Buried in bluff country: Stream and valley sedimentation in the Whitewater River Valley, Minnesota (USA)

A THESIS
SUBMITTED TO THE FACULTY OF THE
UNIVERSITY OF MINNESOTA
BY

Jimmy J. Wood

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Andrew Wickert, Phillip Larson

2023

Acknowledgements

Pursuing my master’s degree has been a most fulfilling experience. The personal connections I have made over the last two years have been equally fulfilling and have both improved my research and helped me maintain my well-being.

To Andy Wickert and Phil. The eager and easygoing conversations we shared during our first meetings were major factors that helped me choose the University of Minnesota (UMN) as the place to undertake my graduate study. Thank you for your invaluable guidance in the field and the office.

To Joe. You are a great teacher, and I am glad you could be on my thesis committee. You have a knack of empathizing with the difficulties of student/scientist’s life that always helped lessen the load for me. Thank you for that.

To Katia, Lauren, and Taylor. Thank you for the hundreds of hours you collectively put into my research, digging through, and organizing historical archives, and entering raw data for analysis. I would never have finished “on time” without your effort. Related to that, thank you Terri and Andy Bloedorn, and for your generous assistance archiving at the University of Wisconsin La Crosse’s Murphy Library and the Winona County Historical Society, respectively. The historical documents found at these locations were a cornerstone of my research.

To my research group at UMN: Jeffrey, Hima, Shanti, Nilay, Jabari, Eric, and Alisa. Thank you for being there and always letting me bother you with questions about my research and whatever else. You helped me innovate my work at a speed I would never have been able to accomplish alone and made my work better. Special thanks to Jeffrey for loaning me your crusty old laptop to play *Dawn of War* in my free time. No better way to relax.

To my subject experts, Laurie, Doug Christiansen, Sara, and Jeremy. Thank you for teaching me about the Whitewater Watershed's history. It is a fascinating and beautiful place, and I am glad to know more about it. Special thanks to Laurie for donating the treasure trove of data that this research investigates. I would not have been able to work on this project, or accomplish as much as I have, without it.

To affiliated group members at the University of Wisconsin Eau Claire and Minnesota State Mankato: Garry, Douglas Faulkner, Zach, Andy Brown, Ron, Abi, Grace, and Hunter. Thank you for your advice and collaboration during monthly meetings and fieldwork. I am glad to have had the opportunity to discuss my research with people outside of my central research group and to have helped you with yours. And thank you all for making fieldwork extra fun, despite the mosquitos and racoons.

To Stafford Happ and the surveyors responsible for building this dataset. Thank you for not only creating the data that I used in this thesis but also ensuring that it survived the decades separating us.

To Emily. Thank you for your support in all things. I couldn't balance all of life's happenings without it.

To the Legislative-Citizen Commission on Minnesota Resources and the National Science Foundation. Thank you for the financial support. This work would not have occurred without it.

For all of this, and for the things and people I've forgotten to mention, I am grateful. Until next time.

Dedication

To 2018 Jimmy. You picked a good path.

Abstract

Erosion and sedimentation are natural and beneficial surface processes but when accelerated by anthropogenic activities related to agriculture yield negative economic and ecologic consequences. European style agriculture spread through 16th to 19th century colonialism has had a profound effect on erosion and sedimentation rates across the globe. The Upper Mississippi River Valley (UMRV) region of the United States, where the Whitewater River Watershed is located, has been particularly affected by European style agriculture implemented in the mid-20th century. From the 1890s through 1920s, increased erosion, sedimentation, and flood frequency precluded land from agricultural production and damaged property and infrastructure in the Whitewater basin. Living and working conditions became untenable and most of the lower valley was abandoned by the 1960s. This geomorphic upheaval invited scrutiny by Soil Conservation Service geologist Stafford Coleman Happ who established a basin-wide sedimentation survey in 1939. He and assistant surveyors established 94 valley transects upon which the distribution and thickness of Euro-American Legacy Sediment (ELS) was measured through auger boring and surface elevation surveys. Repeat field surveys in the 1960s, 1970s, and 1990s were conducted along with an aerial lidar survey in 2008 yielding a robust, over 150-year, record of river valley changes and sedimentation throughout the basin. We use this historical transect sedimentation data to ask how sedimentation rates in the Whitewater watershed have changed since the implementation of soil conservation measures around 1940. Mean sedimentation rates are calculated per transect between floodplain cross-sections or from soil bore depth measurements and are then compared statistically with Welch’s ANOVA and the Games-Howell tests. Between 1939 and 1994, mean transect sedimentation rates for the basin decrease from 0.92 to 0.22 cm/yr.

We speculate that this is due to improved soil conservation measures implemented in the basin around 1940. An analysis of land use and land cover change over this time should be completed to corroborate this assumption. The 1994 to 2008 time interval indicates that sedimentation has increased over the last 14 years of this record, but we lack the spatial data coverage to make conclusions about basin wide changes. Still, this change may likely be attributed to the effects of large floods to mobilize sediment, such as the record flood of 2007, as well as anecdotally reported land use intensification since the 1990s. Downstream spatial patterns of sedimentation from the uplands, through the middle gorges of the Whitewater River, to the bluff bordered lower valley appear to follow trends reported in other basins of the UMRV in relation to valley and channel geometry characteristics. These should be investigated in turn to understand how sediment is being routed throughout the river network.

Table of Contents

Introduction

Like primordial climatic and tectonic processes, anthropogenic activities fundamentally drive geomorphic change; one significant way this occurs is through the alteration of hydrologic and sedimentologic regime (Magilligan, 1985). Accelerated rates of erosion and deposition and dramatic adjustments within erosional systems—fluvial, hillslope, aeolian, etc.—are prevalent in landscapes where humans have intensively used the land. Both erosion and deposition (or sedimentation) are natural Earth surface processes—fundamental components of the geologic cycle—that can yield positive environmental impacts. For example, they contribute to soil development and, where soils are fertile, allow us to grow life sustaining food. Erosion and sedimentation also yield ecological benefits by influencing environmental sediment flux (Happ et al., 1940). Erosion and deposition create landforms such as coastal tide pools, hillslope talus, and cliffs. that form unique animal habitat and promote biodiversity. Sediment transport also influences the flux of nutrients and minerals through the environment and can thereby influence ecosystem health (Nerbonne & Vondracek, 2001). Accelerated erosion and sedimentation occur at much greater rates than is reported on geologic timescales and is generally viewed negatively due to their widespread economic and ecologic consequences (Kemp et al., 2020). Excess erosion depletes agricultural productivity due to topsoil loss (Nerbonne & Vondracek, 2001) and destabilizes hillslopes increasing the potential for natural hazards to both human and ecological communities (Happ et al., 1940). Excess sedimentation can pollute streams, harming aquatic communities (Nerbonne & Vondracek, 2001), and has historically induced flooding by raising streambeds and reducing channel conveyance capacity (Happ et al., 1940). Frequent sedimentation induced flooding has even been shown to exacerbate local malarial conditions by converting once arable land to marsh thus yielding epidemiological concerns (Happ et al., 1940).

Understanding how anthropogenic activity modifies geomorphic processes adds to, and supports, the concept of the Anthropocene in the geosciences (Goudie, 2020). First introduced by Crutzen (2002), the Anthropocene has been proposed as the latest epoch of geologic time and is chiefly characterized by the profound effect of human activity on landscape forming processes (Goudie, 2020). With further research into our collective impact, scientists, engineers, and public agencies can best approach the consequences of anthropogenic activities with appropriate mitigation strategies to prevent disaster and environmental degradation.

Agriculturally accelerated erosion & sedimentation

Running water combined with the erosion potential of agriculturally primed landscapes have long been recognized to accelerate erosional processes and increase rates of sedimentation in fluvial systems (Knox, 2006). A generalized sequence of events begins with soil eroded from upland farms and devegetated hillslopes through precipitation or snow melt. The eroded soil then accumulates downhill at foot slopes or in lowland valleys on floodplains or in lakes (Goudie, 2020).

Agriculture emerged independently on most land masses throughout the Holocene (since about 11.7 ka) in diverse physical and human geographies. The earliest written of agricultural soil erosion was recognized by at least 2,500 years ago and can be traced to both Greece and China (Dotterweich, 2013). The presence of valley deposits across Europe dated to the Bronze and Iron Ages, up to 3,300 BCE, demonstrate its occurrence far into antiquity, which is to be expected given length of time humans have farmed (Goudie, 2020).

Legacy sediment

Around the world

Anomalously high accelerated sedimentation has been attributed to the spread of European land use practices following imperialist expansion from the 16th to 19th centuries (Portenga et al., 2016). The subversion of well-established indigenous agricultural methods with the large-scale conversion of forests, grassland, and wetland to monocultures and overgrazing transformed erosion and sedimentation rates and in some cases so severely degraded soil fertility to force land abandonment (Dotterweich, 2013). The resulting valley deposits have been termed post-settlement alluvium (PSA) and they are found all over the planet (Portenga et al., 2016).

This specific agricultural treatment has even been shown to have had a significant effect on the depositional record of the late Holocene. Worldwide, there are consistent reports of floodplain sedimentation yielding a tenfold increase following European colonization and land use practice implementation [33p]. Knox (2006), with the following statement, puts that into context, "human influences expressed mainly through agricultural land use of the last 200 years produced greater impacts on floodplain morphology and floodplain sedimentation than any natural environmental changes of the last 10,000 years." Evidently, not only are we capable of influencing landscape change like the climate, tectonics, and other natural forces but we may even rival them in significance.

James (2013) reviewed PSA research and shared that anthropogenic deposits (including PSA) have been increasingly described as "legacy sediment"—first by Novotny (2004). Following this trend, we exchange PSA with Euro-American legacy sediment (ELS) to reference deposits derived from European style agriculture and land use. Despite its wide use in a variety of contexts, our departure from PSA is in recognition of the fact that indigenous cultures and agriculture were well established in the United States (where this research takes place) prior to European arrival and in recognition that they were also capable of influencing erosion and sedimentation.

Around the US

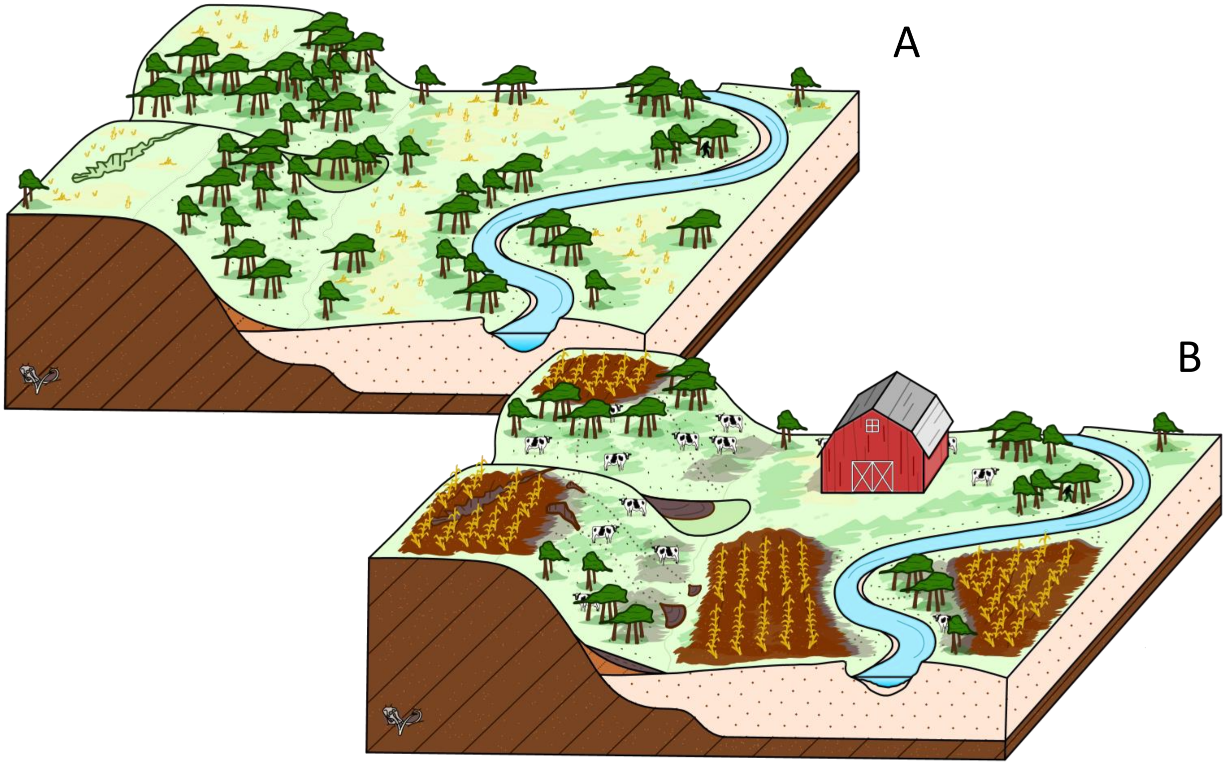
The soils of the US, loosened by felling axe and plow, have (not surprisingly) eroded to yield vast quantities of ELS. Dotterweich (2013) provides a review of early descriptions of ELS development from the US up until the mid-19th century and credits John Bartram—American botanist-horticulturalist-explorer—as the first to document it. In the mid 18th century, penned in a letter to Jared Eliot—famous farmer-physician—Bartram shares his observations from colonies in New England and the mid-Atlantic:

> above 20 years past when the woods was not pastured and full of high weeds and the ground light then the rain sunk much more into the earth and did not wash and tear up the surface (as now). [...] but now the rains [on] the surface is collected into the hollows which it wears to the sand and clay which it bears away with the swift current down to brooks and rivers whose banks it overflows.

This excerpt alone describes the significance of natural vegetative cover on erosion and the resulting effects of excess stream sedimentation on flooding, themes that will repeat themselves around the nation (Dotterweich, 2013).

Happ et al. (1940) share an extremely comprehensive review of early reports of ELS (described as “culturally accelerated stream and valley sedimentation”) from the beginning of the 19th century through the 1930s (Trimble, 2008). This period of literature is significant as it coincides with the spread of European style agriculture throughout the contiguous US and culminates near the beginnings of the federally initiated soil conservation movement. Starting with Moore's (1801) report of half buried posts and the silting of creeks, mill ponds, and rivers due to the "wastage from upland fields," they describe the ubiquitous formation of ELS around the nation as wagon trains, steamboats, and railroads plied the boundaries of a nascent country.

Land treated with European agricultural practices underwent similar transformations (**Figure 1)**. The natural vegetation—forest, prairie, etc.—was cleared to make room for development. All soils but those mantling the steepest slopes were broken and sown for crop cultivation and the rest left for grazing pasture (Happ et al., 1940). The removal of rooting vegetation, intensive farming, and overgrazing increased surface runoff on crop fields and grazeland and as a result increased soil erosion (Magilligan, 1985). Prolonged soil exposure without vegetative cover concentrated flow eventually carving gullies into the earth that accelerated the erosion of topsoil and colluvium and accelerated sedimentation downslope. Streams draining these areas of excessive erosion aggraded without the capacity to effectively



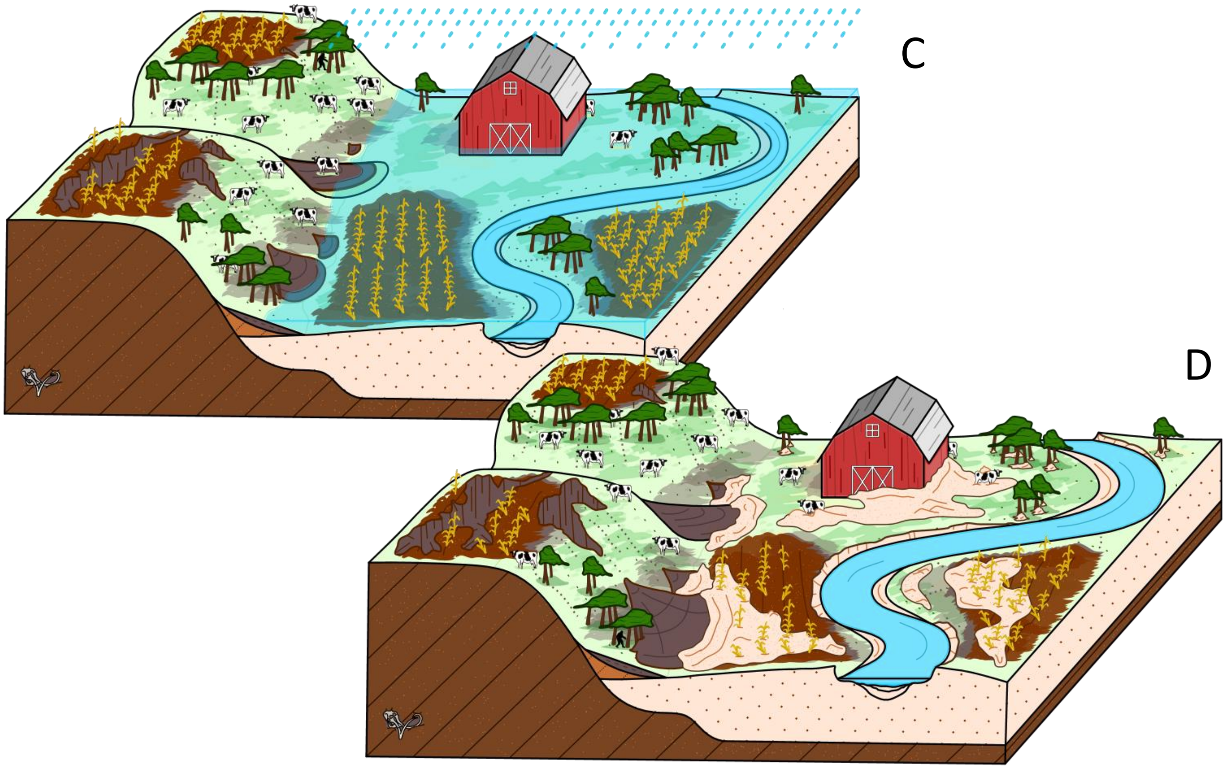


Figure 1. Landscape transformation due to European style land use. A. Pre-intensive farming: Forest and prairie cover the landscape. Existing erosional and depositional features such as gullies and alluvial fans have naturally stabilized. **B. Accelerating erosion & sedimentation:** Natural vegetation is cleared to make room for crops and pasture on all usable surfaces. Gullies form on the ridges bordering the upland surface and form alluvial fans downslope. Relict gullies and fans reactivate, and the channel aggrades. **C. Erosion & sedimentation induced flooding:** Gullies and fans increase in size, taking land out of food production, and continued channel aggradation causes a flood, damaging property. **D. Flooding induced erosion & sedimentation:** Retreating floodwaters bury the floodplain in alluvium, damaging property. Changing hydraulics induce bank erosion and gullies and alluvial fans continue to increase in size. All effects take more land out of agricultural production. Modified from Happ et al. (1940).

transport the added sediment load and as mentioned previously this exacerbated flood heights and frequency (Happ et al., 1940). Bonsteel (1912) succinctly described this process and some of its consequences in the Piedmont of the eastern US:

> The sudden torrential rains of winter and early spring frequently remove vast quantities of this disintegrated rock [sourced from upslope], which is further comminuted by its grinding passage down the stream beds. Such a sand-laden torrent may suddenly cover broad, fertile lowlands in the middle course of the stream with a deposit of white granitic sand having a depth of 2 to 15 feet. Destruction is doubly accomplished in such instances

> through the removal of soil-forming material from the eroded uplands and its deposition upon the fertile bottom lands. It is sparsely mingled with organic matter in its new position; it is completely washed of all fine earth suitable for the immediate sustenance of the economic forms of plant life; it covers and destroys growing crops; and it obliterates the fertile, tillable land whose surface it covers.

Their rhetoric also provides insight into the perspective through which the negative effects of accelerated and erosion were perceived scientifically. Using words like “destruction” and “damage” point to one focused on the economics of such phenomena. This perceived sentiment is echoed by Happ et. al (1940) whose review repeatedly cites sedimentation damage to crops by burial, the disruption of river navigability for commerce by sedimentation, erosion damage to farmland by gullying, and related flood damage to infrastructure as primary concerns and rationale for research (Happ et al., 1940).

The portion of the Upper Mississippi River Basin in northeast Iowa, northwest Illinois, southwest Wisconsin, and southeast Minnesota is region of the US that was particularly affected by ELS deposition (Happ et al., 1940) between the early 18th and 19th centuries. Rich sulfide ore deposits—galena (lead) & sphalerite (zinc)—encouraged rapid development of the Zinc-Lead District, an area mostly located in Wisconsin and Illinois and to a lesser extent in Iowa, during the 1820s and 1830s. Rich soils further encouraged development through farming which naturally led to grazing. As expected, land use accelerated erosion, sedimentation, and flooding ensued, and was further promoted by the steep, dissected bluff topography (Knox, 2006).

Soil conservation

As early as 1908, accelerated erosion and sedimentation were recognized as national problems (Chamberlin, 1909), however, two decades would pass before they received the national attention that would initiate the development of viable solutions to curb them. In 1929, US congress formally recognized erosion as a serious threat to soil productivity (Belby et al., 2019) and the occurrence of the Dust Bowl over the next half decade fully thrust the concept of soil conservation to the forefront of national agricultural policy (Helms et al., 1996). Two laws in 1933 and 1935 created the agency responsible for investigating and implementing soil conservation practices on farms across the country (Helms et al., 1996). The first law established the Soil Erosion Service (SES) as a temporary agency of the US Department of the Interior. The second superseded the SES through the establishment of a permanent Soil Conservation Service under the US Department of Agriculture (Geiger, 1955).

Quickly, the SES established their first project, the Upper Mississippi Valley Erosion Experiment Station near La Crosse, Wisconsin. Here, they treated erosion and sedimentation problems with erosion control measures that reduced the erosivity of running water by promoting infiltration over overland flow and by shielding soil with denser vegetative cover. Some of these practices included hillslope terracing, contour farming, strip cropping, gully and streambank stabilization, and removing moderate to steep slopes from production (Belby et al., 2019).

Not long after, the SES chose nearby the Coon Creek watershed as the nation's first watershed scale soil conservation demonstration project (Geiger, 1955). While the purpose of the experiment station near La Crosse was to investigate soil conservation practices, the purpose of the Coon Creek Demonstration Project was to implement them through cooperative partnerships with local farmers (McKelvey, 1939). At this time, soil conservation was not a new concept for farmers in the Upper Mississippi River Valley; most practiced crop rotations to maintain soil fertility but actively contributed to accelerated erosion with few solutions, desire, or funds to better control it (Helms et al., 1996). Within the projects boundaries—essentially the watershed divide—landowners interested in assistance signed agreements with the SES (Geiger, 1955) and worked with technicians to design plans for their farms (Brown & Nygard, 1941) that incorporated erosion control measures developed at the experiment station (Belby et al., 2019). Through this partnership, the landscape transformed yet again (**Figure 2**). Rectangular farm fields running up and down hills were reshaped to follow the land's contours and better fit the topography. Steep slopes made bare for plow and cow were revegetated to stabilize the soil, typically with forest cover. Other areas prone to rill and gully formation were similarly treated with grassed waterways (Belby et al., 2019).

Figure 2. Transforming land use in the Coon Creek Watershed, Wisconsin. Repeat aerial imagery immediately before the widespread implementation of soil conservation measures focused on erosion control (**A**) and roughly three decades later (**B**). Note how rectangular fields have been contoured to the landscape and are therefore of more irregular geometry. Gully systems that extended through fields in 1934 and are no longer visible in 1967 (Trimble, 2013).

The success of the Coon Creek Demonstration Project in controlling erosion off farmland led experienced staff to establish other project sites in the region (Belby et al., 2019). By mid-1935, the (now) SCS managed 38 other projects including ones in the relatively nearby Gilmore Creek and Root River watersheds across the Mississippi River in Minnesota (Brown & Nygard, 1941).

Since not all land could conveniently lie within the boundaries of a SES/SCS demonstration project, other initiatives were formed to make erosion control assistance more widely available. For example, the Civilian Conservation Corp—another Depression/Dust Bow Era development—implemented erosion control measures throughout the Upper Mississippi River Valley in the early 1930s (Belby et al., 2019). Later that decade in 1937 the state of Minnesota also passed a law permitting the organization of soil conservation districts which would make the technical assistance more accessible (Brown & Nygard, 1941).

SCS stream and valley sedimentation surveys

A classic publication: Happ, Rittenhouse, & Dobson (1940)

SCS personnel Stafford Coleman Happ, Gordon Rittenhouse, and G. C. Dobson, authored *Some Principles of Accelerated Stream and Valley Sedimentation* (1940) which is considered one of the earliest (or perhaps the first) critical studies of these topics. Trimble (2008) succinctly reviews this publication and its major contributions to the field (as well as the impact of Happ's career) so we limit our review to the contributions that are most relevant to this study. Happ et al. (1940) examine accelerated erosion and sedimentation in the Tobitubby and Hurricane Creek watersheds of north central Mississippi through basin scale sedimentation surveys conducted between 1935 and 1937 (Happ et al., 1940). Specific goals of this research included tracking the magnitude and distribution of ELS to assess sedimentation damage to farmland and its effect on flood conditions, identifying sediment sources, studying stream deposits, and estimating future sedimentation rates. Through their observations they developed 45 principles, or statements, that were meant to serve as "practical considerations in the field of stream- and valley-sedimentation problems (Happ et al., 1940)." Many of these principles have had major impacts on our ability to accurately quantify ELS deposition and its movement through the fluvial system (Trimble, 2013).

Principles one through three form the criterion through which we can identify the contact between ELS and the original floodplain surface prior to ELS deposition, thus enabling the accurate measurement of valley aggradation due to land use change. The first principle involves the identification of a buried dark (black) and relatively structureless soil horizon overlain by a (light) brown, laminated layer of sediment (Kunsman, 1944) (**Figure 3**). Here, the former is interpreted as the top of the floodplain surface prior to European style land use and the latter as ELS (Magilligan, 1985). Their contact is then the base of ELS accumulation and, temporally, is considered the start of agriculturally accelerated sedimentation. This declaration functions on the assumption that the more natural sedimentation rates before ELS formation were slow enough to promote the development of dark, organic rich soils while also destroying preexisting structure through the soil forming process (Happ, 1944). The remaining two principles provide guidance for instances in which this dark horizon is missing or poorly developed due to local conditions. They enable identification from distinct bleaching and “hard ferruginous concretions”, and, where water table interference is expected, a distinct color transition from brown to gray (Happ et al., 1940). This criterion has been used to identify the depth of ELS deposits across the US through streambank exposures and boreholes, and, combined with well documented local histories provide firm constraints on the timing of accelerated stream and valley sedimentation (Magilligan, 1985).

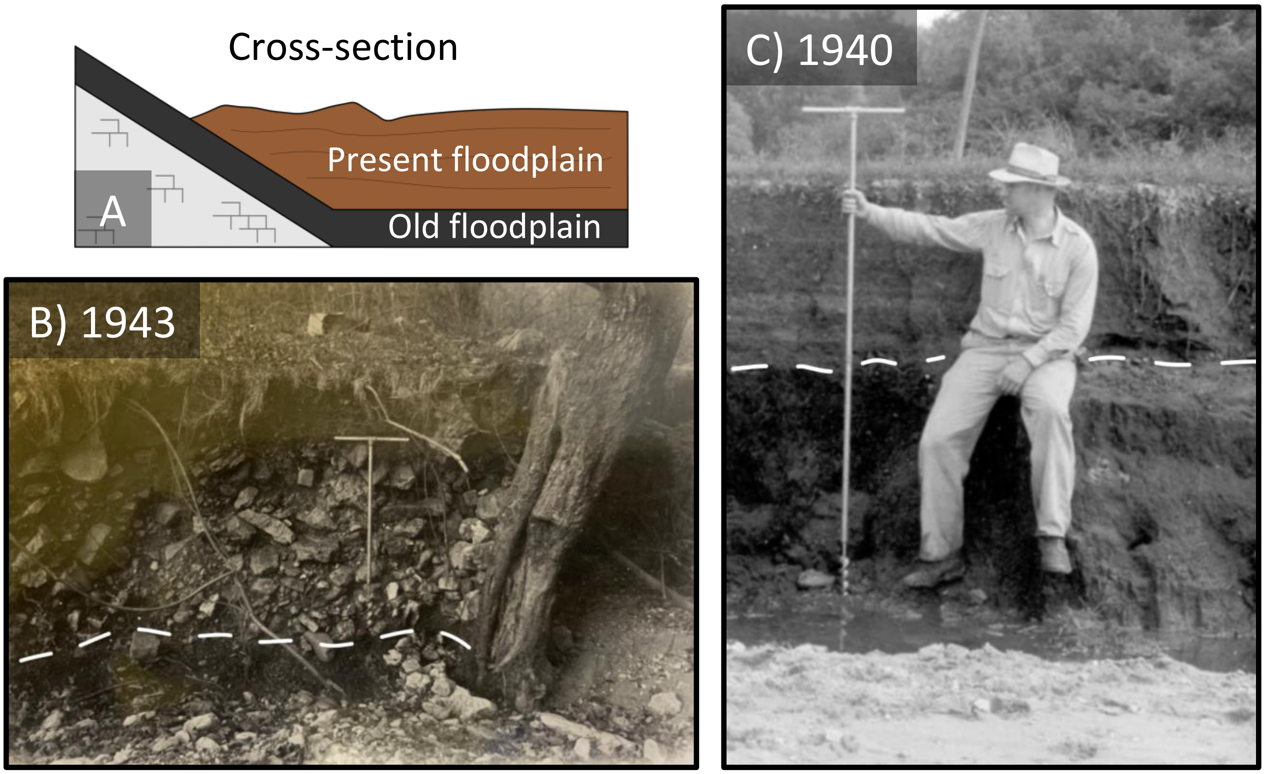


Figure 3. Measuring ELS accumulation through identification of the Pre-Euro-American agriculture floodplain surface. A. Diagram showing how ELS brown and laminated deposits bury the original black and structureless floodplain soil in cross-section. Modified from Happ et al. (1940). **B.** Bank exposure along Trout Creek in the Whitewater River watershed, Minnesota, showing a 60-year-old tree growing out of the old soil buried by about 1.5 m of gravel sized ELS. The contact is marked by the dashed line (Happ, 1943). **C.** Happ sits on a ledge of a bank exposure in an unknown tributary of the Whitewater River. Here the old soil lies buried under about 60–90 cm of ELS (Trimble, 2008).

Other contributions of note have improved our understanding of sediment routing in landscapes destabilized by agriculturally accelerated erosion and sedimentation. Happ et al. (1940) widened the pool of significant sources of sediment from sheet and rill erosion to gullying, valley trenching (the initiation of a new channel in valleys without a preexisting one), and bank erosion (Happ, 1940). Gullying was, in fact, found to be a more significant source than sheet erosion (principle 13). They also further contributed to the sediment budget idea by demonstrating the inapplicability of sediment yield as an estimate of erosion within a basin (principle 18) and instead suggested sediment storage in floodplains and other deposits as a more accurate measure of upland erosion. The temporary nature of this storage led to principle 25 which partially states, “Valley deposits will shift down valley” (Happ et al., 1940). Gilbert (1917) observed sediment “waves” pulsing through the intensively mined watersheds of the Sierra Nevada Mountains of California post-gold rush. Accelerated sedimentation in this context was widely recognized as having a far larger impact than sedimentation from agriculture in any part of the US (Happ et al., 1940). Inspired by these findings and informed by Happ’s extensive experience in agriculturally disturbed basins (Trimble, 2008), Happ et al. (1940) surmised that these waves may still appear in the farmed landscape but at rates slower than that observed in the Sierras, potentially causing further damage down valley later (Happ et al., 1940).

Sedimentation survey sites

As head of the Stream and Valley Section of the Sedimentation Division of the Office of Research (Happ, 1944), Happ simultaneously oversaw multiple projects comparable in scope and design to the sedimentation survey of the Tobitubby and Hurricane Creek watersheds (Happ et al., 1940). Happ (1975) highlights these efforts and describes the sedimentation surveys of sixteen watersheds around the country (**Figure 4**). Of these sixteen studies, five were clustered in the bluff country of the Upper Mississippi River Valley: the Whitewater River in Minnesota; Coon Creek, Beaver Creek, and the Kickapoo River in Wisconsin; and the Galena River straddling the border of Wisconsin and Illinois.

General survey methods

In all cases, the primary effort of a sedimentation survey was to determine the magnitude and distribution of ELS throughout the river corridor along up to a few dozen survey line transects, called ranges (Svien, 2012). These lines were then surveyed to construct profiles of the

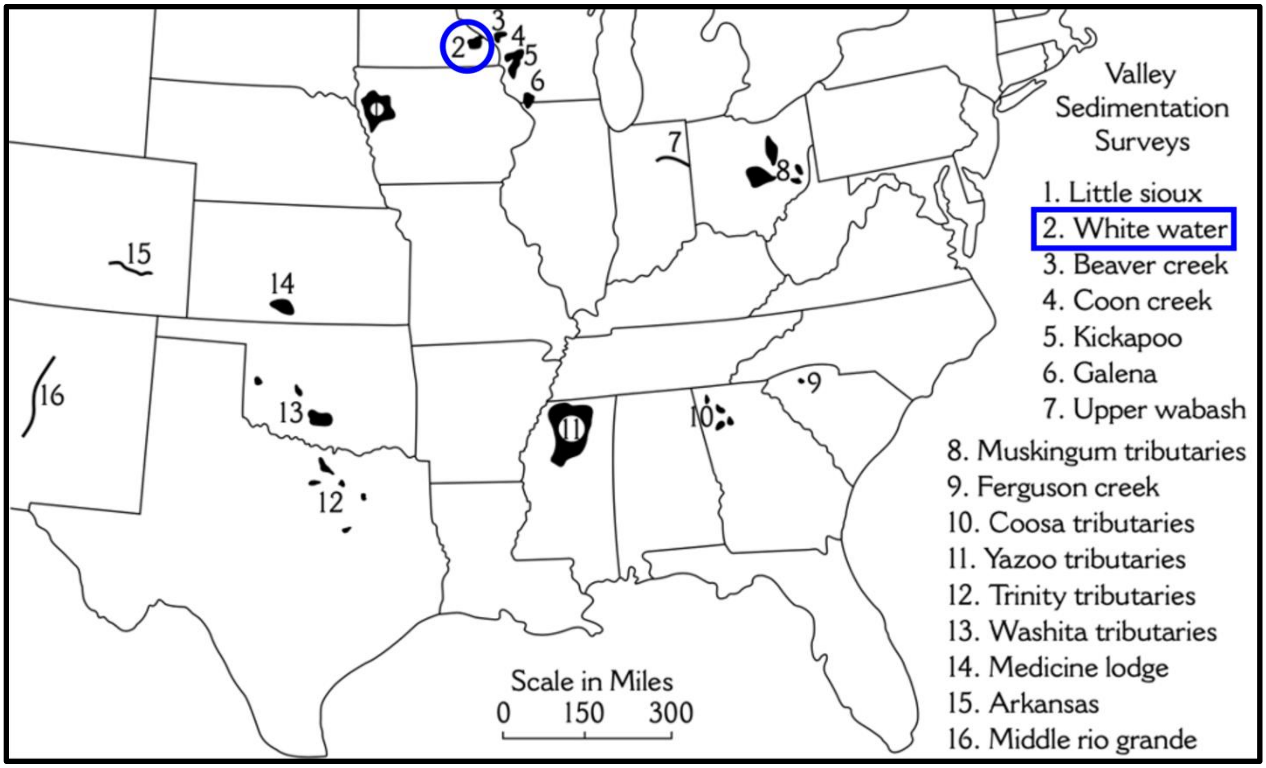


Figure 4. SCS stream and valley sedimentation survey project sites directed by Happ. These 16 projects were all established and initially surveyed between 1935 and 1941. The location of the Whitewater watershed is circled for reference. Note the concentration of sites in the Upper Mississippi River Valley. Modified from Happ (1975).

pre- and post-Euro-American floodplain surface, from which the thickness and volume of ELS could be calculated. In this context, surveying refers to the science of accurately measuring elevations on the surface of the earth (Brinker & Wolf, 1984). The full breadth of survey activities from field reconnaissance to data analysis is described in detail by Happ (1939)—*Instructions for Stream and Valley Sedimentation Surveys*—but we limit our discussion to information pertaining to the survey transects alone since this thesis will solely focus on their survey data.

Survey range location, extent, and spacing are designed to maximize the distinguishability of ELS from the old soil. They are aligned sub-orthogonally to the main valley axis where ELS was present and extended in a straight line between valley margins (Happ, 1939). Those valley margins were typically the toes of the bounding hillslopes but could include those of terraces or a combination of the two (**Figure 5**). Ranges were also established about every 1.6 km downvalley, though local deviations occur to ensure suitable ELS coverage (Svien, 2012). Suitable coverage, in this case, means that ELS is present in measurable quantities and that the contact with the older horizon is distinguishable.

Many, or all, transects for an individual basin were marked with permanent structures in the form of survey benchmarks—here called monuments—which made ranges tangible landscape features. Monuments were typically located near, or exactly at, a range's endpoint and consisted of iron pipes encased in concrete and stamped with their name. Sometimes a benchmark was placed upslope of, or beyond, the floodplain to reach a suitably stable place for establishment and in these instances, they may not even be on the actual line surveyed. Position and orientation metadata for the ranges and their benchmarks were meticulously documented—even mapped onto aerial photos—to aid future recovery (Happ, 1939).

Once established, range lines were first sampled for the thickness of floodplain ELS via a soil boring survey (Kunsman, 1944). At least four test borings were collected per range with extensible soil augers—Iwan (sheath) or screw type (Happ, 1939). Their number and spacing were controlled by the length of the range but primarily the regularity of ELS thickness and the ability to identify the contact of incipient accelerated sedimentation (Happ et al., 1940). In the Whitewater River watershed boring spacings primarily vary between about 7 to 30 m but can have less or greater spacing depending on local conditions. Borehole offset, or the distance down range, was measured by chaining, graduated tape, and pacing (Happ 1975). Soil samples were

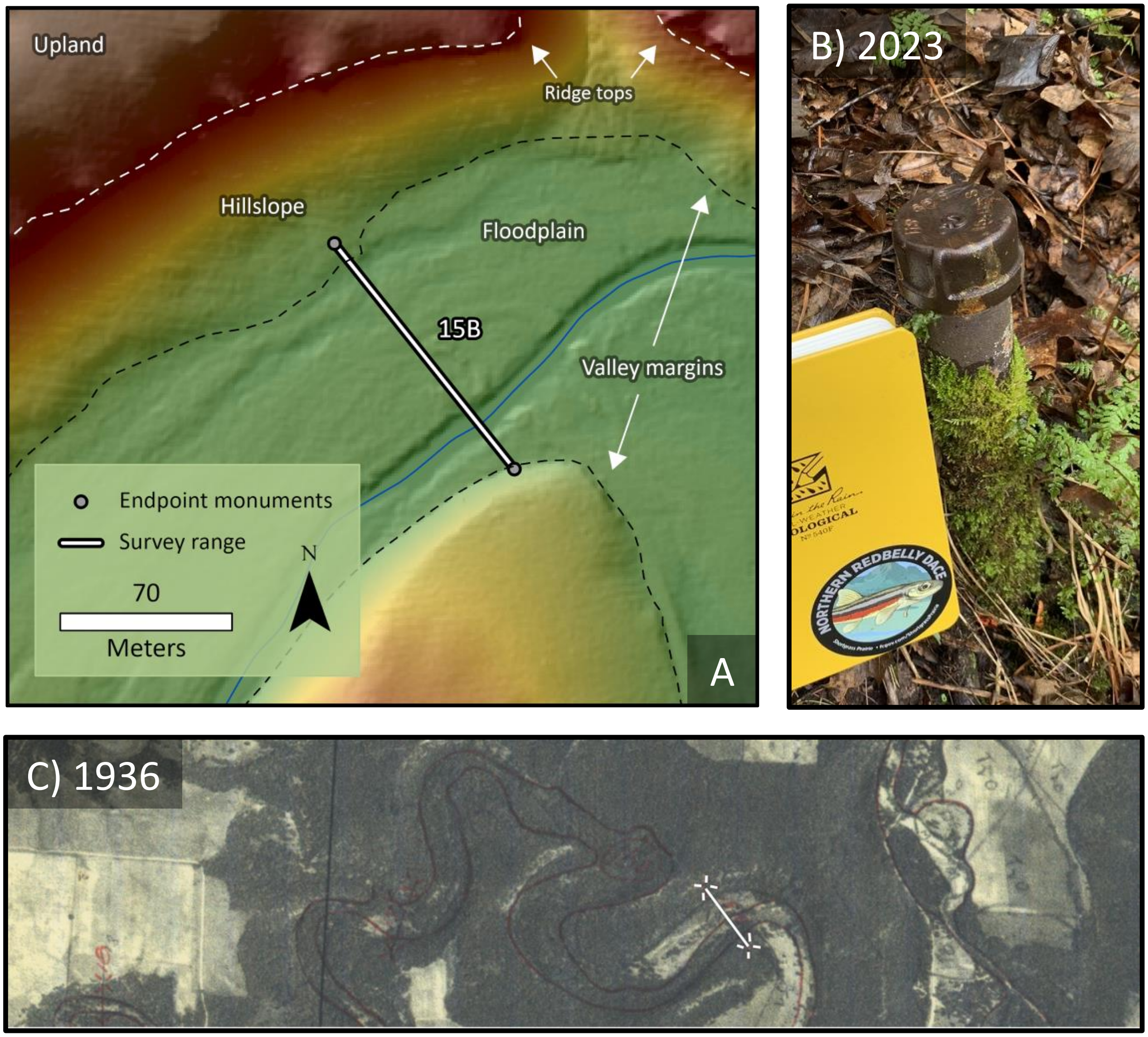


Figure 5. Example of a survey transect (range) in the Middle Fork of the Whitewater River Watershed. A. Map of Middle Fork 15B. The range line is approximately orthogonal to the longest valley axis and ends near the valley margins. Monuments are emplaced to mark the line and enable future recovery. **B.** Monument Middle Fork 15B-S marking the southern end of the range. The pipe is stamped "SCS 15-B-S" denoting the agency responsible for its establishment, range name, and monument identifier. Note how even up close the pipe blends into its surroundings. **C.** Aerial photo from 1936 of Middle Fork 15B. The valley of the Middle Fork as well as the ranges were annotated by an SCS surveyor. Note markings for Middle Fork 18 at the far left side of the photo.

incrementally extracted with the auger and characterized until the old soil horizon (original floodplain surface) was identified and the depth of fill was recorded (Happ, 1939).

Following the auger borings, a surface profile was collected on the transect through plane surveying (Brinker & Wolf, 1984). In the direction of the original survey, elevations were sampled with optical surveying equipment—such as a spirit level and sighting scope—about every 6 m or at an offset interval stratified by relative changes in ground surface slope. Through this scheme, points on the floodplain with relatively little lateral variation in elevation could be farther apart than points near or within the stream channel, where one might expect great differences between the elevation of the thalweg and tops of banks. Measurements were also taken over every borehole for later comparison to the previously collected dataset (Happ, 1939). Where local vertical control was available, elevations were tied to a geodetic vertical datum through survey leveling procedures (Brinker & Wolf, 1984). For these early surveys, they mostly tied monument elevations to the National Geodetic Vertical Datum of 1929 (NGVD 29) which was the current standard datum (Zenk, 2007). Elsewhere, where vertical control was not available, elevations were left in a local datum relative to the arbitrary height of a range benchmark or other survey reference point.

A second surface profile of the Pre-Euro-American floodplain configuration was extrapolated from the present floodplain surface through the borehole data. Data points with coincident offset positions from both surveys were identified and new points were generated by subtracting the depth of ELS fill from the present elevation. Plotted in tandem, these surface profiles form floodplain cross-sections that yield direct estimates of accelerated stream and valley sedimentation through planimeter (Happ, 1939).

Resurveys

Surveyors permanently emplaced survey benchmarks in the landscape to enable range recovery and future resurveys at these 16 SCS sites to measure changes in sedimentation through time. To avoid confusion in the following description of resurvey efforts, we will use a parenthetical data range to indicate the dates of a project's first survey. Of the 90 transects established in the Middle Rio Grande, New Mexico (1936–1937), only 47 were resurveyed in 1941–1942 (Happ, 1948). Twelve ranges underneath railroad bridges were resurveyed in the Kickapoo River in 1939 despite there being 63 total and form another partial resurvey (Happ, 1944). Unfortunately, World War II disrupted continued work and shifted SCS priorities toward phasing out stream and valley fieldwork (Heynen, 1981); few of these planned, large-scale resurveys would be realized.

Throughout the rest of the 20th century, other resurveys were completed but through other government agencies or individual scientists. Cross-sections in the Whitewater River (1939–1941) and about half of the Yazoo-Tallahatchie tributaries in Mississippi (mid-1930s), were resurveyed in 1964–1968 and 1965–1969 (Happ, 1970, 1975), respectively. The former involved a complete resampling of 94 ranges (Svien, 2012), though it is unclear how many lines exist in the latter system; 53 were known to be established in the Tobitubby and Hurricane Creek Watersheds (1935–1937) and 4 in the North Tippah Creek (1939). All transects in the North Tippah Creek were resurveyed in 1969 (Happ, 1970). A resurvey of Coon Creek's 120 ranges (1938) took place in 1974–1979 (Trimble, 2013) in support of academic research rather than a government project. Similarly, Frank Magilligan resampled 23 of the Galena River's near 70 ranges (1939) in 1979 (Magilligan, 1985).

That we know of, Coon Creek and the Whitewater are the only project sites that have experienced more than two surveys. Coon Creek saw a limited resurvey in 1982 and another on 82 ranges in 1991–1995 (Trimble, 2009). The Whitewater mirrors this, with a limited resurvey in 1975, another in 1978, and a complete resurvey of all 94 transects in 1993–1995 (Svien, 2012). Without evidence to the contrary, it's possible that only these 6 of 16 sites have experienced any transect resurveys yielding relatively small spatial and temporal sedimentation data coverage.

Data (un)availability

Despite the lack of resurveys, these stream and valley sedimentation studies are still exceptional in scope, though most seem to solely exist in obscure, unpublished media such as internal agency reports authored by Happ or, in some cases, master's theses supervised by him. Referencing the scale and comprehensiveness of this work, Happ (1975) declares that "Most of the pertinent information on valley sedimentation and related valley erosion is limited to results of investigations by the Soil Conservation Service during 1935–1941". Today, most of that raw data and its revelations remain largely inaccessible and do nothing to promote the advancement of topics in fluvial geomorphology, sediment transport, and their relationship to land use. Trimble's prolific work on sedimentation in the Coon Creek watershed—described in Science (1999) as "the most comprehensive study of its kind in the world,"—is a prime example of the sheer impact access to this data can have on the science. Happ (1975) provides hints to the collective whereabouts of the sedimentation survey data:

> The records of most of the sediment surveys are in the Cartographic Division of the National Archives or in Soil Conservation Service files, but efforts have failed to locate the Yazoo and Kickapoo data, which were left in Forest Service custody.

This would generally be confirmed by Heynen (1981) in their inventory of said cartographic records. By then, field notebooks were accounted for all but Ferguson Creek, South Carolina; the Coosa tributaries, Georgia; the Washita tributaries, Oklahoma; and the Medicine Lodge River, Kansas. Most of these notebooks are also said to accompanied by various maps and plotted cross sections (Heynen, 1981). Given that about a little over four decades has passed since that writing, it's a question whether some of these records even exist anymore.

Research focus

Here, we use and augment the SCS sedimentation survey dataset of the Whitewater River Watershed in southeast Minnesota to address the above limitations regarding present data availability and to investigate spatio-temporal patterns of sedimentation in the basin. Besides Coon Creek, the Whitewater watershed is likely to be the only multi-surveyed basin of the SCS's stream and valley sedimentation survey sites. Each of its ranges have been field surveyed 3 to 6 times yielding datasets representing the 1850s, 1939–1941, 1964–1968, 1975, 1978, and 1993–1995, with high measurement fidelity. This field component alone easily rivals that of Coon Creek's dataset though it has never been significantly studied nor studied in its entirety. Building off Svien (2012), we have further augmented this set through the construction of cross-sections collected from elevation products derived from aerial lidar obtained in 2008, yielding an unprecedented window into sedimentation over 150–160 years at temporal resolutions of 3–84 years. With this sedimentation survey data, we ask:

> How have transect sedimentation rates in the Whitewater River Watershed changed post-1939 since the widespread implementation of soil conservation practices in the region?

Background

The physical landscape

Within the Whitewater watershed, the branches and major tributaries of the Whitewater River flow through distinctly changing topography in southeast Minnesota's scenic bluff country (Svien, 2012; **Figure 6**). The Whitewater's three forks, the Middle, North, and South, emerge from a low relief, subtly rolling upland plain and meander across its wide openness punctuated

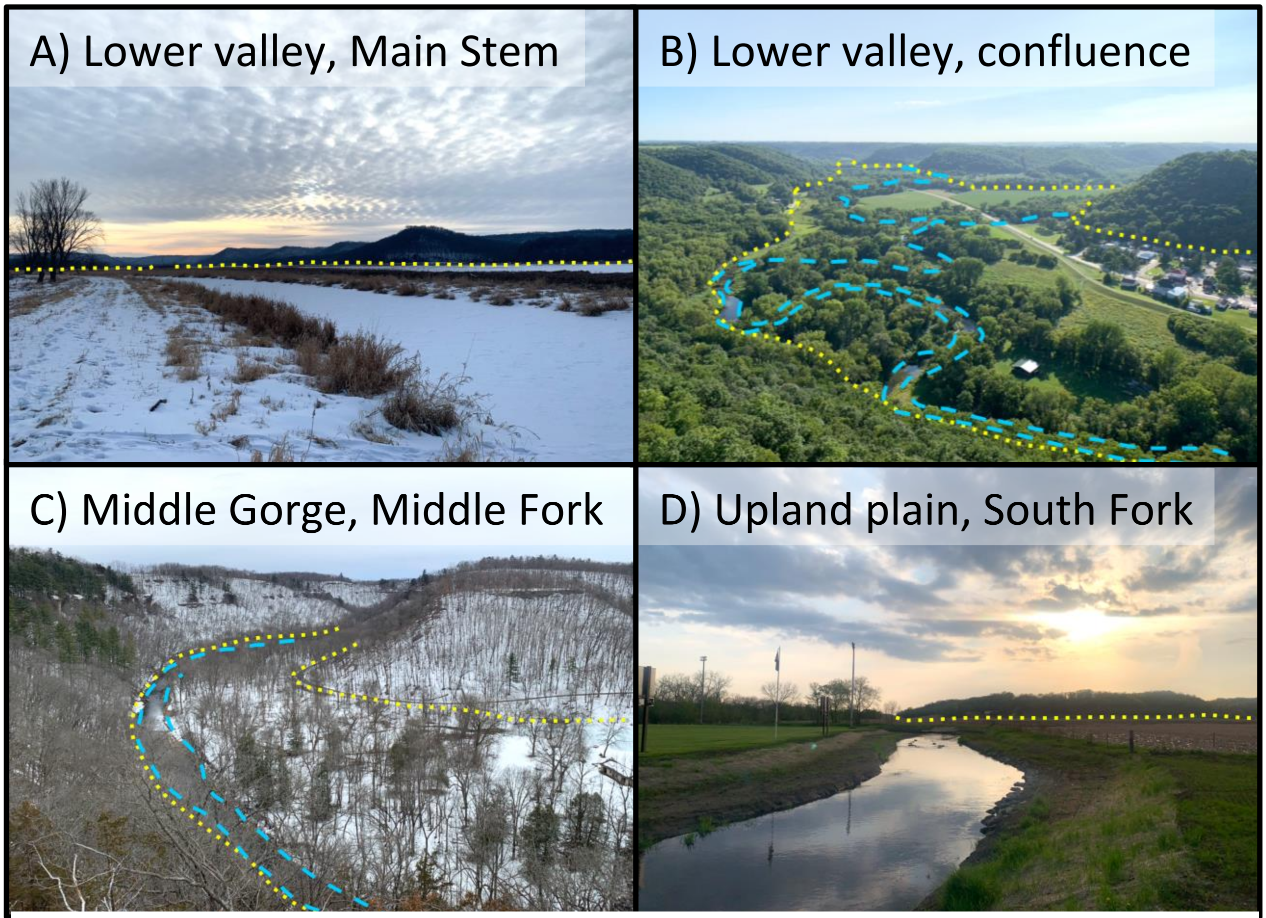


Figure 6. Changing topography along the Whitewater River. Annotations outline the valley margins with a dotted line and, where applicable, the river with a dashed one. **A.** View (SW) near range Middle Fork 2 adjacent to the Dorer pools of the lower valley of the Main Stem. The floodplain is very wide here and the bluffs tall (Feb. 2022). **B.** View (W-SW) from ridge top up the Elba fire tower of the lower valley confluence of the Middle and North Forks. The valley has narrowed and the rivers meander. Some farm fields can be seen towards the background (Aug. 2021). **C.** View (SW) from Chimney Rock in Whitewater State Park up the middle gorge of the Middle Fork. The valley narrows further, and the river ceases its meander to be pinned by bedrock on one side (Mar. 2023). **D.** View (W) from walkway at St. Charles City Park of the uplands on the South Fork. The valley widens again, and the river resumes its meander. Note how land use has changed. There river channel is adjacent to a baseball field on one side and a farm field on the other (May 2023).

by carbonate bedrock ridges. The middle reaches of each branch transitions into a toiling carve as they steeply drop through narrower gorges of dolostone. About 150–180 m below the upland surface the river branches level out, resuming their slow meander, and successively converge to form the Main Stem of the Whitewater River flanked by terraces, alluvial fans, and sentinel

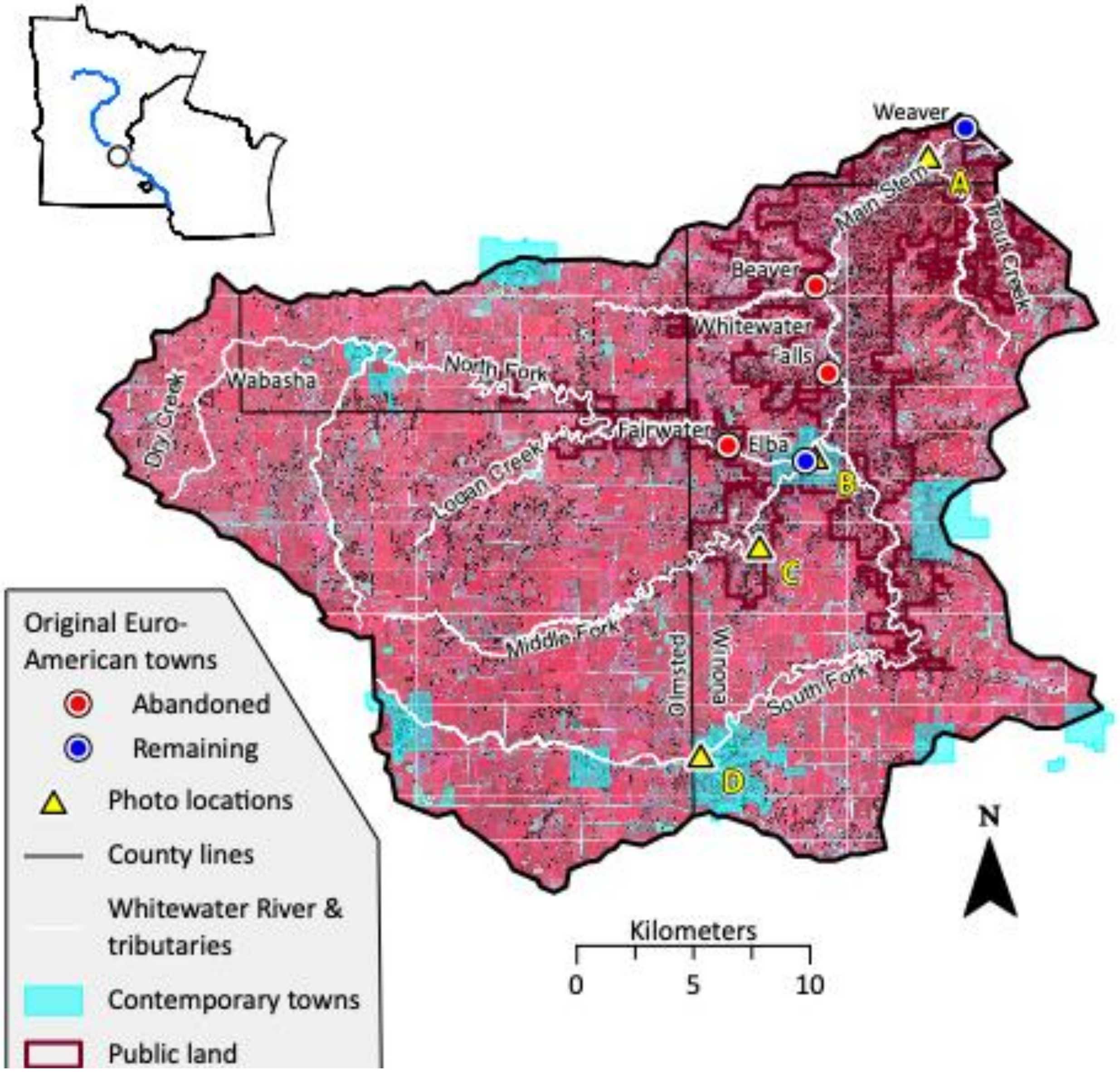


Figure 7. Geography of the Whitewater River Watershed. Inset map shows the location of the Whitewater watershed in reference to greater Minnesota, Minneapolis (circle), and the Mississippi River. Basin Map details the course of the forks and major tributaries of the Whitewater River and the location of historic and contemporary towns. Land use changes from dominantly agricultural on the upland surface in the southwestern part of the basin and gives way to forest and forest-grassland in the middle and lower valleys of the northeastern part of the basin. The boundaries between private and public land generally coincides with this transition from farm to forest. Photo locations refer to **Figure 6**.

bluffs (Johnson, 1957). Four major tributaries pour into these rivers, Dry and Logan Creeks in the North Fork basin, and Beaver and Trout Creeks in that of the Main Stem (**Figure 7**). Underlying geology and glacial processes during the last Ice Age have shaped the scenic topography of the Whitewater River Valley (Johnson, 1957). During the early Paleozoic (545–530 Ma), oceans deposited the package of sub-horizontal carbonates, sandstones, and shales that characterize local bedrock (Runkel, 1996)—dolostone dominates the stratigraphy (Brown & Nygard, 1941) (**Figure 8**). Eras later in the late Quaternary (2.5–0.8 Ma) deep incision of the upper Mississippi River lowered the base level of its tributaries and the Whitewater River dissected its bedrock (Wickert et al., 2019). Today, near vertical bluffs in the wide lower valley and narrow middle gorges hint at this history (Runkel, 1996), exposing layers of Oneota Dolostone over Jordan Sandstone at their base (Johnson, 1976). It's worth mentioning that this part of the state remained ice free during the latest Wisconsin episode of glaciation and consequently lacks the surficial glacial deposits that blanket most of Minnesota (Runkel, 1996);

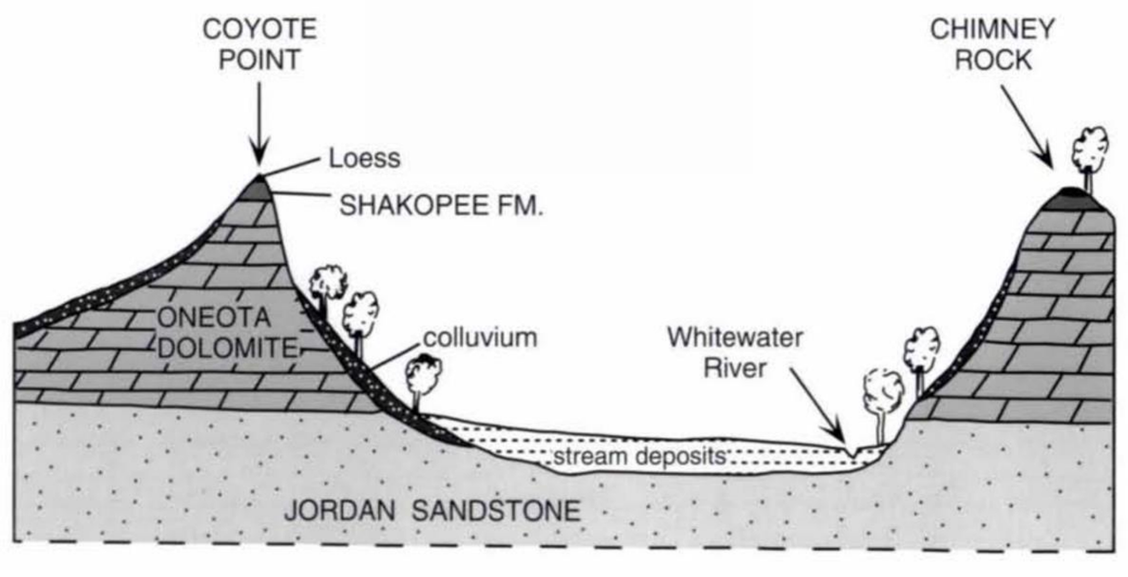


Figure 8. Geology of the lower Whitewater River Valley. Cross-section through Whitewater State Park from Coyote Point to Chimney Rock. Jordan Sandstone forms the valley bottom in the lower reaches of the Whitewater River and tributaries and promotes valley widening through lateral incision into the valley walls that undermines the strength of the dolostone above. Upstream in the middle gorges the streams are instead pinned against the more resistant dolostone, and which yields narrower valleys as they lack the power to erode them **(**Runkel, 1996**)**.

however, this area is not a part of the “Driftless” area since sparse evidence of ancient glaciers exist from older events, even limited quantities in the Whitewater River drainage basin (Faulkner, 2015).

The watershed’s topographic transitions are mirrored by its vegetative assemblage. Land surveyors mapping southeastern Minnesota in the early to mid-1850s generally described the location of the Whitewater it as coinciding with the east-west transition from hardwood forest to open prairie. In the Whitewater, the former covered the lower valley and slopes of the middle gorges while the latter primarily proliferated on the upland surface (Johnson, 1957). Today, farm fields and pasture occupy the prairie lands, having long been cleared and converted to promote food production (Nerbonne & Vondracek, 2001). The valley bottom forests have largely been replaced by herbaceous material (lacking woody parts) such as invasive reed canarygrass and willow. The lower valley of the basin has also been largely converted to public land following land abandonment due to sedimentation problems in the early to mid-20th century and now consists of state park, wildlife management area, and state forest land (Svien, 2012). The resulting conglomeration of public lands are a haven for fishing, hunting, camping, hiking, bird watching, and more outdoor recreation activities (Holger, 2019).

The human landscape

The lands comprising Minnesota had been inhabited for thousands of years prior to the arrival of Euro-American migrants. Most recently, southeastern Minnesota was home to the Dakota who were forcibly displaced to reservations along the Minnesota River through the Treaty of Traverse des Sioux of 1851. Their legacy is most visible in local place names such as Minneiska, a town situated near the mouth of the Whitewater River, which translates to “white, water”. This is also the source of the name of the river itself and describes its traditional annual transformation to milky white, as spring snowmelt eroded light-colored clays along the riverbank and incorporated them into its swollen flow (Holger, 2019).

Post-treaty, the turning cogs of US bureaucracy worked to repopulate this land with Euro-Americans. A land survey of southeastern Minnesota was organized in 1853 and the area was mapped to delineate parcel boundaries for eventual sale (Johnson, 1957). Starting on May 22, 1855 (Johnson, 1976), white Americans from New England and the Midwest and white Europeans from Germany and Luxemburg registered 102 claims for land in the Whitewater River valley. Records indicate that individual eagerness outpaced governmental process as non-indigenous people lived in the valley even before its initial survey (Johnson, 1957); Beaver, Minnesota—a whole town—was even established by 1854, before any land could be bought (Holger, 2019). It is also possible that those of African descent, including enslaved peoples, made the Whitewater watershed home given that many are recorded to have dispersed throughout southeastern Minnesota during this time (S. Holger, personal communication, February 16, 2023; Vang, 2022).

The Whitewater River valley’s ample natural resources made it an attractive place to live (**Figure 9**). Springs and sparkling creeks provided widespread access to fresh water and fertile soils were primed for food production. Fish, game, and timber were also all nearby and in abundance for harvesting (Johnson, 1957). In 1955, Alex Siebenaler—former resident—relaying accounts of his parents described this Whitewater area as “Just a little short of paradise” on account of these conditions (Trimble, 2013). By 1890, about a hundred farms and five villages were established in the middle and lower valleys of the watershed—plenty of farmsteads also covered the uplands. Travelling upstream from the Whitewater's outlet these towns were Weaver, Beaver, Whitewater Falls, Elba, and Fairwater (Holger, 2019).

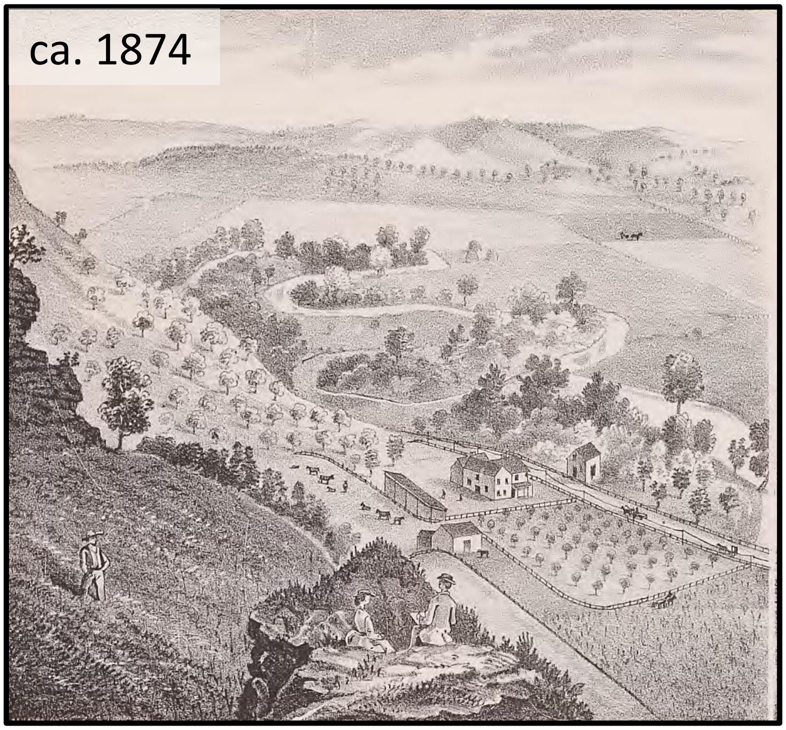


Figure 9. "Birds eye view" illustration of farm and residence of H. B. Knowles, just NE of Beaver, MN, in Whitewater township, ca. 1874. The Main Stem of the Whitewater River flows through the fore- and mid-ground (Andreas, 1874).

Throughout the latter half of the 19th century, most of the watershed's land surface was converted to support food production (Nerbonne & Vondracek, 2001). As expected, as soon as farmers were able, they cleared the natural vegetation with hand tools wherever seed could be reasonably sown: flat uplands, terraces, and valley bottoms (Johnson, 1976). Wheat dominated the economy (soon followed by corn) and was supported by mill dams on individual farms and in towns. Harvests were so abundant to label the encompassing counties—Olmsted, Wabasha, and Winona—major production areas (Johnson, 1957). Any land unsuitable for crops such as the steep, forested hillsides were similarly cleared of timber and left bare to be grazed by livestock

(Svien, 2012)—mostly cattle for beef, then dairy by the turn of the century (Brown & Nygard, 1941).

Erosion, sedimentation, floods

As Euro-Americans and their land use practices spread throughout the Whitewater River Valley, geomorphic systems destabilized and accelerated erosional processes. Individual generations of landowners observed the topsoil, subsoil, and regolith beneath wash away from their fields (Johnson, 1957). By the 1890s–1900s, this affected most of the farms in the valley (Holger, 2019). Sheetwash actively eroded these lands, but gullying was especially prevalent on upland ridges and hillslopes. Gullies actively destroyed land as they increased in size and retreated headward, and effectively eliminated acreage with farming or grazing potential. By the 1930s–1940s, thousands of gullies large enough to justify the construction of erosion mitigation structures gouged out the valley walls and bluff rims (Trimble, 2013).

Gully erosion accelerated downslope sedimentation and formed alluvial fans that buried the valley bottom with gravel–boulder or sand sized particles depending on the location of their source gully. Over 200 grew large enough to be mapped on aerial photos in 1939. The largest fan recorded covered over 26 ha and one even laterally displaced a 0.8 km reach of the Main Stem by about 240 m. Accelerated sedimentation by alluvial fan formation made life more difficult as buried fields yielded waning harvests and buried roads became impassable.

Valley-bottom sedimentation caused streambed aggradation and, by reducing conveyance capacity, increased flood frequency (Trimble, 2013). According to early migrants, around 1854 the Whitewater River only ever experienced overbank floods during spring snowmelt and significant rainfall with water clarity relatively intact. About four to five decades later, much smaller hydrologic inputs raised the river to flood stage which would flow as a muddy slurry. By the 1920s, flooding became routine with farmsteads inundated up to 20 times per year. Beaver, (un)favorably situated at the confluence of the Main Stem and Beaver Creek, flooded 28 times in 1938 alone (Holger, 2019). This exacerbated every problem previously incurred by erosion and sedimentation with added damage due to the floodwaters themselves. Fields and pasture drowned and eventually converted to swampland as frequent floods raised the water table. This, in turn, promoted the increasingly intensive use of a decreasing portion of arable land. Flooding routinely washed away roads, bridges, mill dams, and fences, causing significant damage to infrastructure and private property. Lastly, receding floodwaters left behind thick blankets of alluvium, filling several buildings up to their second floors (Trimble, 2013).

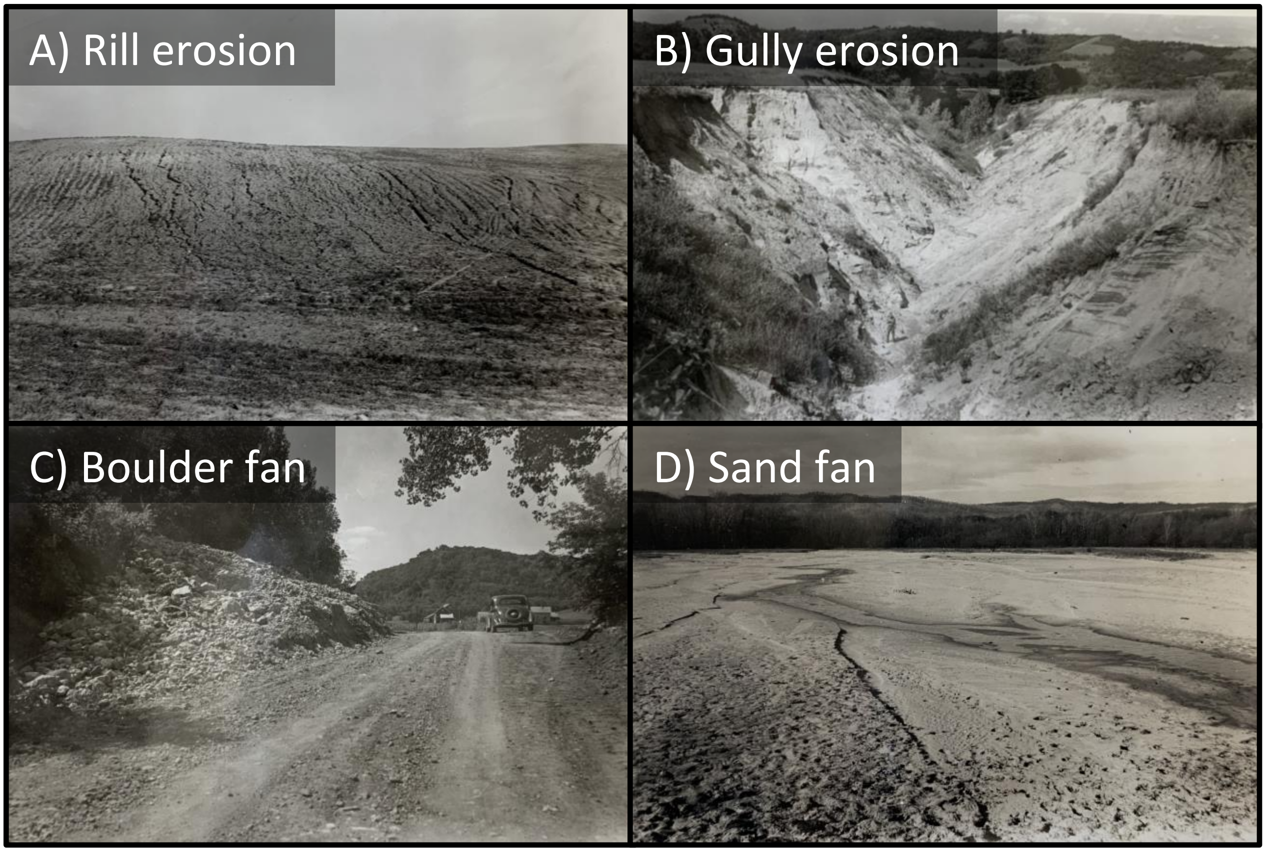


Figure 10. Accelerated erosion and sedimentation. A: Rill erosion carves field, 5–20 cm (2–8 in) deep, in Wabasha or Dakota Co, MN. **B:** View down “big gully” about 3.2 km (2 mi) SW of Weaver. Note man standing in center foreground at gully base.

C: Boulder fan overtakes hwy W of Beaver. **D:** 10 ha (25 ac) sand fan buries a floodplain in Buffalo River Valley, WI (All photos by Happ from 1942).

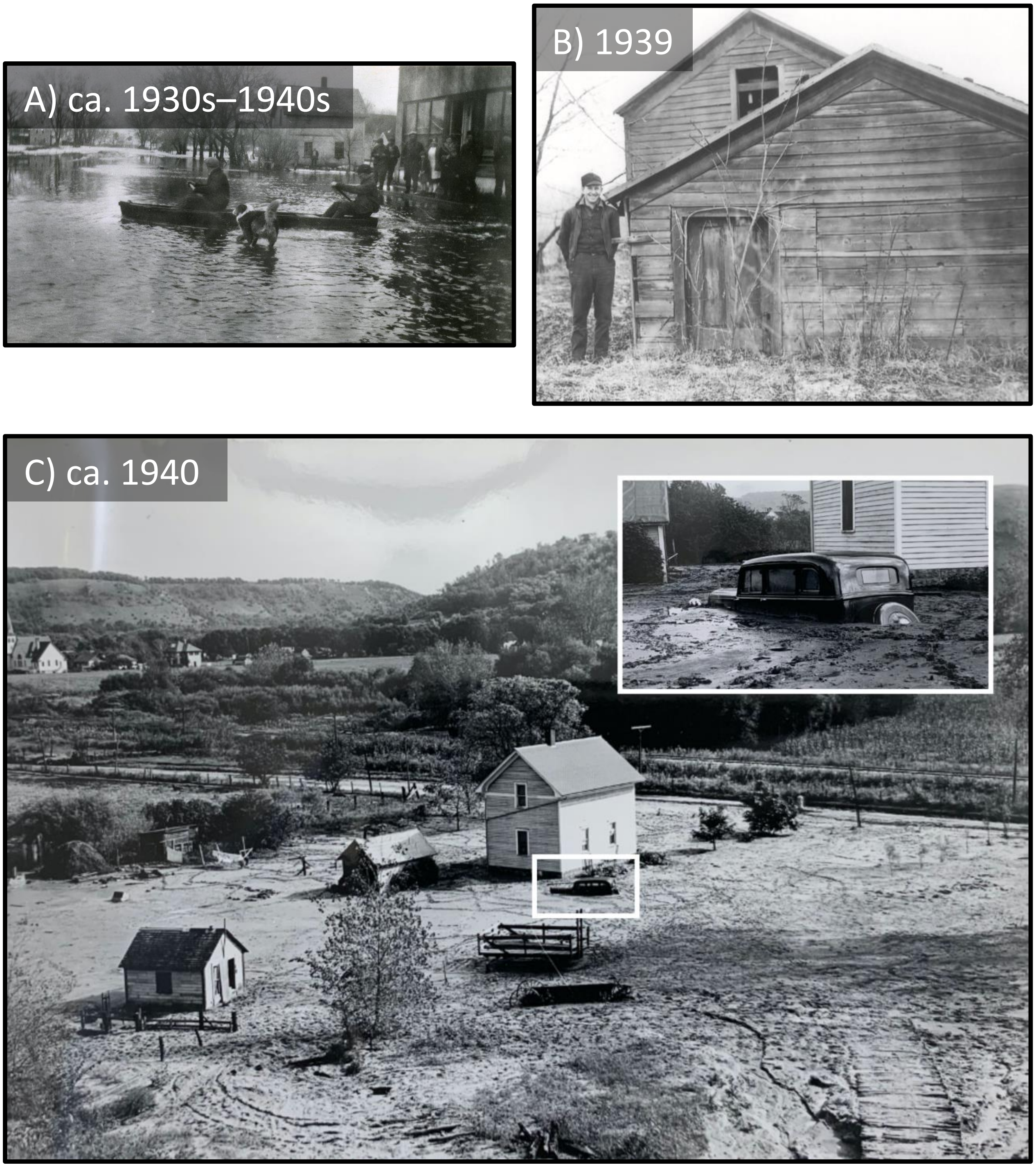


Figure 11. Flooding damage. A. Residents of Beaver, Minnesota canoe through their inundated town (Winona County Historical Society). **B.** A partially buried house in Beaver (Trimble, 2013). **C.** Buried farmstead. The inset details the sheer amount of mud deposited on the floodplain relative to the perceived height of the car roof (University of Wisconsin La Crosse Murphy Library).

The effects of this multi-part environmental devastation reverberated throughout the Whitewater River valley. Beaver is now marsh land. Whitewater Falls—in decline by 1888—disappeared, any trace of the village and rapids of its namesake buried under ELS. Elba, originally on high ground roughly 3 m above the floodplain now requires a levee for flood protection. Fairwater was devastated as the North Fork widened 2–3 times its original size, consuming farmland and destroying both bridges in town (Trimble, 2013). Weaver, situated on a terrace at the mouth of the Whitewater River, seems to have escaped this geomorphic upheaval relatively unscathed; though it was partially inundated by formation of Pool 5 when Lock and Dam No. 5 downstream on the Mississippi was completed in 1935 (US Army Corps of Engineers, n.d.). Elba, Weaver, a few farms, and up to 4.5 m of ELS accumulation are all that remain of this history in the basin.

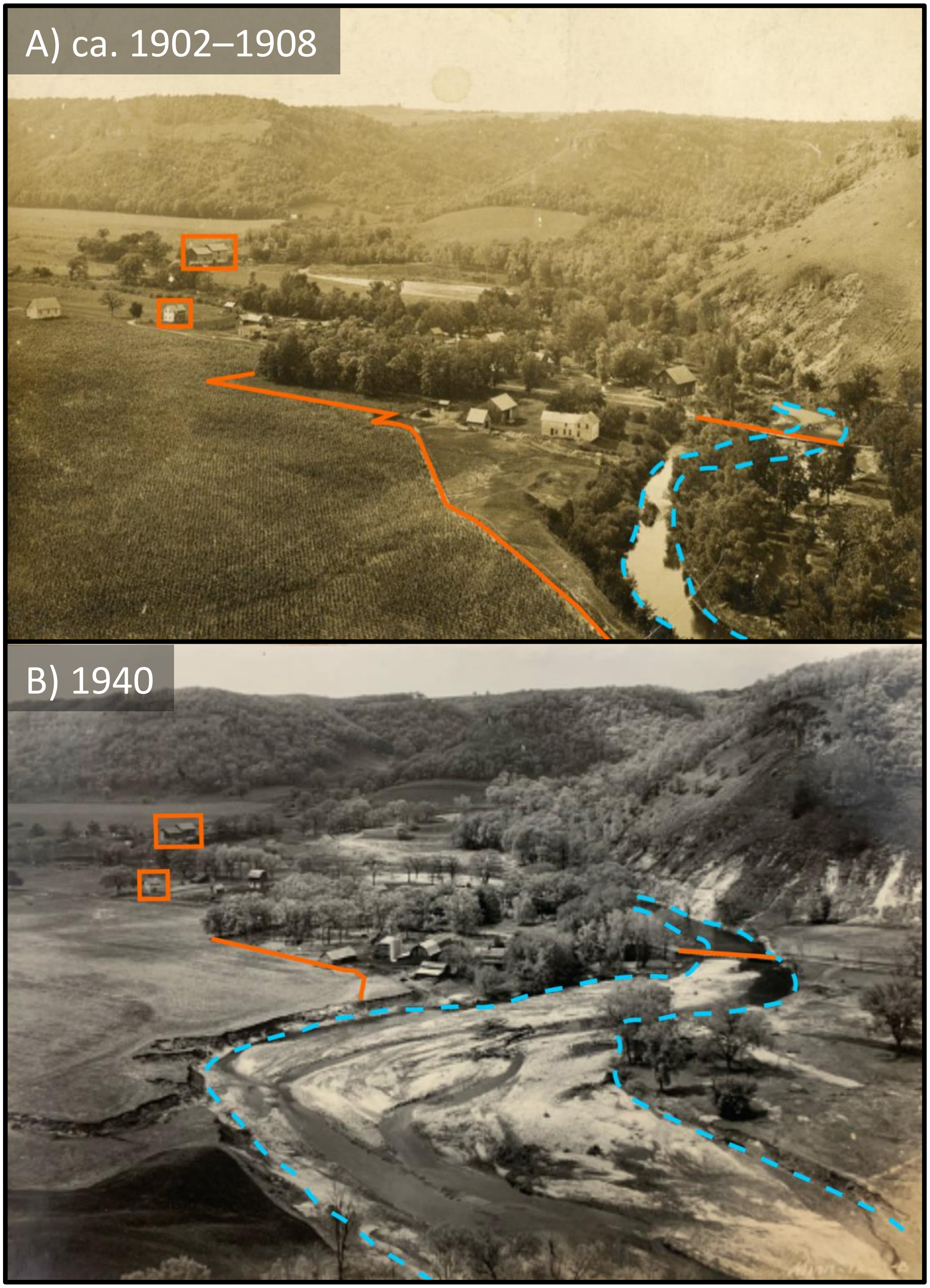


Figure 12. North Fork transformation. Solid annotations note landscape features that are shared between the photos. Dashed line marks the approximate riverbanks. Note how much wider the stream is in 1940. (University of Wisconsin La Crosse Murphy Library).

Land abandonment

Significant financial losses (and resultant tax delinquency) encouraged residents to leave the lower valley and they began converting their private holdings to public land (Johnson, 1976). In 1931, landowners partnered with the Izaak Walton League to initiate this effort. The next year, they organized the sale of a farm located at the present site of the Crystal Springs Hatchery in the lower valley of the South Fork to begin forming a game refuge (Holger, 2019). Later that decade the SCS would recommend the purchase of over 12,000 ha along the lower three forks of the Whitewater, the Main Stem, and Beaver and Trout Creeks. With agricultural productivity spent and structures left ramshackle and derelict, land acquisition proceeded rapidly up until the 1950s (Johnson, 1976). The Appleby farm about 1.2 km north of Beaver, one of the area's oldest and most prosperous, sold for only $4,400 despite its 89 ha while farms of similar caliber and size were once evaluated at about $50,000 (Trimble, 2013). By the 1960s, purchasing came to a standstill and the assemblage of public lands enjoyed today were formed. It should be noted that the effort to form Whitewater State Park on the Middle Fork beginning in 1919 was driven by the desire to preserve the area's scenic beauty for recreation and was unrelated to the erosion and sedimentation conditions (Johnson, 1976).

Sedimentation surveys

In the early 1930s, Dr. Happ followed rumors of buried roads, bridges, and farms to the bluff country of the Upper Mississippi River Valley where he would initiate a sedimentation survey of the Whitewater River Watershed between 1939 and 1941 (Trimble, 2013). All 94 survey ranges in the basin were established, documented, and bored, however, only 32 surface profiles from these ranges were surveyed in the lower valleys of the three forks and the entirety of Beaver Creek, Trout Creek, and the Main Stem. Presently, it is unknown why sampling was not continued upstream throughout the basin, though, we speculate that this may be related to agency reprioritization at the onset of WWII.

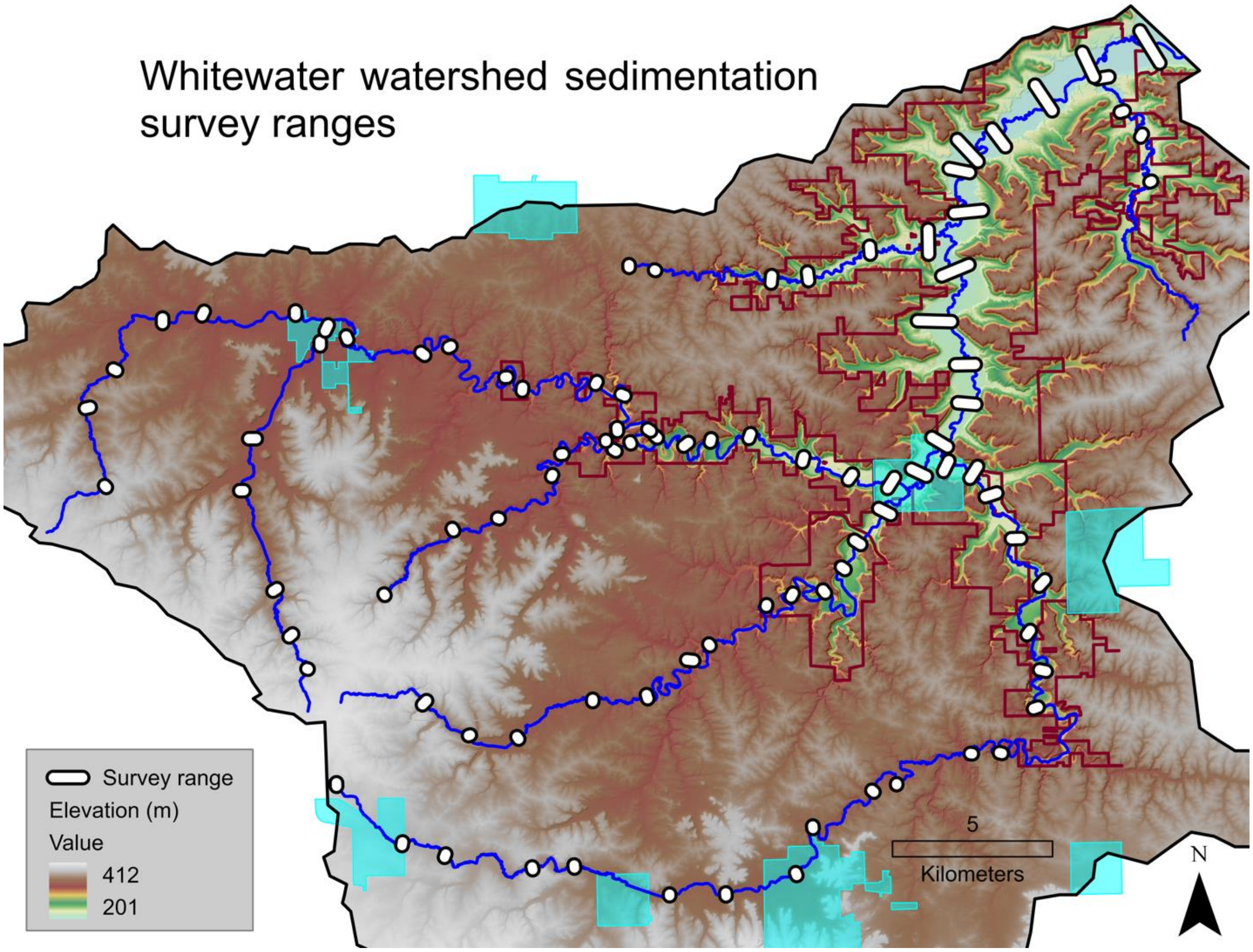


Figure 53

The United States Geological Survey funded the next large-scale survey from 1964 to 1968. Surface profile coverage was extended to all ranges towards the headwaters of the Middle, North, and South forks, including Logan and Dry Creeks. Ranges without a previous surface profile underwent a second borehole survey from 1967 to 1968 to measure the aggradation since Euro-American land use began. Some ranges had to be reestablished on the uplands where the site of previous lines was highly disturbed by construction and the activities of private farmers. Other resurvey complications arose because features previously established to help locate survey ranges such as fence lines, witness trees, endpoint markers, etc., disappeared, were destroyed, or otherwise disturbed. Often, benchmarks also had to be replaced and surveyors recorded new documentation for future locating.

Three more field surveys took place in 1975, 1978, and the 1990s. The 1970s surveys were limited to range 11B on the Main stem where SCS staff were interested to gauge the effect of recent, high profile floods on sedimentation in Elba. The Natural Resources Conservation Service (NRCS)—successor of the SCS—with the help of Winona County Soil and Water Conservation District staff, and volunteers initiated a basin wide resurvey between 1993 and 1995. They resurveyed all 94 transects with modern electronic equipment such as a total station yielding more precise measurements with quicker acquisition. This survey was also the earliest effort to record range monument locations with GPS—then, novel—to enable quicker range recovery in the future (Svien, 2012). The same complications encountered in the 1960s involving range or monument disturbance were also encountered during these surveys and likely will be for any future efforts.

Lidar flown over southeast Minnesota in 2008 is considered a fourth topographic survey. It includes all the Whitewater basin and is the last available large-scale survey dataset to date. This was commissioned in response to the large flood event of 2007 and was collected during leaf-off conditions in November of the following year. A variety of elevation data products derived from this collection such as digital elevation models (DEMs) and contour lines vector files are publicly available (Svien, 2012).

Between 2009 and 2011, Svien (2012) resurveyed range benchmarks to improve the coordinate dataset originally collected during the 1993–1995 NRCS field survey. Even without considering the nascent state of GPS at the time, the quality of the coordinates collected during the 1990s survey were fraught with inaccuracies. Dense canopy cover or whole hillsides often precluded quick measurements, leading survey personnel to wander up to about 60 m from the monument until a position was locked. Plenty of monuments were also never found and data coverage was incomplete. On top of these issues, 15 years had passed, and Svien recognized that more could have already disappeared. Range 11B is a perfect example. It took less than 11 years between 1964 and 1975 for one of its benchmarks to be lost without a trace. With a mix of handheld Garmin GPS units and GNSS equipment (Trimble R8 and GeoXT), Svien (2012) located all end points including those missed during the 90s survey, greatly augmenting the existing dataset with increased precision and coverage. Some of the points recorded by Svien (2012) are for benchmarks that were confirmed to be destroyed or missing. The approximate location of these points was identified by referencing three successive eras of monument documentation in the field notes and are believed to be within a meter of their original position. It is worth noting that many of these points lie on private property, primarily on the farmed uplands. Svien (2012) observed that many people with a survey monument on their land were uninformed as to their purpose (Svien, 2012); some, no doubt, were destroyed due to that ignorance.

Methodology

Data collection & entry

This research began with a massive data entry effort to assemble all the Whitewater River watershed's transect sedimentation survey data into a single, analyzable format. Svien (2012) provided scanned primary source material from all previous field surveys and their benchmark survey of 2009–2011. This material largely consists of copies of original field notebooks, hand drawn and printed maps, field photos, and limited correspondence. The notebooks were particularly significant because they contained the raw data of the surface-profile and auger-boring range surveys. In this archive, I found the individual survey datasets for most of the transects and identified data gaps. Data gaps occurred where field notebooks were missing pages, therefore yielding a partial dataset, or where no corresponding notebook pages could be found.

To cover these gaps, Svien pointed us to the Stanley Trimble special collection at the University of Wisconsin La Crosse's Murphy Library, where Happ SCS materials were said to be located. There I, two undergraduates, and one other graduate student, performed archival research that greatly augmented our understanding of the sedimentation survey activities performed in the Whitewater watershed. A vast set of Happ's saved correspondence going back to at least 1935 and unpublished reports stored in the archive provided especially invaluable insight. Data gaps that still existed after this endeavor were covered with tabular data printouts that served as secondary sources based off the lost field notes.

When we collected all the available sedimentation survey data, I and two undergraduate research assistants meticulously entered the data into an Excel workbook. We verified our data entry by visual check verification, which is a simple procedure involving the visual comparison of the source data and entered data.

We also sampled lidar cross-sections for the year 2008 from a 1 m digital elevation model (DEM). Our digitization procedure was inspired by Svien (2012) and involves extracting elevation values to points distributed along a survey range at spacings of about 6 m ArcGIS Pro. Lidar cross-section coverage is limited to ranges whose survey datasets have geodetic vertical control, and is, therefore, primarily limited to the lower valley of the Whitewater River.

Data preprocessing

All range survey elevation values were transformed to a consistent vertical datum to enable dataset comparison through time. The Whitewater watershed's sedimentation survey data spans decades of data collection and has thus been leveled to various vertical standards. Surveyors until the 1990s primarily utilized NGVD 29 but also used the Fourth General Adjustment of 1912 (FGA 12), an Upper Mississippi Region legacy datum (Zenk, 2007). Most data collected in the last field survey utilized the more recently adopted North American Vertical Datum of 1988 (NAVD 88); however, in some convenient cases where original range benchmarks could be found and were assumed undisturbed, surveyors once again collected data referencing NGVD 29. We transformed all elevation data to NAVD 88, because it supersedes the other systems, using the National Oceanic and Atmospheric Administration's vertical datum transformation tool, Online VDatum. The single FGA 12 dataset was first transformed to NGVD 29 by subtracting each elevation by the local adjustment of 0.148 m (Pearson & Mick, 2008) and then converted to NAVD 88 through the method above.

Mean sedimentation rate calculations

Sedimentation rates are calculated between subsequent surveys for each of the Whitewater ranges. Throughout the rest of this thesis, we will reference multi-year surveys by a single year—1939, 1964, 1994—and set the year representing the beginning of ELS formation in 1855, coinciding with the first official sale of land in the Whitewater watershed to Euro-Americans. The time between surveys, or survey periods, under investigation are listed in **Table 1**. Main Stem 11B is the only range surveyed in 1975 and 1978.

Table 1. Whitewater watershed sedimentation rate calculation intervals

Survey period	Date range	Years elapsed
1	1855–1939	86
2	1939–1964	25
3	1964–1994	30
4	1994–2008	14

Date range	Years elapsed
1964–1975	11
1975–1978	3
1978–1994	16

Rates of topographic change are calculated with a self-developed Python code. Generally, this program selects the surface profiles of subsequent survey datasets and linearly interpolates them onto the same x-coordinates to enable their comparison (**Figure 10**). At each interpolation point i, we calculate a sedimentation rate $\dot{\eta}_i$ with eq. 1 by dividing the sediment depth d_i by the years elapsed between surveys Δt.

$$\dot{\eta}_i = \frac{d_i}{\Delta t} = \frac{z_{2,i} - z_{1,i}}{t_2 - t_1} \quad (1)$$

We calculate d_i by subtracting the elevation at point i of the older surface, $z_{1,i}$, from that of the

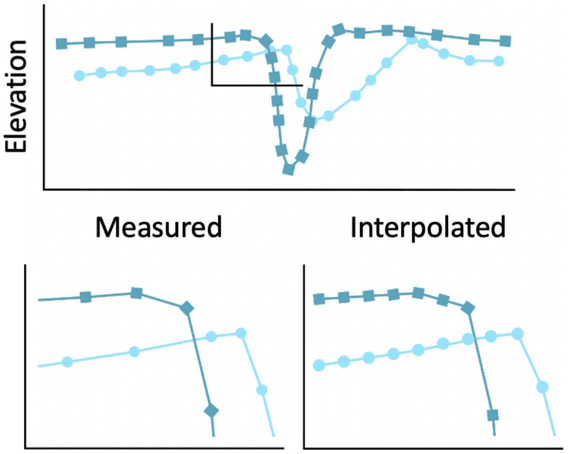


Figure 14. Surface profile comparison interpolation procedure. The data between two cross-sections are inherently incomparable when their points have different sets of x-values. Linearly interpolating the surface profiles together creates a new set of data point with the same set of x-values and enables the depth point calculations that are required for the calculation of sedimentation rates.

younger surface, $z_{2,i}$. Once this calculation is complete for all N interpolation points, we calculate $\dot{\eta}$, the mean sedimentation rate over the entire cross-section with eq. 2.

$$\dot{\eta} = \frac{1}{N}\sum_{i\to N}^{N} \dot{\eta}_{i} \quad (2)$$

This procedure was modified for discontinuous surface profiles by omitting regions that lack survey measurements. Similarly, when using the 2008 lidar cross-sections, interpolation points that coincide with wetlands along ranges in the lower valley of the Whitewater River were omitted from sedimentation calculations because the data does not penetrate the water column.

Where surface profile datasets were not available, we calculated mean sedimentation rates from borehole datasets alone. This occurs on the uplands and middle valley where a 1939 surface profile was not surveyed and where an 1855 surface profile could not be reasonably extrapolated from the data. For the first time interval between 1855 to 1939, we calculated mean sedimentation rates directly from ELS fill depths measured during the first survey. For the next interval the mean fill depths of the temporally overlapping auger borings collected in 1939 and 1964 were differenced to calculate the rate.

Statistical comparison

Mean transect sedimentation rates were grouped by time interval into sample groups for statistical analyses to determine if sedimentation rate change over time is statistically significant. The most common hypothesis tests for sample comparisons of this type are some rendition of one-way Analysis of Variance (ANOVA). To decide whether to use a parametric or nonparametric approach, we assessed the compatibility of our sample groups with the ANOVA test's underlying assumptions of normality and homoscedasticity (equal variance) (Ståhle &

Wold, 1989). We gauged normality both graphically with Q-Q plots and numerically with the Shapiro-Wilk and Kolmogorov-Smirnov tests for group sizes of less than and greater than 50, respectively (Ghasemi & Zahediasl, 2012). Homoscedasticity was determined with Levene's test (Celik, 2020). All statistical tests are carried out at the most common level of significance (α) of 0.05 [63p]. The results of these tests pointed towards the use of the parametric Welch's ANOVA to test the hypotheses:

Null (H_0): Mean sedimentation rates between survey intervals are the same.

Alternate (H_1): Mean sedimentation rates between survey intervals are not the same.

Following a rejection of H_0, we use the nonparametric Games-Howell post hoc pairwise comparison test to determine which exact time periods have statistically significant different sedimentation rates.

Results

The description of our results will be split into two parts. In the first we characterize mean transect sedimentation rates for each individual time interval. All mean transect sedimentation rates are provided in **Table A1** in the **Appendices**. For convenience, this characterization will largely occur at the river scale following the organization scheme of the survey ranges themselves. We also analyze sedimentation rates by stream because land use changes since the 1940s differs between river valleys. Because the Whitewater River network flows through distinct topographic divisions—flat uplands to steep gorges to flat lowlands—with changing hydrogeomorphic conditions, we will also describe river sedimentation rates with a focus on downstream trends. In part two of the results, we describe the outcome of our statistical analysis.

Mean sedimentation rates

Time interval 1: 1855–1939

Floodplain sedimentation rates between 1855 and 1939 vary from 0.03 to 2.20 cm/yr (**Figures 15** & **16**). Sedimentation behavior throughout the basin is purely aggradational and most transects experienced mean deposition rates of 0.5 to 1 cm/yr. Results are unavailable for 9 of the 94 ranges because the surface elevation comparison could not be made due to missing datasets. These data gaps exist for upland and middle gorge ranges and are concentrated along the South Fork and Logan Creek.

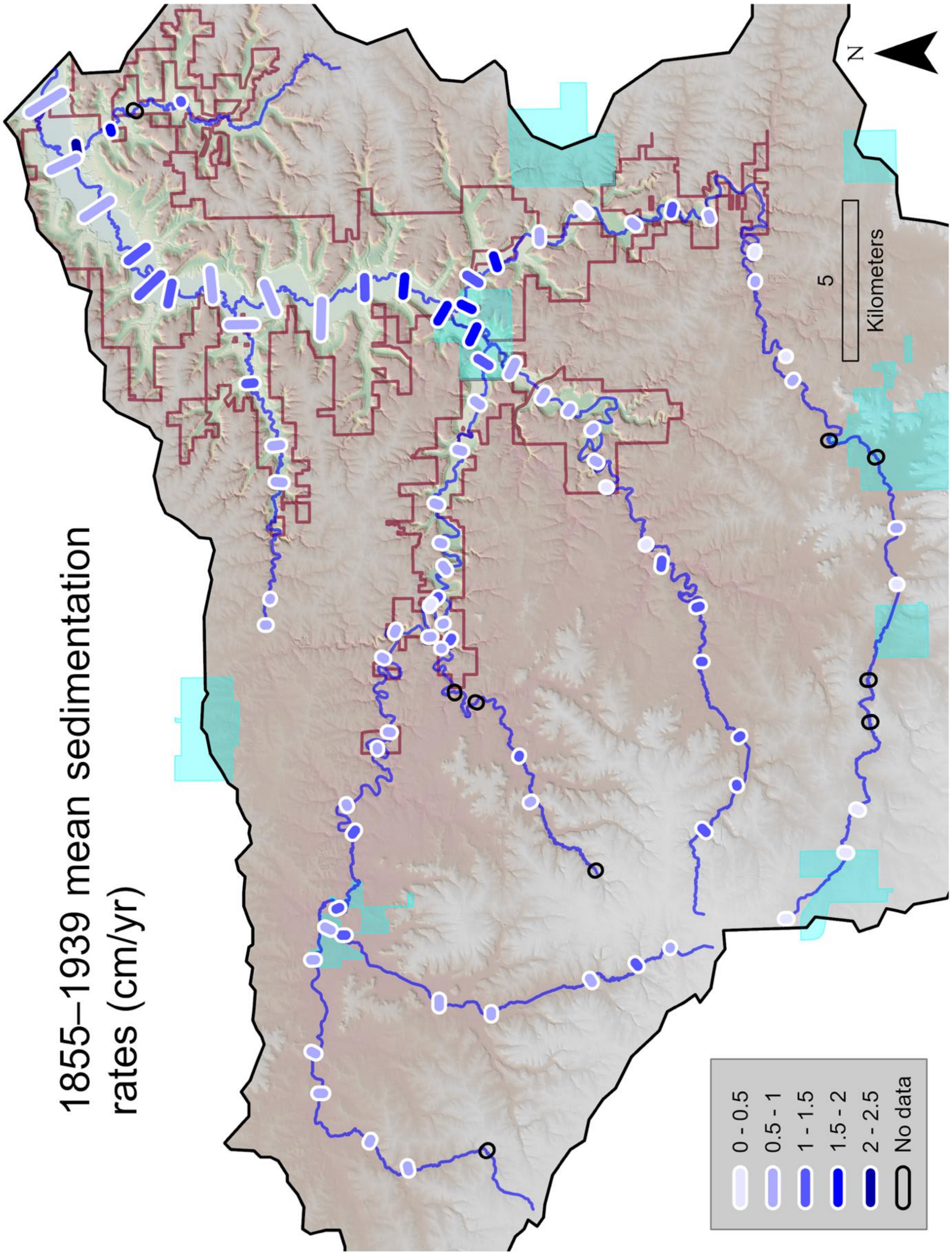

1855–1939 mean sedimentation rates (cm/yr)
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
No data
5
Kilometers
N

Figure 15

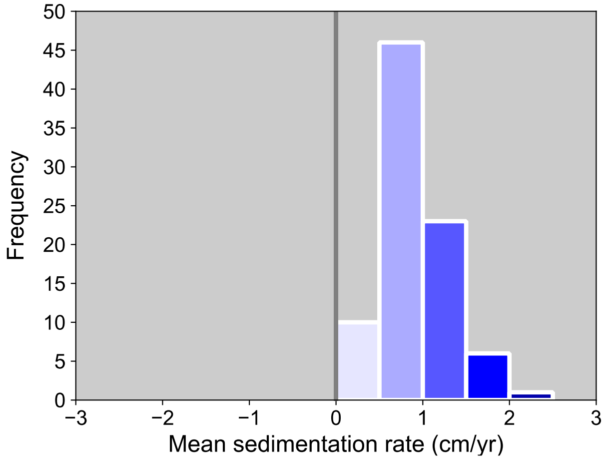


Figure 66. Mean sedimentation rate histogram for 1855 to 1939. Most sedimentation rates are between 0.5 and 1.0 cm/yr.

During the first time interval of our sedimentation record, the three forks of the Whitewater River have distinct sedimentation behaviors (**Figure 17)**. The Middle Fork experiences an overall decrease in aggradation rate downstream. Aggradation rates are highest on the upland surface where they stay relatively constant and average 1.18 cm/yr. They abruptly drop near the river's middle-gorge transition and steadily increase over the remainder of its course. Aggradation rates in the South Fork valley instead increase downstream. Upland and middle-gorge transect rates are generally low, averaging 0.58 cm/yr. The lowest recorded rate in the basin for this time interval occurs at South Fork 25, 0.03 cm/yr. These very gently increase downstream until reaching the wider floodplain of the lower valley where rates effectively triple. North Fork sedimentation rates further depart from its neighbors by remaining relatively constant along its length. Local departures from this trend occur near its confluences with Dry Creek and Logan Creek, where aggradation rates reach their highest values at a little over 1.4 cm/yr. Rates also peak in the lower valley at North Fork 0B, its furthest downstream range. Sedimentation in Dry and Logan Creeks mimic that of the North Fork, with little changes in aggradation rates downstream; they average 0.68 and 0.93 cm/yr, respectively.

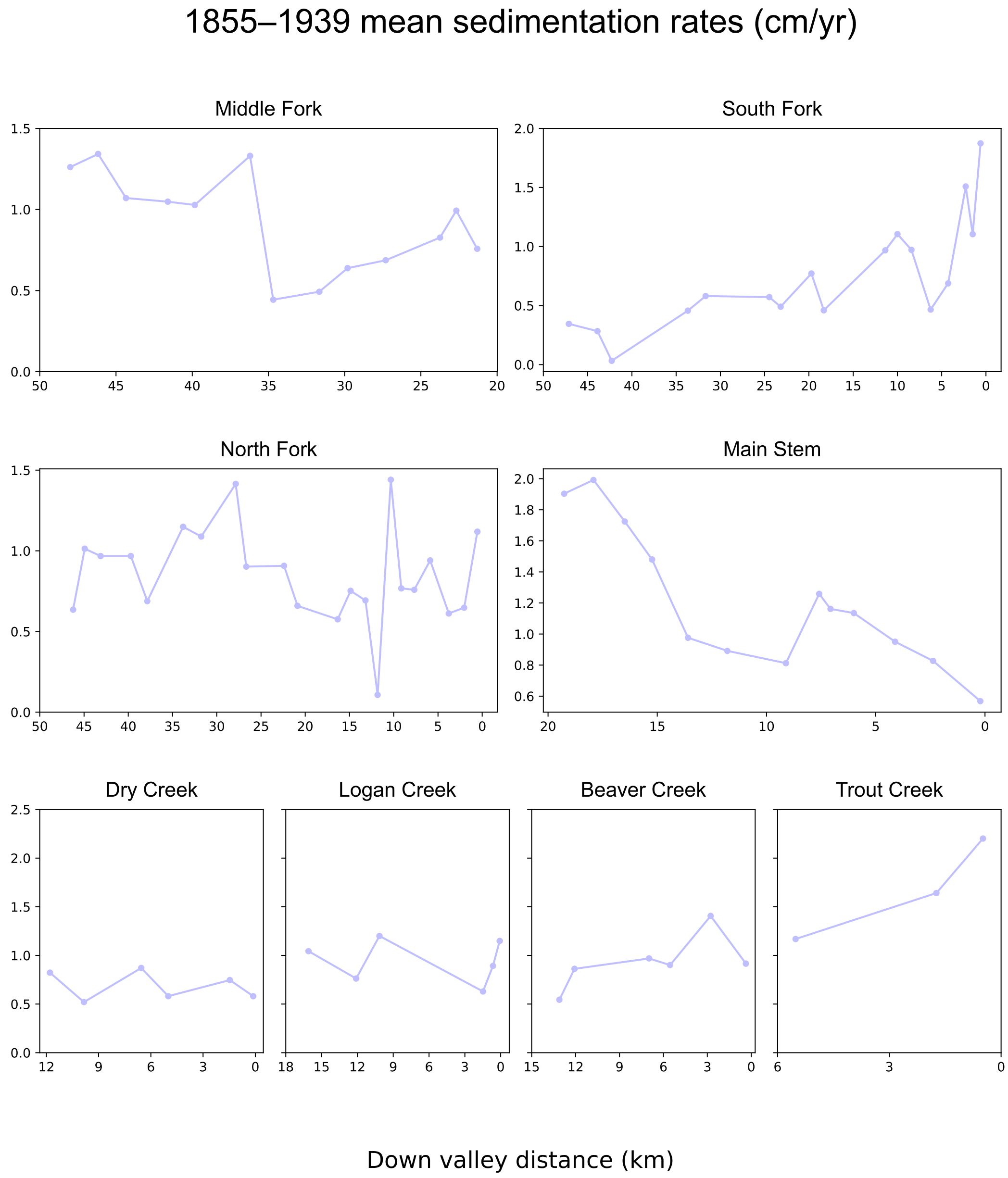


Figure 17. Downstream mean sedimentation rates trends on the Whitewater rivers and tributaries.

Sedimentation rates in the Main Stem (MS) floodplain are the highest observed for an individual river valley and are characterized by alternating zones of high and low rates. Aggradation rates are highest near the two confluences of the three forks and reach 2.00 cm/yr at Main Stem 10C. This decreases by almost 4 times to 0.57 cm/yr at Main Stem 1 near Whitewater’s outlet. Between Beaver Creek and Trout Creek, where the dominant valley axis bends from N–S to NE–SW, a local maximum in aggradation briefly interrupts this decreasing trend. Unlike the North Fork system, sedimentation rate peaks do not appear closer to the confluences of the Main Stems two tributaries. Beaver Creek behaves like Logan Creek: sedimentation rates do not change appreciably downstream and average 0.93 cm/yr. Aggradation rates in Trout Creek are incredibly high compared to the rest of the basin. Rates increase downstream by 2.5 times and reach the highest value for this time interval, 2.20 cm/yr, at Trout Creek 0 near its mouth in the lower valley.

Rapid aggradation with distinct downstream patterns occurs from 1855 to 1939. The highest rates mostly concentrate in the lower valley and near confluences. The lowest rates are observed throughout the upland and middle gorge regions. Each river maintains a consistent downstream trend in sedimentation whether this be an increase, decrease, or little overall change. The Main Stem also exhibits a pattern of alternating regions of high and low deposition reminiscent of the valley sediment plugs described by Gilbert (1917) and Happ et al. (1940).

Time interval 2: 1939–1964

Transect sedimentation rates between 1939 and 1964 vary between -2.59 and 2.55 cm/yr (**Figures 18** & **19**). A negative “sedimentation” rate indicates net erosion. During this time interval, aggradation dominates the survey transects with about 30 of the 85 measured valley cross-sections experiencing aggradation rates of 0 to 0.5 cm/yr. Twenty-five transects record net erosion. Results are unavailable for 9 of the 94 ranges and most of these data gaps coincide with the data gaps of the last time interval.

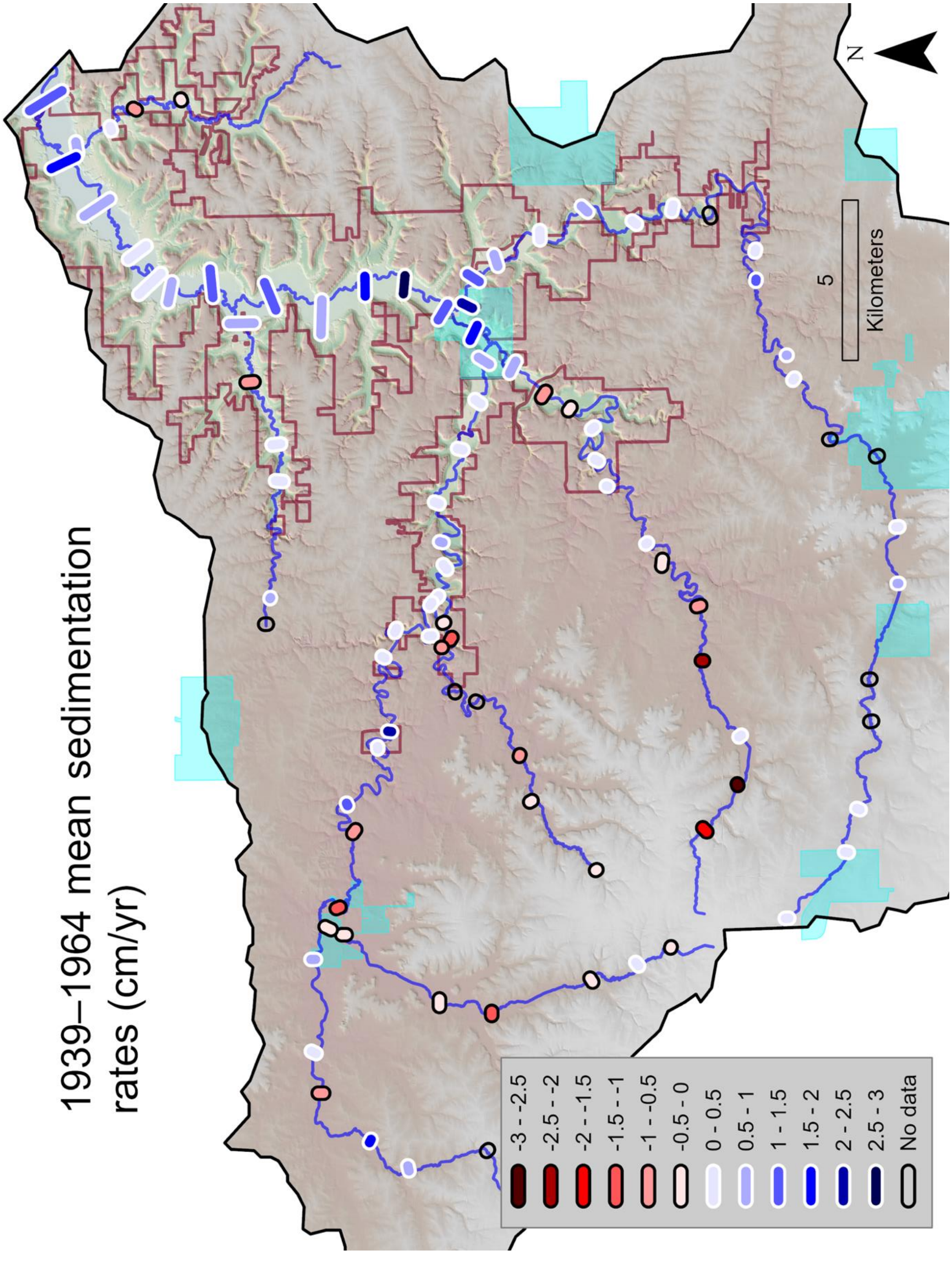

1939–1964 mean sedimentation rates (cm/yr)
-3 - -2.5
-2.5 - -2
-2 - -1.5
-1.5 - -1
-1 - -0.5
-0.5 - 0
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
No data
5
Kilometers
N

Figure 18

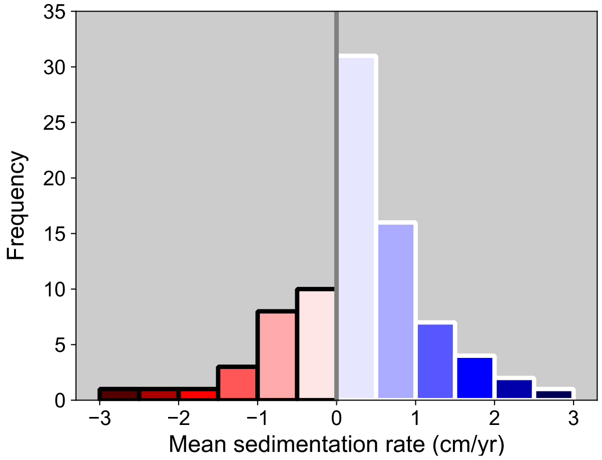


Figure 19. Mean sedimentation rate histogram for 1939 to 1964. Most sedimentation rates are between 0 and 0.5 cm/yr.

Over these 25 years, the three forks of the Whitewater begin to lose some of the distinction between their sedimentation behaviors (**Figures 20**). Middle Fork sedimentation rates generally increase downstream and is highest in the lower valley at 0.56 cm/yr on Middle Fork 12B, its furthest downstream range. Upland ranges mostly experience net erosion and yield the three greatest denudation rates in the basin, the highest being -2.59 cm/yr at 27B. Erosion rates decrease as the river flows through the middle gorge and are replaced by low rates of aggradation. Sedimentation in the South Fork also increases downstream, starting with relatively low rates throughout the upland and middle gorge, averaging about 0.41 cm/yr, that increase sharply in the lower valley. No net erosion is recorded on any transect for this river. North Fork sedimentation rates are highly variable. Like along the Middle Fork, upland transects on the North almost exclusively experience net erosion—6 out of 7 do so. The rest of the river valley from the middle gorge to the lowlands is dominantly aggradational. There exist three sedimentation rate peaks, two downstream of the Dry Creek and Logan Creek confluences and one again at North Fork 0B. The first of these peaks is anomalously high at 2.14 cm/yr. Sedimentation rates in Dry and Logan Creeks decrease downstream. Rates in the former exhibit great variability while those in the latter exhibit increasing erosion. All Logan Creek ranges also experience net denudation averaging -0.52 cm/yr.

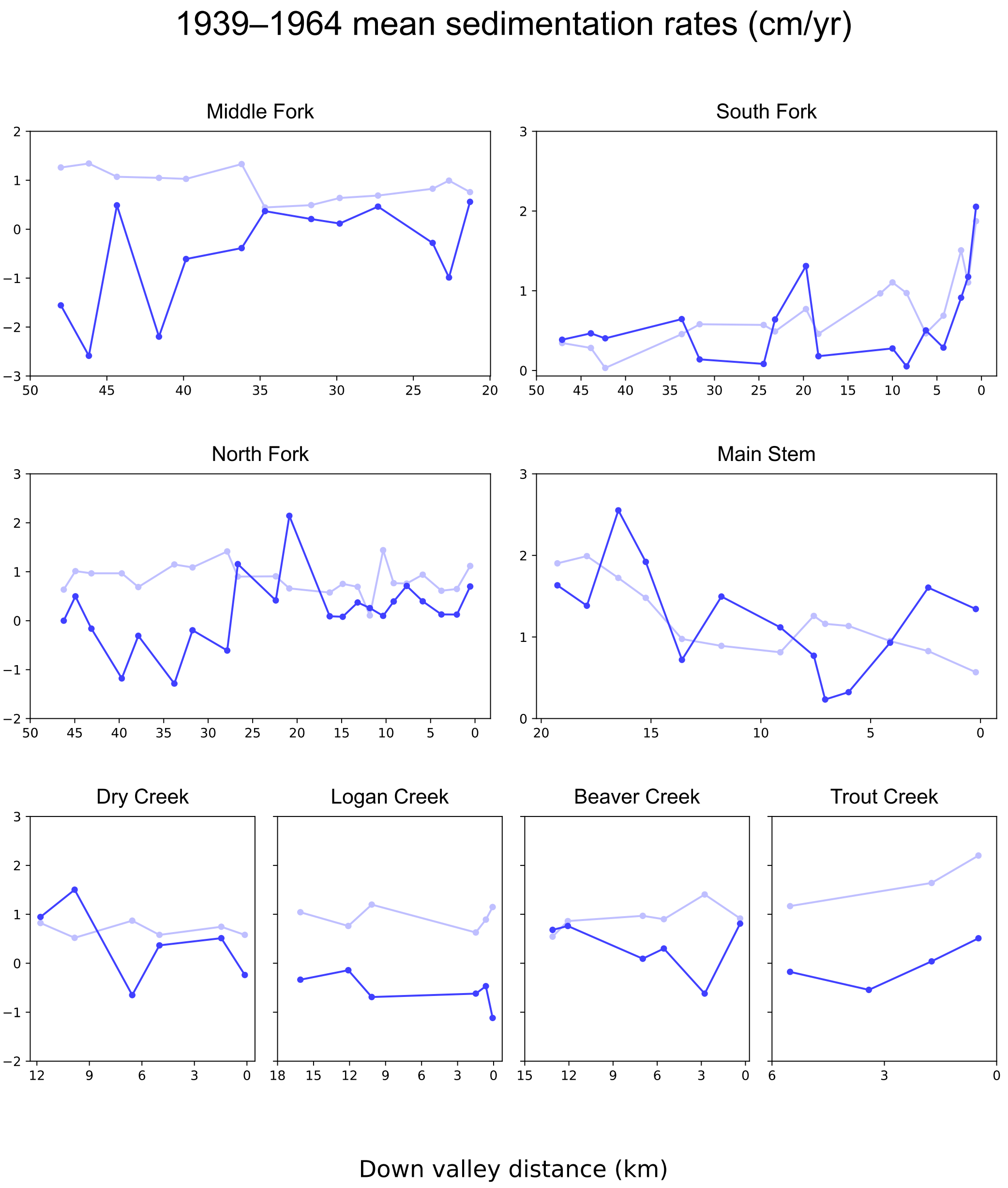


Figure 20. Downstream mean sedimentation rates trends on the Whitewater rivers and tributaries. The current time interval is plotted onto the previous in a darker color. The dashed line denotes the boundary between erosion and deposition.

The highest sedimentation rates in the basin are mostly distributed throughout the Main Stem valley. Main Stem transects experience a net buildup that generally decreases downstream.

The highest rates are concentrated around the three fork confluences, around the confluence with Beaver Creek, and towards mouth of the Whitewater. Main Stem 10 yields the highest rate of 2.55 cm/yr. Sedimentation rates in Beaver Creek are generally low, averaging 0.27 cm/yr. They decrease for most of its length except in the lower valley at Beaver Creek 0 which experiences the highest rate. Trout Creek sedimentation rates increase downstream with its upper two ranges recording denudation and its lower two aggradation.

Mean sedimentation rate generally decrease across the basin from 1939 to 1964. Maximum aggradation rates in the Middle, North, and South Forks have increased since the last time period but most ranges experience lower deposition and even net erosion. Most high sedimentation rates are still concentrated in the lower valley at the confluence of the three forks and now that of Beaver Creek and the Main Stem. Other previously identified local maxima at confluences on the North Fork have shifted downstream by up to a few valley miles. The lowest deposition rates, and all net erosion, is recorded throughout the middle gorge and uplands. Previously existing downstream sedimentation trends have been disrupted for all but the South Fork and Main Stem—Logan Creek transects have completely reversed their behavior and are now dominantly erosional. The Main Stem continues its alternating aggradation pattern downstream with two peaks located at previous sedimentation lows. Aggradation rates at Main Stem 1, located at the mouth of the Whitewater River near the third peak are over double that of the previous time period.

Time interval 3: 1964–1994

Mean sedimentation rates between 1964 and 1994 span -2.35 to 2.13 cm/yr (**Figures 21** & **22**). Transects are dominantly aggradational and most experience rates between 0 to 0.5 cm/yr while 27 show net erosion. Results are available for all 94 ranges, i.e., there is complete coverage for the basin.

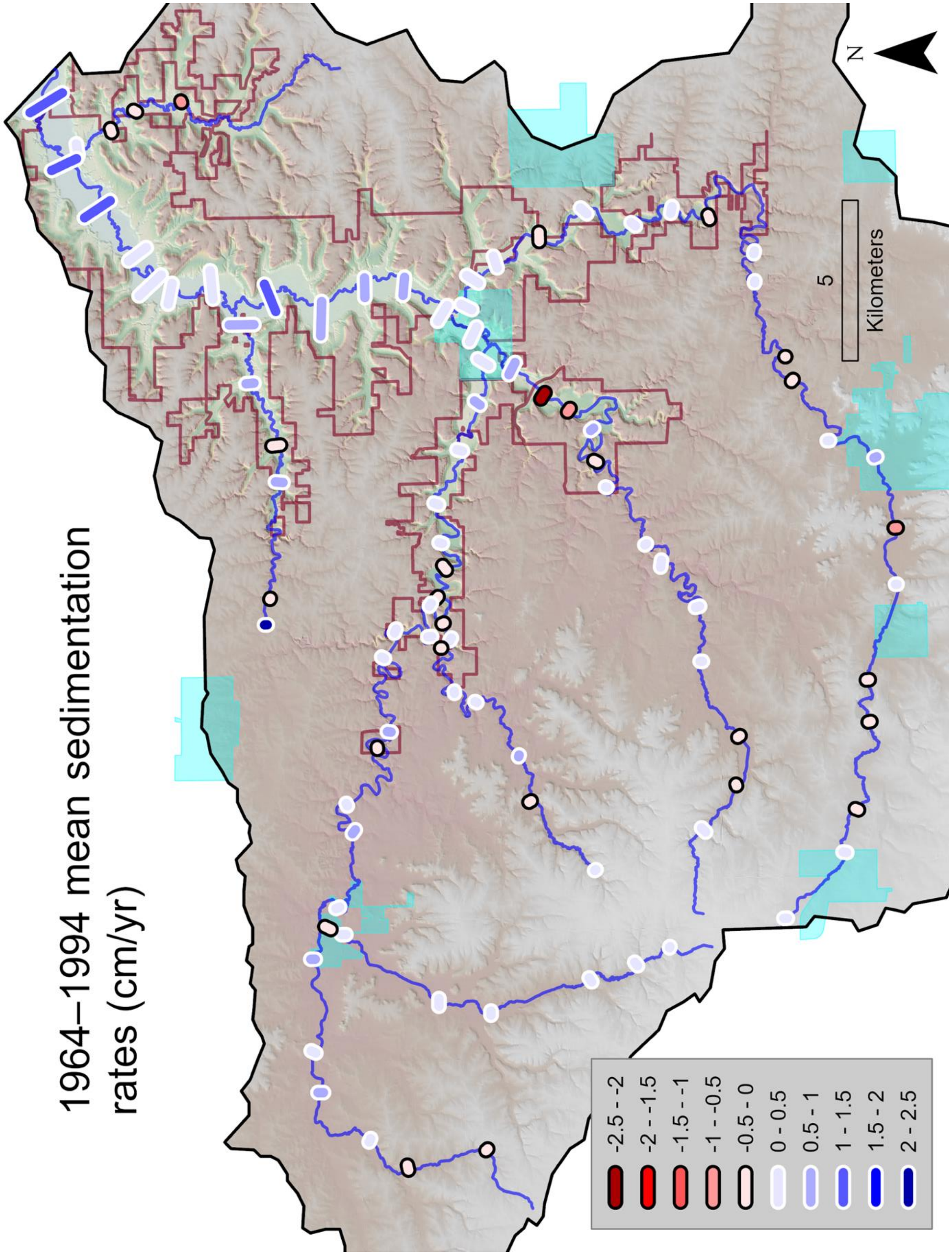

1964–1994 mean sedimentation rates (cm/yr)
N
5
Kilometers
-2.5 - -2
-2 - -1.5
-1.5 - -1
-1 - -0.5
-0.5 - 0
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5

Figure 21

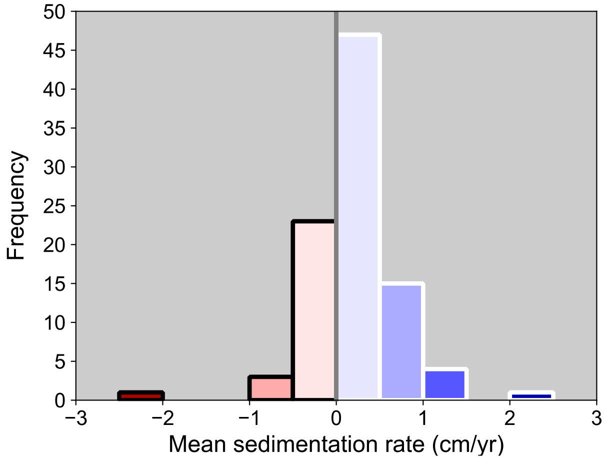


Figure 22. Mean sedimentation rate histogram for 1964 to 1994. Most sedimentation rates are between 0 and 0.5 cm/yr.

Transect sedimentation rates in the three forks conform to similar behavior during this time interval (**Figures 23**). In each, low rates of erosion and deposition are distributed downstream and remain roughly constant. In the Middle Fork this trend is punctuated by extreme erosion at range 13A where rates reach -2.35 cm/yr. This is the highest erosion rate in the basin—almost 4 times as large as the next highest value—and occurs where the river appears to be actively laterally incising into a terrace. The South and North Forks see no appreciable changes in sedimentation rate downstream—even near the latter's tributary confluences. The Middle, South, and North Fork sedimentation rates average -0.09, 0.07, and 0.25 cm/yr, respectively. Sedimentation rates in Dry and Logan Creeks are similar to the three forks with no noticeable downstream trends and low rates of transect erosion and deposition. These average -0.26 and 0.12 cm/yr, respectively.

Main Stem transects solely experience net aggradation and rates generally increase downstream with three peaks in sedimentation. The lowest rate in this river valley, 0.25 cm/yr, occurs at Main Stem 11B and the highest rates are concentrated at the three lowest ranges—Main Stem 2 experiences the highest aggradation rate within the valley at 1.49 cm/yr. Between these zones, sedimentation reaches local maxima between Elba and the Beaver Creek confluence. Along most of Beaver Creek sedimentation rates closely hover around 0.31 cm/yr, but the furthest upstream range, Beaver Creek 6C, experiences the highest aggradation rate for this time interval at 2.13 cm/yr. Transect rates in Trout Creek increase downstream with all but Trout Creek 0 towards the mouth recording net erosion.

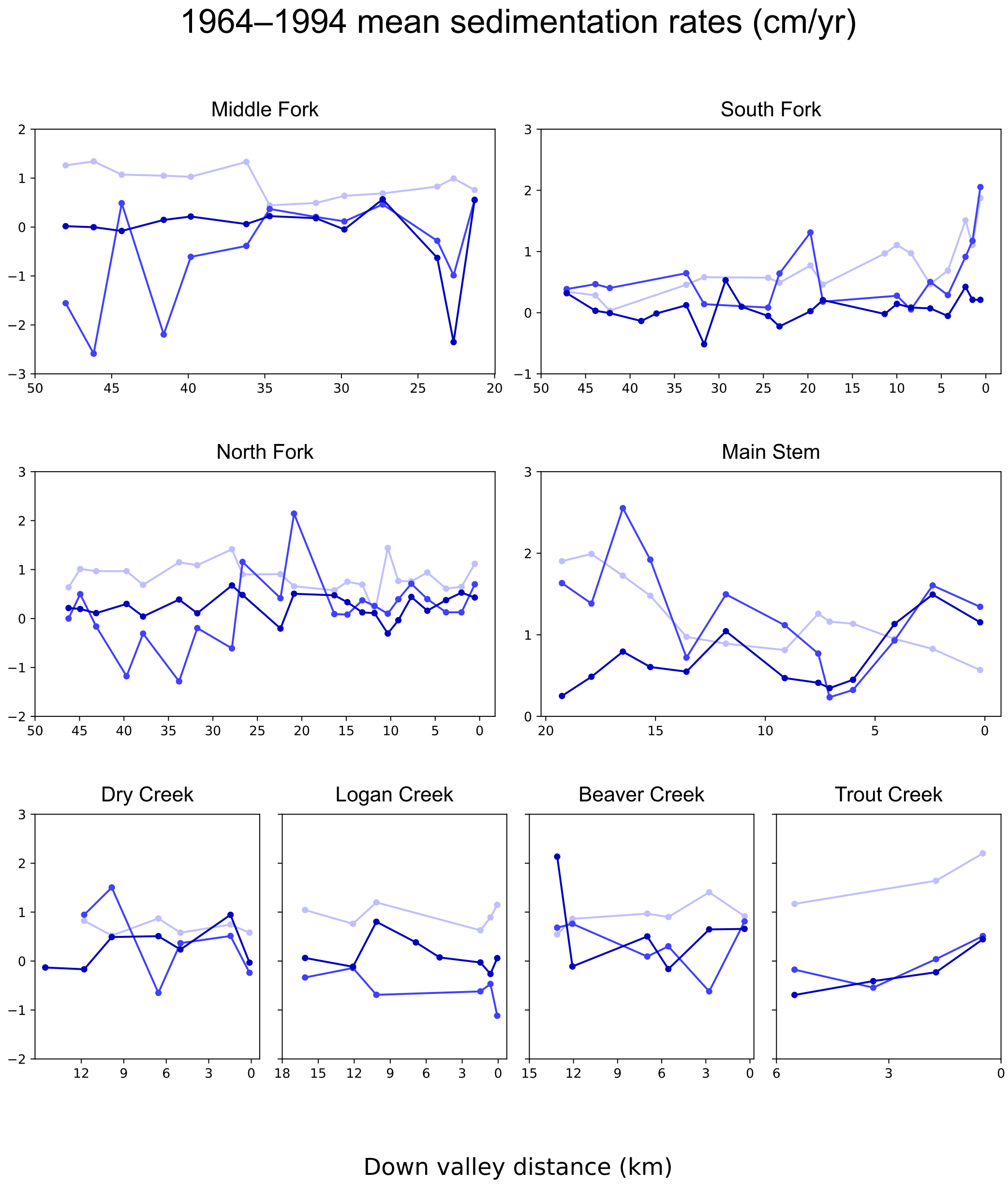


Figure 23. Downstream mean sedimentation rates trends on the Whitewater rivers and tributaries. The current time interval is plotted onto the previous in a darker color. The dashed line denotes the boundary between erosion and deposition.

Over the 30 years between 1964 and 1994, deposition and erosion rates decrease across the basin as do the frequency of extremely high rates. Lowland ranges still purely record net aggradation and contain most of the highest rates in the watershed. However, the zones of greatest deposition have wholly translated downstream of the three-fork confluence to the mouth of the Main Stem. Range proximity to confluences no longer corresponds to a measurable increase in sedimentation rate. The uplands and middle gorge continue to have both the lowest aggradation rates and all recorded net erosion. Reductions in both erosion and deposition have made sedimentation rates relatively constant in the downstream direction for the three forks of the Whitewater and their major tributaries except for Trout Creek. Sedimentation rates in the Main Stem now increase downstream but remain punctuated by peaks.

Time interval 4: 1994–2008

1994 to 2008 has low data coverage with results for only 30 of the 94 ranges (**Figures 24 & 25**). The Main Stem and Trout Creek have full coverage whereas the rest of the streams, in most cases, have only one data point. There is no data for Logan Creek whatsoever. Mean sedimentation rates vary from -1.11 to 2.91 cm/yr. Most ranges record aggradation between 0.5 to 1 cm/yr, and 3 record net erosion.

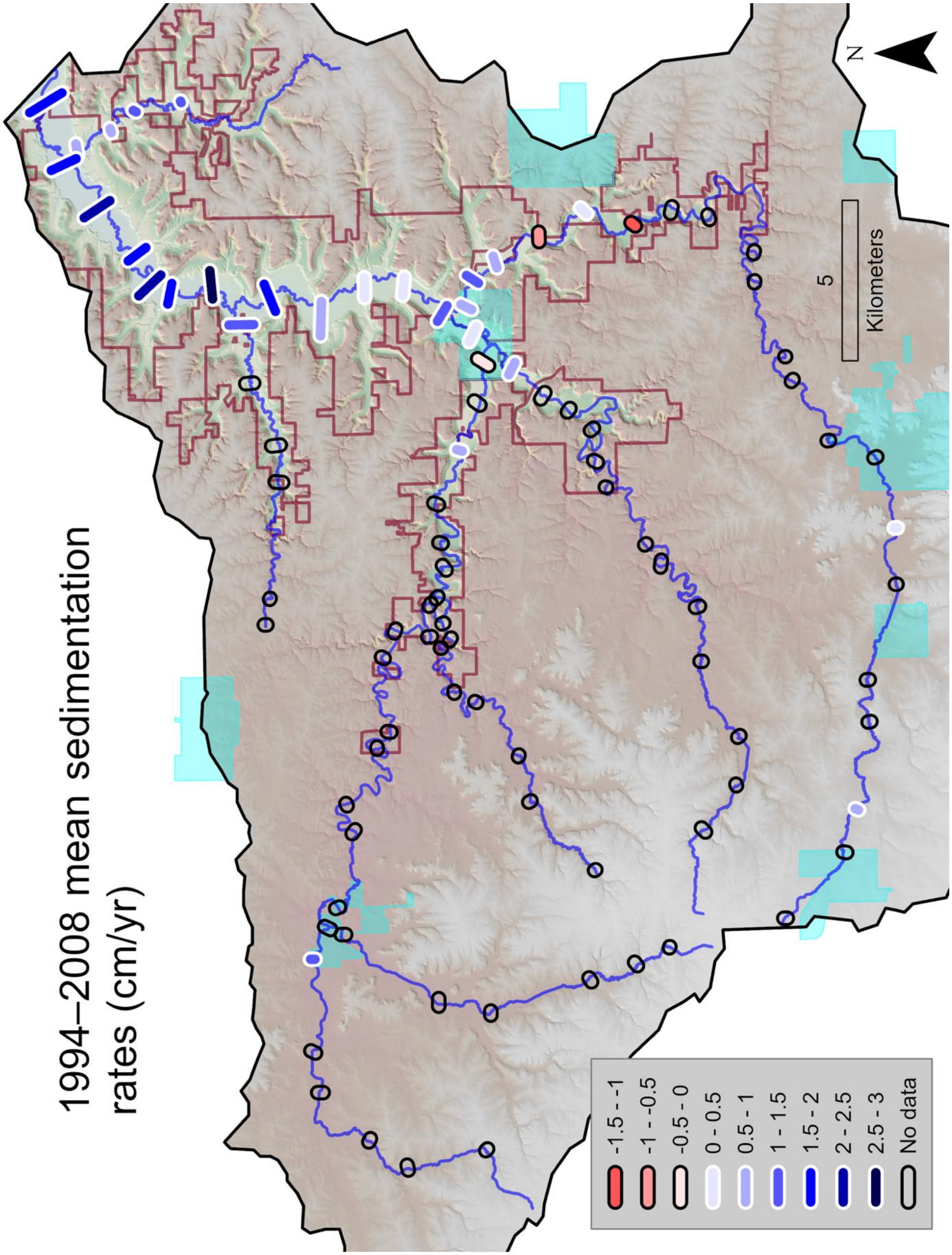

1994–2008 mean sedimentation rates (cm/yr)
-1.5 - -1
-1 - -0.5
-0.5 - 0
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
No data
5
Kilometers
N

Figure 24

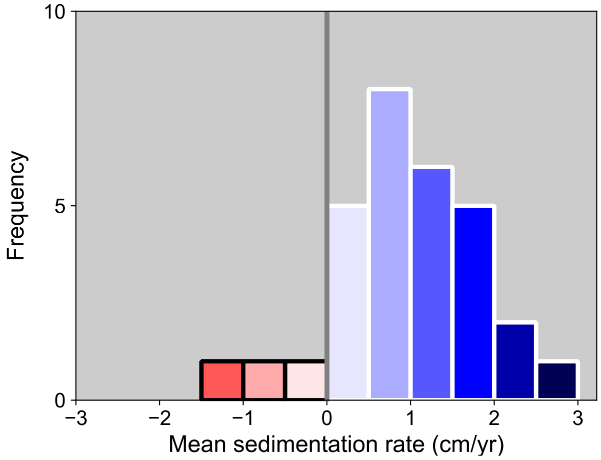


Figure 25. Mean sedimentation rate histogram for 1994 to 2008. Most sedimentation rates are between 0.5 and 1 cm/yr.

Downstream trends are only discernible for part of the South Fork, the Main Stem, and Trout Creek (**Figures 26**). Generally, all transect rates are high relative to previous time intervals—only 5 ranges experience deposition rates less than 0.5 cm/yr. Sedimentation rates in the South Fork increase downstream through the middle-gorge–lowland transition and change from net erosional to net aggradational towards the mouth. Aggradation in the Main Stem valley is high, averaging 1.5 cm/yr, and increases greatly downstream. The upper portion of its valley between Elba and Beaver experiences the lowest sedimentation rates while the highest, 2.91 cm/yr, is located just down-reach of the Beaver Creek confluence on Main Stem 5C. That is almost a seven-fold increase in sedimentation rate compared to the Main Stem's furthest upstream range. Post peak, rates remain generally constant to the outlet of the Whitewater. Sedimentation rates in Trout Creek are all positive and so are purely aggradational, averaging 0.87 cm/yr. These rates also decrease in the downstream direction

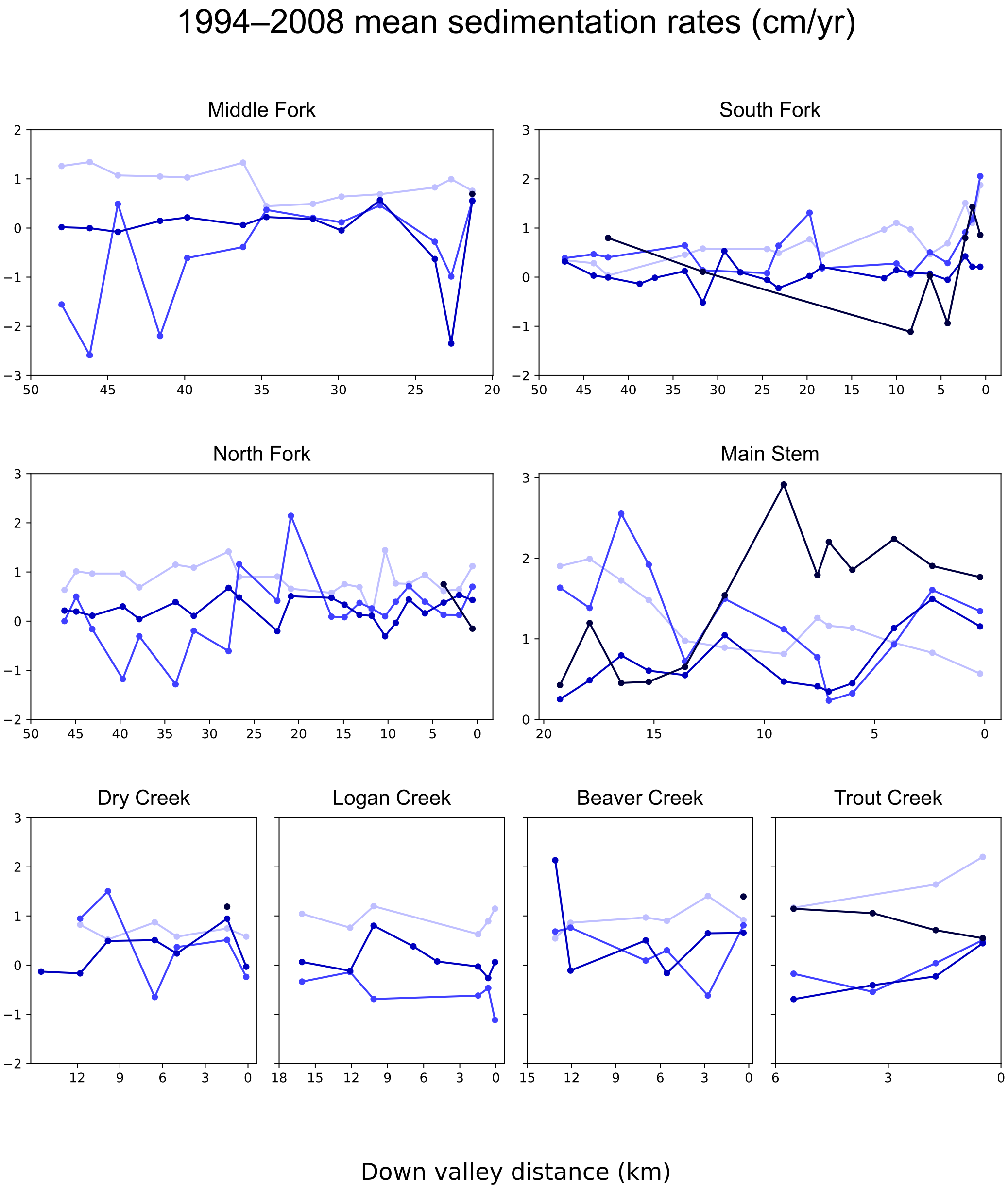


Figure 26. Downstream mean sedimentation rates trends on the Whitewater rivers and tributaries. The current time interval is plotted onto the previous in a darker color. The dashed line denotes the boundary between erosion and deposition.

Mean sedimentation rates between 1994 and 2008 have largely increased. For about half of these ranges, sedimentation has increased to levels that either exceed or meet their previous maximum rates. Net erosion has finally been recorded in the lower valley, but this region is still dominated by aggradation. The greatest aggradation rates occur throughout the lower half of the

Main Stem. Here, we see a continuation of the previously observed trend of high sedimentation rates appearing to move upstream from the mouth of the Whitewater River. Upland and middle gorge sedimentation rates are largely unknowable, though pockets of increased aggradation occur in the former and increased erosion the latter. The Main Stem's downstream sedimentation trend established in the previous time interval continues with an even greater departure between upstream and downstream sedimentation rates. Trout Creek's downstream trend reverses for the first time and decreases in sedimentation rate.

Statistical analysis

Overall, stream and valley sedimentation rates in the Whitewater River Watershed generally decrease from 1939 to 1994 and then increase to 2008. Sample group mean sedimentation rates compared with Welch's ANOVA and the Games-Howell test are provided in **Table 2**. Sample distributions are also visualized with box plots in **Figures 27** and 2**8**. And lastly, sample group size can be found in **Tables A2** and **A3** located in the **Appendices**.

Table 2. Mean sedimentation rates (cm/yr) - Whitewater River branches & tributaries

Stream	1855–1939	1939–1964	1964–1994	1994–2008
Middle Fork	0.917	-0.492	-0.089	0.692
South Fork	0.745	0.595	0.069	0.246
North Fork	0.842	0.174	0.248	0.298
Dry Creek	0.687	0.406	0.264	1.189
Logan Creek	0.926	-0.562	0.122	n/a
Main Stem	1.206	1.233	0.707	1.493
Beaver Creek	0.933	0.269	0.611	1.395
Trout Creek	1.670	-0.042	-0.222	0.866
Watershed	0.919	0.273	0.218	0.957

For the Whitewater watershed, the p-value of Welch's ANOVA test is less than our level of significance (0.05) and we reject the null hypothesis and conclude that mean sedimentation rates are not the same between time intervals (**Table 3**). The following post hoc comparisons indicate that 1855–1939 sedimentation rates differ from the those of the two subsequent time intervals but not the most recent one. Similarly, 1994–2008 sedimentation rates are statistically different from those calculated between 1939 and 1994. Note that mean rate comparisons with time interval 4, at both the basin and river scales, are affected by sampling a bias; for all but Main Stem and Trout Creek ranges, the sample size of the 1994–2008 group is much smaller than the others. No other comparisons yield statistically significant differences which corroborates our statement opening this sub-section that sedimentation rates declined post-1939 and have increased post-1994.

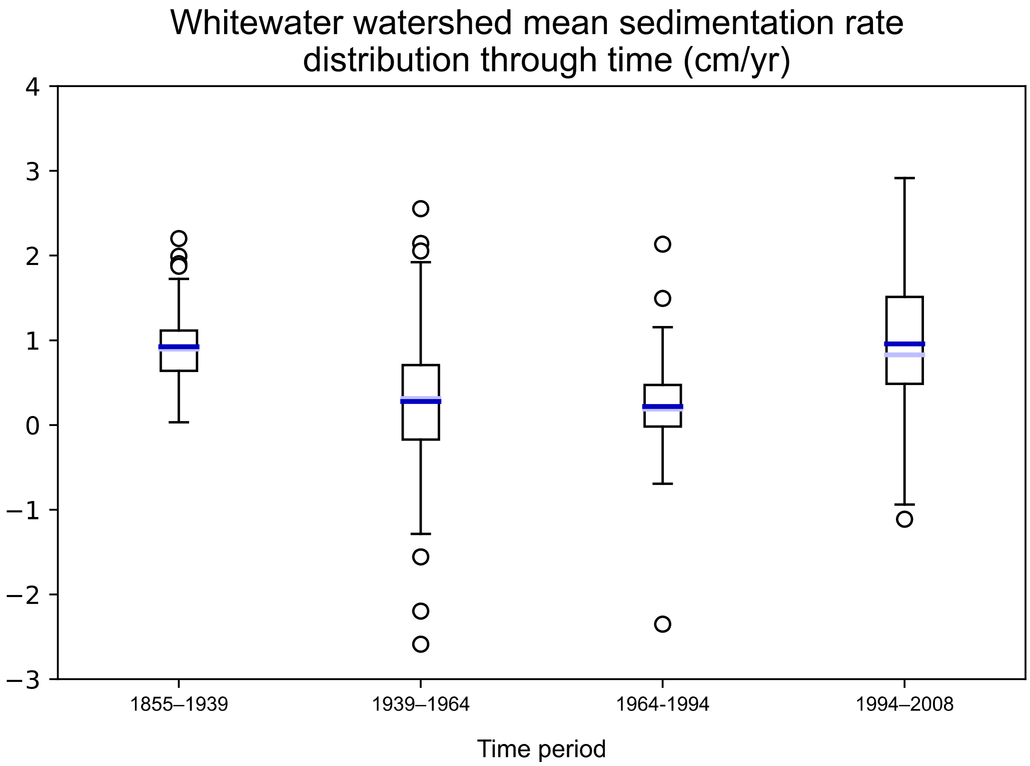


Figure 28. Watershed sample group box plots. The dark solid line inside a boxplot is the sample mean and the lighter is the median.

Table 3. Welch's ANOVA & Games-Howell mean sedimentation rate comparison results

Test	Result	Comparison	Middle Fork	South Fork	North Fork	Dry Creek	Logan Creek	Main Stem	Beaver Creek	Trout Creek	Watershed
Welch's ANOVA	F	1-2-3-4	12.220	12.252	15.352	41.865	42.420	5.389	1.831	9.755	41.865
	P	1-2-3-4	1E-05	8E-05	7E-03	0.14	7E-06	5E-03	0.18	0.01	1E-17
Games-Howell	P	1-2	2E-03	0.83	2E-03	0.82	2E-05	0.99	0.17	0.03	5E-09
		1-3	2E-03	9E-05	3E-08	0.13	3E-04	0.03	0.81	0.02	6E-14
		1-4	---	0.49	0.71	---	---	0.67	---	0.25	0.99
		2-3	0.68	8E-03	0.97	0.98	8E-03	0.09	0.90	0.94	0.95
		2-4	---	0.75	0.99	---	---	0.80	---	0.06	4E-03
		3-4	---	0.94	0.99	---	---	0.02	---	0.04	6E-04

The individual rivers of the Whitewater watershed show different statistical relationships than the basin. The omnibus test yielded at least one statistial difference between mean sedimentation rates for all but Dry and Beaver Creeks. In the Middle and North Forks, sedimentation rates during time interval 1 was distinct from 2 and 3. In the South Fork, sedimentation during time interval 3 is distinct from the previous two. Logan Creek is the only river valley where all time periods yield statistically different sedimentation rates. Main Stem sedimentation rates are only different between the last two time intervals and the behavior of

Trout Creek most closlty mimics the basin. Nowhere do the results of Welch's ANOVA or Games-Howell contradict for the same sample group.

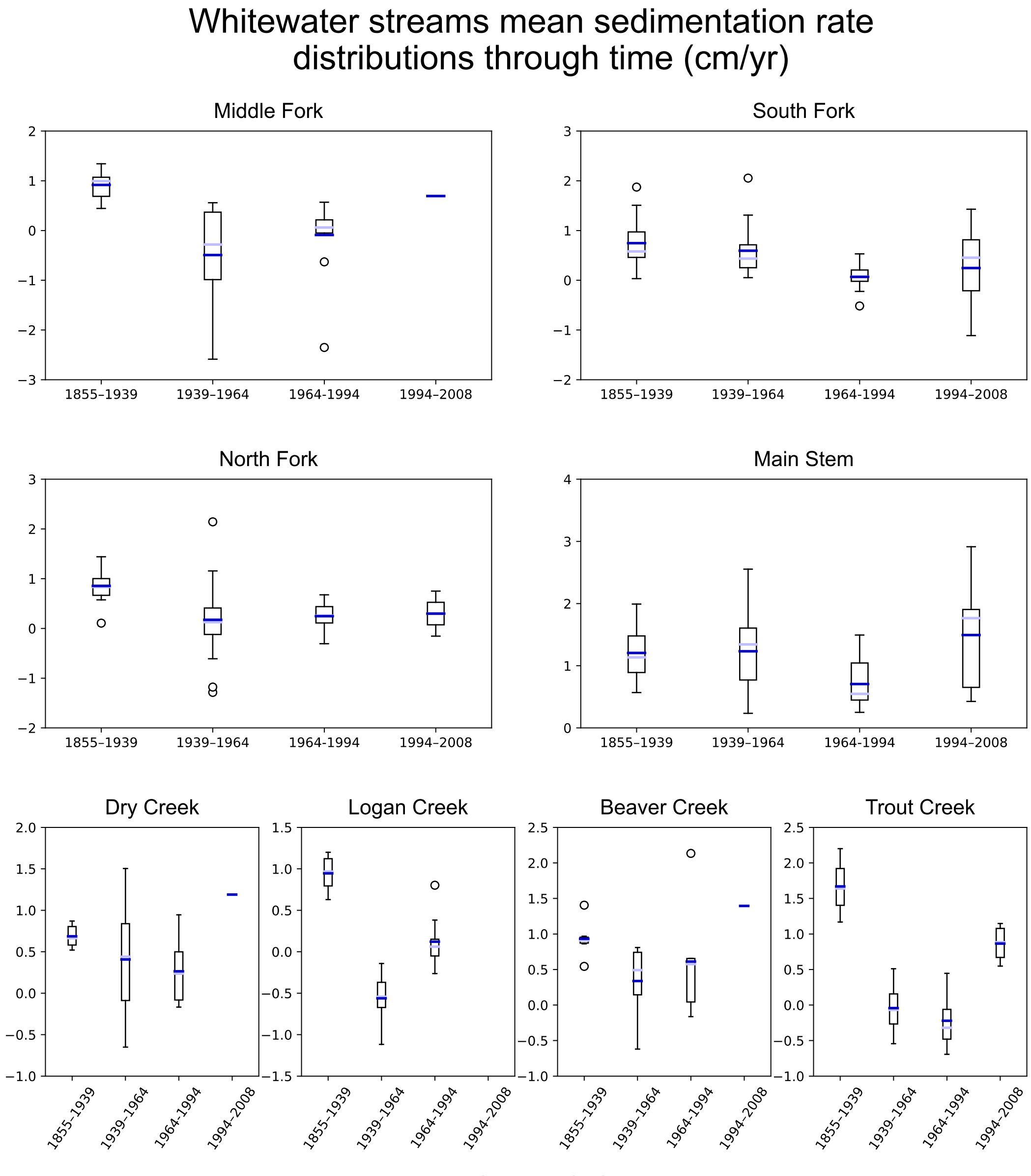


Figure 29. River sample group box plots. The dark solid line inside a boxplot is the sample mean and the lighter is the median.

Discussion & Conclusions

Our results suggest that mean sedimentation rates in the Whitewater River Valley vary considerably through time and space. We begin our discussion of those results by describing the implications of source data on calculated rates and sample size on the outcomes of our statistical tests. Following this, we discuss the spatio-temporal distribution of basin wide sedimentation rates through controls on sediment availability and sediment routing.

Source data implications

Mean transect sedimentation rates are calculated from data collected through three methods: auger borings, field elevation surveys, and an aerial lidar survey. Each procedure yields unique implications for the quality and representativeness of our results warrants examination.

Auger boring surveys

Measurement accuracy

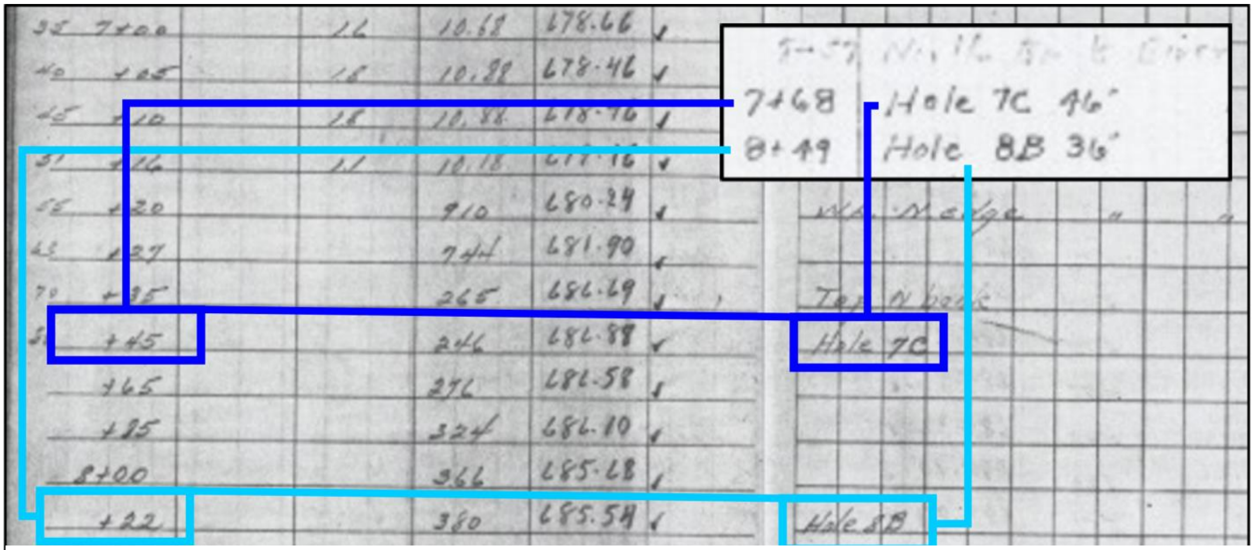
Auger boring measurements yielded floodplain ELS thickness and are used to calculate sedimentation rates in the first two time intervals between 1855 and 1964. The accuracy of recorded borehole fill depths are primarily controlled by the accurate recognition of the soil horizon that corresponds to the Pre-Euro-American floodplain surface (Kunsman, 1944). Happ (1944), while working in the Kickapoo River basin, concluded that when the contact is sharp and easy to distinguish in a soil core, the uncertainty of the depth measurement could be as small as about 2.5 cm, especially when using a graduated tape. This is essentially the maximum precision of any unconsolidated soil core depth measurement and where the contact is more difficult to locate uncertainty would no doubt increase.

A review of SCS auger boring field notes from the Whitewater watershed indicate that most identifications of the Pre-Euro-American horizon were obtained with confidence. This kind of information was generally conveyed by underlined declarations of "OLD SOIL", "Pre-modern", etc., and a corresponding depth. These points are assumed to be measured at the uncertainty reported by Happ (1944), ± 2.5 cm. Other borehole notes indicate less confidence in the measurement with more puzzled statements such as , "possibly old soil?". These points yield greater uncertainty but make up a much smaller proportion of the dataset and are therefore believed to have little effect on computed transect sedimentation rates. Magilligan (1985) worked with SCS sedimentation survey data collected in the Galena River basin and dealt with these implications by wholly omitting ranges from analysis in part because of Adams' (1940) inability to clearly identify the sub-surface horizon and establish accurate depths. Borehole fill depth measurement confidence could be more thoroughly investigated in the Whitewater watershed through its collection of field notes to determine if any measurements should be omitted from future analyses.

1855 surface profile extrapolation procedure

Borehole ELS thicknesses are used in conjunction with the 1939 elevation surveys to generate a surface profile of the Pre-Euro-American floodplain that was used to calculate mean sedimentation rates for over half the ranges during the first time interval. For a given range, the accurate generation of the previous floodplain surface primarily depends on the accuracy with which the investigator can match borehole positions to the corresponding surface elevation measurements. These locations control the geometry of ELS fill and the distribution of calculated depths and sedimentation rates; thus, the location of each borehole has direct implications for calculated mean sedimentation rates.

In the Whitewater River Valley, matching borehole positions with the corresponding surface elevation measurement was complicated by survey methods. Survey offset (the position of a measurement along a range) was typically measured by pacing for the boring surveys and taping for subsequent surface profiling. Pacing consists of counting steps (paces) within a distance, and though much coarser—having greater uncertainty—than measurements from a graduated tape, is considered sufficiently accurate for this application and others where time may be valued above precision (Brinker & Wolf, 1984). The difference in the precision of these two methods is precisely what makes pairing them difficult. At minimum, paced and taped distances are recorded to every 1.5 m and 3 cm, respectively, so rarely do offsets from the two measurement types coincide. This complication was overcome for ranges in the lower valley because the surface profile field notes explicitly indicated the location of most boreholes, and they could be placed with great confidence. For boreholes not listed on the surface profile field notes, or on missing pages, we considered it acceptable to match the boring offset to the nearest elevation offset, given that the recorded paced and taped distances for the same point could vary



35	7+00	22	10.68	678.66	✓	
40	+05	26	10.88	678.46	✓	
45	+10	28	10.88	678.76	✓	
[illegible]	+16	21	10.18	[illegible]	✓	
55	+20		910	680.24	✓	
[illegible]	+27		744	681.90	✓	
70	+35		265	682.69	✓	Top N bank
[illegible]	+45		246	682.88	✓	Hole 7C
	+65		276	682.58	✓	
	+85		324	682.10	✓	
	8+00		366	685.28	✓	
	+22		380	685.54	✓	Hole 8B

7+68 Hole 7C 46"
8+49 Hole 8B 36"

Figure 30. Survey offset complications. The difference between paced and taped positions of two consecutive auger borings on Main Stem 4C from 1939–1941 field notes. The inset of boring survey notes shows Holes 7C and 8B at offsets of 768 and 849 ft (234 and 259 m), respectively.

by a dozen meters (**Figure 30**). To avoid further assumptions about borehole positions, this procedure was only undertaken for ranges with these kinds of corroborating field notes.

Sample size calculation sensitivity

Average sedimentation rates on ranges where cross-sections are not available, or could not be established from auger borings, were calculated directly from borehole ELS thicknesses. These calculations utilize relatively small samples—between 3 and 10 depths—compared to the cross-sectional method—about 1,000 to 30,000 depths after interpolation. Therefore, the borehole method utilizes much less information to determine the mean and will yield rates that are more sensitive to extreme depth values while the latter method likely produces results that are more representative of the true mean (Well et al., 1990). We assume that results calculated directly from borehole depths still reasonably approximate actual sedimentation rates due to the sampling scheme of the boring survey. Auger boring sample sites were stratified by the regularity of ELS depths along a range and with fewer borings we can expect that ELS depth is relatively constant and that extreme values make up few of the measurements. Still, this sample size limitation could be mitigated by generating cross-sections from all borehole datasets and synthetically increasing sample size of the mean sedimentation rate calculation through interpolation.

Measurement limitations

All mean sedimentation rates for the first time interval yield net aggradation; however, the soil bore datasets they are derived from can only record aggradation as their collection requires burial. Subtracting elevations along subsequent cross-sections can yield erosion only when an interpolation point on the more recent surface is lower than the corresponding point on the older surface. The Pre-Euro-American cross-section lies almost entirely underneath the 1939 surface because most of the old floodplain was buried by ELS. These surfaces also coincide at points of intersection. They intersect only where ELS depths are zero and since there is no geologic information to indicate that any material was eroded, these points must instead be recorded as lateral edges of fill. Because net erosion cannot be calculated on any range between 1855 to 1939, mean sedimentation rates over the intervening 84 years are potentially overestimated. Despite this inherent dataset limitation, we believe that these rates are representative of actual conditions because of the sheer severity of accelerated sedimentation in the Whitewater River watershed. Happ (1940) lends credence to this assumption, describing all valleys of the watershed as almost completely buried by deep deposits of ELS.

Range reestablishment

For the 1939 to 1964 time interval, mean sedimentation rates were also calculated from overlapping auger boring datasets. These calculations took place on the uplands and the upper middle valleys of the three branches of the Whitewater River and most of its major tributary streams and are partly affected by range reestablishment between the two sampling eras. In this case, reestablishing a survey range involved shifting its position up or downstream. It is not clear why some ranges were moved but we believe that the original lines simply could not be recovered, either because blazed trees could not be located, or because the original lines had not yet been monumented. A close review of scheduled correspondence in the form of summary reports between Happ and field surveyors would reveal more about the timing of the establishment of range monuments. Surveyors often attempted to place the new line as close as possible to the original. Reported estimations were found to be as small as 3 m but others were quite large such as for on Dry Creek 6 at 122 m.

Mean sedimentation rates calculated with this method are likely less representative of the true mean when this shift is large because the input data comes from two different transect positions. This is likely the cause for the anomalously high sedimentation at Dry Creek 6 during this time interval. For this research, this effect was considered acceptable to enable the widest spatio-temporal data coverage of sedimentation rates in the Whitewater watershed. Still, as with ELS depth uncertainty, range shift estimations should be determined from the auger boring field notes and criteria for data omission established for future research.

Field elevation surveys

Measurement accuracy

Profile surveying, as it is applied in the Whitewater watershed, measures the elevation and position of points along a range line to create a cross-section of the land surface. The accuracy of this cross-section is largely controlled by the accuracy of its elevation measurements. This accuracy is primarily quantified through differential leveling procedures such as a bench level circuit (NRCS, 2006). A bench level circuit begins at a point of known elevation, often a benchmark and proceeds through the following steps:

1. The instrument level is placed further along the circuit line and pointed back towards the benchmark where the surveyor takes a reading of the height of a survey rod placed atop the benchmark, in the plane of the instrument, called a backsight.
2. The backsight is added to the benchmark elevation to calculate the height of the instrument level (HI).
3. Next, the rod is moved down the line past the instrument level and the surveyor takes a new rod height reading called the foresight.

4. The foresight is subtracted from the HI to calculate the elevation of the ground in reference to the elevation of the starting benchmark.

5. The level is moved past the survey rod and steps 1 through 4 are repeated with the previous foresight point serving as the new backsight point (Beaman, 1928).

This procedure continues until the surveyors have returned to the starting benchmark, called closing the circuit, where a last foresight is recorded and subtracted from the standard elevation to calculate the error of closure. This is the primary value through which we evaluate leveling and elevation accuracy (NRCS, 2006).

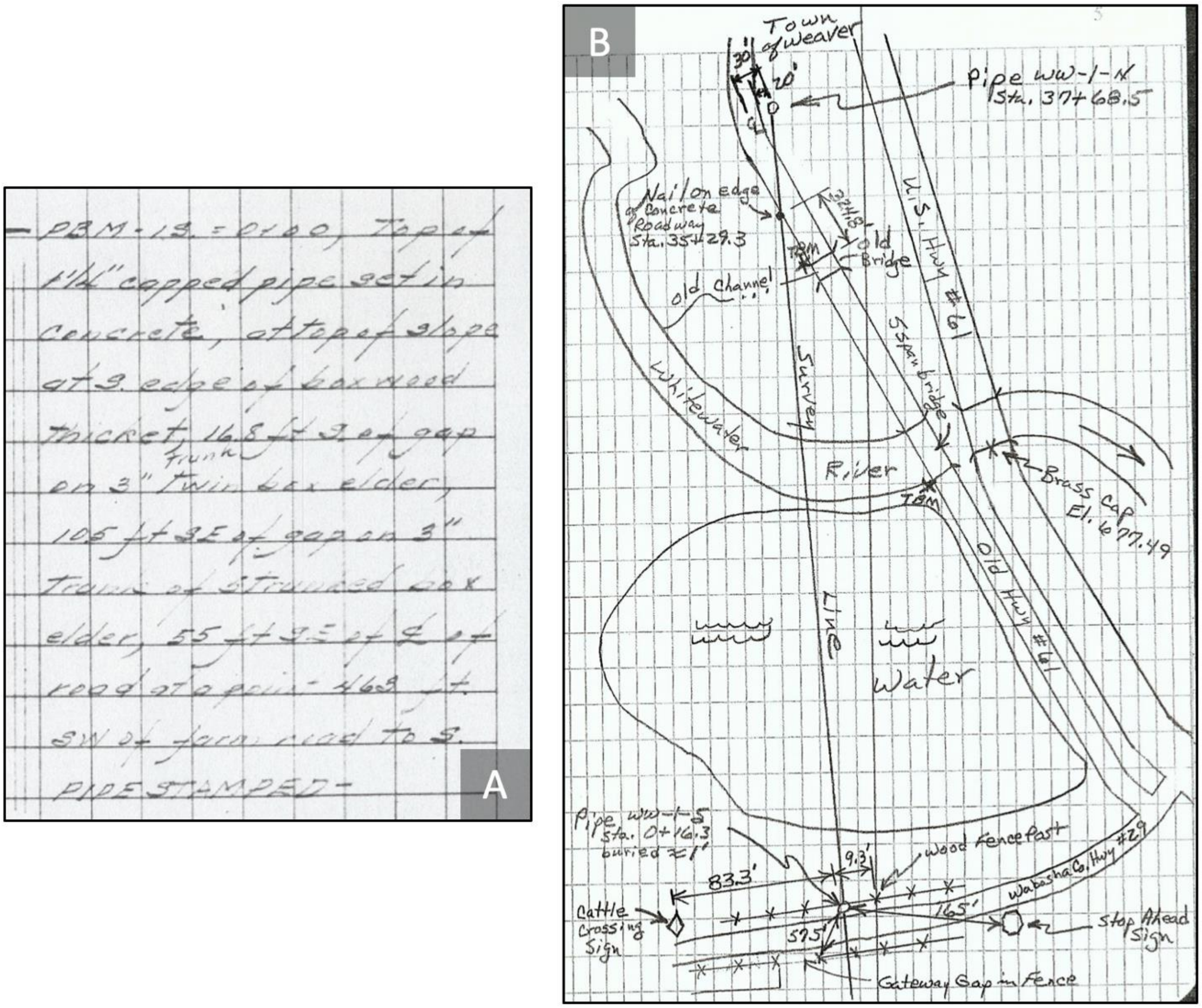
Since 1925, leveling accuracy standards based on closure have been developed for federal surveying and mapping endeavors. In order of decreasing accuracy, these standards are classified as either first, second, third, or fourth order leveling (Brinker & Wolf, 1984) and are primarily based on limits of closure from 0.5 cm to 1.5 cm. Fourth order limits include any closure beyond 1.5 cm. These limits demonstrate the necessity of maintaining precise readings throughout a bench level as individual, seemingly insignificant, errors may accumulate to produce improper closure (Beaman, 1928).

We assume that the accuracy of field survey data collected in the Whitewater watershed are of at least fourth order. Happ (1939) instructs that surveyors performing stream and valley sedimentation surveys tie in elevations with fourth order bench level circuits, so this is a reasonable assumption. Though this is the lowest order of accuracy it is considered appropriate for applications in soil and water conservation work (Brinker & Wolf, 1984).

Despite our assumption, many ranges from each survey period had closures much smaller than fourth order tolerances and often approached those of first and second order. Some even exceed first order tolerances with closures of 0.3 cm. So, it appears that no matter the chosen leveling order, maintaining the highest possible survey accuracy was important to early and late surveyors. This is confirmed anecdotally by Trimble (2008) for the early period coinciding with the first two surveys. Having worked with Happ in Coon Creek, Trimble (2008) spoke to his high measurement standards, especially when closing level lines. Witzgall, an engineer heavily involved in the Whitewater watershed surveys, had a similarly strong penchant for measurement accuracy, and was said to have frequently closed long lines with less than 0.03 cm of error (Trimble, 2008). We assume that mean sedimentation rates calculated from survey cross-sections have low uncertainty—the lowest of any data type. This can be quantified through propagation of errors by more thoroughly investigating the closure error of the Whitewater River range surveys, which may be found in the field notebooks.

Monument reestablishment

Survey range monuments were reestablished when they were made irrecoverable due to damage or destruction. Reestablishment during the first resurvey in 1964 would typically involve a complete replacement of the benchmark—a new capped pipe set in concrete—while subsequent reestablishments more often involved driving a length of rebar into the ground. Either way, the positions of the replacement monument was triangulated through field notes, sometimes successive years of field notes where replacement had to be undertaken more than once (**Figure 31**). Since witness trees and other landscape features originally used to identify monument positions have disappeared, it is possible that replacements do not perfectly coincide with original monument positions. Most often, only one benchmark needs to be reestablished, and this may minutely rotate a range from its original bearing. Because of the length of time this study has persisted, monument shift by reestablishment is unavoidable, and we assume that it does not have a measurable effect on mean sedimentation rates, particularly because the induced angular range rotation is much smaller than the length of the range.



PBM-1S = 0+00, Top of
1¼" capped pipe set in
concrete, at top of slope
at S. edge of boxwood
thicket, 16.8 ft S.E. of gap
trunk
on 3" twin box elder,
105 ft S.E of gap on 3"
trunk of stranded box
elder, 55 ft S.E of ℄ of
road at a point 463 ft.
SW of farm road to S.
PIPE STAMPED-

Figure 31. Historical field notes yield a wealth of context. Samples of monument position information from field notes. **A:** Text description of location of monument 1S on Main Stem 1 (Sept. 18, 1939). Note the monument description and use of local trees as conspicuous features, “1 1/4” [in] capped pipe set in concrete, at top of slope at S. edge of boxwood thicket.” **B:** Map of Main Stem 1 including monument positions and relevant geographic features. North points up in the map and monument 1S can be found at the bottom end of the range (Feb. 3, 1994).

Efforts to eliminate this complication should focus on updating monument coordinate data and public engagement. The field notes contain a wealth of knowledge on benchmark positions and how to locate them but are generally made obsolete by the time of the next survey due to human activity. Svien’s (2012) set of GPS points augments that knowledge by enabling an investigator to walk right up to a monument in the field. These points should be resurveyed with high grade equipment of contemporary accuracy and precision and new notes detailing their locations and local conditions should be developed to further assist in future recovery. We also recommend public engagement to better inform residents and local governmental agencies of the monuments' purpose. Svien (2012) provides insight into the state of public's knowledge of these objects ca. 2010, "Some [people] were well versed in what they were and what they represent while others... had been mowing and trimming around them for 25+ years, never knowing what they were or why they existed." It's likely that many monuments were destroyed because of this unfamiliarity.

Landform inclusion

Mean sedimentation rates calculated from cross-sections are averaged along the entire extent of the transect that coincides between the two surveys of note and therefore includes calculations from landforms other than the floodplain. These landforms include valley hillslopes and human-built levees and roads, which means our rates capture processes that do not relate solely to floodplain sedimentation or erosion. We assume that the positions and geometries of these features on an individual transect are, in general, temporally invariant, e.g., hillslopes stay in the same place over time. This will yield many small sedimentation rates at interpolation points which will contribute to reducing the mean sedimentation rate for the transect. Because the lateral extent on a transect of non-floodplain features is typically much smaller than that of the floodplain itself, we believe this effect to be small. Rates calculated for the first time interval are least affected by this because the 1855 cross-section encompasses the floodplain alone. Future research should remove these features from analysis when an isolation of floodplain processes is crucial.

Aerial lidar survey

Measurement accuracy

Cross-sections for 2008 are sampled on a 1 m DEM derived from the 2008 lidar collection in southeast Minnesota. The quality of this kind of elevation product is principally described by its vertical accuracy. According to the lidar metadata provided by the Minnesota Department of Natural Resources, the fundamental vertical accuracy of this data—that which allows comparison to other datasets (ASPRS, 2004)—is 0.161 m. Vertical accuracy is lower for transects under dense canopy because lidar pulses refracted off trees reduce ground point density (Dietterick et al., 2010.). This should occur in the middle gorges of the Whitewater where forest covers all but the very centers of stream channels when observed directly overhead. Lidar was collected in leaf-off conditions to maximize canopy penetration and the data's supplemental vertical accuracy reported for forest cover are only marginally lower at 0.165 m, so the effect of trees on DEM elevations are likely small. Nevertheless, lidar cross-sections yield the coarsest resolution elevation data used in this study and likely overestimate mean sedimentation rates for the fourth time interval. Svien (2012) created similar lidar cross-sections to calculate floodplain fill volumes and noted that this coarse resolution yielded great variability in adjacent point elevations over relatively small lateral distances. He attributed this to the presence of heavy reed canarygrass cover (Svien, 2012) that has proliferated through the lower valley bottomlands following Euro-American land abandonment (DeLaundreau, 2018).

Measurement limitations

The 2008 lidar system's inability to gather information underwater also effects how we calculate mean sedimentation rates and results. Underwater topography is not sampled by a lidar scanner because the water's surface effectively reflects laser pulses back to the sensor and scatters the rest. Therefore, all water features on a transect show up as a flat, horizontal line at the elevation of the water level. Note that the presence of herbaceous vegetation in wetlands will cause this line to deviate from perfectly flat. Calculating sedimentation rates along these features would yield anomalous aggradation rates. For this reason, we excluded wetlands from our analysis, but the water-filled portions of stream channels remained. This also adds to the uncertainty of mean sedimentation rates for the last time interval from measurement resolution because net aggradation is measured in most channels; however, because the channel is much narrower than the floodplain this effect is believed to be small. For future lidar collections, this water induced limitation can be overcome with accompanying bathymetric surveys of the riverbed and wetlands though survey timing would be crucial.

Digitization quality

Despite the above measurement accuracy concerns, the quality of our lidar cross-sections is primarily controlled by the quality of transect digitization. The 2008 cross-sections were modeled after the 1994 lines, which were themselves digitized from the monument coordinates. Therefore, coordinate quality controls the digitization of the 2008 cross-section. Svien (2012) reported that the horizontal positional uncertainty of points captured with conventional GPS units was around 0.5 to 3 m. The measurement uncertainty of coordinates captured with GNSS units are unreported, though are believed to be less given the equipment’s greater precision. These uncertainties have laterally shifted most of the lidar cross-sections to some extent. This leaves landscape features that can be reasonably assumed to be temporally invariant at this timescale, such as stable hillslopes, misaligned. Cross-sections in the Main Stem appear to have very little or no shift but others, such as those in the North Fork, were shifted significantly enough to warrant their resulting sedimentation rates be thrown out. Because cross-sectional shift is often greater than the horizontal accuracy of the DEM—about 0.4 m—it is believed to have a greater effect on our calculation of mean sedimentation rates. Digitization can be improved with greater quality monument coordinates and by developing a methodology to perform corrective lateral transformations on cross-sections to realign landforms. Lidar cross-section data coverage should also be expanded further up valley to the heads of each stream on the ranges whose survey data remain in local elevation systems. The added results would provide valuable insight into sedimentation on the upland and middle gorges for time interval 4 and help us understand why rates have increased in the lower valley.

Source data improvement

We have made numerous recommendations for improving the quality of the SCS survey data used in this research and further suggest performing double entry data verification to improve data entry accuracy. Double entry involves entering the data of interest a second time and comparing the new entry to the original to ensure that they match. This is often lauded as the most accurate data verification method because of this built-in check (Barchard & Verenikina, 2013). One study by Barchard and Pace (2011) even found that double entry can yield almost 3000% fewer errors than a single round of visual checking—the method used in this research. Because the data must be entered twice, double entry costs much more time than any other verification method but we consider its high level of error capture as an appropriate tradeoff.

Statistical power

Mean sedimentation rates were collected into sample groups by time interval and subjected to a suite of statistical tests to determine whether there is a statistical change through time. In sequence, we tested sample normality, group homoscedasticity (variance equality), and mean equality with omnibus and post-hoc pairwise comparisons. The outcome of each test is reliant upon the significance of their resultant p-values. With reliable data, a significant p-value indicates that there is sufficient evidence to favor the alternate hypothesis and reject the null. On the other hand, a non-significant p-value indicates that there is not enough evidence to support the alternate and we fail to reject the null. Great care must be taken when interpreting these outcomes as the latter could mean either that the null hypotheses is true, or that there is not enough data (evidence) to show that it is false (Rusticus & Lovato, 2014). This second point is related to the concept of statistical power which is defined as the probability of correctly rejecting a false null hypothesis (Serdar et al., 2020). The higher the power, the more likely a given statistical outcome can be trusted.

In general, group sample size is one of the principal controls on statistical power, particularly for the outcome of normality tests (Serdar et al., 2020). This has implications for the reliability of hypothesis testing with any one-way ANOVA—including Welch's ANOVA—since it assumes that samples come from normal distributions. Assessing normality is relatively simple with there being several quantitative tests available; however, their power when performed on small samples is generally low and they generally pass the test regardless of the distribution shape (Ghasemi & Zahediasl, 2012). This could lead to erroneous conclusions in the tributary valleys of the Whitewater watershed where group sample sizes are as low as 3. Indeed, every applicable Shapiro-Wilk test in Dry, Logan, Beaver, and Trout Creeks indicate the groups are normally distributed. Power can be increased by increasing sample size but given that contemporary research with historical data is dependent upon previous collection efforts—sometimes taking place decades earlier—this is not a likely possibility (Serdar et al., 2020).

It may be prudent to perform an equivalent non-parametric test which lack a normality requirement when group sample sizes are small. In this case, one could use the Kruskal-Wallis test (which also allows for departures from equal variance; Guo et al, 2013). Application of this test is most often followed by Dunn's pairwise multiple comparison test (Ruxton & Beauchamp, 2008). Unfortunately, the Kruskal-Wallis test also has a sample size restriction of 5, which still exceeds that of some of our samples. Turner et al. (2020) suggests another alternative when concerned with the normality assumption: perform both test types (parametric and nonparametric), and if they yield similar results there is reassurance that the parametric test is reliable and may be used. Parametric tests are favored here since they should always have more power than their non-parametric equivalent because they use more information about the data to draw conclusions (Turner et al., 2020). Despite the group sample size restriction of some of our data, we performed this comparison and concluded that parametric ANOVA was an appropriate test which was further refined to Welch's ANOVA after variance inequality was discovered among the sample groups of South and North Forks.

Sample size limitations on the statistical power of normality tests can also be overcome through the Central Limit Theorem. This allows samples to violate the normality assumption when they contain at least 30–40 observations and allows parametric procedures to be used without diminished reliability (Schuenemeyer & Drew, 2011). When sample size exceeds 100 this violation becomes largely insignificant (Öztuna et al., 2006). The sample groups used for tests at the whole basin scale all meet or exceed 30 observations—they approach 100 for the first three time intervals—so we are confident in the power of their mean comparison tests. To improve test power at smaller spatial scales we recommend taking advantage of the benefits of the Central Limit Theorem by grouping data to synthetically increase sample size. In the

Whitewater watershed, if interested in sedimentation at the river scale, this could be accomplished by grouping transect sedimentation rates by subbasin, though, one would lose insight into the complexity of sedimentation between rivers. Results from Dry and Logan Creeks could be grouped with those from the North Fork and a similar design could be established for the Main Stem, Beaver Creek, and Trout Creek. Given the spatial distribution patterns of sedimentation rates between the uplands, middle gorge, and lower valley, grouping data by topographic division could also be satisfactory and yield greater sample sizes.

Sedimentation rate change

1939-1994 decrease

Stream and valley sedimentation rates are tied to the volume of sediment that is available for downslope transport that is more than a stream's transport capacity. Our recounting of the Euro-American history of the Whitewater River Watershed has demonstrated the profound effect that improper farming and grazing practices can have on sediment availability; the more intensive the land use, the more susceptible the soil is to erosion by runoff and the greater the downslope sedimentation. In theory, controlling accelerated sedimentation should be possible by controlling accelerated sediment erosion, in this case through soil conservation.

Throughout the 1930s, the SES and SCS began efforts to combat soil erosion on farmland in the Upper Mississippi River Basin through the largely successful Coon Creek Demonstration Project. Trimble and Lund (1982) reported a significant reduction in erosion and sedimentation in the Coon Creek watershed between 1935 and 1975 following the widespread implementation of soil conservation measures through this project. They also noted that this decrease occurred even though the proportion of cropland and grazing land in the watershed did not change appreciably over the intervening 4 decades. Therefore, they concluded that improved land management practices were responsible for the measured decrease in sedimentation conditions (Trimble & Lund, 1982). Helms et al. (1996) extends this discussion to the greater Upper Mississippi River Basin and use the Universal Soil Loss Equation to calculate that erosion from all croplands should have halved between 1930 and 1992 from 54 to 26 million metric tons/yr.

We assume that the decreasing mean sedimentation rates observed in the Whitewater watershed from 1939 to 1994 are also the result of improved agricultural land management through soil conservation. This is a reasonable assumption given the abundant regional evidence corroborating that relationship but there is also a local precedent through basin and state led initiatives. The Whitewater Soil and Water Conservation District formed in the early 1940s and actively brought erosion control practices to the Whitewater watershed (DeLaundreau, 2018). Later, laws like Public Law 566 in the 1950s and 1960s further supported Minnesota farmers in their efforts to conserve soil by helping them build check dams and stabilize gullies and streambanks (Vondracek, 2019).

The observed decrease of mean sedimentation rates from 1939 to 1994 also occurs despite reported time interval bias dubbed the Sadler effect (Romans, 2007). Sadler (1981) compiled about 25,000 sedimentation rates from samples representing various time intervals and yielded a robust negative accumulation trend with increasing time duration. This was attributed in part to sediment compaction via burial but primarily to the spasmodic nature of depositional events and the fact that greater time intervals naturally invite more erosion. This trend is not present in our results. The greatest time interval, the 84 years between 1855 and 1939 yield the greatest sedimentation rates while the subsequent, shorter time intervals of 25 and 30 years yielded much lower rates.

1994-2008 increase

For the streams with completed 2008 cross-section coverage, mean sedimentation rates increase significantly from 1994 to 2008. The average Main Stem rate doubles from 0.71 to 1.49 cm/yr Trout Creek's changes from -0.22 to 0.87 cm/yr. This may be due to an intensification of food production activities that have been observed in the last few decades. Svien (2012) shares that, ca. 2010, watershed farms had been moving towards more intensive row cropping and dairy farms were consolidating into larger operations with a greater impact on erosion. He also speculates that economic drivers had pushed many farmers to remove certain conservation measures to improve work efficiency and income. This has been confirmed anecdotally through conversations with local public lands personnel. Despite this seeming reversal, soil conservation remains important in the basin. Since the mid-1990s state and local government agencies have implemented erosion control measures such as sediment basins and farm terraces and in 2009 a farmer led council of the Whitewater River watershed—the first of its kind in the state—was established to better control runoff from agricultural fields (Willette, 2012).

Another potential cause for increasing sedimentation rates during this time interval are large floods. Rates of overbank sedimentation, such as those calculated from the survey transects of the Whitewater River valley, have long been recognized to reflect the magnitude and frequency of floods (Wolman & Leopold, 1957). The larger the flood, the more sediment is likely to be deposited on the floodplain, and an especially powerful flood event occurred in 2007 (Nelson, 2019). This flood was caused by record setting precipitation that dropped 20–35 cm of rain in the headwaters of the Whitewater River alone (Trimble, 2013). Damage to buildings, bridges, and roads were significant and the storm even claimed lives (Svien, 2012). The flood also caused significant geomorphic change: a section of the Middle Fork in Whitewater State

Park laterally migrated by about 30 m (Stachura, 2008) and relict gullies—long stabilized by decades of conservation—reactivated from the heavy rainfall (Trimble, 2013).

Trimble (2013) investigated the area shortly after the storm and noted some of the flood's impacts. Floodplain deposition was significant but with irregular distributions up to 60 cm thick. Bank erosion was also severe, particularly where rain was the greatest on upland reaches of the Whitewater River. Perhaps most significantly, Trimble (2013) found no visible rill or gully erosion on fields that utilized no-till farming, even where precipitation was most severe, indicating the power of the soil conservation measures implemented throughout the basin. We believe that most of the added sedimentation recorded between 1994 and 2008 in the Whitewater watershed are due to overbank sedimentation from this flood event. Extending the 2008 cross-sections upstream to the headwaters of the Whitewater River may capture net erosional ranges because of the reported severity of upstream lateral incision and may therefore provide insight into the sources of this increased lower valley sedimentation.

Other high-impact floods of note occurred in 1974, 1975, and 1978 (Nelson, 2019). Range 11B in Elba was resurveyed in the latter two years, however, the 1978 resurvey unfortunately predates that year's storm by a few weeks, so the effect of the flood could not be gauged. The 1974 and 1975 storms both dropped about 6 cm of rain centered on the town of Eyota on the uplands of the South Fork, and in Whitewater State Park on the Middle Fork, respectively (Welvaert, 2004). **Table 4** indicates that these two flood events had little effect on mean sedimentation rates on Main Stem 11B since rates continue to decrease considerably up to 1994. It is difficult to extrapolate conclusions from these singular calculations, but the different outcomes of these large floods on sedimentation rates may indicate that the nature of floods—their magnitude, frequency, and effect on the landscape—are changing.

Table 4. Mean sedimentation rates (cm/yr) - Main Stem 11B

1855–1939	1939–1964	1964–1975	1975–1978	1978–1994	1994–2008
1.903	1.633	0.743	0.200	-0.078	0.426

Future research

Land use has significantly controlled landscape erosion and sedimentation rates in the Whitewater River watershed but has not been investigated in detail. We propose conducting land use and land cover change detection analyses to quantify the effects of changing land use on sedimentation rates since the early 20th century to the present. The Whitewater watershed area has exceptional aerial photo coverage with near decadal temporal resolution starting from 1936. Collection dates also closely coincide with each of our survey periods so the timing of land use and sedimentation changes can be appropriately constrained. Land use and cover changes before 1936, during the early and middle stages of intensive Euro-American agriculture, could also be investigated through governmental plat and surveyor maps and notes.

Climate change is also likely exerting greater control on sedimentation rates in southeastern Minnesota as average annual rainfall and the frequency of high magnitude floods increase (Reed et al., 2020). Without proper adaptation to these conditions, such as more intensive soil conservation measures, soil erosion rates are projected to double in the Upper Mississippi River basin in the next few decades (Belby et al., 2019). Therefore, the effect of large floods in the Whitewater should be investigated.

Patterns of floodplain storage

Magilligan (1985) suggested that patterns of floodplain sediment storage could be explained by valley width through his investigations of the distribution of ELS in the Galena River watershed. Along the Galena River, floodplains narrow where the resistant Galena dolostone form the valley walls adjacent to the river. During a high magnitude flood, the valley acts as a channel and these constrictions increase flow velocities and depths to maintain flow continuity. An increase in the speed and depth of the flow increases its ability to transport sediment which may reduce deposition or cause erosion. Further downstream, when floodwaters escape this constriction and spread throughout a wider valley, flow velocity and depths should decrease and promote deposition on the floodplain (Magilligan, 1985). Therefore, wider valleys have deeper overbank flood deposits than narrow ones and the latter should be more likely to have reaches that experience net erosion. This model, therefore, has direct implications for stream and valley sedimentation rates.

Strong controls on the distribution of floodplain sediment due to valley width has been observed elsewhere in the Upper Mississippi River Basin and likely controls sedimentation rates in the Whitewater River watershed. Indeed, each time period included in our analysis yielded sedimentation rates that conform to Magilligan's (1985) model. The middle gorges of the Whitewater streams are characterized by a valley constriction and are also typically the locations of least deposition as well as some of the only areas that record net erosion, overall. The lower valley, immediately below the middle gorge, has very wide floodplains and in all time intervals has the greatest sedimentation rates.

Lecce (1997) further contributed to this model by investigating the role of valley cross-sectional stream power in the Blue River watershed in Wisconsin. This basin has a topography, geology, and history like the Galena and Whitewater River valleys. He showed that historical floodplain sediment storage decreases with increasing cross-sectional stream power which inversely corresponds to valley width. As we have discussed above, relatively narrow valleys have higher flood velocities and therefore greater cross-sectional stream power and can more effectively transport sediment downstream and, locally, deposit very little material. Wide valleys, on the other hand, have lower flood velocities and lower cross-sectional stream power and without the capacity to continue sustaining sediment transport, deposit its sediment load (Lecce, 1997). Clearly, the controls of valley width on sedimentation are inherently intertwined with that of stream power.

Valley slope, or gradient, also effects cross-sectional stream power by changing flow velocities through the force of gravity. We see gradient effect sedimentation in the Whitewater watershed at the confluences of the three forks. Here, each fork enters the Main Stem valley, which has a much gentler gradient and encourages deposition. This zone of high deposition rates disappears in the third time interval which may suggest that upstream sediment sources have ceased producing material.

Gradient further controls sedimentation in the lower valley of the Whitewater River through the backwater formed by the construction of Lock and Dam No. 5 on the Mississippi River in 1935 (US Army Corps of Engineers, n.d.). This dam inundated the Mississippi floodplain with Pool 5, to which the Whitewater now drains. The water surface of Pool 5 is higher than that of the original channel, thereby raising the base-level of the Whitewater River (Fremling et al., 1973). This has effectively reduced the gradient of the Main Stem (Knox, 2006) which induces aggradation and much further upstream than it would have occurred under more natural conditions pre-dam (Fremling et al., 1973). This backwater effect on base-level likely explains the pattern of increasing sedimentation rates in the lower reaches of the Main Stem observed since 1964.

This description of some of the spatial controls on overbank floodplain sedimentation has focused on how floodwaters are routed through the valleys due to their geometry, but the geometry of a river channel itself has been shown to be equally as important. The capacity of a meander belt—channel enlarged through lateral erosion and confined between terraces or valley walls—has been suggested by Woltemade (1994) as potentially having greater consequences for flood routing and overbank sedimentation than valley geometries. An enlarged section of a channel may preclude flooding entirely, as it is better equipped to convey floodwaters downstream (Lecce, 1997). Therefore, one can expect less sedimentation where channels are enlarged. The same can be said channels enlarged by vertical incision (Faulkner, 1998). Lecce (1997) observed that meander belts formed in all reaches of the Blue River except in the lower valley. This encouraged little sedimentation in the upland and middle gorges and deposition in the lower valley as its smaller channel was incapable of conveying floodwaters that spread over the floodplain and deposited its load. The channels of the Whitewater River also exhibit enlargement over time, through both lateral erosion and vertical incision, and may be partially responsible for flushing sediment through the system and yielding the great reduction in sedimentation observed by 1994.

Future research

The spatial distribution of ELS and later floodplain deposits in the Whitewater River watershed should be investigated in relation to the valley and channel geometry traits noted above. Valley geometry characteristics such as floodplain width and gradient could be collected in the field or through GIS and the cross-sections can provide insight into channel geometry changes. Magilligan (1985) and Lecce (1997) perform linear regression analysis to investigate the correlation between these traits and sedimentation and similar methods could be used in the Whitewater basin.

References

Andreas, A. T. (1874). An Illustrated Historical Atlas of the State of Minnesota.

ASPRS. (2004). *ASPRS Guidelines Vertical Accuracy Reporting for Lidar Data.*

94

Barchard, K. A., & Pace, L. A. (2011). Preventing human error: The impact of data entry methods on data accuracy and statistical results. *Computers in Human Behavior*, *29*, 1917–1922. http://dx.doi.org/10.1016/j.chb.2013.

Barchard, K. A. & Verenikina, Y. (2013). Improving data accuracy: Selecting the best data checking technique. *Computers in Human Behavior*, *29,* 1917–1922. http://dx.doi.org/10.1016/j.chb.2013.02.021

Beaman, W. M. (1928). *Topographic instructions of the United States Geological Survey. Topographic mapping.* United States Geological Survey.

Belby, C. S., Spigel, L. J., & Fitzpatrick, F. A. (2019). Historic changes to floodplain systems in the Driftless Area. *The Geological Society of America Special Paper 543*, 119–145. https://doi.org/10.1130/2019.2543(07)

Brinker, R. C., and Wolf, P. R. (1984). *Elementary Surveying.* Harper & Row.

Bonsteel, J. A. (1912). Soils of the Eastern United States and Their Use – XXXIX Meadow. *U.S. Bureau of Soils Circulation, 68.*

Brown, M. H. and Nygard, I. J. (1941). *Erosion and Related Land Use Conditions in Winona County Minnesota, Erosion Survey No. 17.* United States Department of Agriculture Soil Conservation Service.

Celik, N. (2020). Welch's ANOVA: Heteroskedastic skew-t error terms. *Communications in Statistics – Theory and Methods*, *51*(9), 3065–3076. https://doi.org/10.1080/03610926.2020.1788085

Chamberlin, T. C. (1909). Soil Wastage. *Proceedings of a conference of Governors in the White House, May 13–15, 1908.*

Crutzen, P. J. (2002). Geology of mankind. *Nature*, *415*, 23.

DeLaundreau, M. (2018). Fields: The Transformation and healing of the. Whitewater Valley. *Open Rivers: Rethinking Water, Place & Community, 20*.

Dietterick, B., White, R., & Hillburn, R. (2010). Comparing LiDAR-Generated to Ground-Surveyed Channel Cross-Sectional Profiles in a Forested Mountain Stream.

Dotterwiech, M. (2013). The history of human-induced soil erosion: Geomorphic legacies, early descriptions and research, and the development of soil conservation—A global synopsis. *Geomorphology, 201*, 1–34. https://dx.doi.org/10.1016/j.geomroph.2013.07.021

Faulkner, D. J. (2015). Historical Agriculture and Soil Erosion in the Upper Mississippi Valley Hill Country. *The AAG Review of Books, 3*(1), 27–29. https://doi.org/10.1080/2325548X.2015.985536

Fremling, C. R., Gray, D. V., & Nielsen, D. N. (1973). Environmental Impact Assessment Study Pool 4 of Northern Section of the Upper Mississippi River. *US Army Corps of Engineers.*

Geiger Jr., R. L. (1955). *A chronological history of the soil conservation service and related events; U.S. Soil Conservation Service.* United States Soil Conservation Service.

Ghasemi, A. and Zahediasl, S. (2012). Normality Tests for Statistical Analysis: A Guide for Non-Statisticians. *International Journal of Endocrinology & Metabolism, 10*(2), 486–489. https://doi.org/19.5812/ijem.3505

Glbert, G. K. (1917). *Hydraulic-mining debris in the Sierra Nevada.* United States Geological Survey Professional Paper 105.

Guo, A., Zhong, S, & Zhang, A. (2013). Privacy-preserving Kruskal-Wallis test. *Computer Methods and Programs in Biomedicine, 112*(1), 135145. https://doi.org/10.1016/j.cmpb.2013.05.023

Goudie, A. (2020). The human impact in geomorphology – 50 years of change. *Geomorphology, 366*. https://doi.org/0.1016/j.geomorph.2018.12.002

Happ, S. C. (1939). *Instructions for Stream and Valley Sedimentation Surveys.* United States Department of Agriculture Soil Conservation Service.

Happ, S. C. (1940). *Sedimentation Related to Flood Problems in the Whitewater River Valley, Minnesota.* United States Department of Agriculture Soil Conservation Service.

Happ, S. C. (1944). Effect of Sedimentation on Floods in the Kickapoo Valley, Wisconsin. *The Journal of Geology*, *52*(1), 53–68. https://www.jstor.org/stable/30063357

Happ, S. C. (1948). Sedimentation in the Middle Rio Grande Valley, New Mexico. *Bulletin of the Geological Society of America, 50*, 1191–1218.

Happ, S. C. (1970). *North Tippah Valley Sedimentation Survey*. United States Department of Agriculture Soil Conservation Service.

Happ, S. C. (1975). Present and prospective technology for predicting sediment yield and sources. *Proceedings of the Sediment-Yield Workshop, USDA Sedimentation Laboratory, Oxford, Mississippi, November 28–30, 1972.* https://hdl.handle.net/2027/uiug.30112004283039

Happ, S. C., Rittenhouse, G., & Dobson, G. C. (1940). *Some Principles of Accelerated Stream and Valley Sedimentation.* United States Department of Agriculture.

Helms, J. D., Pavelis, G. A., Argabright, S., Cronshey, R. G., & Sinclair Jr., H. R. (1996). National Soil Conservation Policies: A Historical Case Study of the Driftless Area. *Agricultural History*, *70*(2), 377–394. https://www.jstor.org/stable/3744543

Heynan, W. J. (1981). *Preliminary Inventory of the Cartographic Records of the Soil Conservation Service.* National Archives & Records Service General Services Administration.

Holger, S. (2019). Whitewater State Park: 100 Years in Paradise. *Open Rivers: Rethinking Water, Place & Community*, *15*. https://doi.org/10.24926/2471190X.6512

James, L. A. (2013). Legacy sediment: Definitions and processes of episodically produced anthropogenic sediment. *Anthropocene*, *2*, 16–26. https://doi.org/10.1016/j.ancene.2013.04.001

Johnson, H. B. (1957). Rational and Ecological Aspects of the Quarter Section: An Example From Minnesota. *Geographical Review*, *47*(3), 330–348.

Johnson, H. B. (1976). *Order Upon the Land: The U.S. Rectangular Land Survey and the Upper Mississippi Country*. Oxford University Press.

Kemp, D. B., Sadler, P. M., & Vanacker, V. (2020). The human impact on North American erosion, sediment transfer, and storage in a geologic context. *Nature Communications*. https://doi.org/10.1038/s41467-020-19744-3

Knox, J. C. (2006). Floodplain sedimentation in the Upper Mississippi Valley: Natural versus human accelerated. *Geomorphology, 79*, 286–310. https://doi.org/10.1016/j.geomorph.2006.06.031

Kunsman, H. S. (1944). *Stream and Valley Sedimentation in Beaver Creek Valley, Wisconsin* [Unpublished master's thesis]. University of Wisconsin.

Lecce, S. A. (1997). Spatial patterns of historical overbank sedimentation and floodplain evolution, Blue River, Wisconsin. *Geomorphology, 18*, 265–277.

Magilligan, F. J. (1985). Sedimentation in the Galena River Basin, Wisconsin and Illinois. *Annals of the Association of American Geographers, 75*(4), 583–594. https://www.jstor.org/stable/2563114

McKelvey, V. E. (1939). *Stream and valley sedimentation in the Coon Creek Drainage basin, Wisconsin* [Unpublished master's thesis]. University of Wisconsin.

Moore, T. (1801). *The Great Error of American Agriculture Exposed; And Hints for Improvement Suggested.* Bonsal and Niles.

Nelson, P. (2019). 'The Paradise of Minnesota': The history of Whitewater State Park. *MinnPost*. https://www.minnpost.com/mnopedia/2019/10/the-paradise-of-minnesota-the-history-of-whitewater-state-park/

Nerbonne, B. A., & Vondracek, B. (2001). Effects of Local Land Use on Physical Habitat, Benthic Macroinvertebrates, and Fish in the Whitewater River, Minnesota, USA. *Environmental Management, 28*(1), 87–99. https://doi.org/10.1007//s002670010209

NRCS. (2006). Engineering Field Handbook.

Öztuna, D., Elha, A. H., & Tüccar, E. (2006). Investigation of Four Different Normality Tests in Terms of Type 1 Error Rate and Power under Different Distributions. *Turkish Journal of Medicine*, *36*(3), 171–176.

Pearson, C. and Mick, D. (2008). Height Datums on the Mississippi and Illinois River Systems: An Inconvenient Feast. *Surveying and Land Information Science*, *68*(1), 15–19.

Portenga, E. W., Westaway, K. E., & Bishop, P. (2016). Timing of post-European settlement alluvium deposition in SE Australia: A legacy of European land-use in the Goulburn Plains. *The Holocene*, *26*(9), 14721485. https://doi.org/10.1177/0959683616640047

Richardson, J. M., Fuller, I. C., Holt, K. A., Litchfield, N. J., and Macklin, M. G. (2014). Rapid post-settlement floodplain accumulation in Northland, New Zealand. *Catena*, *113*, 292–305. http://dx.doi.org/10.1016/j.catena.2013.08.013

Reed, T., Mason, L. R., & Ekenga, C. C. (2020). Adapting to Climate Change in the Upper Mississippi River Basin: Exploring Stakeholder Perspectives on River System Management and Flood Risk Reduction. *Environmental Health Insight*, *14*. https://doi.org/10.1177/1178630220984153

Romans, B. (2007, July). Sediment accumulation rates and bias: The Sadler effect. *Wired.* https://www.wired.com/2007/07/sediment-accumulation-rates-and-bias-the-sadler-effect/

Runkel, A. C. (1996). The Geology of Whitewater State Park. *Minnesota Geological Survey Educational Series 9.*

Rusticus, S. A., & Lovato, C. Y. (2014). Impact of Sample Size and Variability on the Power and Type I Error Rates of Equivalence Tests: A Simulation Study. *Practical Assessment, Research, and Evaluation, 19*.

Ruxton, G. D., & Beauchamp, G. (2008). Time for some a priori thinking about post hoc testing. *Behavioral Ecology*. https://doi.org/beheco/arn020

Sadler, P. M. (1981). Sediment Accumulation Rates and the Completeness of Stratigraphic Sections. *The Journal of Geology*, *89*(5), 569–584. https://www.jstor.org/stable/30062397

Serdar, C. C., Cihan, M., Yücel, D., & Serdar, M. A. (2020). Sample size, power and effect size revisited: simplified and practical approaches in pre-clinical, clinical and laboratory studies. *Biochemical Medicine (Zagreb)*, *31*(1). https://doi.org/10.11613/BM.2021.010502

Schuenemeyer, J. H., & Drew, L. J. (2011). *Statistics for Earth and Environmental Scientists.* John Wiley & Sons, Inc.

Stachura, S. (2008). Whitewater's habitat wakes up post-flood. *MPR News*. https://www.mprnews.org/story/2008/03/06/whitewaterrecovers

Ståhle, L. and Wold, S. (1989). Analysis of Variance (ANOVA). *Chemometrics and Intelligent Laboratory Systems, 6*, 259–272.

Svien, L. (2012). *The Restoration of a Historical Sediment Study and the use of LiDAR in the Determination of Elevations in the Whitewater River Valley* [Unpublished master's thesis]. Pennsylvania State University.

Trimble, S. W. (2008). Happ, S.C., Rittenhouse, G., and Dobson, G.C. 1940: Some principles of accelerated stream and valley sedimentation. US Department of Agriculture Technical Bulletin 695. *Progress in Physical Geography, 32*(3), 337–345. https://doi.org/10.1177/0309133308091947

Trimble, S. W. (2009). Fluvial processes, morphology and sediment budgets in the Coon Creek Basin, WI, USA, 1975–1993. *Geomorphology, 108*(1–2), 8–23. https://doi.org/10.1016/j.geomorph.2006.11.015

Trimble, S. W. (2013). *Historical Agriculture and Soil Erosion in the Upper Mississippi Valley Hill Country*. CRC Press.

Trimble, S. W., & Lund, S. W. (1982). Soil conservation and the reduction of erosion and sedimentation in the Coon Creek Basin, Wisconsin. *United States Geological Survey Professional Paper 1235*. https://doi.org/10.3133/pp1234

Turner, R, Samaranayaka, A., & Cameron, C. (2020). Parametric vs nonparametric statistical methods: which is better, and why? *The New Zealand Student Medical Journal, 30*.

US Army Corps of Engineers. (n.d.) *Lock & Dam 5*. US Army Corps of Engineers. https://www.mvp.usace.army.mil/Missions/Navigation/Locks-Dams/Lock-Dam-5/

Vang, Gia. (20222, February 9). Think African Americans arrived in Minnesota in the 1900s? Think again. KARE 11.

https://www.kare11.com/article/news/local/kare11-sunrise/minnesota-african-american-heritage-museum-and-gallery-black-history-exhibit/89-7c11fd17-094f-46bf-a2c9-c8d8c86e5f99

Vondracek, B. (2019). Driftless Area Land Cover and Land Use. *Annual Driftless Area Symposium Special Publication, February 5–6, 2019.*

Well, A. D., Pollatsek, A., Boyce, S. J. (1990). Understanding the Effects of Sample Size on the Variability of the Mean. *Organizational Behavior and Human Decision Processes*, *47*, 289–312.

Welvaert, M. (2004). Major Historical Floods and Flash Floods in the La Crosse (ARX) Hydrologic Service Area. *Historical Floods for southeast MN, northeast IA, and western WI.* https://www.weather.gov/arx/historicalfloods

Wickert, A. D., Anderson, R. S., Mitrovica, J. X., Naylor, S., and Carson, E. C. (2019). The Mississippi River records glacial-isostatic deformation of North America. *Science Advances, 5*.

Willette, J. K. (2012, March 8). Farmers take lead in Whitewater conservation efforts. *Post Bulletin*. https://www.postbulletin.com/news/farmers-take-lead-in-whitewater-conservation-efforts

Wolman, M. G., & Leopold, L. B. (1957). River flood plains: Some observations on their formation. *United States Geological Survey Professional Paper 282–C*. https://doi.org/10.3133/pp282c

Zenk, D. (2007). *Geodetic History in Minnesota.* Minnesota Department of Transportation Geodetic Services Unit.

Appendices

Table A1. Mean transect sedimentation rates in the Whitewater River Watershed

Data IDs			Mean sedimentation rate (cm/yr)			
River valley	Range	#	1855–1939	1939–1964	1964–1994	1994–2008
Main Stem	1	1	0.57	1.34	1.15	1.77
	2	2	0.83	1.61	1.49	1.90
	3	3	0.95	0.93	1.13	2.24
	4	4	1.14	0.32	0.45	1.86
	4C	5	1.16	0.23	0.35	2.20
	5A	6	1.26	0.77	0.41	1.79
	5C	7	0.81	1.12	0.47	2.91
	7A	8	0.89	1.50	1.04	1.54
	8A	9	0.98	0.72	0.55	0.65
	9A	10	1.48	1.92	0.60	0.47
	10	11	1.72	2.55	0.79	0.45
	10C	12	1.99	1.38	0.49	1.20
	11B	13	1.90	1.63	0.25	0.43
Middle Fork	12B	14	0.76	0.56	0.55	0.69
	13A	15	0.99	-0.99	-2.35	---
	14	16	0.83	-0.28	-0.63	---
	15B	17	0.69	0.46	0.57	---
	17	18	0.64	0.12	-0.05	---
	18	19	0.49	0.21	0.18	---
	20	20	0.44	0.37	0.22	---
	21	21	1.33	-0.39	0.06	---
	23B	22	1.03	-0.61	0.21	---
	24B	23	1.05	-2.20	0.15	---
	26B	24	1.07	0.49	-0.08	---
	27B	25	1.34	-2.59	0.00	---
	28B	26	1.26	-1.56	0.02	---
North Fork	NF-0B	27	1.12	0.70	0.43	-0.15
	NF-1	28	0.65	0.13	0.53	---
	NF-2	29	0.61	0.13	0.38	0.75
	NF-3	30	0.94	0.40	0.16	---
	NF-4	31	0.76	0.71	0.44	---
	NF-5A	32	0.77	0.39	-0.04	---
	NF-6	33	1.44	0.10	-0.31	---
	NF-7	34	0.11	0.26	0.11	---
	NF-8	35	0.69	0.37	0.12	---
	NF-9	36	0.75	0.08	0.33	---
	NF-10	37	0.58	0.09	0.47	---
	NF-13	38	0.66	2.14	0.51	---
	NF-14	39	0.91	0.41	-0.20	---
	NF-17	40	0.90	1.16	0.48	---
	NF-18	41	1.42	-0.61	0.68	---
	NF-21	42	1.09	-0.20	0.11	---
	NF-20	43	1.15	-1.29	0.39	---
	NF-23C	44	0.69	-0.31	0.04	---
	NF-24C	45	0.69	-1.18	0.30	---
	NF-27	46	0.97	-0.16	0.11	---
	NF-28	47	1.01	0.50	0.19	---
	NF-28B	48	0.63	0.00	0.21	---

Table A1. Mean transect sedimentation rates in the Whitewater River Watershed

Data IDs			Mean sedimentation rate (cm/yr)			
River valley	Range	#	1855–1939	1939–1964	1964–1994	1994–2008
South Fork	S-0	1	1.87	2.05	0.21	0.86
	S-0B	2	1.10	1.17	0.21	1.43
	S-1	3	1.51	0.91	0.42	0.80
	S-2	4	0.69	0.29	-0.05	-0.94
	S-3	5	0.47	0.50	0.07	0.03
	S-4	6	0.97	0.05	0.08	-1.11
	SF-5	7	1.11	0.28	0.14	---
	SF-6	8	0.97	---	-0.02	---
	SF-10	9	0.46	0.18	0.21	---
	SF-11	10	0.77	1.31	0.02	---
	SF-13	11	0.49	0.64	-0.22	---
	SF-14	12	0.57	0.08	-0.05	---
	SF-16C	13	---	---	0.10	---
	SF-17	14	---	---	0.53	---
	SF-18C	15	0.58	0.14	-0.52	0.11
	SF-20	16	0.46	0.65	0.12	---
	SF-22	17	---	---	-0.01	---
	SF-23	18	---	---	-0.14	---
	SF-25	19	0.03	0.40	-0.01	0.80
	SF-26	20	0.28	0.47	0.03	---
	SF-28	21	0.34	0.39	0.32	---
Trout Creek	T-0	22	2.20	0.51	0.45	0.55
	T-1	23	1.64	0.04	-0.23	0.71
	T-2	24	---	-0.54	-0.41	1.06
	T-3	25	1.17	-0.18	-0.69	1.15
Beaver Creek	B-0	26	0.92	0.81	0.66	1.40
	B-1	27	1.41	-0.62	0.65	---
	B-2	28	0.90	0.30	-0.16	---
	B-3	29	0.97	0.09	0.50	---
	B-6	30	0.86	0.76	-0.11	---
	B-6C	31	0.54	---	2.13	---
Logan Creek	L-0B	32	1.15	-1.12	0.06	---
	L-0	33	0.89	-0.47	-0.26	---
	L-1	34	0.63	-0.62	-0.03	---
	L-3	35	---	---	0.07	---
	L-4	36	---	---	0.38	---
	L-6	37	1.20	-0.69	0.80	---
	L-7	38	0.76	-0.14	-0.12	---
	L-9	39	---	-0.34	0.06	---
Dry Creek	D-0	40	0.58	-0.24	-0.03	---
	D-1	41	0.75	0.51	0.94	1.19
	D-3	42	0.58	0.37	0.24	---
	D-4	43	0.87	-0.65	0.51	---
	D-6	44	0.52	1.50	0.49	---
	D-7	45	0.82	0.95	-0.17	---
	D-8C	46	---	---	-0.13	---

Table A2. Sample group normality & homoescedasticity results - Whitewater Watershed

Test	Time interval	Parameter	Watershed
Kolmogorov-Smirnov	1855–1939	Test value	0.5227
		P	2E-22
		N	85
	1939–1964	Test value	0.3116
		P	6E-08
		N	85
	1964–1994	Test value	0.3986
		P	5E-14
		N	94
	1994–2008	Test value	3.0013
		P	0.06
		N	30
Levene's	---	Test value	12.2683
		P	1E-07

Table A3. Sample group normality & homoscedasticity results - Whitewater River branches & tributaries

Test	Time interval	Parameter	Middle Fork	South Fork	North Fork	Dry Creek	Logan Creek	Main Stem	Beaver Creek	Trout Creek
Shapiro-Wilk	1855–1939	Test value	0.9455	0.9305	0.9516	0.8936	0.9473	0.9283	0.8959	0.9975
		P	0.53	0.22	0.34	0.34	0.72	0.32	0.35	0.91
		N	13	17	22	6	5	13	6	3
	1939–1964	Test value	0.8750	0.8498	0.9278	0.9846	0.9695	0.9746	0.8676	0.9940
		P	0.06	0.01	0.11	0.97	0.89	0.94	0.22	0.98
		N	13	16	22	6	6	13	5	4
	1964–1994	Test value	0.6682	0.9600	0.9649	0.9176	0.8764	0.8939	0.8417	0.9391
		P	2E-04	0.52	0.59	0.45	0.17	0.11	0.13	0.65
		N	13	21	22	7	8	13	6	4
	1994–2008	Test value	---	0.9119	---	---	---	0.9191	---	0.9155
		P	---	0.37	---	---	---	0.24	---	0.51
		N	1	8	2	1	0	13	1	4
Levene's	---	Test value	2.7396	5.4058	3.2877	3.0013	0.1441	2.0058	1.0813	0.1419
		P	0.06	2E-03	0.03	0.06	0.87	0.13	0.39	0.93