Assessing Historical Planform Channel Change: Whitewater River Basin, Minnesota, USA

Authors: Jayda Rowen[1,2]*, Henry England[1,2]*, Phillip Larson[1,2], Andy Brown[1,2], Jimmy Wood[3], Andy Wickert[3], Zach Hilgendorf[2,4]

[1]Earth Science Programs, Department of Anthropology and Geography, Mankato, MN, USA; [2]EARTH Systems Laboratory, Mankato, MN, USA; [3]Department of Earth and Environmental Sciences and Saint Anthony Falls Laboratory, University of Minnesota, Minneapolis, MN, USA;
[4]Department of Geography and Anthropology University of Wisconsin-Eau Claire, Eau Claire, WI, USA.

Abstract

The environmental impact of Euro-American agricultural land use within fluvial systems has long been recognized, particularly in the upper Mississippi River basin (UMRB), USA. Few studies in this region have comprehensively looked at the geomorphic response of river channel geometry and planform change following the introduction of Euro-American agricultural land use. As early as the 1890s-1900s, farmers in the Whitewater River valley (WRV), tributary to the UMRB, noted increased erosion of topsoil and hillslopes. By the 1930s-1940s hillslope erosion and valley sedimentation led to aggradation of the valley floor and dramatically increased flood frequency – burying farmland and entire towns. The primary focus of this research is to characterize historic planform change and compare to changes in valley floor fluctuations assessed previously. We analyze aerial imagery at roughly decadal intervals, from 1938 to 2021, to characterize average planform change. We compare our results to prior work that compiled historic cross-section data recording valley aggradation over a similar time interval. Highest rates of planform change were observed between 1951-1972, likely contributed to by several significant meander cut-offs. This interval of time follows the period of highest sedimentation rates (1855 to 1939) in the WRV and the implementation of soil conservation practices in the 1940s. Planform change was minimal in the most recent intervals between 2003 and 2021. Interestingly, this also occurs during a period of increased valley sedimentation potentially resulting from more intense row cropping practices and a well-noted increase in high magnitude precipitation events throughout the region. The decrease in planform change may be the result of a more entrenched channel form that has adjusted for increased magnitude flows resulting from higher magnitude precipitation events. The overall pattern of decreasing planform change may correlate to conclusions reached by Wood (2023) who suggested improved agricultural land management and soil conservation practices reduced mean sedimentation rates in the WRV until recently. We hypothesize that these conservation practices may be allowing the river to become less erratic and more stable within the Whitewater valley over time. However, the later period of rejuvenated sedimentation may reverse this trend in the future.

Introduction

Anthropogenically-driven changes in climate and land-use have been shown to significantly alter hydrologic and geomorphic processes within fluvial systems (e.g. Miller et al., 1993; Dikau et al., 2005; Arnell et al., 2013; Harden, 2013; Shellberg et al., 2016; Sunde et al., 2018). This is especially true of the impact of Euro-American settlement and land-use, alongside contemporary climatic change, within the upper Mississippi River basin, USA (UMRB; Boucher et al., 2004; Kelly et al., 2017; Rockström et al., 2014; Schottler et al., 2013). Anthropogenic-induced fluvial system change is readily observed across this region and frequently indicated by accelerated erosion, increased potential for erosional hazards, sediment loads, changes in flow regime, altered channel geometry, and river restoration efforts (Belmont et al., 2011; Kelley & Nater, 2000,). In addition, enhanced erosion, changes in flow regime, and agricultural land-use have resulted in much of the UMRB being designated as impaired for excessive nutrient loading and/or turbidity, reducing water quality and ecosystem health (Turner et al., 2003; Stark et al., 1995-98). To establish strategies that could serve to mitigate these environmental issues and manage the fluvial systems into the future, it is imperative that we comprehensively understand how the geomorphic and hydrologic processes within the fluvial systems are changing over time. A limited number of studies in this region have comprehensively looked at the geomorphic response of river channel geometry and planform change following the introduction of Euro-American agricultural land use.

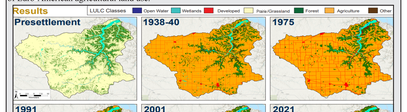


Figure 1. This figure created by Seidling Schommer and Fitzgerald (2024) shows the land use land-cover (LULC) change in the WRV from presettlement to 2021. Natural prairie cover was reduced from ~83% in 1847 to ~3% by 2021 and agriculture land use increased from ~0% in 1847 to ~66% by 2021.

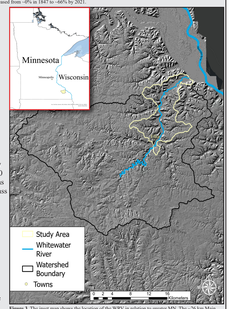


Figure 2. Figure taken from Wood 2023: A.) Rill erosion on a field in the WRV. B.) Gully erosion SW of the Mississippi confluence. C.) Boulder fan on a highway west of Beaver. D.) 25-acre sand fan burying a floodplain in Buffalo River Valley, WI, analogous to what would have been seen in the WRV.

The Whitewater River Valley (WRV) of southeastern Minnesota (Figure 4) is an ideal natural laboratory for investigating a highly anthropogenically impacted river system in the UMRB. Over the past 150 years, much of the Whitewater River Valley (WRV) has been converted from native vegetation, such as tall-grass prairie and hardwood forest, to agricultural land/row crops (Wood, 2023). Between 1855 and the mid 20th century, intensive agricultural practices stripped away the natural vegetation and, without vegetative cover, runoff and concentrated flows eroded uplands, hillslopes, and carved gullies that resulted in sedimentation downslope and in the valley bottom (Happ et al., 1940; Trimble, 2008; Wood, 2023). Accelerated erosion caused extensive alluvial fan formation in the WRV. In his research, Wood mapped over 200 alluvial fans that formed within the valley since 1938. Not only was there significant geomorphic change, but these destabilized systems resulted in repeative natural hazards for communities in the WRV. For example, the village of Beaver was flooded 28 times in 1938 alone. Beaver no longer exists, as these devastating events led to its burial and abandonment (Holger, 2019).

Introduction (cont.)

The State of Minnesota began buying land from farmers, who were desperate to leave the WRV, in 1931 (Johnson, 1976). The farmland was fruitless, resulting from the intense and frequent flooding events and sedimentation. Restoration and soil management practices were implemented in 1939 and continue today (Wood, 2023). Later, Lock and Dam 5 was constructed, creating pool 5 on the Mississippi River and altering the base level of the Whitewater River. (US Army Corp of Engineers, n.d.). And, in the 1950s, a portion of the river was channelized to manage flooding in the WRV. The water was routed to waterfowl impoundments (Kallok, 2008). Previous work in the WRV has focused on valley floor sedimentation and clearly documented a period of destabilization of WRV hillslopes and the fluvial system associated with Euro-American land use (Happ et al., 1940; Wood, 2023). However, no study has investigated planform channel change of the Whitewater River (channel width, sinuosity, stream length, lateral migration) over the same or similar historic time interval. It is well established that changes in river channel form are tied to discharge and sediment supply (e.g. Bridge, 1993; Savenije, 2003; Eaton et al., 2004; Pfeiffer et al., 2017). Thus, the purpose of this research is to comprehensively investigate planform change over the historic record obtained from aerial photographs and, if possible, compare sedimentation and planform data to look at channel geometry and river behavior change over the historic record.

Methods

In order to assess historical planform channel change, physical copies of aerial photography were acquired from the Borchert Map Library at the University of Minnesota. Aerial photography for the years 1938, 1951, 1972, 1980, 2003, 2010, and 2021 were acquired. The 1991 aerial photography was acquired through MNGeoWMS, in which the 1991 image had been previously digitized and mosaiced.

Digitizing

Banklines were digitized for each year at a scale of 1:2000 on ArcMap. The scale was chosen for consistent and accurate results. The banklines underwent the digitization process three times; each by a different student. The banklines were then compared, and the most accurate lines were chosen as the reference lines.

Mosaicing

Scanned imagery was cleaned and cropped with the Historical Image Pre-Processing (HIPP) tool to equalize histograms and improve reconstruction (Knuth et al., 2023). Images were geotagged with the approximate image centroid, acquired by digitizing georeferenced index maps. Approximate altitudes were estimated based on the scale of the imagery in comparison with comparable historical collections with more complete metadata. Unfortunately, metadata for nearly all of the collections was significantly lacking. Images were then processed using Agisoft Metashape (V2.X.X) to align photos, refine point clouds, and generate a single orthomosaic image. This orthomosaic image was exported as a TIFF and brought into ArcGIS Pro (V3.X.X) to be georectified using consistent ground control points that were visible in both the historical orthomosaic and a modern National Agricultural Imagery Program (NAIP) high resolution orthomosaic from 2021.

The mosaiced images were then brought in ArcMap 10.8.2 and registered to a common coordinate system (NAD 83 UTM Zone 15N). To reference the images, the 1938 mosaiced image was used as a base layer. Each image was assigned a minimum of eight ground control points with preferential placement near the river and surrounding floodplain to avoid distortion from local terrain relief (Libby, 2017). A third order polynomial transformation was applied to all the images in order to correct for some of the radial error presented by the earth's curved surface, unavoidable geometric error presented by local topography, and lens distortion (Libby, 2018).

NCED Toolbox

The National Center for Earth-Surface Dynamics (NCED) Planform Statistics Toolbox was used to calculate channel migration in the following steps:

1. The Centerline Interpolation Tool was used to collapse banklines to a centerline.
2. The NCED "Migration" tool was then used to make migration measurements along all seven centerlines.
   A. Measurements were taken at 10-meter intervals.
   B. Tables were exported as CSV's for analysis.
3. The "Lateral Measurement" tool was used to create trajectory files measuring lateral channel movement, along with a file storing width measurements. The tool prompts users to select the "to" (later date) and "from" (earlier date) centerlines from each time interval.
4. The program creates trajectory graphic lines that were then converted to a polygon shapefile.
5. The trajectory lines needed to be inspected and edited to correct any false measurements made by the tool. This was most commonly seen where cut-offs occurred.
6. The output data from step 1 was entered into Lea and Legleiter's (2016) "ChannelChangeSignT" MATLAB script in order to determine which measurements of migration are statistically significant (exceed the amount of error).
7. The tabular output data from step 3 was entered into another program, created by Libby (2018), ArcMap tool to automate the process of tying the tabular data to the spatial data along with updating fields.

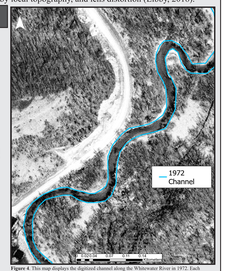


Figure 4. This map displays the digitized channel along the Whitewater River in 1972. Each bankline was digitized at a 1:2,000 scale so that measurements stayed consistent for each time interval.

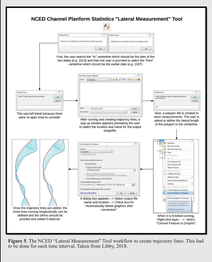


Figure 5. The NCED "Lateral Measurement" Tool workflow to create trajectory lines. This had to be done for each time interval. Taken from Libby, 2018.

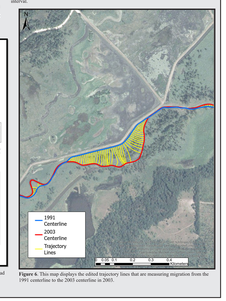
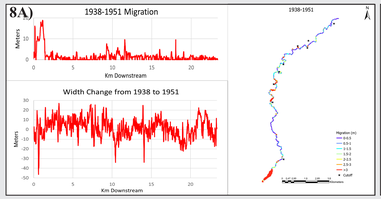
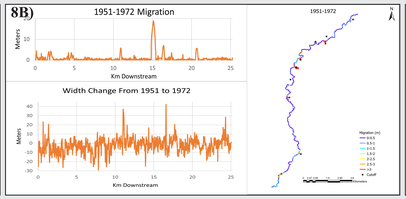


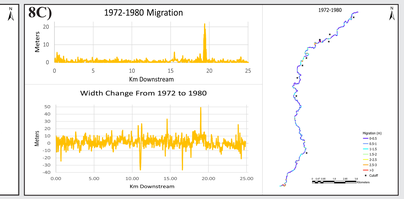
Figure 6. This map displays the edited trajectory lines that are measuring migration from the 1991 centerline to the 2003 centerline in 2003.

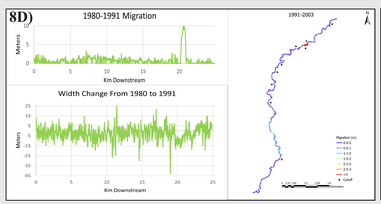
Results

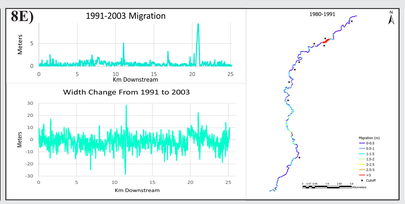
Aggradation, Migration, Length, and Width

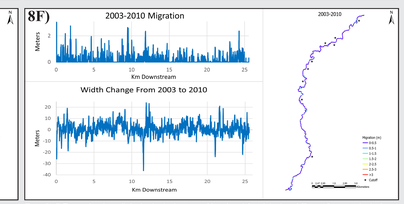


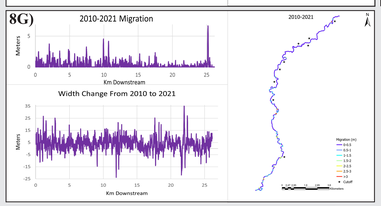












Figures 8A-G) These graphs and maps display the migration downstream of the study reach for each time interval. **Figure A)** Represents migration from 1938-1951 and width from 1938. **Figure B)** Represents migration from 1951-1972 and width from 1951. **Figure C)** Represents migration from 1972-1980 and width from 1972. **Figure D)** Represents migration from 1980-1991 and width from 1980. **Figure E)** Represents migration from 1991-2003 and width from 1991. **Figure F)** Represents migration from 2003-2010 and width from 2003. **Figure G)** Represents migration from 2010-2021 and width from 2010.

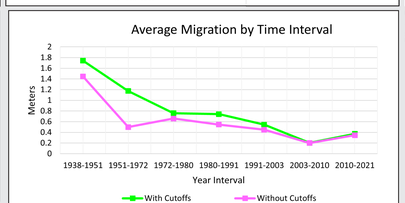


Figure 11. Average rates of migration of the Whitewater River with and without cutoffs for each time interval. In the time span, the study area experienced 10 cutoffs. Cutoff data skew overall migration trends. They are part of a river's natural life cycle but do not reflect minute changes in river behavior that may indicate anthropogenic influences. For this reason, migration is presented both with and without cutoffs.

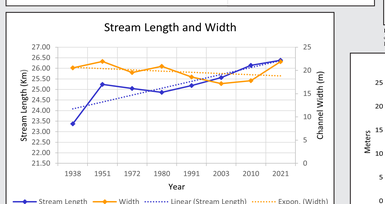


Figure 9. Graph of stream length and width for each year.

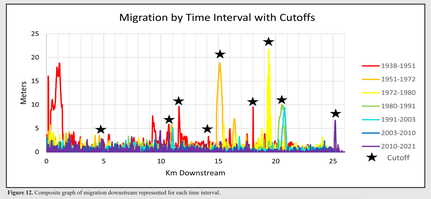


Figure 12. Composite graph of migration downstream represented for each time interval.

Time Interval	Migration Rate per Year in Time Interval (m/yr)	Width Change per Year in Time Interval (m/yr)
1938-1951	0.124	0.121
1951-1972	0.044	-0.111
1972-1980	0.096	0.168
1980-1991	0.071	-0.209
1991-2003	0.047	-0.123
2003-2010	0.029	0.094
2010-2021	0.032	0.436

Figure 13. Table displaying migration rates and changes in width for each time interval.

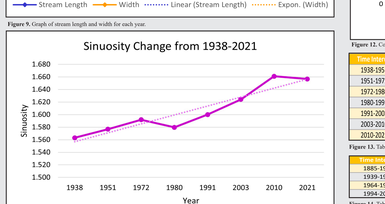


Figure 10. Sinuosity change over time in the Main Stem of the Whitewater River.

Time Interval	Aggredation Rate per Year in Time Interval (cm/yr)
1885-1939	0.245
1939-1964	0.523
1964-1994	0.259
1994-2008	1.23

Figure 14. Table displaying aggradation rates for each of Wood's (2023) time intervals.

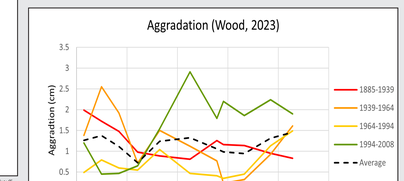


Figure 14. Rates of aggradation plotted downstream of the Main Stem for each of Wood's time intervals. The second order polynomial trend line has an R^2 value of 0.5624.

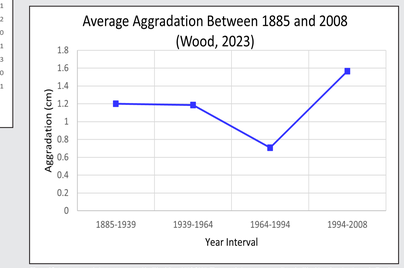
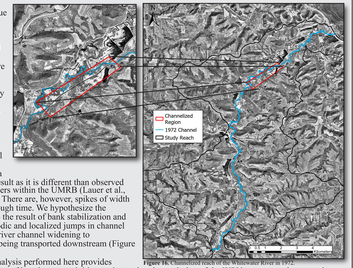


Figure 15. Average aggradation rates measured by Wood from 1885-2008. The aggradation rates were split up by Wood into four time intervals. Trend lines were applied to all four time intervals but are not displayed. 1885-1939 and 1939-1964 trended downward; aggradation decreased with distance. 1964-1994 and 1994-2008 trended upward; aggradation increased with distance. There is an increase in aggradation over time.

Discussion

The results reveal that, generally, migration rates of the Whitewater River decrease over time (Figure 12). River migration decreases from 1938 until 2003. It then begins to increase until 2021. The results also show an increase in stream length and sinuosity from the beginning of the dataset (1938) until the end (2021). This is despite 10 cutoffs and channelization of 26% of the total stream length in the study area (Kallok, 2008; Figure 14). The increase in stream length is correlated to the measured increase in sinuosity (Figures 9; 10). We hypothesize that the migration rates began to decrease as the Whitewater River began to relax following the catastrophic flooding and valley sedimentation during the late 19th and early 20th century. The implementation of soil conservation practices may have stabilized the channel banks and reduced sediment loading, reducing measured migration rates until 2003. Increased length and sinuosity may be tied to the increase in base level caused by the installation of Lock and Dam 5.

It is important to note that due to limitations in available aerial imagery, the temporal intervals used in our data will not be identical. Efforts were attempted to make the intervals close as possible for comparison, but were limited by available data. Since the temporal intervals are not identical, the magnitude data may not be useful for direct comparisons. In order to address potential issues with the magnitude data, rates with of migration, width change, and aggradation were calculate for each year with different temporal intervals (Figures 13; 14).



Measured channel width shows a decrease over time (Figure 9). result as it is different than observed channel width trends on other rivers within the UMRB (Lauer et al., 2018; Libby, 2018; Jones, 2023). There are, however, spikes of width increase in localized reaches through time. We hypothesize the decrease in width over time to be the result of bank stabilization and conservation practices. The episodic and localized jumps in channel width are likely the result of the river channel widening to accommodate slugs of sediment being transported downstream (Figure 17).

In addition, while the data analysis performed here provides insights into many different aspects of how human activities are impacting the evolution of the WRV, many questions remain unanswered. The increased length of the Whitewater River and its relatively stable width over time suggest it is telling a different story than many other rivers in Minnesota watersheds (Schottler et al., 2014). In their analysis of the 21 different Minnesota rivers, Schottler et al., found that, "rivers with increase flow have experienced channel widening of 10–40%", a trend not seen in the Whitewater River. Future work will examine streamflow measurements at a USGS gauge on the Whitewater River to more fully understand if similar changes in flow regime have occurred on the Whitewater River.

The temporal intervals used in our data will not be identical to Wood's temporal intervals. At this time, this limits our ability to make direct comparisons. However, for those focused on understanding the Whitewater River and establishing appropriate conservation practices, we suggest soe interesting spatial patterns that make observations and this data significant. For example, aggradation rates show a decreasing trend from 1855 until 1994. It then begins to increase until 2008. Comparing the average migration rate with Wood's aggradation rate reveals a complicated system. There are observed periods in which migration rates are decreasing as aggradation rates are decreasing. However, when aggradation rates begin to increase, the migration rate continues to decrease. Eventually, migration rates do increase in the latest time interval (2010-2021). This may be a delayed response to increased aggradation and may coincide with an increase in channel width over that same interval as well. It seems the trend of data is changing towards more instability over the past 20-30 years. Ongoing and future field and remote measurements are encouraged to monitor this in the WRV. Such change, if real, could be important to study to understand the complexity of fluvial system response to perturbation – though the cause of this most recent spectral change is unknown at this time.

Figure 17. Depicted above is the river channel reacting to an increase in sedimentation. The image on the left is where the sediment slug is first seen in 1991. The middle and right images shows the channel width increasing in response to the sediment in 2003 and 2010.

In summary, our results reveal a river system that was heavily perturbed by Euro-American land use in the late 19th and early 20th century and seemed to adjust through time towards a more stable system. However, in the last 20-30 years, it appears the Whitewater River may be shifting from that trend. Channel width, aggradation, migration, and length/sinuosity all appear to be increasing. The cause of this increase is unknown, but future work analyzing stream gauge data may help link these increases to hydrologic changes within the WRV.

Broader Impacts

The Whitewater Watershed Project has been dedicated to restoring the Whitewater watershed for the past thirty-fifty years. Conservation is a result of the commitment of landowners, local, state, and federal conservation officials to restore the watershed (Whitewater Joints Power Board, 2017). However, changes in river morphology and land use has caused subtle reversals to conservation progress. In spite of significant success, the Whitewater River still ranks as one of the highest streams in Minesota with severe erosion and sedimentation problems (Whitewater Joints Power Board, 2017). A future study could analyze the spatial, temporal, and specifics of conservation efforts through time and determine whether or not these efforts correspond to trends in our data and the overarching impact they have in furthering restoration of the WRV.

In addition, the WRV is part of the ancestral homeland of the Dakota (Peterson and LaBatte, n.d.). By the time Euro-Americans came to the WRV, the Dakota had called the land home for at least 800 years (Arzigian, 2008). Taking advantage of the WRV's natural abundance, the Dakota used the valley as a summer campsite. Migrating in and out of the valley with the seasons and in yearly cycles, the land of the WRV was the home of these people for generations (Holger, 2019). The Dakota caused little degradation to the natural landscape, practicing mainly hunting and gathering and horticulture (Holger, 2019; Minnesota Department of Administration: OSA, n.d.). Interactions between the earliest Euro-American settlers of the WRV and the Dakota were reportedly mostly amicable (Holger, 2019). The homelands of the Dakota were quickly taken away after the arrival of Euro-Americans in the WRV. Through the Treaties of 1851 and 1858, the Dakota of the WRV and all other Dakota people in the state were forced onto a 10-mile strip of land on the banks of the Minesota River (Peterson and LaBatte, n.d.). The importance of this land to the Dakota should not be overlooked in future work in the WRV. Although forced from the WRV, the legacy of the Dakota lives on in many ways. The name of the Whitewater River itself is a direct translation of the Dakota name for the river. A physical cultural legacy was left behind by the Dakota as well, much of which is likely now buried as a result of Euro-American land use and valley sedimentation. Future work should consider this when investigating the geomorphology of the WRV and note any potential archeological sites they may uncover.

References Cited

See Attached