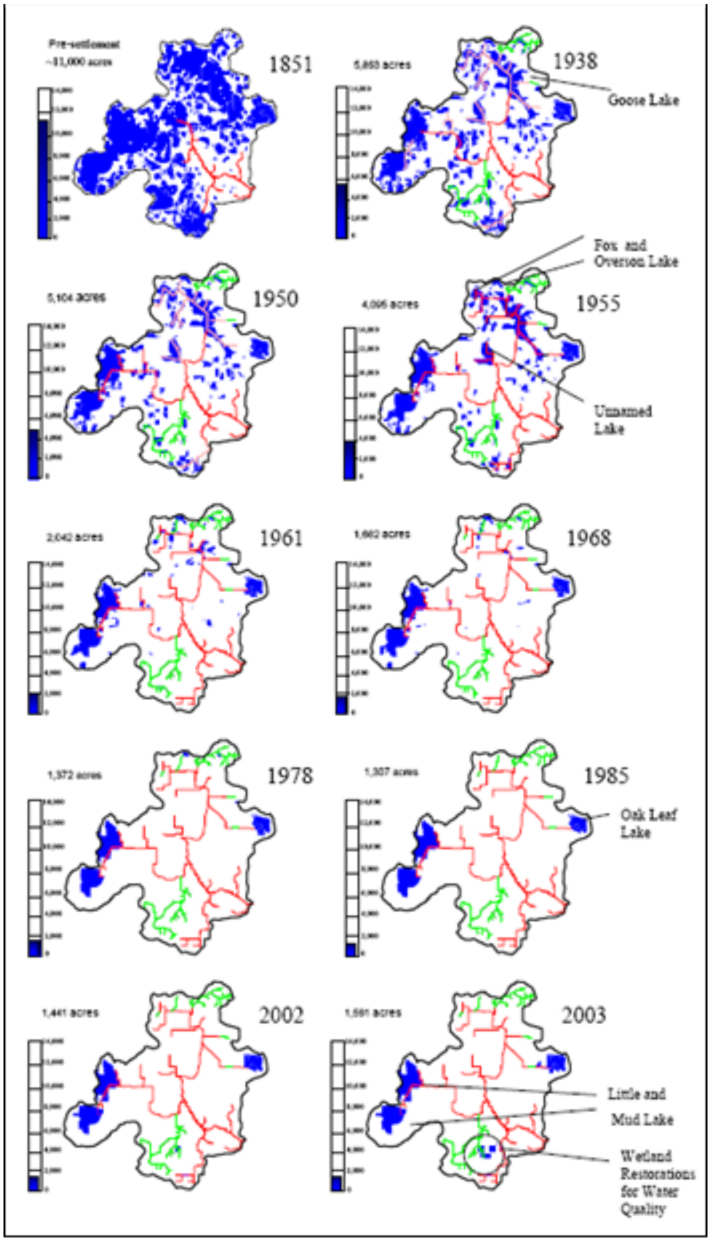


Figure 24. Historical distribution of wetlands in Seven Mile Creek Watershed, show the time trends of wetland drainage.

2.1.2 SUMMARY OF HISTORICAL DATA FROM BERT BURNS

In 1954, Bert Burns, a Ph.D. candidate at the University of Nebraska Lincoln, conducted a detailed study on the agronomic and economic advantage of installing artificial drainage. His Thesis, "Artificial Drainage in Blue Earth County, Minnesota", was a detailed look at land use, geography and drainage patterns in Blue Earth County (Burns, 1954). He wanted to determine the nature and extent of the wetlands of Blue Earth County, find the manner in which their drainage had been accomplished, and measure the physical and cultural results of their drainage. He proposed that the trends and observations in Blue Earth County were representative of the northern Midwest and the results of his study could be applied across the region. His work provides a snapshot of the conversion of wet prairie, wetlands, and poorly drained depressions to cultivated land in the middle of the 20th century.

Methods

Burns used land survey notes, maps, as well as soils and vegetation to determine the original extent of wet prairie. In his thesis, the implementation of artificial drainage was determined from the drainage records recorded by Blue Earth County. Engineer's maps and descriptions were used to delineate the drainage systems. Finally, Burns had sample farms from within the county he used to document the different types of drainage networks used on different types of soils. He showed detailed drainage techniques for various soil conditions as well as the results of drainage upon agricultural land use, crop patterns, field patterns, and land valuation.

Findings

The importance of Bert Burn's thesis in our analysis is the fact that his analysis occurred midway between when drainage started occurring in Minnesota until the present. Also, his analysis is a snapshot of drainage in the 1950's when sub-surface drainage (tile) started being heavily used on agricultural lands. The dry periods of the 1930's and the two World Wars were over. Better economic conditions combined with a wetter period than the 1930's yielded a need for drainage to improve the land available for farming and increase production of agricultural areas.

Natural drainage within Blue Earth County was considered by Burns in his thesis as poor because of two reasons. The first reason is the level topography caused by the large scale ponding of glacial melt waters over the drift plain which occurred within the county. The second reason is the relative low porosity of the heavy prairie soils which is caused by the very considerable silt and clay content. In Burns study, about 58% of the county area can be classified as poorly drained land by the soil survey of the time.

Crop patterns appear to have been affected markedly by the development of artificial drainage. Without drainage, the wet areas could not be reliably used for row-crops. Wet lands, when drained, at first could be used for pasture and dairying, but as cash crops became more important economically, the wet lands were used for cash crops. Figure 25 shows the progression of a sample farm as wet areas were drained and fields were squared off to create larger areas for more efficient cultivation and harvest. Most of the land drained was former wet prairie, characterized by level topography, shallow sloughs, and a heavy silt and clay content. Drainage constituted a significant degree of land improvement. When released from the limitations of the wetness, the wet prairie became some of the most productive soils of the county, equaling or surpassing many soils of better natural drainage.

Three important points from Burn's thesis are evident in his conclusions. One, a sizable area of formerly poorly drained prairie which was used largely for wild hay or pasture has been added to the total area of tillable land within the county. Secondly, drainage resulted in a shift from non-tillage crops to tillage crops. Third, the value of artificial drainage and its effect on the productivity of land resulted in increased land valuation of drained lands as compared to undrained lands.

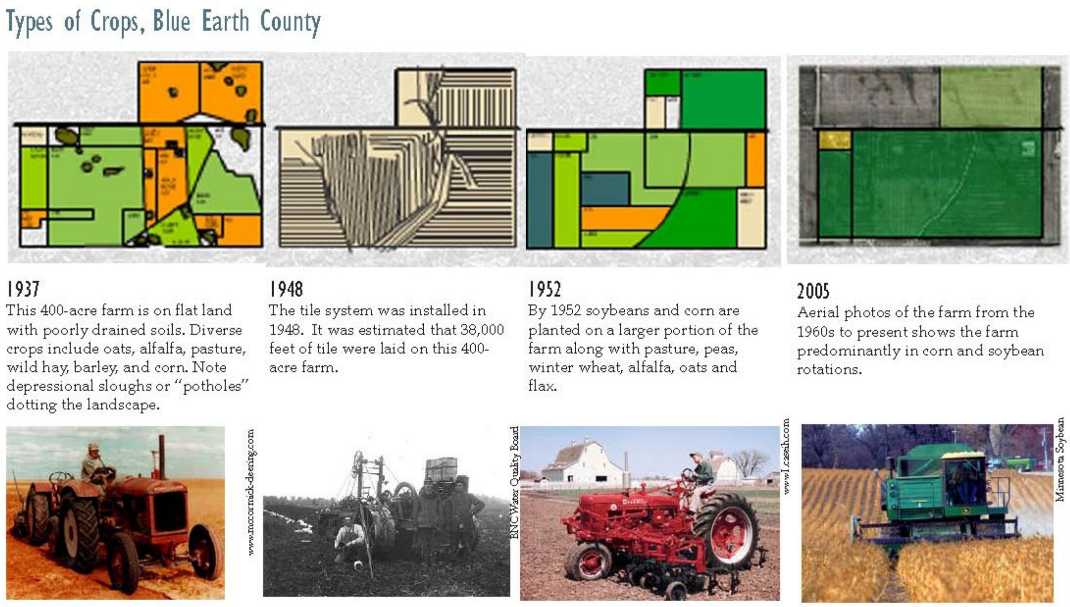


Figure 25. Sample Farm from Bert Burn's Thesis. Progression of land use on the sample farm and the mapping of tile. The removal of wet areas leads to larger, less irregular fields, and a conversion from small grains, hay and pasture to row-crops such as corn and soybeans

2.1.3 SURROGATE WATERSHEDS: BLUE EARTH AND MARTIN COUNTY

Existing data summarized from the Seven Mile creek watershed and Bert Burn's thesis provides a good starting point to quantify trends and extent of artificial drainage installation. To expand our understanding we looked at two different county administered systems, Martin County and Blue Earth County, and used these as surrogate watersheds.

Blue Earth County is essentially a region of gently rolling ground moraine that was deposited by the Late Wisconsin Des Moines lobe, the last glacier to advance over southern Minnesota. The surface relief of the ground moraine descends from three directions, converging from the east, west, and south toward the north central portion of the county. This general slope gave direction to the present drainage pattern. Many of the nearly flat areas of the ground moraine are artificially drained to improve agricultural conditions. The highest surface elevation, about 1190 feet mean sea level, is located in the northeast corner of the county. The lowest elevation, about 750 feet mean sea level, is located in the north central portion of the county where the Minnesota River leaves Blue Earth County to the north. The maximum total relief is approximately 440 feet. The local relief ranges from 10 to 30 feet, except along major river valleys where relief may be as much as 240 feet.

Martin County is in south central Minnesota, and contains portions of the Des Moines and Blue Earth river watersheds. The county has intensive artificial drainage with over a 100 county administered drainage systems throughout Martin County. While these county administered drainage systems do not include all the private systems put in by landowners, Martin County, because of the larger number of drainage systems and the topography of the county, is an excellent surrogate watershed to study the timeline of drainage.

Martin County is a region of gently rolling ground moraine that was deposited by the Late Wisconsin Des Moines lobe, the last glacier to advance over southern Minnesota. The surface relief of the ground moraine descends from the west and south toward the north and east. This general slope gave direction to the present drainage pattern. Many of the nearly flat areas of the ground moraine are artificially drained to improve agricultural conditions. The maximum total relief is approximately 360 feet. Local relief ranges from 10 to 30 feet, except along portions of lake chains where relief may be as much as 80 feet.

Methods

Artificial drainage networks were assessed by looking at the installation patterns across the county and by quantifying wetland loss across the eastern part of the county. The data for the installation of the county administered systems comes from the Public drainage atlas, Blue Earth County, Minnesota, published in 1979.

If we look at the history of drainage as described below, we get a sense of how important drainage was in the early part of the 20th century and how precipitation patterns can affect the need for drainage or not. The following is an excerpt from the publication, “Understanding Minnesota Public Drainage Law – 2002 Overview for Decision-makers”, by the Association of Minnesota Counties.

When the United States was settled, there were approximately ten million acres of vegetated wetlands - or "swamp lands" as they were called - in the area that eventually became the state of Minnesota. They covered about one-fifth of the state's total land area. The Swamp Lands Acts of 1850 and 1860 granted 65 million acres of United States swamp lands to 15 western states, including Minnesota. The grant was intended to ensure that wetlands would be drained, as they were considered to have no value in their natural, marshy condition.

Settlement in Minnesota moved north and west from the Mississippi River in the 1850s. Except for small scale private party and railroad bed drainage, there was not much actual drainage activity.

The first comprehensive public drainage act in Minnesota was passed in 1887. This act provided for a petition process, overview by county commissioners, and the appointment of viewers to survey, locate and prepare a report on the proposed drainage ditch. If the report conformed to the statute; the commissioners could establish the ditch. The act also provided for the payment of damages from the county treasury, the letting of a contract for construction, and the assessment of benefits against the lands to be benefited by its construction. This early drainage law established a process that is remarkably similar to the approach still followed in Minnesota drainage law today.

In 1893, the Red River Drainage Commission was formed to deal with ditches tributary to the Red River. Four years later, in 1897, a three-member Drainage Board of Commissioners was established by the legislature and appointed by the governor. This marked the beginning of state drainage activity.

From 1900 through 1915, there was a proliferation of drainage activity in Minnesota. The State Drainage Commission was formed and it began the construction of drainage systems close to larger trade centers and the railroads. Roads were under construction, and road ditches provided drainage for these new transportation arteries. The state commission conducted regular inspections to ensure that counties fulfilled their duty to repair and maintain the state-funded drainage systems. With the support of the public, the state encouraged drainage of land to enhance its taxable value and productivity.

Around 1916, drainage activity decreased for a number of reasons, including World War I federal policies, a ten-year drought, floods, agricultural depression, tile failures and a change in public and political attitudes toward drainage. The severe flooding of 1918 and 1919 caused the legislature to authorize the establishment of drainage and flood control districts and drainage and conservancy districts. After the end of WWI, land values and agricultural commodity prices rose, but due to high costs, drainage work was primarily limited to improvements and repairs of existing projects. With the advent of the agricultural depression in the mid-1920s, farm prices declined. The drought of the 1930s began, drainage activities again decreased, and existing systems fell into disrepair.

By 1938, normal rainfall returned, and the demand for drainage increased as agricultural prices rose. The existing systems were in poor condition, and the 1945 legislature enacted a bill addressing repairs and improvements. The increasingly confusing drainage laws led the 1947 legislature to authorize district courts and county boards to establish drainage systems after receiving a valid petition. State and township drainage authority was eliminated.

Agricultural prosperity continued during the 1950s, existing drainage systems were repaired and improved, and new systems constructed. Federal programs aided this effort. Drainage by the use of drain tile became widespread.

Installation dates for individual drainage network were taken from county records and integrated into a GIS dataset to define a timeline of drainage installation. The number of systems was recorded by year and the results were analyzed to determine the periods of greatest installation in the Blue and Martin counties

The second analysis, evaluating drainage of wetlands and depressional areas in Martin County and the eastern part of Blue Earth County involved using the Restorable Wetlands Inventory (RWI) layer from the Ducks Unlimited. Aerial photography from the years 1939, 1991, 2003, and 2010 along with the Original Plat Maps of 1855 were used as reference to determine the land use occurring in the polygon of the RWI. The analysis looked at whether the polygon contained evidence of water, vegetation, signs of cultivation or impervious surface. Each polygon was analyzed for the years 1855, 1939, 1991, 2003, and 2010 for these different land uses and was recorded in the GIS attribute table. For Martin County, only the polygons in the area within the Blue Earth and Watonwan River watersheds were analyzed. The resulting data was analyzed for patterns. This analysis is similar to that presented in section 1.1.4 earlier. A benefit of using the Restorable Wetlands

Inventory polygon is that we are comparing the same polygons across the different time periods and the majority of the land use type in that polygon was recorded. .

Findings

With Blue Earth County being a region of gentle rolling ground moraine, the natural topography creates areas where water is going to pool. Whether this water drains or remains on the landscape is dependent on the soil type as well as having an outlet for the water to flow. Where soils inhibited the water to seep into the soil, the need for drainage was required to make the landscape available, either for pasture or for cultivation. As shown in the Figure 26, the installation of open ditch systems occurred mostly in the time frame of 1897 to 1931. A few reasons for this time frame are evident. As stated in the description above, in 1897, the State Drainage Commission was started and drainage activity began in earnest. Also, the advent of mechanized methods of digging ditches became available in the early 1900's. Of the 110 systems listed on the graph, 85 systems were created in the time period of 1897 to 1931. The spatial extents of these systems have not been analyzed but the overall percentage in numbers reflect the vastness of drainage activity in the early 1900's.

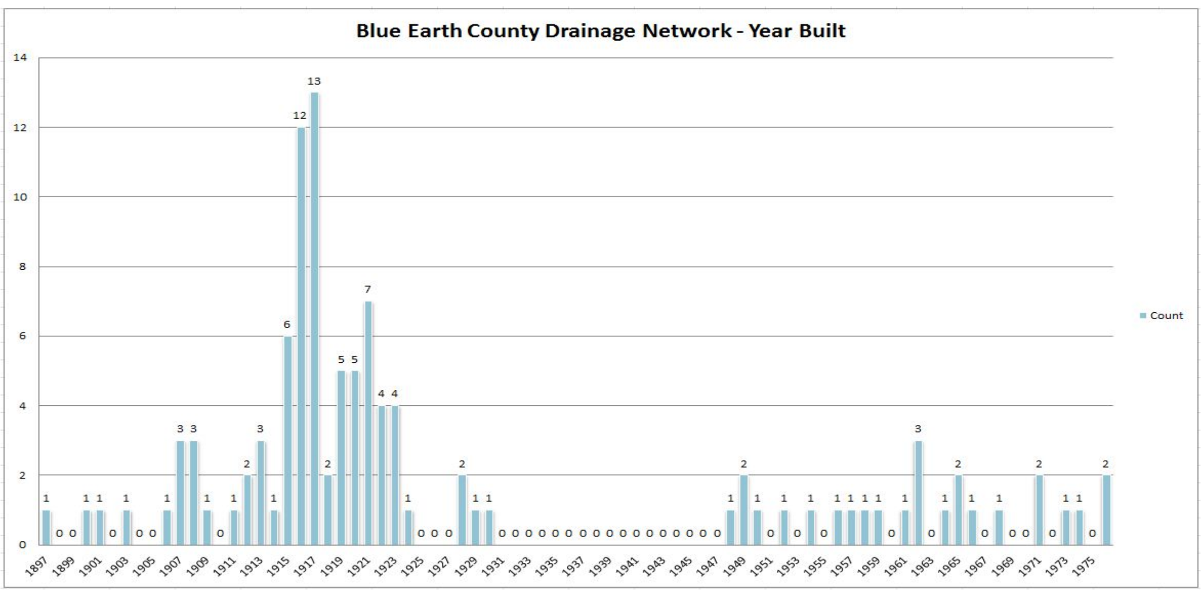
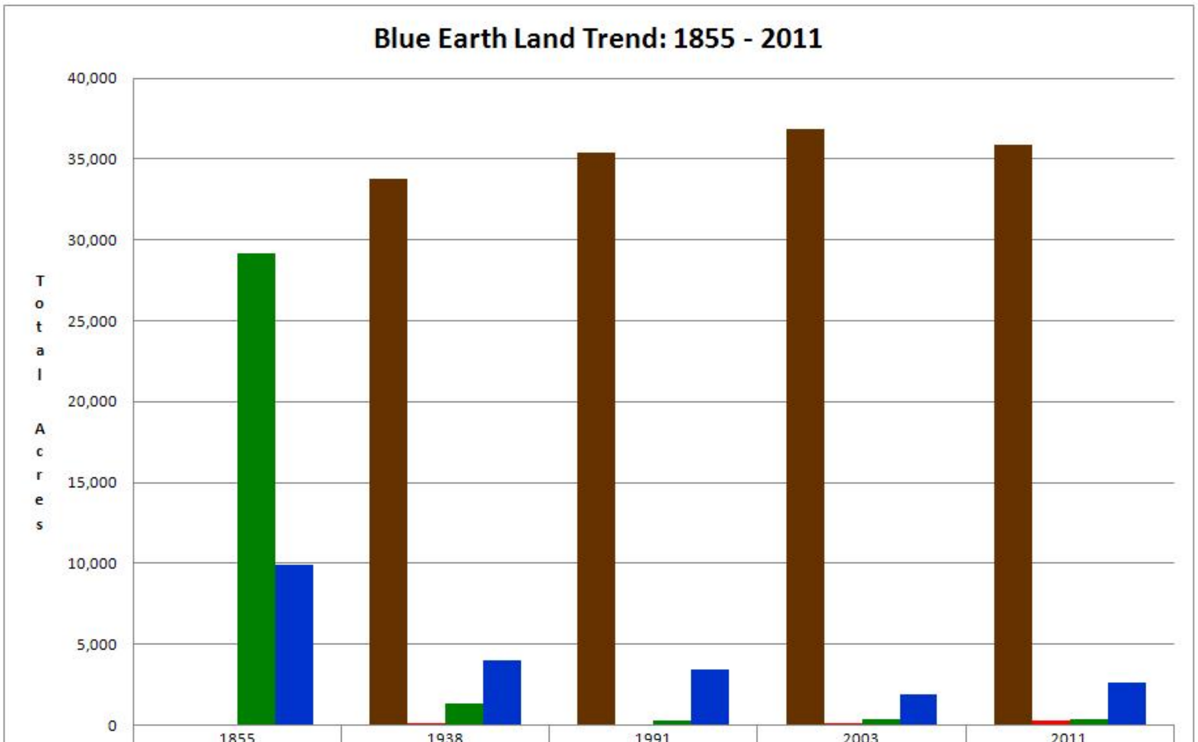


Figure 26. Time trend of installation of open channel drainage systems ("ditches") for Blue Earth County.

Wetland loss and land conversion trends are shown in Figure 27. Historic plat maps created from original land surveyor notes in 1855 can only be used to distinguish wet prairie and wetlands from other land types, but still provide an estimate of the amount of wetlands at onset of modern agriculture. In our analysis of the RWI, we marked the 1855 polygons as either "wet" (wet prairie and wetlands) or "vegetation", thereby lumping prairie, forest, and other native vegetation into a single category. By 1938, most of the native vegetation and about half of the wetlands have been converted to cropland. The drainage of wetlands continues through 1991 and 2003, and by 2003 less than 20% of the original wetlands remain. This data demonstrates that while drainage of wetlands was intense in the early 20th century, the drainage continued throughout the century with significant wetland losses occurring in last decade: i.e. 1991-2003. A small increase in the amount of wet areas occurs between 2003 and 2011 as a result of conversion and restoration programs. This trend was seen in the Seven Mile Creek study area as well.



	1855	1938	1991	2003	2011
cropland	0	33,742	35,391	36,832	35,908
developed	0	4	0	107	254
vegetation	29,185	1,363	291	319	315
wet	9,931	4,008	3,434	1,858	2,639

Figure 27. Land Trends in Blue Earth County based on Restorable Wetlands Inventory Polygons for selected years.

Martin County follows a similar pattern as Blue Earth County. Because Martin County is a region of gentle rolling ground moraine, the natural topography creates areas where water is going to pool. Residence of water in this landscape is dependent on the soil types as well as having an outlet for the water to flow. Where soils inhibited the ability of water to seep into the soil, the need for drainage was required to make the landscape and soil available for row-crops. We mapped the sloughs, marshes, wetlands and any discernible feature that was originally mapped on the 1855 plats. Not surprisingly, when the sloughs, marshes and wetlands are overlaid with the drainage network, the drainage network falls directly on these low areas in a majority of the county.

In Martin County, construction of open channel drainage networks (i.e. ditches) occurs mostly in the early 1900's with most of the ditches installed prior to 1925 (Figure 28). Of the 148 systems listed on the figure, 117 systems were created in the time period of 1904 to 1925. The extent (e.g. total length) of these systems has not been analyzed but the overall percentage in numbers reflects the vastness of drainage activity in the early 1900's. These early systems were mostly surface drainage systems connecting low areas to low areas and then eventually to a natural river system. However, there were some early clay tile systems put into use. In our analysis, we did not differentiate which system was open or tile, we were mostly looking at the date they were installed. A few reasons for this time frame are evident. As stated in the Blue Earth description, in 1897, the State Drainage Commission was started and drainage activity began in earnest. Also, the advent of mechanized methods of digging ditches became available in the early 1900's.

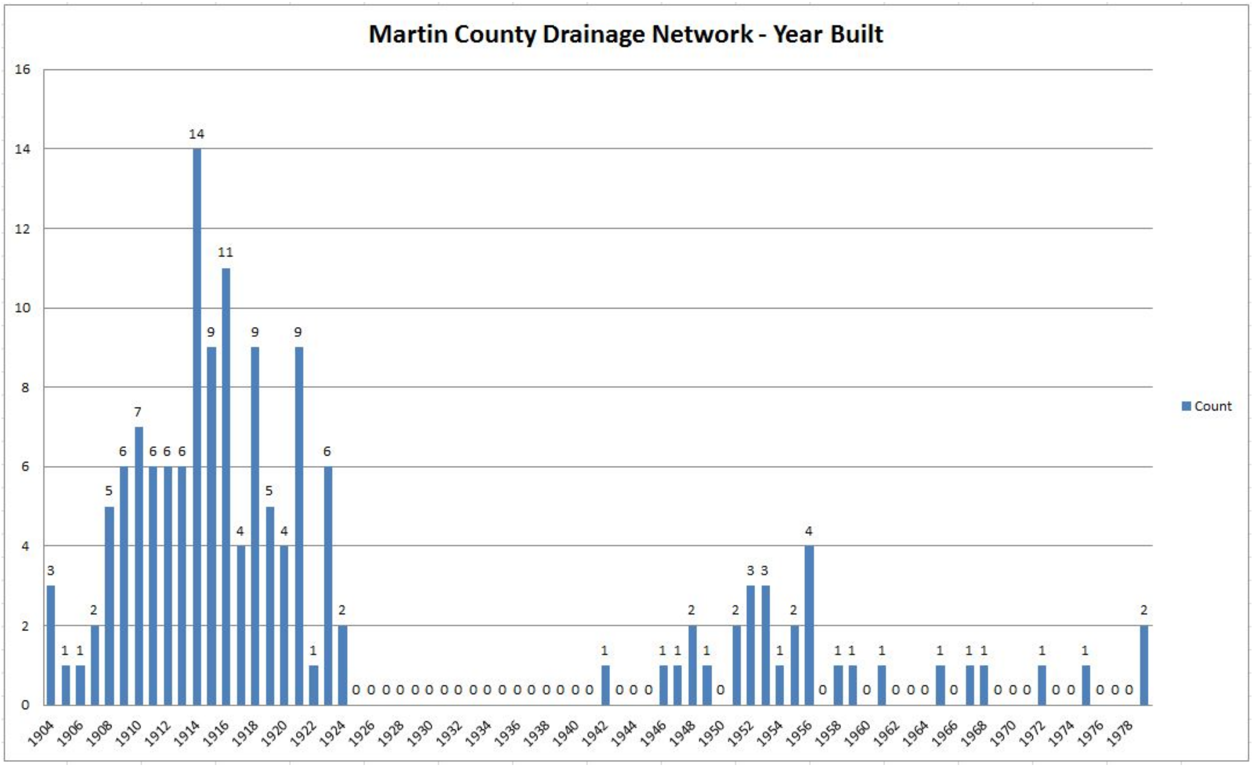
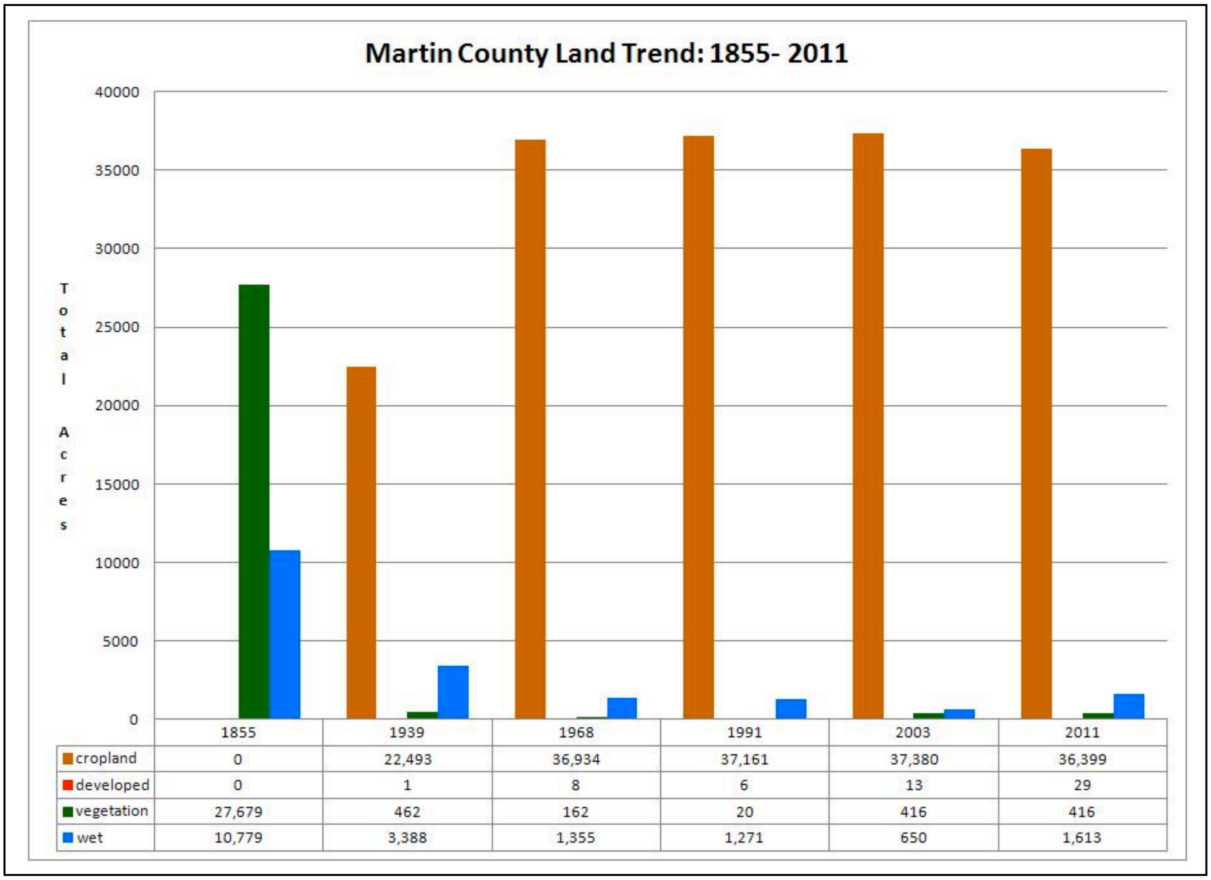


Figure 28. Installation trend of open channel drainage systems in Martin County.

Wetland loss and land conversion trends for Martin County are shown in Figure 29. The trends are almost identical to those in Blue Earth County. By 1939, most of the native vegetation and about half of the wetlands have been converted to cropland. The drainage of wetlands continues through 1968, 1991 and 2003, and by 2003 less than 10% of the original wetlands remain.



	1855	1939	1968	1991	2003	2011
cropland	0	22,493	36,934	37,161	37,380	36,399
developed	0	1	8	6	13	29
vegetation	27,679	462	162	20	416	416
wet	10,779	3,388	1,355	1,271	650	1,613

Figure 29. Land Trends in Martin County based on Restorable Wetlands Inventory polygons for selected years.

RESULT 2: COMPARATIVE ASSESSMENT OF HYDROLOGIC CHANGES DUE TO TILE DRAINAGE

Deliverable	Completion Date
1. Quantification of changes in 14 hydrologic parameters in 21 watersheds.	July 2010
2. Comparative assessment of watersheds to determine the effect of artificial drainage and climate on changes in hydrology.	July 2012
3. Correlation between trends in artificial drainage and acceleration of sediment accumulation rates in Lake Pepin.	July 2012

Summary Budget Information for Result 1: **Trust Fund Budget: $ 150,000**
Amount Spent: $ 150,000
Balance: $ 0

Deliverable	**Completion Date**	**Budget**	**Status**
1. Quantification of changes in hydrologic parameters in 21 watersheds.	July 2010	$ 50,000	100%
2. Comparative assessment of watersheds to determine effect of drainage and climate on hydrology	July 2012	$ 75,000	100%
3. Correlation between trends in drainage and sediment accumulation rates in Lake Pepin	July 2012	$ 25,000	100%

FINAL REPORT SUMMARY:

Result 2: Deliverable 1.
QUANTIFICATION OF CHANGES IN HYDROLOGIC PARAMETERS

Note: The original workplan included 23 watersheds for assessment. After reviewing available data for all watersheds, it was determined that the flow records in two watersheds had more than 15 years of missing data, and could not be reliably used.

2.1.1 Changes in Flow, Runoff Ratio and Precipitation

The hypothesis examined in this study-*have rivers become more erosive*- requires that flow has increased over time. If flow volume or flow characteristics have not changed, it is improbable that the rivers would have become more erosive. Thus, the first endeavor is to quantify the annual and seasonal changes in flow volume. To compare changes in flow volume (i.e. discharge) among watersheds, it is necessary to correct for watershed size.

Water yield, which is flow divided by watershed area, is the parameter used to compare changes in river discharge between the study watersheds.

$$\text{Water yield} = \text{Flow} / \text{Watershed area}. \qquad \text{(eq. 1)}$$

The second basic parameter that is useful for comparing changes in hydrology between watersheds is runoff ratio. Runoff ratio describes the proportionality between river flow and precipitation on a watershed scale and is simply water yield divided by precipitation (eq. 2). In other words, runoff ratio is the fraction of precipitation that ultimately leaves the watershed via river discharge. Among non-hydrologist the term runoff ratio is sometimes misinterpreted to mean surface runoff. This is an unfortunate association with the word runoff. Runoff ratio does not equate to surface runoff, but rather includes all infiltration, groundwater, and surface runoff that contribute to river flow. Runoff ratio essentially normalizes flow to precipitation and is a semi-quantitative first step toward correcting for changes in flow caused by changes in rainfall.

$$\text{Runoff Ratio} = \text{Water yield}/\text{Precipitation} \qquad \text{(eq. 2)}$$

Methods

Changes and trends in water yield, runoff ratio and precipitation were estimated using data from long-term monitoring stations. Daily flow records (m^3/day) starting in 1940 were obtained from USGS monitoring stations at the outlet of each watershed (USGS, 2010). Data gaps of days to months exist for some study watersheds. Gaps were evaluated on a monthly basis and only months that possessed at least 25 valid flow days were used in the study. Total monthly flow for each year was calculated by multiplying the mean of the valid daily flows by the number of days in the month. Monthly data were aggregated into bi-monthly (May-June, July-August, September-October) and annual time periods. The bi-monthly flow aggregates were chosen because May and June together comprise an important focal period for examining the ET effects from cropping changes. Consistent with the May-June focus, the annual dataset ran from the previous year's July to the current year's June, i.e. a June water year. Water yield for each watershed was calculated by dividing flow by the respective watershed area (eq. 1). This normalization to watershed area allows direct water balance comparison to precipitation and ET.

Spatial patterns of precipitation can vary considerably over a watershed such that using a single precipitation monitoring station to represent an entire watershed may introduce significant uncertainty. Moreover, every precipitation station has periods when no data were collected. To better account for spatial variation and to create a complete precipitation record, daily data from multiple precipitation stations were interpolated using the ordinary kriging methodology to produce daily area-weighted precipitation depths for each watershed. In all, 59 precipitation stations from the National Weather Service Cooperative Observer Program (COOP) were used for the interpolation. Climate data were downloaded from the Utah State University Climate Center website (USU, 2010). The interpolation was conducted using PCP_SWAT (Zhang and Srinivasan, 2009), an ArcGIS 9.2 extension written for the SWAT hydrologic model (Arnold *et al.*, 1998). Daily interpolated precipitation values were summed on a monthly basis for analysis.

Most time-series data in this study were found to have non-normal distributions. Therefore, trends were evaluated using non-parametric methods. The data set was split into two equal time periods: 1940 to 1974 and 1975 to 2009 and the Mann-Whitney U test (also known as the "Wilcoxon-rank-sum test") was used to evaluate differences. All analyses were conducted with the R statistical software using the R function *stats*:*wilcox.test (*R Development Team, 2010*)*. This method, comparing two time periods, is similar to the approach used by others (Lenhart *et al*., 2011; Wang and Hejazi, 2011) and is less sensitive to end points when estimating magnitude of change. Kendall-Tau analysis of the continuous record gave similar results, confirming the watersheds with significant trends.

Results

In over half of the watersheds, water yield and runoff ratio show large and significant increases in the spring (May-June), with much smaller changes in the fall (Sept-Oct) (Figure 30). In those watersheds with statistically significant trends, May-June water yields and runoff ratios have increased by 45-200% since the middle of the 20th century (Figures 30 and 31). This two-month increase in water yield accounts for about one-third of the total annual increase in water yield. Equally important is the observation that water yield and runoff ratio show no significant increases in about half of the watersheds (Figure 31). Given the close spatial proximity of the watersheds, the observation that only some show changes in hydrology suggests a local land-use effect rather than a regional rainfall driver.

Several studies have shown increasing precipitation and river discharge over the past century (Nangia *et al*., 2010; Novotny and Stefan, 2007; Zhang and Schilling, 2006), but efforts to decouple rainfall from multiple land-use changes as drivers of hydrologic trends have been incomplete. For the watersheds in this study, annual precipitation over the two time periods increased by less than 15%, with the changes highly skewed by season

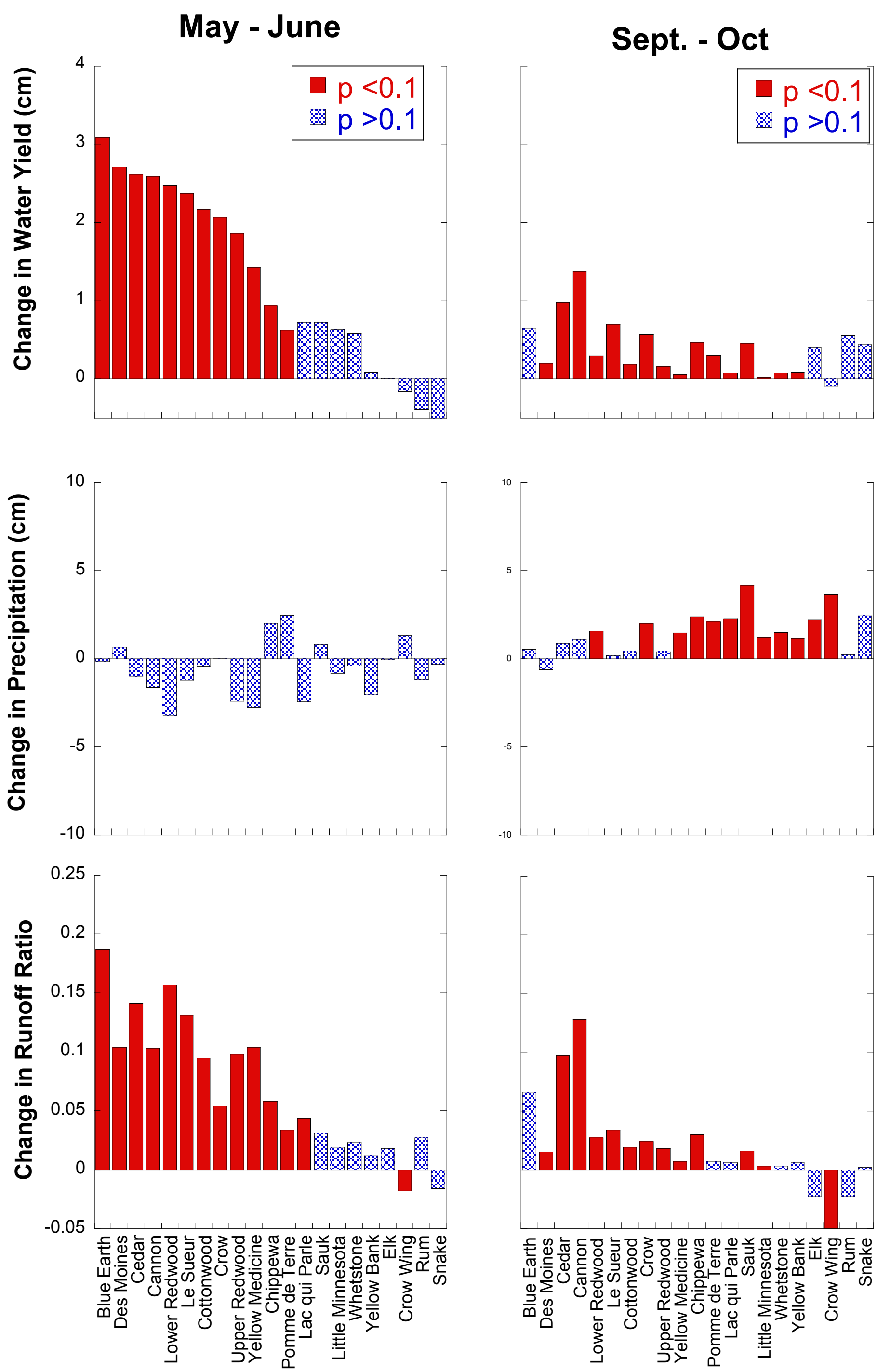


Figure 30. Seasonal changes in water yield (flow volume/watershed area), precipitation, and runoff ratio (water yield/precipitation) for 21 watersheds tributary to the upper Mississippi River. Changes represent the difference between median values for two 35-year periods (1940-1974 and 1975-2009). Blue bars denote watersheds with no significant change in flow. Annual changes follow a similar pattern, with water yield and runoff ratios increasing by >50% in watersheds with significant trends (Fig 31).

(Figure 30). In particular, May-June precipitation has been constant or has decreased since 1940. The fact that the largest changes in water yield and runoff ratio occur during May-June, a period with no increase in precipitation, strongly implies that seasonal changes in river hydrology are not the result of increases in precipitation. Conversely, in the Sept-Oct period, when there is an increase in precipitation, water yields and runoff ratios show only small changes. Drivers of the changes in flow are examined in section 2.2.1 below.

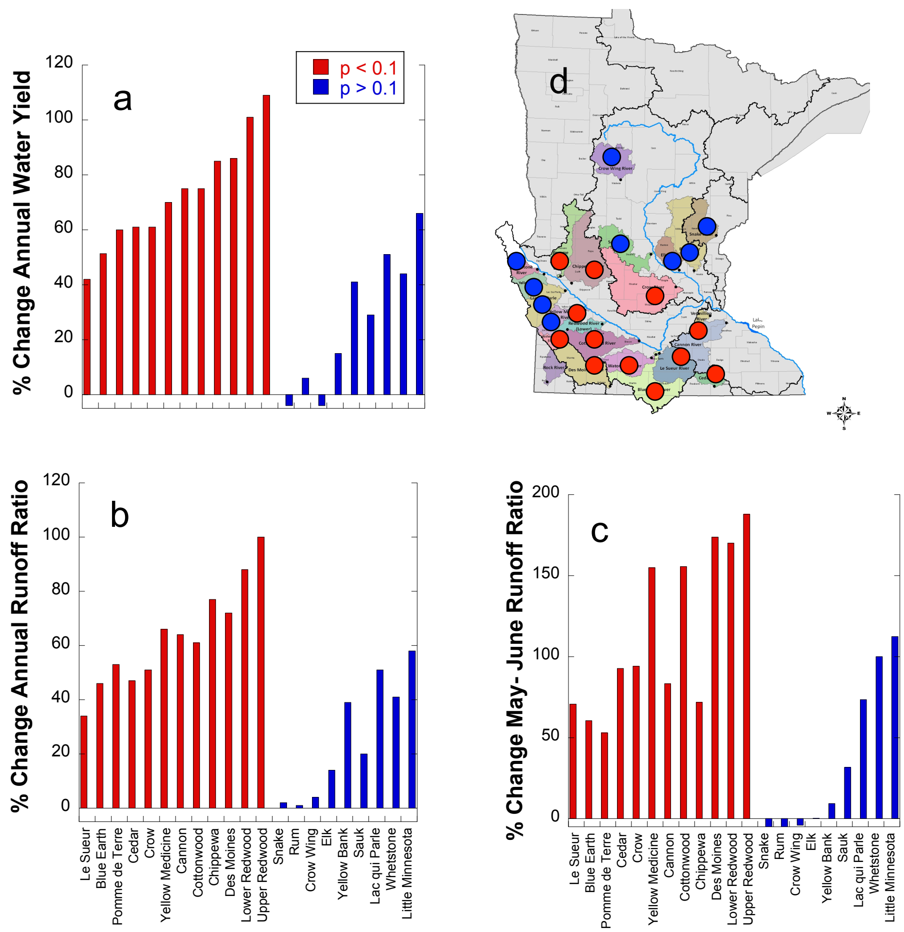


Figure 31. Percentage change in annual water yield (a), annual runoff ratio (b), and seasonal –May-June– runoff ratio for all 21 study watersheds. Red bars and dots denote watersheds with statistically significant changes. Watersheds in blue had no significant changes in flow. The distribution of watersheds with statitistically significant changes in runoff ratio (flow normalized to precipitation) is not random (d), hinting that climate alone cannot be the sole driver of the large observed increases in flow. Changes in annual water yield and seasonal runoff ratio are based on changes in median values between the the two time periods. To minimize effects of yearly antecedant conditions, change in annual runoff ratio was calculated from the total water yield divided by the total precipitation for each 35 year time period.

2.1.2 Changes in Flow Characteristics

It is clear from the analyses presented above that hydrology has changed markedly in many of the 21 watersheds in this study. To get a better idea as to the nature of these flow changes it was proposed that the Indicators of Hydrologic Alteration (IHA) trend analyses be conducted. The IHA was developed to identify long-term flow changes (Richter et al, 1996) that can attributed to watershed hydrologic alteration rather than natural variation, with its primary focus being the biotic impact of flow changes. However, many of the analyses can also be relevant to studies of hydrology and sedimentation. Results of the IHA trend analyses, referred to as parameters, range from changes in low, medium and high flow rates to changes in the characteristics of these flows such as frequency, duration and flashiness.

Methods

The IHA analyses are run from a dedicated software program available from the Nature Conservancy. Daily flow records for each watershed are imported into the software in comma-separated (.csv) format. Analyses may be run in parametric or non-parametric mode. Since the normality of flow data across all watersheds is this study was not consistent, it was deemed necessary to use only the non-parametric mode. Thus, in all cases, the output parameters represent changes in medians between the first (1940-1974) and second (1975-2009) periods. IHA analyses also generated flow duration curves for all watersheds for periods 1 and 2.

Results

Table 2 shows percent changes in shorter-to longer-term moving average flows; 1-day minimums and maximums represent the annual lowest and highest (peak) flows for given watershed, respectively. What is clear from these results is that low flows, i.e., base, winter, and late summer flows, have increased, sometimes substantially, in all but a few watersheds. Conversely, while annual peak flows have not changed consistently or substantially, the 7- and 30-day maximums have. In watersheds with an increase in annual flow volume, the 7- and 30-day maximums have increased 10-60 percent. In watersheds with no increase in annual flow, 7- and 30-day maximums have generally decreased by 10-30 percent. Table 2 also includes the median Julian day of minimum and maximum annual flows. Date of maximum annual flows varied somewhat but show little trend with regard to a significant seasonal shift. However, minimum annual flows in many watersheds exhibited a shift from winter to late summer. It is unclear the extent to which this may be important or the specific mechanisms involved (i.e., higher flow in winter or lower flow in late summer or combination of both) but warrants further investigation.

Table 2. Percent changes in annual minimum (base flow) and short-term "maximum" flows from period 1 (1940-1974) to period 2 (1975-2009) expressed in terms of changes in 1-, 7-, and 30-day moving averages. Values calculated using Indicators of Hydrologic Alteration (IHA) analyses. Red values denote statistically significant changes using 90% confidence interval, values in black are non-significant. NA denotes cases where minimum flow was zero in the period 1.

Watershed	1-day min chg%	7-day min chg%	30-day min chg%	Julian Day of 1-day min Per.1	Julian Day of 1-day min Per.2	1-day max chg%	7-day max chg%	30-day max chg%	Julian Day of 1-day max Per.1	Julian Day of 1-day max Per.2
Blue Earth	275	51	46	26	9	21	25	24	140	122
Cannon	159	92	99	15	215	-3	14	34	94	150
Cedar	46	42	38	22	214	-7	12	48	95	127
Chippewa	743	657	348	17	18	79	52	55	104	101
Cottonwood	150	127	153	24	30	29	12	57	99	118
Crow	142	150	132	5	45	30	28	44	107	111
Crow Wing	0	-2	3	205	234	-28	-27	-22	114	119
Des Moines	333	239	150	19	48	45	46	45	102	134
Elk	10	6	14	49	226	-2	-7	-2	103	119
Lac Qui Parle	NA	NA	586	28	214	-1	6	25	99	106
Le Sueur	80	88	112	32	245	44	39	47	122	121
Little Minnesota	NA	NA	NA	17	240	13	19	58	101	110
Lower Redwood	350	400	392	37	68	35	42	51	99	105
Pomme De Terre	150	159	101	27	18	34	41	74	99	90
Rum	9	13	9	18	27	-20	-14	-2	107	120
Sauk	95	104	81	12	17	-12	-10	5	104	120
Snake	35	41	39	46	224	-37	-33	-17	129	118
Upper Redwood	NA	NA	443	37	68	10	7	9	99	105
Whetstone	200	200	150	40	216	-1	22	21	98	97
Yellowbank	NA	275	200	28	215	64	23	25	100	94
Yellow Medicine	50	100	102	30	225	-12	6	27	101	112

Further IHA analysis explored trends that might be relevant to changes in river erosivity, presumably, those focusing on changes in the frequency, duration and magnitude of so-called "channel-forming flows". These flows are generally accepted to be those at or above bankfull, defined by a recurrence interval between 1 and 2 years. We took a conservative approach with respect to what constituted a channel forming flow, and selected a 2-year return period for use in the IHA analysis. Results show that the median annual frequency and peak flow rate of 2-year or greater events have not changed consistently across study watersheds (Table 3). Flashiness could also be an indicator of erosivity. A change in flashiness can be inferred from IHA parameters that measure slopes changes on the rising and falling limbs of the hydrographs of 2-year or greater flows. Results show that rise and fall rates have decreased significantly in most watersheds, thereby suggesting a decrease in flashiness; and when coupled with increased duration it suggests hydrographs for 2-year or greater flows have become flatter and wider.

The duration of these events is also an important characteristic of flow change. However, the IHA 2-year event duration parameter offers ambiguous or incomplete evidence for evaluating changes in river erosivity as it counts duration from the start to the end of the event (base flow to peak to base flow recession) rather the duration that the flow equaled or exceeded the 2-year return period flow. Given these shortcomings in this IHA method, we used a more traditional approach to evaluate duration of 2-year flow using flow duration curves (FDC).

FDCs integrate many of the IHA parameters and provide the means for better judging changes in all flow ranges. IHA analyses generated FDCs for all 21 study watersheds. Changes in duration of 2-year and 10-year return period flows were used as indicators of change in channel-forming flows. The IHA calculated the 2- and 10-year flow rates from peak flow frequency analysis of period 1 (1940-1974). Changes in duration of these flows were determined by plotting the specific flow rate versus the percent exceedance in the first and second periods. The difference between the first and second period percent exceedance for a given flow rate equals the change in duration. An example FDC for the Blue Earth watershed is shown below (See Figure 32). From the dashed lines in this figure, it is evident that the duration of 2-year return period flow (6,590 cfs) has at least doubled in the 1975-2009 period in the Blue Earth watershed. However, the duration of 10-year or greater flows (greater or equal to ~20,000 cfs) has actually decreased in this recent period. This is illustrated by the divergence of FDCs at 0.1% or less exceedance values (Figure 32). Figure 33 shows changes in 2-year and 10-year flows in all 21 study watersheds resulting from flow duration analysis. Results show

Table 3. Percent changes in annual median 2-year flow characteristics from period 1 (1940-1974) to period 2 (1975-2009). Values calculated using Indicators of Hydrologic Alteration (IHA) analyses. Red values denote statistically significant changes using 90% confidence interval.

Watershed	2-yr flow peak chg%	2-yr flow riserate chg%	2-yr flow fallrate chg%
Blue Earth	-9	-27	-47
Cannon	-14	-60	-56
Cedar	-6	-65	-68
Chippewa	14	-57	-19
Cottonwood	11	-76	-15
Crow	26	-57	-22
Crow Wing	-2	73	-29
Des Moines	-15	10	-28
Elk	-11	-53	-37
Lac Qui Parle	17	-42	-29
Le Sueur	-13	-66	-27
Little Minnesota	0	-42	-17
Lower Redwood	13	27	-11
Pomme De Terre	5	1	-18
Rum	10	-34	-28
Sauk	19	-46	8
Snake	-4	-44	-30
Upper Redwood	12	-13	-30
Whetstone	57	-43	16
Yellowbank	37	-48	3
Yellow Medicine	44	-16	-49

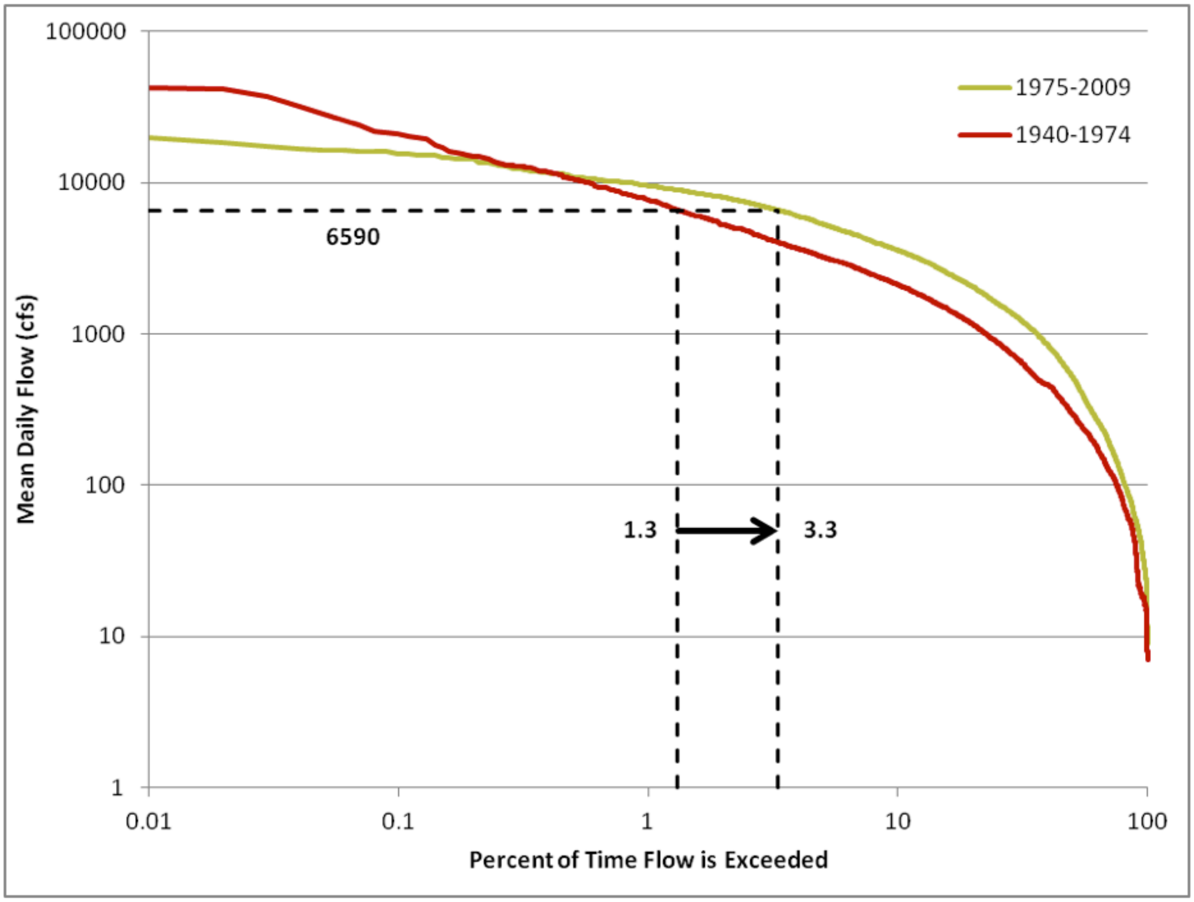


Figure 32. Flow duration curves for Blue Earth watershed for study periods 1940-1974, 1975-2009. Dashed lines denote that the 2-year retun flow (6,590 cfs) was exceeded 2.5 times more frequently in period 2 vs. period 1 (3.3% vs. 1.3%). The fact that the curves intersect and diverge at approximately 15,000 cfs and greater shows frequency of large flood events has decreased in the second period.

the duration of 2-year flows increased in all but four watersheds and this duration has more than doubled in half of the watersheds. Interestingly, in the watersheds with a 2-year flow duration increase, the duration of 10-year flows did not increase to the same extent and actually decreased in five watersheds. These are important distinctions for characterizing changes in the frequencies of flood flows and their potential impact on river erosivity.

The IHA analyses demonstrate that flows have changed in most watersheds in several important ways: (1) base flows have increased, (2) peak flows and flashiness associated with channel-forming flow events (e.g., 2- and 10-year return period) have not increased but, (3) the durations of channel-forming flow events has increased (figure 33). These results are counter to some of the generalizations that are often assumed to result in intensively drained systems. Some watershed managers assume that "tile drainage" increases peak flow and the flashiness of the flow. In our study watersheds, neither characterization was found to be true, however the duration of high flows, notably the bankfull flows, was found to have increased. The significant increases in duration of high flow events coupled with the seasonal and annual increases in total flow are critical parameters, potentially creating more erosive rivers.

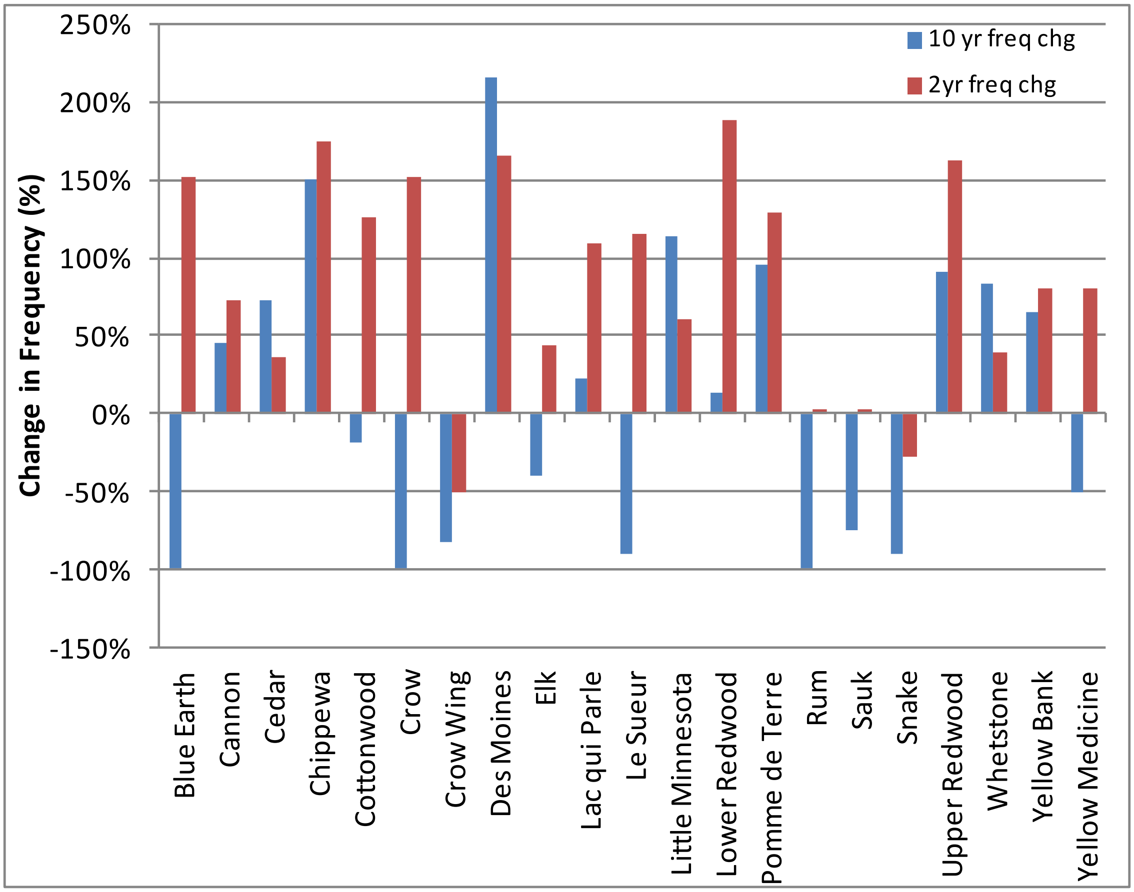


Figure 33. Changes in the frequency (i.e., duration) of 2- and 10-year return period flows in study watersheds. Results show 2-year flow durations increased in most watersheds while 10-year flow durations both increased and decreased.

2.1.3 Changes in Rainfall Intensity

Another possible factor for increased river flow is an increase in rainfall intensity. Increased intensity can result in greater surface runoff for a given depth of rainfall. Therefore, even in cases where total watershed precipitation has not increased, increases in rainfall intensity could be a contributor to increased flows.

Methods

Changes in annual rainfall intensity were analyzed for three event types: 1 inch/hour and 2 inch/day at individual COOP National Weather Service stations, and 1.75 inch/day for the kriged precipitation records generated for each study watershed ("kriged watershed"). These depth-durations represented events with a return period of approximately nine months (0.75 year). Statewide COOP station return periods were determined using the work of Huff (1992). Kriged watershed return periods were calculated within this study using frequency analysis. Analysis of hourly events used 87 stations with records from 1948-2009, and daily events used 59 stations with data from 1940-2009. Change in intensity was defined as a change in the frequency of a given depth-duration event over the period of analysis. The non-parametric Kendall-Tau test was used to determine a change in frequency at the 90% confidence level.

Results

Results of the analysis are shown in Table 4 and Figure 34. Significant increases in event frequency were found in only 5% and 12% of the hourly and daily COOP stations, respectively, while significant decreases were found in 14% and 7%, respectively. No watershed showed a significant increase or decrease in kriged watershed intensity. These results suggest that significant increases in the intensity of the three event types have not occurred during the period of analysis. Perhaps most importantly, the fact that kriged watershed rainfall intensity has not increased or decreased suggests that localized changes in intensity shown in Figure 34 are smoothed out at the watershed scale. Given the lack of change in rainfall intensity it is reasonable to conclude that increases in rainfall intensity are not a driver of increased river flows over the period 1940-2009.

Table 4. Results of Rainfall Intensity Trend Analysis

Type	Number of stations or watersheds	Event depth / duration	Stations or watersheds with sig. increase	Stations or watersheds with sig. decrease
COOP hourly	87	1 inch/1 hour	4	12
COOP daily	59	2 inch/1 day	7	4
Kriged watershed	21	1.75 inch/1 day	0	0

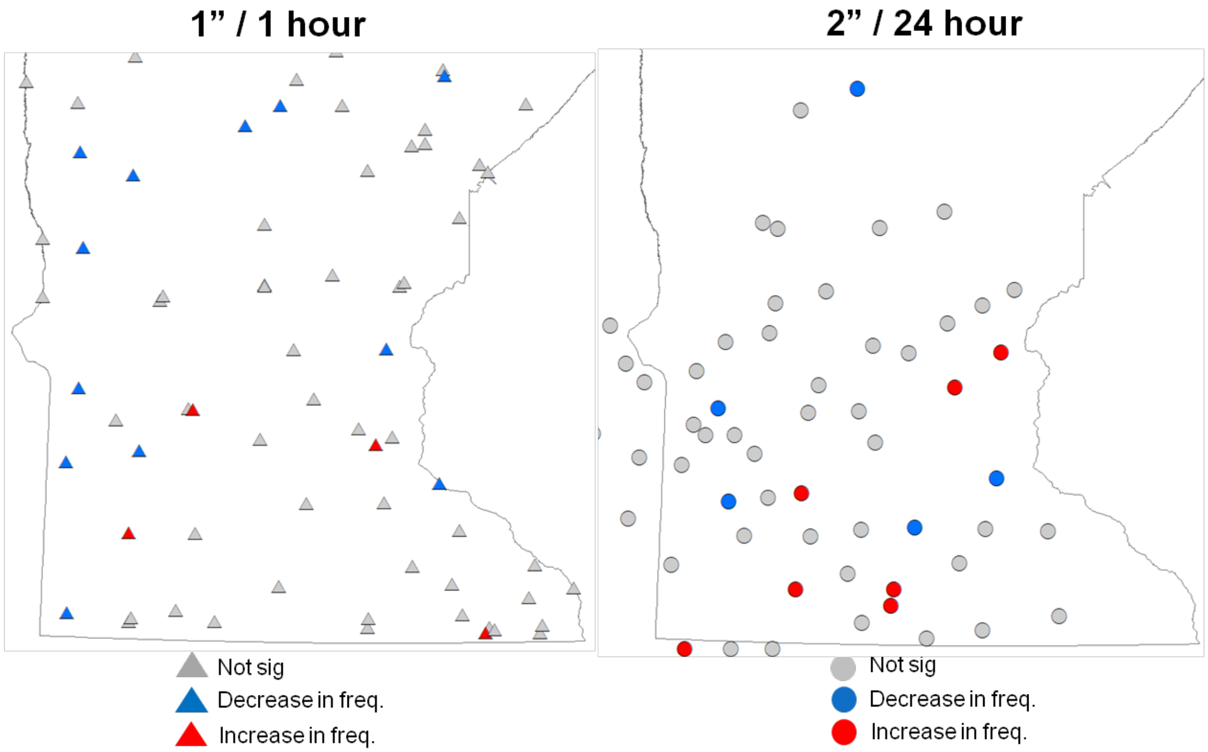


Figure 34. Changes in annual hourly and daily rainfall intensity defined as the change in frequency of 1 inch/1 hour and 2 inch/ 24 hour events, respectively, using the non-parametric Kendall-Tau test at the 90% confidence level. Results show no consistent trend in intensity indicating increases in intensity are not likely factors in observed flow increases.

2.1.4 Estimation of Changes in Potential Evapotranspiration

Evapotranspiration (ET) accounts for nearly three-fourths of Minnesota's annual water budget. In other words, most of the precipitation that falls on the landscape goes back into the atmosphere through ET. Understanding how ET has changed over time is critical to understanding how and why hydrology has changed over time. Crop conversions and artificial drainage can both affect river flow by altering evapotranspiration (ET) from the watershed. Conversion of small grains, pasture, and hay to soybeans changes the evaporative losses in the spring. The former are actively growing in the early spring and "consume water" (returning it to the atmosphere through ET) much earlier than soybeans. Artificial drainage can alter hydrology by changing water residence on the landscape and reducing the amount of time for water to be lost through ET. Changes in temperature, solar radiation and rainfall also affect annual ET. Changes in ET due to crop conversion and climate can be estimated from standard methods evaluating evaporative potential (PET). Changes in ET due to artificial drainage are less straightforward and are examined in the next section.

Method

PET was calculated using specific crop coefficients as defined by the Food and Agriculture Organization of the United Nations (FAO, 1998), the areal proportion of each crop, and an estimate of daily reference ET (RET) (see the SI). RET was calculated by Utah State University (USU, 2010) and downloaded from their climate datasets. PET was calculated by multiplying RET by crop or vegetation coefficients using the FAO method (FAO, 1998).

$$PET = RET \times fc_i \times A_i \qquad \text{(eq 3)}$$

Where fc_i is the crop coefficient for crop(i) and A_i is the areal proportion of that crop in a particular watershed in given year. Yearly crop distributions were calculated using data from the National Agricultural Statistics Service (NASS, 2010) for the years 1940-2009. RET (mm/day) was calculated using the Hargreaves and Samani equation (Hargreaves and Samani, 1985).

$$RET = 0.0023\,(T_{mean} + 17.8)\,(T_{max} - T_{min})^{0.5}\,R_a \qquad \text{(eq 4)}$$

where T_{mean} is monthly mean temperature (C^o), T_{max} - T_{min} is the difference between the daily maximum and minimum temperatures and R_a is extraterrestrial radiation (mm/day). RET was calculated by Utah State University (USU, 2010) and downloaded from their climate datasets.

Table 5. Changes in median and mean values for hydrologic parameters between two 35 year time periods, 1940-1974 and 1975-2009 (June water year). Significance of change was evaluated using the non-parametric Mann-Whitney U test. Significance using the parametric t-test on mean values is shown for comparison. Medians are less sensitive to outliers and were used to evaluate the significance of changes over time. However, to account for the effects of antecedent conditions or delayed response to climate conditions, cumulative amounts (e.g. cumulative annual water yield) divided by the number of years of measurement (e.g. 35 years) were used to in annual water budget calculations, i.e. mean values were used in the annual water budget calculations described in the main text by equations 5-10 .

	Annual Water Yield				Annual Precip				Annual Runoff Ratio				Annual PET			
Watershed	Change Median (cm)	Mann-Whit p value	Change Mean (cm)	t-test p value	Change Median (cm)	Mann-Whit p value	Change Mean (cm)	t-test p value	Change Median (cm)	Mann-Whit p value	Change Mean (cm)	t-test p value	Change Median (cm)	Mann-Whit p value	Change Mean (cm)	t-test p value
Blue Earth	9.33	0.043	10.13	0.011	1.84	0.579	2.47	0.455	0.14	0.014	0.10	0.006	-1.45	0.027	-1.76	0.019
Cannon	9.53	0.000	10.84	0.000	7.13	0.094	4.90	0.087	0.09	0.000	0.10	0.000	-2.10	0.049	-1.35	0.086
Cedar	9.61	0.001	9.98	0.000	10.10	0.020	7.43	0.023	0.08	0.000	0.09	0.000	-0.93	0.159	-1.33	0.137
Chippewa	4.20	0.000	4.44	0.000	2.89	0.239	2.92	0.230	0.06	0.000	0.06	0.000	0.22	0.770	0.17	0.846
Cottonwood	5.81	0.003	5.88	0.003	9.44	0.022	5.67	0.052	0.07	0.005	0.07	0.002	-1.36	0.211	-0.73	0.367
Crow	6.67	0.004	5.61	0.002	8.53	0.077	4.82	0.088	0.09	0.004	0.06	0.002	-1.54	0.014	-1.98	0.019
Crow Wing	0.06	0.718	-0.69	0.534	2.37	0.734	-0.02	0.993	-0.01	0.479	-0.01	0.434	-1.96	0.178	-0.85	0.347
Des Moines	5.79	0.012	6.97	0.002	8.73	0.040	5.52	0.064	0.08	0.007	0.08	0.002	-0.34	0.044	-1.80	0.058
Elk	1.81	0.259	2.48	0.148	-3.93	0.816	1.02	0.707	0.03	0.188	0.03	0.138	2.11	0.000	2.63	0.000
Lac qui Parle	2.23	0.087	2.61	0.028	2.30	0.910	0.07	0.976	0.04	0.054	0.04	0.022	-2.35	0.060	-1.40	0.124
Le Sueur	6.11	0.025	6.13	0.027	5.94	0.094	5.17	0.102	0.06	0.017	0.06	0.017	-2.67	0.021	-1.71	0.027
Little Minnesota	2.54	0.048	2.26	0.040	4.92	0.174	2.83	0.245	0.03	0.044	0.03	0.046	-1.89	0.156	-0.61	0.523
Lower Redwood	6.74	0.000	8.70	0.000	5.50	0.034	4.64	0.083	0.09	0.000	0.11	0.000	0.46	0.198	1.33	0.097
Pomme de Terre	2.37	0.017	2.72	0.005	2.18	0.170	2.86	0.203	0.03	0.015	0.04	0.005	0.03	0.891	-0.14	0.874
Rum	2.93	0.487	1.05	0.534	-4.50	0.290	-2.35	0.408	0.05	0.328	0.02	0.269	-2.86	0.051	-1.19	0.144
Sauk	3.52	0.023	3.00	0.024	4.53	0.071	5.25	0.056	0.04	0.019	0.04	0.028	2.75	0.002	2.59	0.001
Snake	1.51	0.853	-0.89	0.739	-5.70	0.557	-0.94	0.751	0.02	0.836	0.00	0.964	-1.07	0.994	0.67	0.511
Upper Redwood	4.43	0.004	6.71	0.001	2.99	0.225	2.95	0.263	0.07	0.003	0.09	0.001	1.14	0.023	2.06	0.011
Whetstone	0.58	0.296	1.99	0.060	1.71	0.555	1.18	0.636	0.02	0.239	0.03	0.065	-0.67	0.508	-0.30	0.719
Yellow Bank	0.07	0.428	1.81	0.097	0.84	0.672	0.74	0.749	0.01	0.379	0.02	0.105	-0.65	0.637	-0.17	0.836
Yellow Medicine	2.71	0.011	3.96	0.005	1.14	0.374	1.76	0.484	0.04	0.004	0.05	0.003	-2.50	0.039	-1.46	0.115

To simplify the method, crop types were summarized into five classes: corn, soybeans, small grains (composed of barley, flax, oats, rye and wheat), alfalfa hay and non-agricultural (composed of all remaining land uses). Daily watershed PET was estimated using the following steps: (a) mean monthly crop coefficients were calculated for the five crop classes according to FAO growth curves, (b) daily aggregate crop coefficients were determined by multiplying each monthly crop class coefficient by the corresponding yearly crop class areal proportion, and (c) PET was calculated by multiplying aggregate crop coefficient by daily RET. Because crop distributions have changed over time (e.g., less small grains, more soybeans) PET was evaluated on a yearly basis. Yearly crop distributions were calculated using data from the National Agricultural Statistics Service (NASS, 2010) for the years 1940-2009. The crop data were compiled for all counties within the study area. ArcGIS 9.2 was used to calculate annual area-weighted crop distributions at the watershed scale from the county level data. This calculation yielded watershed proportions of each crop class for each year in the study period.

Several important assumptions were required to implement this PET calculation approach: (i) FAO crop growth curves (i.e., days to maturity, harvest, senescence, etc.) were the same regardless of watershed, (ii) planting dates for corn, soybeans and all other crop classes were 4/25, 5/10 and 4/1, respectively, regardless of year or watershed, (iii) the non-agricultural crop class coefficient was the mean of FAO warm- and cool- season grass crop coefficients.

Results

Estimation of changes in PET for the two time periods is summarized in Table 5. The cropping trend in the watersheds was the conversion of small grains, hay, and pasture to corn and soybeans (figure 16.)The method outlined above was sensitive to this trend, and therefore a relatively large decrease in May-June PET (driven by conversion to soybeans) was predicted. However, the predicted May-June decrease was offset somewhat by a predicted July-August increase (due to peak corn and soybean FAO crop coefficients being greater than those in the small grain class), resulting in a small decrease in predicted annual PET. This decrease in PET is consistent with the work of Schilling (Schilling *et al*., 2008; Zhang and Schilling, 2006) conducted in agricultural watersheds of Iowa. The seasonal influence of changes in ET on seasonal flow patterns was beyond the scope of this study but warrants additional investigation.

Result 2: Deliverable 2.

COMPARATIVE ASSESSMENT OF WATERSHEDS TO DETERMINE EFFECT OF DRAINAGE AND CLIMATE ON HYDROLOGY.

INTRODUCTION

Our seasonal and multi-watershed comparisons (Section 2.1.1 and Figures 30, 31) lead to several important conclusions: first, river flow during the early growing season has increased dramatically in certain watersheds, and second, the increase is not proportional to changes in precipitation. The comparative design strategy in this study is powerful and raises the question, why do some watersheds show large hydrologic changes, while others nearby and experiencing the same climatic vagaries do not?

Examination of land-use changes among the watersheds sheds light on why some and not others have experienced such large changes in hydrology. The change in runoff ratio is highly correlated with the magnitude of mid-century crop conversion to soybeans in each watershed (Figure 35a). Conversion to soybeans encompasses two important mechanistic drivers leading to more water entering the rivers – changes in crop ET, and reduction in ET from depressional areas owing to expansion of artificial drainage. Separation of these two components of the water budget is important for effective mitigation of flow and sediment impairments.

Conversion to soybeans has largely displaced forage crops and small grains that actively grow early in the spring and reduce available soil moisture through ET. In contrast, soybeans do not begin consuming water through ET until nearly a month later because they are planted in late spring. The conversion to soybeans thus changes the seasonal loss of upland ET, allowing a greater proportion of precipitation to enter the rivers.

Yields of corn and soybeans benefit greatly from enhanced subsurface drainage, and it is not surprising that 20^{th} century drainage intensification is coincident with the crop conversion trends (Blann *et al.*, 2009; Dahl and Allord, 1996; Kuehner, 2004). The concurrent trends of crop conversion and drainage over the past 70 years confound the ability to draw cause and effect relationships to changes in flow. The amount of poorly drained soil in a watershed is a crude surrogate for the amount of artificial drainage and predicts changes in runoff ratio (Figure 35b) nearly as well as predicted by conversion to soybeans (Figure 35a). These two relationships demonstrate that correlative trends are only a first step in understanding changes in flow, and a rigorous water balance is necessary to quantify the role of each driver.

Artificial drainage, which includes ditching, sub-surface tiling with and without surface inlets, and wetland drainage, affects water yield in two fundamental ways: by permanent decreases in residence time of water on the landscape (thereby reducing evaporative losses) and through continuous incremental installation of sub-surface tile and the attendant one-time reduction in soil profile storage. Although sub-surface pattern tiling continues to be installed on the landscape, changes in storage are probably a minor component of long-term water budgets. For example, if sub-surface tile were incrementally installed over 35 years, lowering the water table by a maximum of 1.25 m (the depth of tile installation) across a watershed with 50% poorly drained soils (an upper value for our watersheds, see SSURGO, 2009) and drainable porosity of 30 percent, this would produce an increase in annual water yield of only ~0.5 cm. This rough calculation is a maximum estimate, and demonstrates that while changes in storage are not zero, they are small. For the purpose of this study, small changes in storage due to drainage are indistinguishable from the larger effect of evaporative losses due to artificial drainage and are thus combined into the single term, $\Delta ET_{drainage}$.

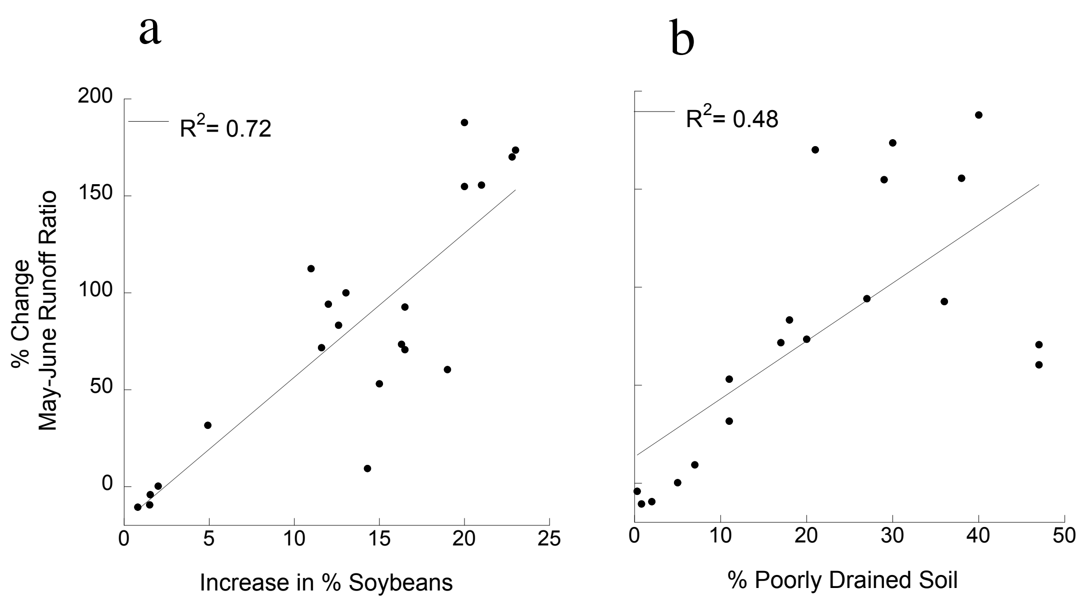


Figure 35. Relationship of conversion to soybeans (a) and poorly drained soils (b) to increases in May-June runoff ratio. The amount of cultivated land that is classified as poorly drained is a crude surrogate for the amount of artificial drainage expected in a watershed. For runoff ratio and conversion to soybeans, change over time is expressed as the difference between the median value of the two time periods: 1940-1974 and 1975-2009. Both conversion to soybean and amount of poorly drained soil correlate well with changes in runoff ratio, making specific cause and effect relationships difficult to disentangle.

The larger impact of artificial drainage on the hydrologic budget is through reduction in ET losses from depressional areas (loss of residence time). These depressions range from former wetlands with significant residence time to extensive ephemeral ponded water in fields. In all cases artificial drainage reduces the amount of time that water is on the landscape and can be lost to ET. Artificial drainage continues to be installed to enhance crop yields on these poorly drained areas, and in much of the Midwestern corn-belt 30-80% of the land is estimated to have some form of tile drainage (Sugg, 2007). Our estimates for the loss of depressional areas using the Restorable Wetlands Inventory (USFWS a, 2011; USFWS b, 2011) datasets show that watersheds with poorly drained soils and a high percentage of cultivated land have high losses of depressional areas (Section 1.1.4, Figure 14). In these watersheds nearly all of the natural wetlands and depressional areas have been altered by drainage, representing a profound hydrological modification of up to 20% of the total watershed area (Figure 14).

2.2.1 Apportionment of Changes in Water Yield.

To separate and quantify the role of crop conversion, rainfall and drainage as drivers of changes in flow it is necessary to construct a water balance model. In general, we used the first time period, 1940-1974, to calibrate the relationship of flow to PET and rainfall, and then applied this model to the 1975-2009 time period to estimate the amount of flow that should result from rainfall and PET conditions in the second time period. With changes in climate and crop conversion accounted for in PET and rainfall measurements, the difference between the estimated flow and measured flow can be attributed to artificial drainage.

Method

Over the long-term (years to decades) changes in river flow can be expressed fundamentally as a function of precipitation and ET (Wang and Hejazi, 2011)

$$\Delta Q = \Delta P - \Delta ET \qquad \text{(eq. 5)}$$

where changes in mean annual water yield (ΔQ) and precipitation (ΔP) between the two periods (1940-1974 and 1975-2009) are measured values. Recognizing that there are multiple mechanisms for ET, this expression can be expanded to:

$$\Delta Q = \Delta P - \Delta ET_{climate} - \Delta ET_{crop} - \Delta ET_{other} \qquad \text{(eq. 6)}$$

Total evapotranspiration can change over time due changes in precipitation, temperature and solar radiation ($\Delta ET_{climate}$) or because of changes in vegetation due to crop conversions (ΔET_{crop}). ET_{other} represents changes to the water budget that are not captured in the estimation of $ET_{climate}$ or ET_{crop}. The watersheds in this study have negligible irrigated land and minimal population changes upstream of the monitoring stations (UMN, 2010), but many have extensive artificial drainage networks (Sugg, 2007). Thus, in the absence of any other drivers to ET, it is reasonable to hypothesize that ET_{other} is the result of drainage, and

$$\Delta ET_{other} \cong \Delta ET_{drainage} \qquad \text{(eq. 7)}$$

Changes in actual ET cannot be measured directly, but a relationship between calculated PET and measured water yield for the first time period can be developed and used to predict Q in the second period. The difference between the predicted and measured water yield in the second period is the change in water yield due to non-crop, non-climate factors. To evaluate the contributions of climate and

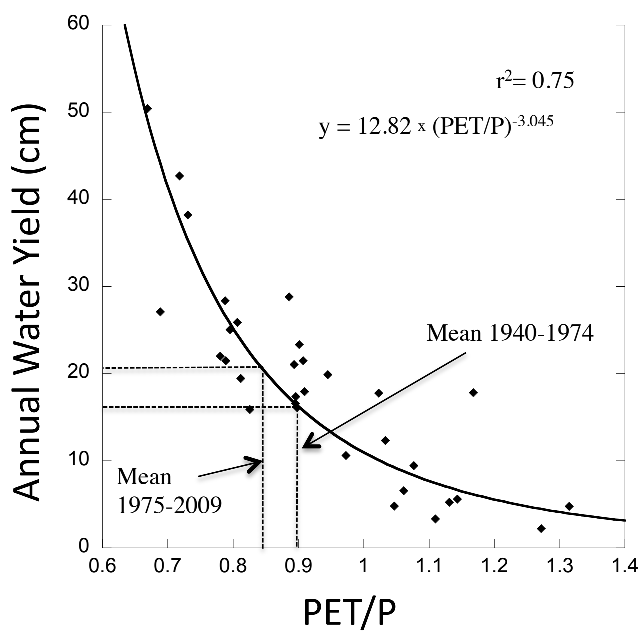


Figure 36. Calibration of the response of water yield to climate, precipitation, and cropping characteristics using annual values for the initial 35 year period (1949-1974): an example for the Blue Earth watershed. The mean PET/P ratio changed from 0.9 to 0.85 from the first period to the second (dashed lines). Applying this change in PET/P to the calibration curve, predicts a 3.35 cm increase in annual water yield in the second time period due climate and crop conversions combined.

crop-ET to changes in flow, we first calibrated the relationship of water yield to PET and precipitation (P) over the initial 35-year period (1940-1974) (see Figure 36 for example). This relationship is non-linear and can be expressed as a unique power function for each watershed:

$$Q = A \times (PET/P)^{-B} \quad \text{(eq. 8)}$$

where A and B are empirical coefficients, and Q is the predicted annual water yield. Change in water yield due to crop conversion and changes in climate between the two time periods ($\Delta Q_{climate + crop}$) is estimated by solving equation 8 using the mean PET/P ratio for each period and subtracting the two values (Equation 9). To estimate a representative PET/P ratio for a 35-year period, mean PET/P is defined as cumulative PET divided by cumulative P for each time period.

$$\Delta Q_{climate + crop} = A \times ((PET/P)^{-B}_{75\text{-}09} - (PET/P)^{-B}_{40\text{-}74}) \quad \text{(eq. 9)}$$

This method, using a calibrated response to PET/P in one time period to apportion changes in a second time period, is similar to that used by Wang and Hejazi (2011), but here directly relates PET and P to measured water yield.

The change described by equation 9 can be further apportioned between climate and crop conversion using the relative changes in the variables used to calculate the PET:P ratio. The combined change in water yield ($\Delta Q_{climate + crop}$) predicted by changes in PET and P is proportional to changes in P, RET and fc and can be partitioned between climate and crop by comparing the relative changes in the three variables (equations 10 and 11)

$$\Delta Q_{crop} = \Delta Q_{climate + crop} \times [\ \%fc/(\%RET + \%P + \%fc)] \quad \text{(eq.10)}$$

$$\Delta Q_{climate} = \Delta Q_{climate + crop} \times [(\%RET + \%\ P)/(\%RET + \%P + \%fc)] \quad \text{(eq. 11)}$$

Where %RET and %P are the relative changes in RET and P respectively between the two time periods. Because PET is RET multiplied by each areally weighted crop coefficient, the relative change in mean crop coefficient (%fc) is simply the mean PET:RET of period two divided by the mean PET:RET ratio of period one.

The change in water yield due to drainage is then estimated by difference from the measured total change in water yield ($\Delta Q_{measured}$) between the two periods.

$$\Delta Q_{drainage} = \Delta Q_{measured} - \Delta Q_{climate} - \Delta Q_{crop} \quad \text{(eq.12)}$$

Results

The method used in this study to apportion increases in water yield shows that changes in precipitation (climate) and crop ET account for only a fraction of the total change in water yield (Figure 37). In our study watersheds, PET/P changes by less 10% between 1940-1974 and 1975-2009, and this relatively small change in climate and crop conversion is simply not enough to account for a >50% increase in water yield. The surplus water yield is a consequence of other changes to ET, namely large reductions in depressional ET resulting from artificial drainage. While changes in annual water yield vary considerably among the 21 watersheds, on average more than half of the change is attributable to drainage (Figure 37). Three of our watersheds were also studied by Wang (2011) with comparable results, where less than half of the increase in water yield observed from 1948-2003 could be explained by climate alone. Our study offers additional insight into the non-climate drivers of change.

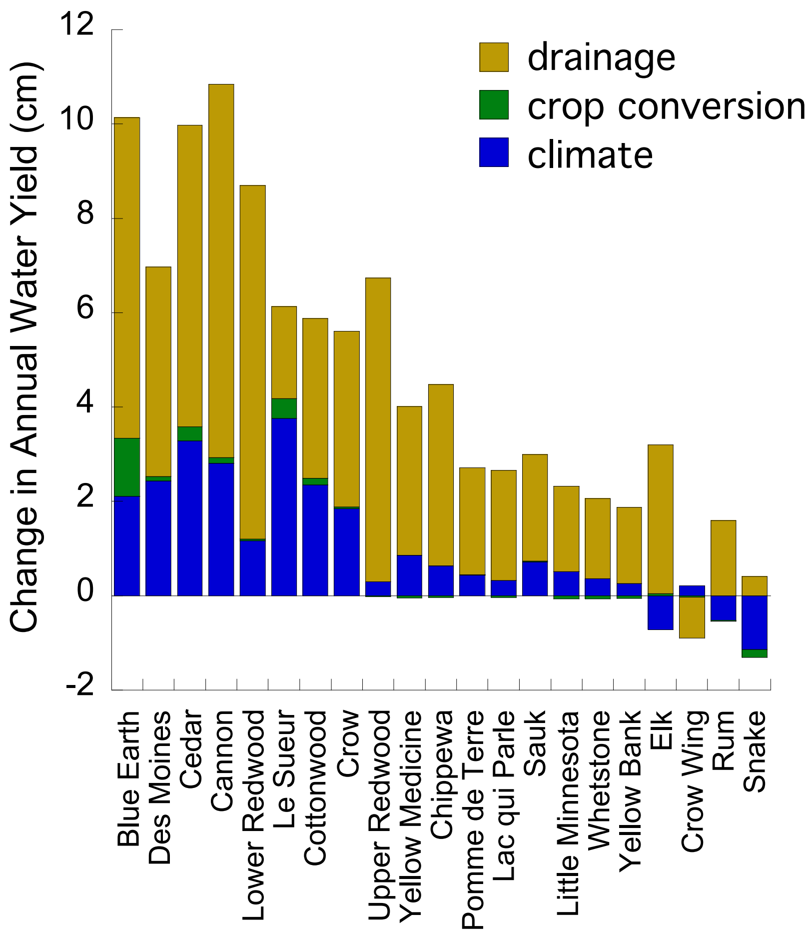


Figure 37. Apportionment of changes in mean annual water yield for each watershed. In rivers with significant changes in flow, climate and crop conversions account for less than half of the total change in water yield. Excess water yield is the portion that cannot be attributed to changes in crop-ET and climate and is hypothesized to result from artificial drainage ($\Delta Q_{drainage}$).

The total change in water yield not accounted for by climate and crop conversion represents the excess water yield that must result from other drivers – specifically, artificial drainage, as we hypothesize above. A principle purpose of artificial drainage is to facilitate agricultural practices by reducing the amount of time water is ponded in a field. The success of drainage in meeting this intent is unquestionable. Quickly routing ponded water through drainage systems reduces the amount of time available for ET and increases the proportion of precipitation that ends up as river flow. This attribution is supported by the correlation of excess water yield with the estimated loss of wetlands and depressional areas in each watershed (r^2 = 0.6; Figure 38). This relationship strongly suggests that artificial drainage – the rapid removal of water from depressional areas, which significantly reduces depressional ET – is a major driver of increased river flow. This analysis cannot define which forms of artificial drainage or pathways are most important. What is clear is that precipitation that was once lost to ET is now being transported to the rivers.

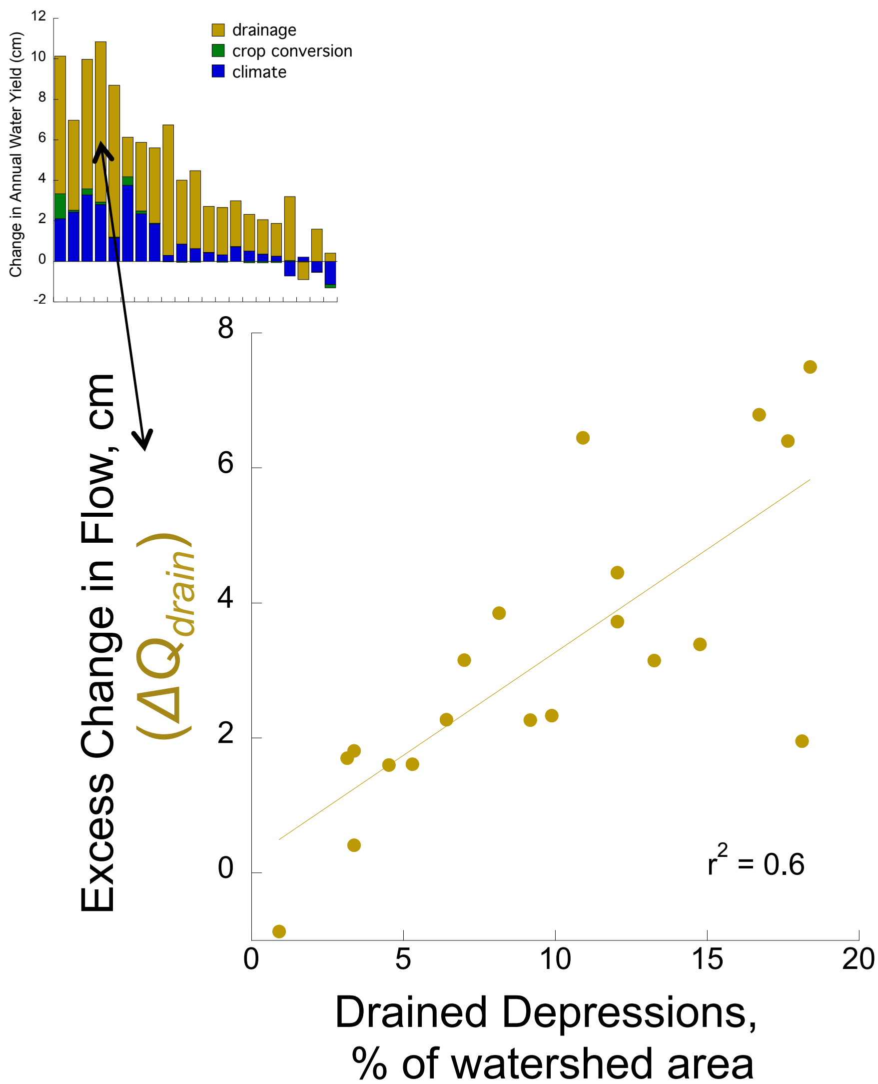


Figure 38. Correlation between the increase in water yield attributed to drainage ($\Delta Q_{drainage}$) and the loss of depressional areas. The increase in water yield that could not be attributed to climate or crop conversions was hypothesized to result from artificial drainage (see figure 37). While correlative, the strong relationship between drained depressional areas and $\Delta Q_{drainage}$ offers supporting evidence for this hypothesis- that drainage is a driver of increased flow. Estimation of drained depressional areas is discussed in Result 1.1.4

Result 2: Deliverable 3

CORRELATION BETWEEN TRENDS IN DRAINAGE AND SEDIMENT ACCUMULATION RATES IN LAKE PEPIN.

2.3.1 Relationship of Channel Widening to Changes in Flow

In the results above we confirm that about half of the rivers in this study have had significant increases in flow and changes in hydrologic characteristics over the past 70 years. This means that these rivers have potentially become more erosive, but the flow changes alone do not prove this assertion. To support this assertion it is important to document actual changes in erosive features along the rivers. Increases in stream channel width are one possible outcome of increased flows and provide measureable evidence of changes in river erosivity. A river that has had a stable flow regimen over a long period will have a channel width that is in equilibrium with this flow. It may have eroding banks but this will be balanced by depositional point bars and the net channel width over a given reach will not change. If flows increase, the stream will need to adjust to this new energy and this may result in either downcutting, channel widening, or changes in sinuosity. For this study, we quantified channel widening for several watersheds using historical aerial photography dating back to the late 1930s. Channel widening estimates were done with assistance from Dr. Patrick Belmont, Utah State University and Dr. J. Wesley Lauer, Seattle University.

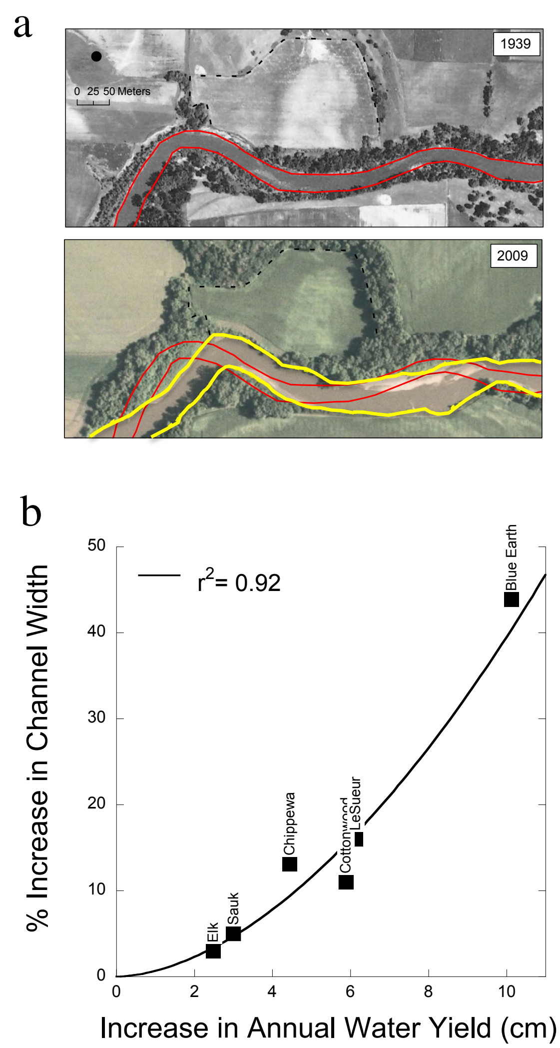


Figure 39. Channel widening related to increases in flow. (a) Photos show widening on the Blue Earth River. Red line is the bankfull width in 1939; yellow line is 2009. (b) Widening is the percent change in mean width between the two time periods (1940-1974 vs. 1975-2009) and is strongly related to the increase in annual water yield. The four rivers with the greatest amount of widening are all tributaries to the Minnesota River, which has experienced a 33% increase in mean channel width over the same time period.

Methods

Channel width was measured by digitizing polygons representing the active channel, defined by vegetation boundaries, on historic and recent air photos. Polygons were approximately ten meander bends long and the area of each polygon was divided by polygon length to obtain a reach-average width. Measurements were made on a minimum of four and as many as 12 sets of air photos for each location (Table 6). Each location had a set of air photos dating back to 1937-1939, which provides the oldest channel width measurement used in this study. Multiple air photo sets were available between 2000 - 2010 for most locations, providing multiple constraints on modern channel widths as well as an estimate of uncertainty associated with bank classification. Typical channel widths for tributaries ranged from 30-60 m for tributary channels and 85-105 m for the mainstem Minnesota River. Typical reach lengths ranged from approximately 5 -10 km.

Results

Table 6. Channel widening summary for six study watersheds and the mainstem Minnesota River. Numbers in parentheses are one standard deviation of all measured channel widths for a time period.

			Mean Bankfull Width (m)	
Reach Name	**Midpoint Coordinate**	**Photograph Years**	**Pre-1975**	**Post- 1975**
Minnesota R.@ Jordan	93°37'29"W, 44°42'49"N	1937, 1940, 1951, 1963, 1964, 1991, 2003, 2004, 2005, 2006, 2008, 2009	82.8 (8.3)	105.5 (2.8)
Minnesota R. @ Ft. Snelling	93°27'46"W, 44°48'23"N	1937, 1940, 1951, 1960, 1962, 1967, 1971, 1991, 2003, 2004, 2005, 2006, 2008, 2009	74.4 (5.8)	90.4 (1.1)
Minnesota R. @ Judson	94°7'34"W, 44°10'56"N	1938, 1949, 1950, 1958, 1964, 1971, 1991, 2003, 2004, 2005, 2006, 2008, 2009	56.4 (9.7)	85.4 (7.3)
Cottonwood R.	94°32'33"W, 44°17'11"N	1938, 1955, 1991, 2003, 2004, 2005, 2006	35.6 (3.7)	39.5 (1.4)
Le Sueur R.	94°01'51"W, 44°06'26"N	1939, 1949, 1950, 1958, 1964, 1971, 1991, 2003, 2004, 2005, 2006, 2008	39.0 (4.6)	45.3 (2.7)
Blue Earth R.	94º05'52"W, 44º01'59"N	1939, 1949, 1973, 1991, 2003, 2004, 2005, 2006, 2008, 2009	35.8 (1.9)	51.5 (3.3)
Chippewa R.	95º47'43"W, 45º05'57"N	1938, 1956, 1991, 2003, 2006, 2008, 2009, 2010	30.7 (1.1)	34.7 (1.5)
Sauk R.	94º19'37"W, 45º 29'8" N	1938, 1958, 1978, 2004	31.2 (2.1)	32.9 (0.7)
Elk R.	93º40'20"W, 45º20'56"N	1939, 1953, 1991, 2009	40.4 (3.0)	41.8 (0.5)

Changes in channel width for six tributaries and three reaches along the mainstem of the Minnesota River are presented in Table 6. For the six watersheds quantified, channel widening was related to the historic increase in water yield (Figure 39), which in turn is a function of crop conversion in general, and artificial drainage in particular. Rivers that experienced only small changes in water yield have responded with similarly small changes in channel width, while those with large increases in water yield have increased their widths by 10-42%.

Figure 39 presents a strong relationship between changes in water quantity (water yield) and channel widening but does not describe which flows are responsible for the instability. However, examination of flow duration curves (see Result 2.1.2) in watersheds with significant increases in annual water yield shows that nearly all flow regimes have increased since 1940 (Figure 32 for example). The excess water yield is manifest not only as increases in baseflow as shown by studies in other agricultural watersheds (Schilling and Helmers, 2008; Zhang and Schilling, 2006) but also as increases in the duration of high flows (Figure 33). Interestingly, the very highest flows, those with exceedance probabilities of <0.1 percent have not increased over the 70 year record.

The results presented here clearly demonstrate that changes in flow have increased river erosivity, however it is not clear which flows (high flows, flow volume, high flow duration) need to be managed in order to reduce channel widening. The relationship between changes in flow volume and flow rate as conditions for channel widening warrants further investigation.

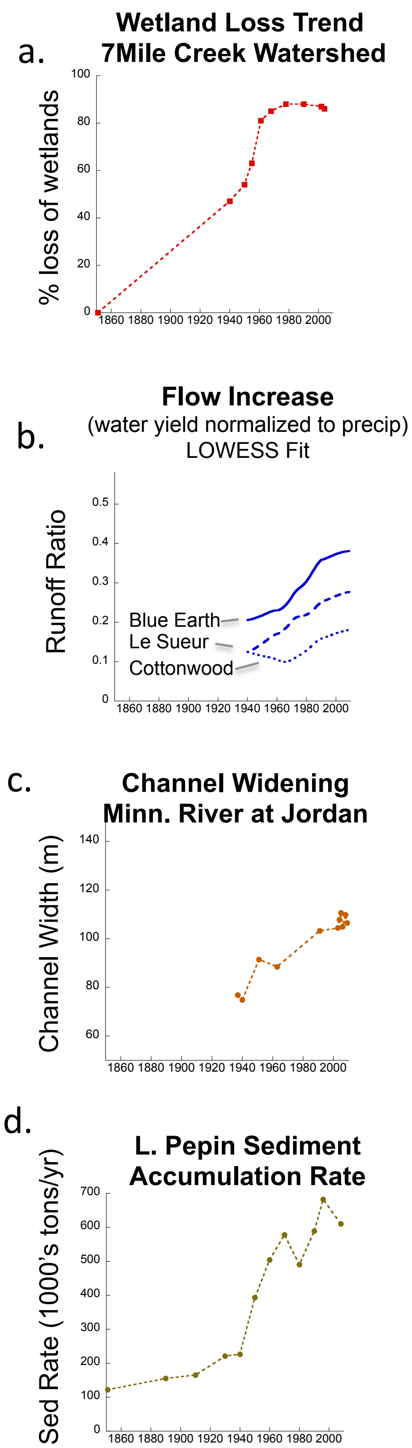
2.3.2 Correlation to Lake Pepin Sediment Trends

These changes in hydrology have important water-quality consequences: increased river erosion including stream-channel widening, which results in greater sediment export and increased river turbidity. The increase in sediment loading over the past century is reflected in sediment cores from Lake Pepin. Not only have sediment loads increased since the onset of modern agriculture (Engstrom *et al*., 2009), but over 50% of the present-day load is from non-field sources (Belmont *et al*., 2011; Johnson *et al*., 2009; Schottler *et al*., 2010). Importantly, over 40% of this sediment load is delivered in the May-June period (MCES, 2010). These observations are consistent with the seasonal increases in flow and channel widening documented here.

Source apportionment coupled with sediment accumulation rates in Lake Pepin suggest that eroded inputs from streambanks and channel bluffs has increased nearly 5X over pre-European settlement conditions (Schottler *et al*., 2010). The observed increase in sediment loading from near channel sources was a basis for the hypothesis that rivers have become more erosive over time. While there are multiple causes for this change, the hydrologic and channel widening changes shown in this study are correlated with the increases in sediment loading to Lake Pepin, thus implicating artificial drainage in combination with climate as an important driver of increased suspended sediment loading.

Results

Figure 40 highlights four key time trends that illustrate the linkage between artificial drainage and Lake Pepin sediment loads. Although the relationships in figure 40 are correlative, they are mechanistically linked and offer strong supporting evidence that artificial drainage has created more erosive rivers with increased suspended sediment loads. The linkage presented in figure 40 fits together as follows:



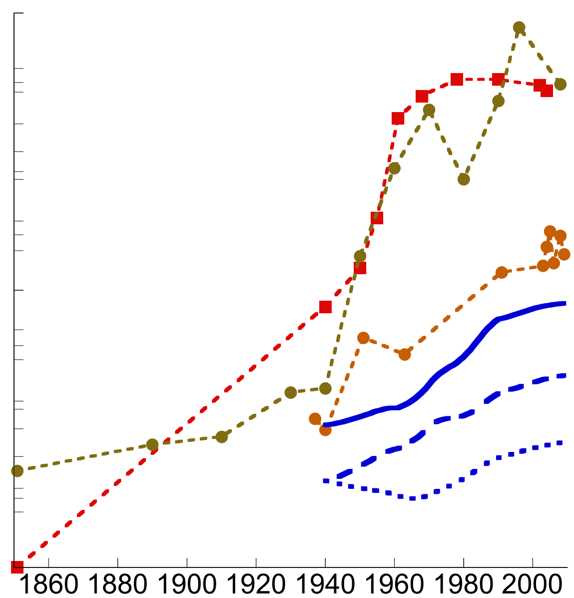


Figure 40. Qualitative relationship linking land use and hydrologic changes to increases of sediment loading to Lake Pepin. Wetland loss, as exemplified in the Seven Mile Creek Watershed (a), has lead to an increase in flow in some rivers (b). This increase in flow has caused rivers to widen (c), thereby increasing suspended sediment loads as reflected in Lake Pepin sediment cores (d). Data for a, b, and c are presented in this report. Lake Pepin sediment accumulation rates are from Engstrom *et al*., 2009. The correlations presented here are not intended to imply that drainage is the sole driver creating more erosive rivers, in fact, precipitation and crop conversion trends would offer similar correlations. Rather, the purpose of this figure is to demonstrate the mechanistic linkage of drainage routing more water the rivers, making them erosive… a watershed scale process that is in part integrated and archived in the sediment record of Lake Pepin.

Wetland loss. Artificial drainage reduces residence time in wetlands and depressional areas, thereby reducing ET from the landscape and routing this water to the rivers. In other words, because of artificial drainage, a greater proportion of precipitation is routed to the rivers rather than returned to the atmosphere through ET. Wetland loss in Seven Mile creek (see Result 1.2.1, and Figure 40a) was used to illustrate this time trend.

Runoff Ratio. With a greater proportion of precipitation routed to the rivers, seasonal and annual flow volumes increase. LOWESS fits of trends in the runoff ratio of the Cottonwood, LeSueur, and Blue Earth rivers illustrate how the proportionality between flow and precipitation has increased over the last 70 years (Figure 40b). These rivers were chosen for this illustration because they supply over one-third of the annual sediment load to the Minnesota River.

Channel Widening. Increases in river flow lead to channel widening. The trend in channel widening along the Minnesota River at Jordan mirrors the change in runoff ratio of the major tributaries (Figure 40c).

Pepin Sediment Loading. Channel widening increases the total suspended sediment load in the rivers. Time trends in annual suspended loads are reflected in the accumulation rates recorded in Lake Pepin sediment cores (Figure 40d).

The information presented in figure 40 cannot be used to quantify the amount of sediment loading caused by artificial drainage, and is not meant to imply the drainage is the sole driver of changes in sediment load. The purpose of this exercise was to show that mechanisms linking drainage, flow and channel widening are consistent with the time trends in Lake Pepin and support the hypothesis that drainage has created more erosive rivers.

CONCLUSIONS

Increased flow and sediment loading from our study watersheds is a serious problem for the Minnesota and upper Mississippi rivers, where such changes have been noted but without adequate explanation. The findings presented in this study have implications for the entire intensively cultivated corn belt of the Midwest USA, where former wetland depressions have been drained, and in general wherever agricultural drainage has reduced water residence on the land surface. Twentieth century crop conversions and the attendant decreases in ET from depressional areas due to artificial drainage have combined to significantly alter watershed hydrology on a very large scale, resulting in more erosive rivers. While the widening we document cannot continue indefinitely, particularly if future increases in discharge are modest, chronically high discharges could result in essentially permanent increases in sediment supply originating from the toe of bluffs and from the erosion of high streambanks through natural bank migration processes.

Apportionment of causes of changes in flow in this study and others tend to focus on annual measurements. The seasonal differences highlighted in Figure 30 deserve additional investigation, as the effects of climate versus land-use could be different at different times of the year. This point becomes especially salient as strategies to manage excess water and channel widening develop. While the impact of agriculture on the world's rivers is highly variable (Walling and Fang, 2003), the results from this study offer an important lesson: crop conversions that require artificial drainage pose a risk to riverine water quality. Efforts to mitigate excessive sediment loads and turbidity must include strategies to manage watershed hydrology and reverse conditions contributing to higher river flows.

ACKNOWLEDGEMENTS

We thank the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources and the Minnesota Pollution Control Agency, Section 319 program for funding this project. We appreciate the contribution of Drs. Patrick Belmont (Utah State University, Utah) and J. Wesley Lauer (Seattle University, Washington) for their assistance in estimating channel widening. These channel width estimate are the product of excellent GIS the work by their students: Caitlyn Echterling, Jenny Graves, Justin Stout and Shannon Belmont. We also thank Dr. Xuesong Zhang for his assistance in creating the kriged watershed precipitation dataset.

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V. TOTAL TRUST FUND PROJECT BUDGET:

Personnel:	$ 112,200
Contracts:	$ 150,000
Equipment/Tools/Supplies:	$ 2,800
Other (Graduate Student stipend):	$ 35,000

TOTAL TRUST FUND PROJECT BUDGET: $ $ 300,000

Explanation of Capital Expenditures Greater Than $3,500: None

VI. PROJECT STRATEGY:

A. Project Partners:

Result 1 will be contracted to Minnesota State University-Mankato, Water Resources Center. Staff in the MSU-Water Resources center has extensive experience in delineating and mapping artificial drainage systems. The Water Resources Center (WRC) at Minnesota State Mankato was created in 1987 to serve as a regional center for environmental research and information exchange. The WRC staff has completed drainage inventory projects for the Blue Earth River Basin and a drainage ditch buffer study for the Board of Water and Soil Resources. The WRC has also been coordinating numerous TMDL projects and have several ongoing research studies involving the hydrologic, nutrient, and bacterial influences of tile on water quality.

B. Project Impact and Long-term Strategy:

Findings from this project will be paramount in guiding statewide decision making on water quality issues statewide and will directly affect implementation strategies for turbidity TMDLs. Results will provide some of the first watershed scale quantification on the effect of tile drainage on hydrology.

C. Other Funds Proposed to be spent during the Project Period:

The Minnesota Pollution Control Agency (MPCA) will provide $300,000 in matching funds secured from EPA sponsored section 319 funds. This matching money will be distributed between the SCWRS and MSU-WRC, with 60% of the funds going to the SCWRS.

D. Spending History:

Funding from MPCA ($297,000) Lake Pepin TMDL to fingerprint sediment sources. Original funding to develop sediment fingerprinting method provided by LCMR, 1999, $350,000.

VII. DISSEMINATION:

Results of this study have been submitted for publication to the journal Hydrological Processes and have been accepted pending final review. Summaries and findings and implications of this study have been presented at more than 30 technical meetings in Minnesota and nationally. Many of these presentations have been in conjunction with local watershed groups, and have an audience of County Commissioners, farmers, SWCD staff, and agricultural consultants. These meetings have been highly successful at delivering the findings of this study to people who are directly involved in watershed management but are less likely to attend scientific meetings or read scientific journals.

VIII. REPORTING REQUIREMENTS:

Periodic work program progress reports were submitted in February and August of 2010, 2011 and 2012. The above document is submitted as the final report for this project.

IX. RESEARCH PROJECTS: Original Research addendum is available upon request

Project Title: Intensified Tile Drainage Evaluation

Project Manager Name: Shawn Schottler

Trust Fund Appropriation: $ 300,000

2009 Trust Fund Budget	**Result 1 Budget:**	**Amount Spent Previous**	**Amount Spent this period**	**Total Amount Spent**	**Balance 8-1-11**	**Result 2 Budget:**	**Amount Spent previous**	**Amount Spent this period**	**Total Amount Spent**	**Balance 8-1-11**	**TOTAL BUDGET**	**TOTAL BALANCE**
	Quantification of extent of artificial drainage					Comparative assessment of hydrologic changes						
BUDGET ITEM												
PERSONNEL: wages and benefits Shawn Schottler (30% time, 3 yrs = $74,400) Jim Almendinger (25% time, 2 yrs= $37,800)						112,200	105,000	7,200	112,200	0	112,200	0
Explanation of Benefits: FTE's only = 28% Medical: Single ~$200/month, Family ~720/month Retirement- Employer Contribution = 4% of salary												
Contracts												
Professional/technical (Minnesota State University-Mankato; Water Resource Center. Responsible for completing Result 1)	150,000	103,806	46,194	150,000	0						150,000	0
Supplies lab supplies						2,800	2,000	800	2,800	0	2,800	0
Other **Graduate Student stipend**						35,000	35,000	0	35,000	0	35,000	0
COLUMN TOTAL	**$150,000**	$103,806	$46,194	**$150,000**	**$0**	**$150,000**	$142,000	$8,000	**$150,000**	**$0**	**$300,000**	**$0**