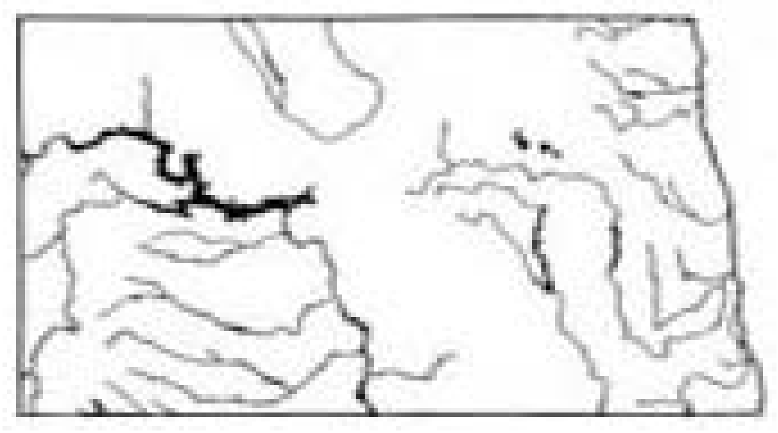

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EFFECT OF GLACIAL ISOSTATIC ADJUSTMENT ON RIVERS AND DRAINAGE BASINS IN THE RED RIVER VALLEY, NORTH DAKOTA AND MINNESOTA, U.S.A.

by

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November 2017

North Dakota Water Resources Research Institute
North Dakota State University, Fargo, North Dakota
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ABSTRACT

This thesis investigates the relationship between glacial isostatic adjustment and watershed asymmetry of tributaries in the Red River Valley, North Dakota, U.S.A. After the draining of glacial Lake Agassiz, drainage networks began to develop and were affected by isostatic adjustment. This adjustment began after the receding of the Laurentide Ice Sheet and is still occurring today, but on a lesser degree. Adjustment in the Red River Valley, which has varied since the ice sheet retreated, is determined from differences in the elevation of the horizontally deposited beach ridges which are the ancestral beaches of glacial Lake Agassiz. The Red River Valley is currently experiencing 1 to 4 mm of uplift per year.

Rivers in the Red River Valley are constantly under continental scale tectonic forces. Little work has been conducted regarding the effect of isostatic adjustment on the pattern of post-glacial rivers and watersheds in the Red River Valley in its entirety. Isostatic adjustment is greatest in the northern Red River Valley where the ice was thickest, which has resulted in greater asymmetry in the watersheds farther north in the valley.

The purpose of this thesis is to determine if watersheds of Red River tributaries within the former glacial Lake Agassiz basin are asymmetric. The study further documented if asymmetry is the result of 1) changing watershed boundary; 2) a shifting river channel position; or 3) a combination of both a changing watershed boundary and a shifting river channel.

Symmetry of each watershed was determined by comparing the following landscape measurements: Transverse Topographic Symmetry Factor (TTSF), Asymmetry Factor (AF), and the total net change in area between pre-adjustment watersheds and current watersheds. Along with the measurements listed above, paleo-channels were identified in the Red River Valley to determine if there has been a uniform shift in drainage between Lake Agassiz stages and isostatic

adjustment. Twelve of the sixteen watersheds analyzed in this thesis have positive TTSF values indicating the main river channel is in the southern portion of the watershed. Watersheds displaying the most asymmetry based on TTSF are farther north in the Red River Valley. Similarly, AF values reveal that the most asymmetric watersheds are also near the northern part of the Red River Valley and suggest greater tilting has occurred, compatible with isostatic adjustment. Furthermore, analysis of the change in watershed boundaries revealed that all but one displayed a northward shift in watershed boundary. Finally, most paleo-channels identified are north of their current river channel showing that rivers have shifted south. This study suggests that asymmetry in the watersheds is the result of a changing watershed boundary and a shift in river position, likely associated with glacial isostatic adjustment. We believe that these methods can be used to investigate isostatic adjustment on tributaries in other landscape settings.

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CHAPTER I

INTRODUCTION

The drainage network in large watersheds develops uniquely because of many factors, including lithology, soils, geological structure, and basin slope (Schumm, 1956). In many tectonically active areas, both epeirogenic and orogenic deformation cause surface-water processes and channel patterns to adjust to new topographic conditions (Burnett and Schumm 1983; Clark et al., 2012; Holbrook and Schumm, 1999; Ibanez et al., 2014). The effects of tectonic forces on channel patterns are found in the early development of drainage (Clark et al., 2012), present drainage patterns (Burnett and Schumm, 1983; Brizga and Finlayson, 1990), and might be observed in the future development of drainage patterns, but not as frequently (Clark et al., 2012).

Untested in the Red River Valley is the notion that large-scale isostatic adjustment of the Earth's crust and mantle following continental glaciation influenced the pattern of incipient post-glacial rivers and their tributaries. During the Pleistocene, large continental ice sheets covered parts of North America and Europe, which exerted downward force and created crustal subsidence. On the North American continent, the Des Moines Lobe and later Red River Lobe of the Laurentide Ice Sheet extended south into the Red River of the North basin during the last glacial maximum (Mickelson and Colgan, 2003) (Figure 1), resulting in crustal subsidence. As continental ice diminished at the end of the epoch, the weight on the crust dissipated rapidly, leaving a broad crustal basin with a gentle slope along its outer margin. Rapid retreat of

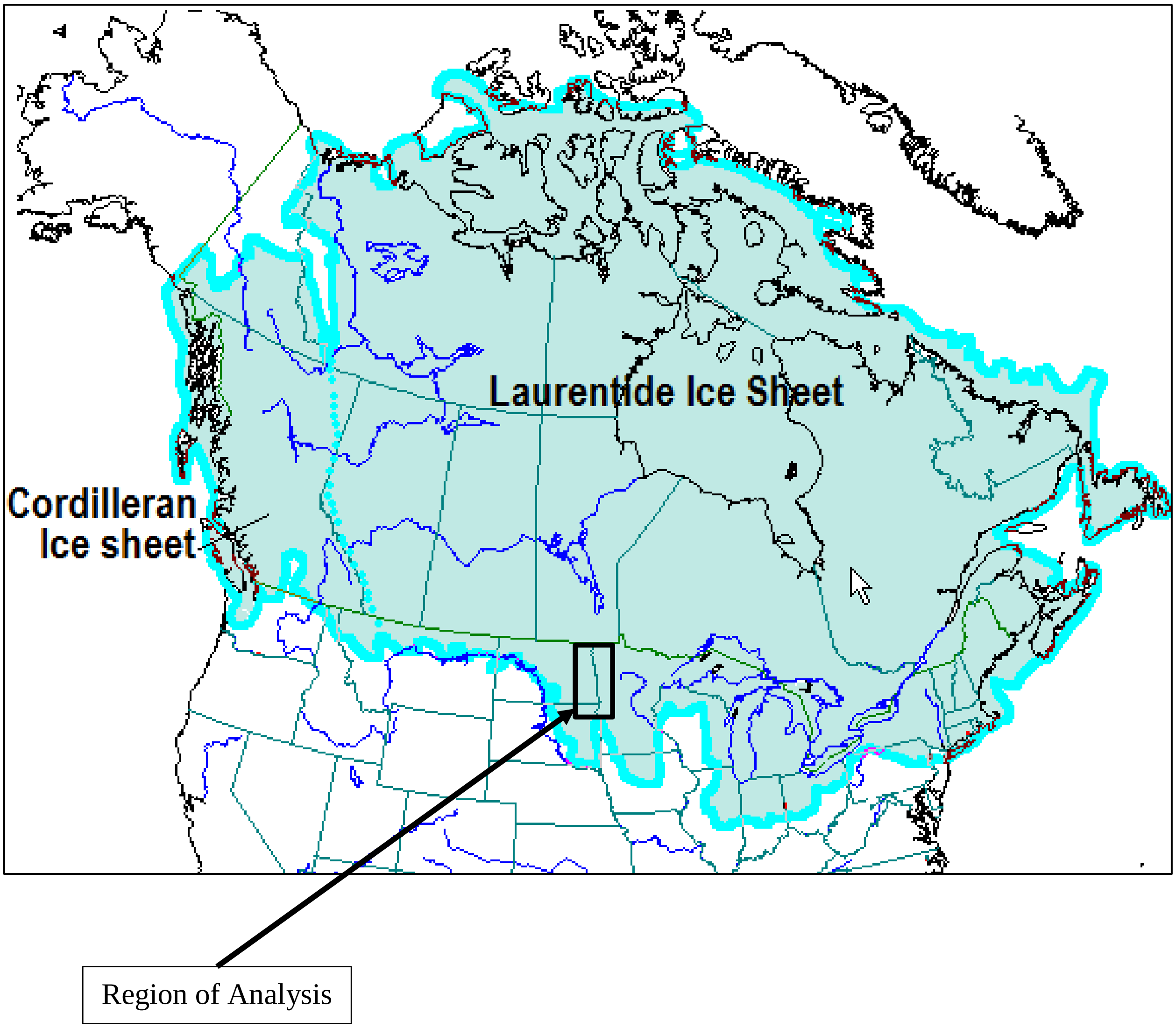


Figure 1. North American ice sheets including the Laurentide Ice Sheet extending into the Red River Valley approximately 15,000 years ago (Modified from Earle, 2015).

continental glaciers at the end of the Pleistocene and at the beginning of the Holocene led to crustal disequilibrium, creating strong isostatic adjustment in the Red River Valley. Greater uplift continues to occur in the areas occupied by the thickest ice, accompanied by declining elevations within the originally upward displaced margins (Upham, 1896; Andrews, 1974; Peltier, 1989; Sella et al., 2007). This glacial isostatic adjustment occurs at exponentially decreasing rates in the millennia following disappearance of the ice (Andrews, 1970).

During the waning stages of glaciation, proglacial Lake Agassiz occupied areas along the southwestern margin of the Laurentide Ice Sheet, including the Red River basin (Figure 2). Glacial Lake Agassiz received large amounts of fine sediment from rivers, which led to the deposition of up to 90 meters of lacustrine sediment in the center of the basin (Brevik and Reid, 2000), thus forming a substrate that is generally topographically smooth, level, and easily eroded by incipient surface-water drainage channels. Lake Agassiz drained and in the formerly ice-covered regions, new surface-water drainage patterns and watersheds developed and were influenced by changing base level caused by a rising sea level (Peltier, 2001). Many factors can exert control on the pattern of streams and rivers in the flat post-glacial terrains whose regions are composed of thick, unconsolidated, and easily erodible underlying sediments. These conditions may be the best and perhaps the only areas where the effect of isostatic adjustment on channels alone might be observed. Because of the landscape and sediment homogeneity present between the eastern and western strandlines of glacial Lake Agassiz, the Red River basin provides an ideal region to test the hypothesis that channel patterns and watersheds migrated in response to the large isostatic adjustment that occurred soon after the melting of Pleistocene glaciers.

Purpose

Rivers in the Red River Valley are constantly under continental scale tectonic forces. Little work has been conducted regarding the effect of isostatic adjustment on the Red River Valley in its entirety. The following thesis explores the role of isostatic adjustment on the watershed boundaries and the patterns of streams and rivers draining the Red River basin. Symmetry of watersheds, which is the relationship of the watershed areas lying on either side of the main channel, indicate whether there has been a change in drainage patterns and if it is the

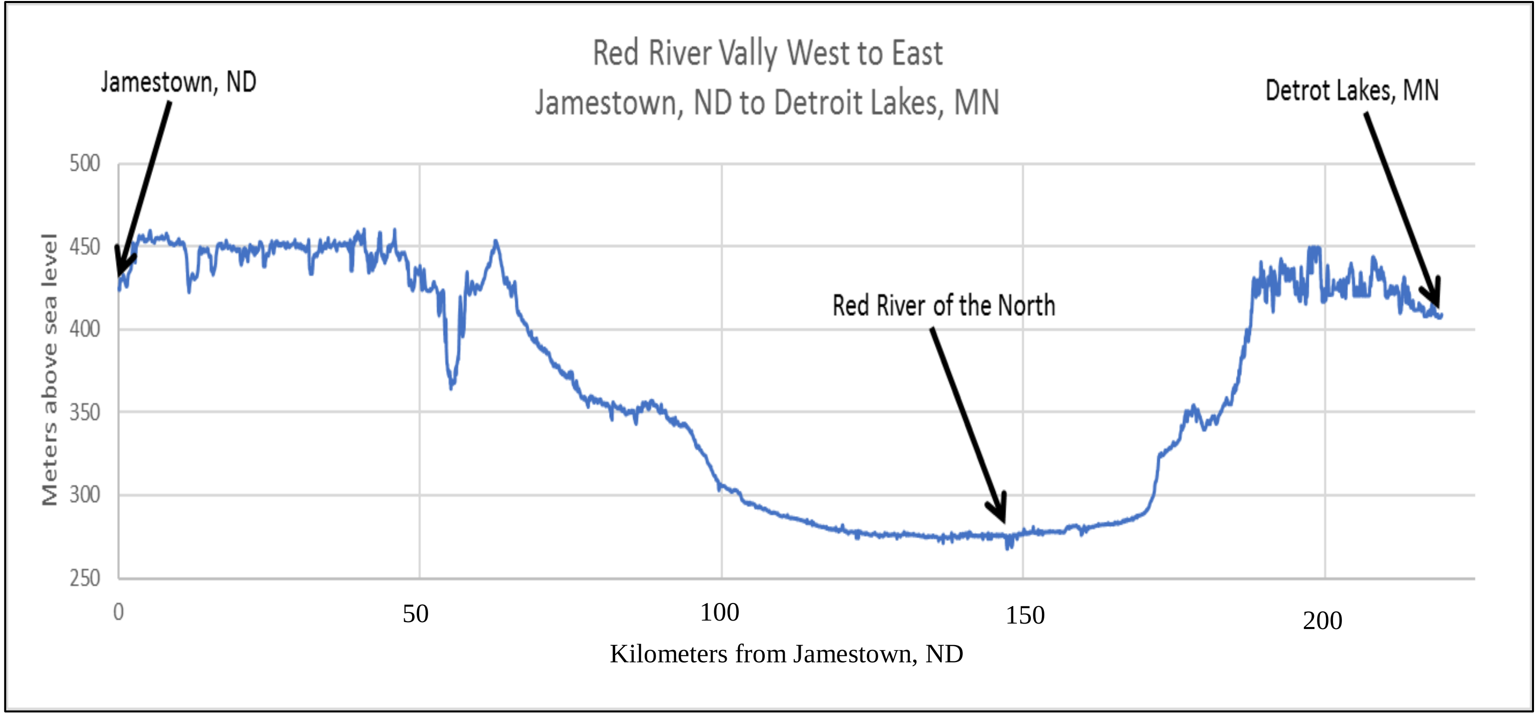


Figure 2. Cross section of the Red River Valley from Jamestown, North Dakota to Detroit Lakes, Minnesota. Distance on x-axis is meters east of Jamestown, ND.

result of tectonic forces. The effects of isostatic adjustment on the asymmetry of the tributary watersheds were determined by identifying if asymmetry was the result of a 1) changing watershed boundary, 2) a shifting river channel position, or 3) a combination of both a changing watershed boundary and a shifting river channel.

Background

Glacial Lake Agassiz

Lake Agassiz formed toward the end of the last glacial maximum 12,000 years ago, which persisted until 8,000 years ago (Clayton and Moran, 1982; Teller and Bluemle, 1983; Thorleifson, 1996; Teller and Leverington, 2004). As the footprint of the continental glacier changed, different outlets were exposed and blocked. Lake Agassiz drained primarily out of one outlet at a time with drainage entering the Mississippi River, Great Lakes, and Mackenzie basins at different stages of the glacial lake (Thorleifson, 1996). The changing of outlets also affected the size and shape of the lake. As Lake Agassiz fluctuated in size, beaches were deposited along the shore as ridges. These beach ridges are usually less than 0.8 kilometers wide (Clayton et al., 1980; Bluemle, 1991). The beach ridges were deposited parallel to each other as Lake Agassiz drained or changed area.

Beach ridges were formed at each stage of Lake Agassiz when different outlets were active. Just over 11,000 years ago, during the Lockhart Phase, the Herman beach ridge was deposited as Lake Agassiz drained into the Mississippi River. At this stage of the lake the area covered the entire Red River Valley. About 10,900 years ago, during the Moorhead Phase, drainage of the lake shifted to the Lake Superior outlet. At this stage, the shore of Lake Agassiz began to retreat north out of the Red River Valley. Drainage shifted back to the Mississippi River about 9,900 years ago during the beginning of the high-water Emerson Phase (Arndt, 1975).

Lake Agassiz once again occupied the Red River Valley after the shift and had a surface area of 260,000 km^2 (Figure 3) (Leverington et al., 2000). The Campbell beach ridge was deposited during the Emerson Phase about 9,400 years ago (Leverington et al., 2000). Between 10,900 and 9,900 years ago the Red River Valley region was exposed and fluvial drainage patterns emerged. The fluvial sediments were submerged about 9,900 years ago when the outlet shifted back to the Mississippi River (Thorleifson, 1996; Bluemle, 1991).

The Red River Valley is dominated by the lacustrine sediment deposited by Lake Agassiz. The region is topographically smooth except for submerged river delta deposits. As the lake level changed, the inlets of the rivers and their deltas also changed in location and size. Major deltas are associated with the Sheyenne, Pembina, and Assiniboine River (Clayton et al., 1980; Thorleifson, 1996).

Glacial Isostatic Adjustment

Glacial isostatic adjustment is the equilibration process of the land once covered by glaciers. The notion of glacial rebound (now termed isostatic adjustment), was first proposed by Jamieson (1865) and was further advanced by Upham (1896). Jamieson (1865) suggested that the weight of the continental glacier would have depressed the crust and the melting of the ice would also allow for the crust to rise back. As the ice exerted stress on the crust, the crust and underlying mantle around the glacial mass bulged. The affected terrain is now coming to an equilibrium through the process of crustal uplift and subsidence. Coming to equilibrium varies on the thickness of the ice present and crustal properties and has been studied in North America regarding the Laurentide Ice Sheet (Brevik, 1994; Peltier, 1989; Peltier, 2004). The greatest uplift currently underway in North America underlies Hudson Bay, where the ice sheet was the thickest and remained the longest. Hudson Bay is rebounding 10mm/yr (Peltier, 1989). The

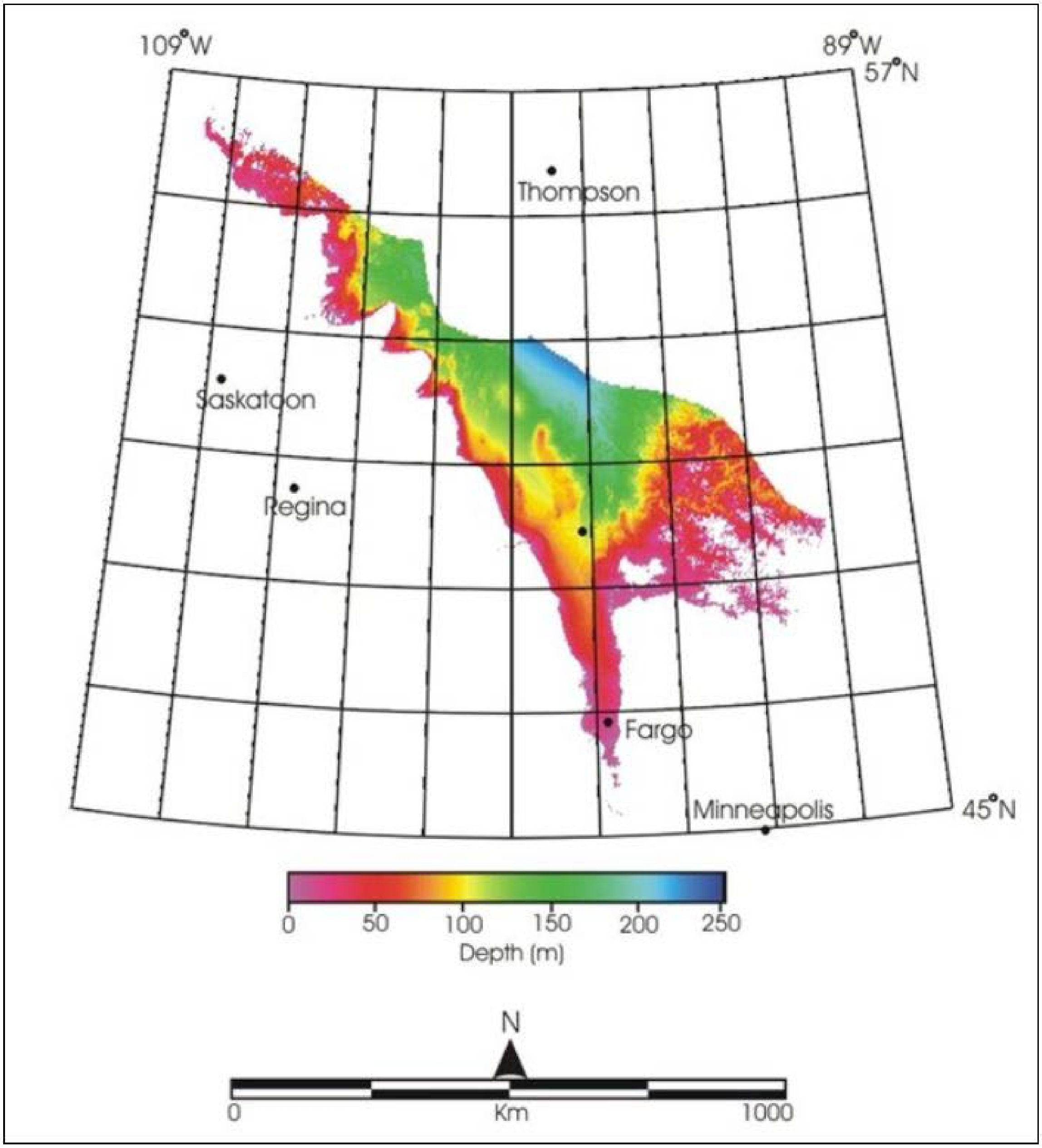


Figure 3. Bathymetry of Lake Agassiz during Upper Campbell stage approximately 9400 ^{14}C yr BP. The lake had a volume is about 22,700 km^3 and surface area of 260,000 km^2 (Modified from Leverington et al., 2000).

Army Corps of Engineers also has recorded that the northeastern corner of the Lake Superior basin currently rebounds at least 5 mm/yr (US Army Corps of Engineers, 2007).

Four different viscosity structure models composed of ice thickness data and rheological effects all indicate that the Red River Valley is predicted to experience between 0 mm/yr and 4 mm/yr of uplift (Sella et al. 2007). Another model, ICE-5G (VM2) predicts the vertical motion of the crust is currently between 1 mm/yr and 4 mm/yr in the Red River Valley (Figure 4) (Peltier, 2004). Positive vertical motion in the Red River Valley is predicted to continue because of the crustal depression caused originally by the margin of the continental ice sheet lying within Red River Valley. The continental glacier that occupied the Red River Valley during the last glacial maximum was between 280 and 1040 meters thick based on crustal depression, and between 425 and 986 meters thick based on Mathews' method (Mathews, 1974; Brevik, 1994). Brevik (1994) calculated the force exerted on the lithosphere from the ice and deformation that occurred. This land is now subsiding and land that was beneath the glacier is rebounding.

Isostatic adjustment affected the elevation of portions of the horizontally deposited beach ridges along the perimeter of Lake Agassiz. More uplift has occurred farther north which is recorded from beach ridges. Since the entire beach ridge is affected by this adjustment, the difference in elevation from north to south for a distinct beach ridge is the minimum isostatic adjustment for the area (Brevik, 1994). Isostatic adjustment determined from the beach ridges is not the entire rate of adjustment since the lake formed along the ice margin, only after the glacier had receded or melted from that location. It is likely that some isostatic adjustment occurred before the formation of the beach ridges. As much as 73% of the total rebound could have already occurred before the deposition of the Herman beach ridge, highest major beach ridge (Brevik, 1994).

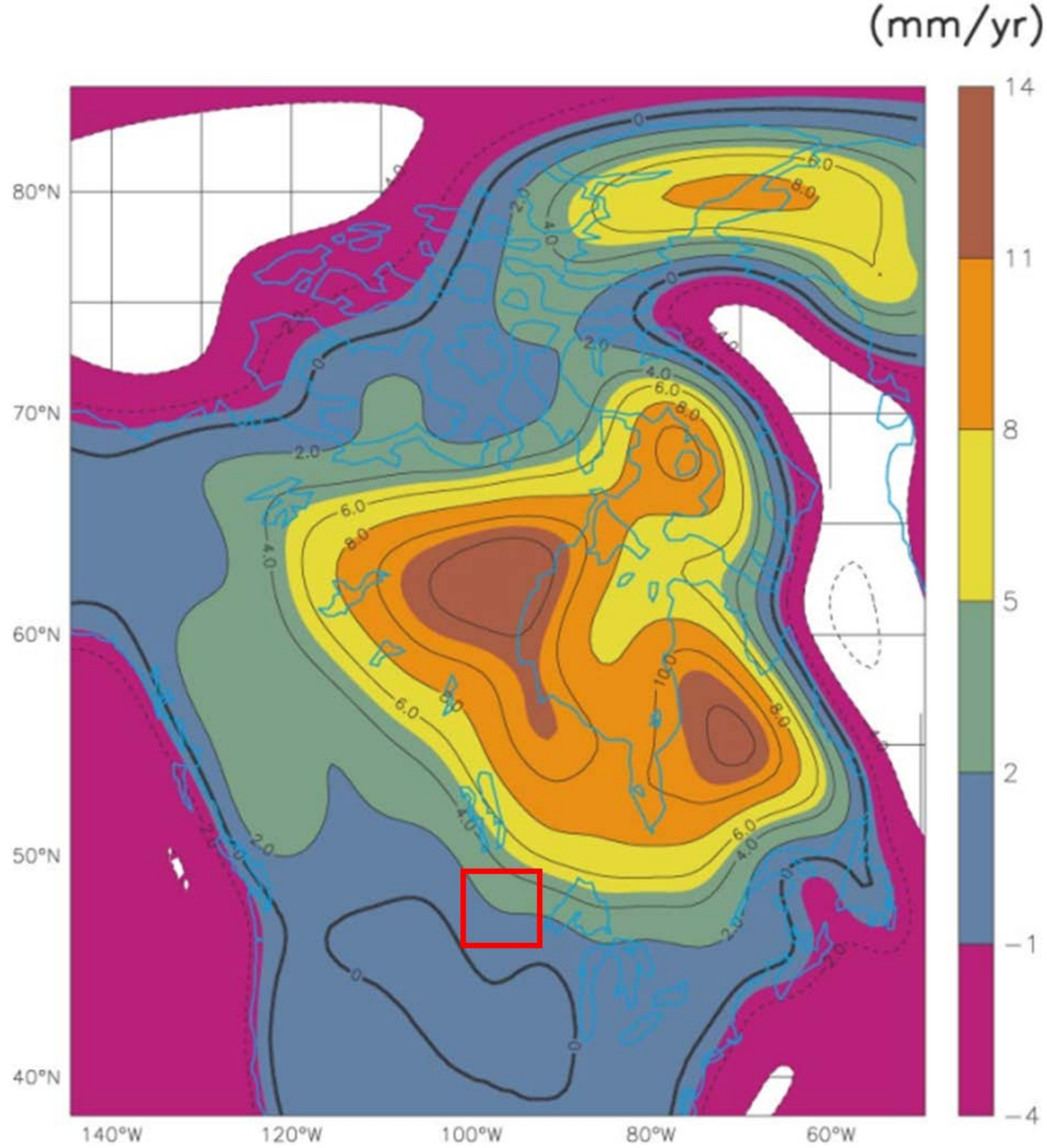


Figure 4. ICE-5G (VM2) prediction of current vertical motion of Earth’s crust. Red box rougly outlines eastern North Dakota and western Minnesota (Modified from Peltier, 2004)

Basin Asymmetry

Drainage basin symmetry relates the boundary of the watershed to the main branch of the river. Transverse Topographic Symmetry Factor (TTSF) (Cox, 1994) and Asymmetry Factor (AF) (Hare and Gardner, 1985) are two methods used to measure the symmetry of watersheds. TTSF was developed as a rapid technique to identify tilting in the Mississippi Embayment. Since the initial application in 1994, the technique has also been used to detect tilting in the central Amazon region (Ibanez et al., 2014), Guadiamar drainage basin, Spain (Salvany, 2004), and Gulf of Corinth, Greece (Tsodoulos et al., 2008). These studies determined that asymmetry of the watershed is entirely or partially the result of tectonic forces. TTSF can reveal whether there are external forces applied to the region that has led to a preferred asymmetry, or if the asymmetry is random and due to internal fluvial processes (Cox, 1994).

The Asymmetry Factor detects tectonic activity within drainage basins and is sensitive to tilting perpendicular to the river (Tsodoulos et al., 2008). AF was first implemented by Hare and Gardner (1985) in the Nicoya Peninsula, Costa Rica to detect neotectonic deformation. Changes in AF values are attributed to varying amounts of tilting. TTSF and AF are complementary and can be calculated for the same basins (Tsodoulos et al., 2008; Salvany, 2004).

Paleo-Channels

Paleo-channels, or compaction ridges, are one form of relic channels from previous drainage systems preserved in a palimpsest landscape. Streams and rivers incise into soft lake clays and silts and then had their channels filled with coarse fluvial sediments. Lake levels rose and submerged the channels. More lake sediments were deposited on top of the already present lake and fluvial sediments. As the lake drained, the sediments became dehydrated and the clay and silt consolidated more than the coarse fluvial sediments. The differential compaction of the sediments created a reversed topography of what was there before lake levels rose (Arndt, 1975; Manz, 2016).

Paleo-channels in the Red River Valley are the remnants of a drainage pattern that was present in the Lake Agassiz lake plain from about 10,900 to 9,900 years ago while Lake Agassiz drained through the Lake Superior outlet. During the Lockhart Phase of Lake Agassiz, about 11,000 years ago, silt and clay were deposited offshore. As lake levels dropped about 10,900 years ago during the Moorhead Phase, rivers and streams developed a drainage network within the lake plain. After the rivers established themselves and deposited sand and gravel, lake levels rose about 9,900 years ago during the Emerson Phase and again occupied the region where these rivers had been established (Thorleifson, 1996). Differential compaction of the lake and fluvial sediments created a paleo-drainage system preserved as a palimpsest landscape. Dennis et al. (1949) suggested that the ridges might be moraines, but the lack of ground-moraine deposits disproved that notion. Incised channels in the underlying lake sediment were filled with sand and gravel which supports the fact that these ridges were once rivers that had incised into lake sediment and then covered by more lake sediment (Dennis et al., 1949).

Compaction ridges within the Red River Valley are displayed in the most recent geological map of North Dakota and described in the accompanying text (Clayton et al., 1980). Details on the individual ridges are found in county geological reports, but these reports end at county borders and do not reveal the full extent of the ridges within the valley. Identified compaction ridges in the Red River Valley include the Sheyenne, West Fargo, Fargo, and Maple Ridges in Cass and Clay County (Dennis et al., 1949; Klausing, 1968), Kelso Ridge in Traill County (Bluemle, 1967), and the Horgan Ridge in Pembina County. Surface geology maps produced by the North Dakota Geological Survey occasionally identify the paleo-channel ridges, as seen in the map produced by Anderson (2009) (Figure 5). Like the county geological reports, the map does not extend beyond the West Fargo North Quadrangle, North Dakota.

River Avulsion

River avulsion is the abandonment of either an entire river channel or just a portion of it. Local avulsion has the river abandoning a portion of the river and then reconnecting with the original river downstream (Slingerland and Smith, 2004). Avulsions happen at different rates. Some examples from literature are the Yellow River and the Meuse-Rhine delta. The Yellow River in China was a catastrophic avulsion where the river was perched 7-10m above the flood plain. It has been recorded that the Yellow breached its levee seven times, which eventually led to full avulsions (Qian, 1990; Zhou and Pan, 1994). Other systems like the Meuse-Rhine delta in the Netherlands took up to 1250 years to avulse completely (Stouthamer and Berendsen, 2001).

Bluemle (1991) discussed the avulsion of the current Red Lake River that had once flowed in the channel of the Grand Marais River in western Polk County, Minnesota, but had avulsed to the current Red Lake River channel. The Grand Marais Creek is too small for the valley it occupies, and that the river channel down river of the Red Lake River and Red River confluence is straighter, which indicates an increase in water volume (Bluemle, 1991b, p. 82). Isostatic adjustment has varying effects on rivers depending on the orientation of the river. A river perpendicular to the tilt hinge, which is the boundary separating uplift from subsidence, might react differently than a river that is parallel to the tilt hinge. A river that is near parallel to the tilt hinge might abandon its channel (the abandonment of the channel being termed avulse) in favor of a channel with steeper gradient (Bluemle, 1991b, p 82; Sella et al., 2007). Both the abandoned channel and the new channel of the Red Lake River have characteristics that indicate that the rivers are not fit for their channel.

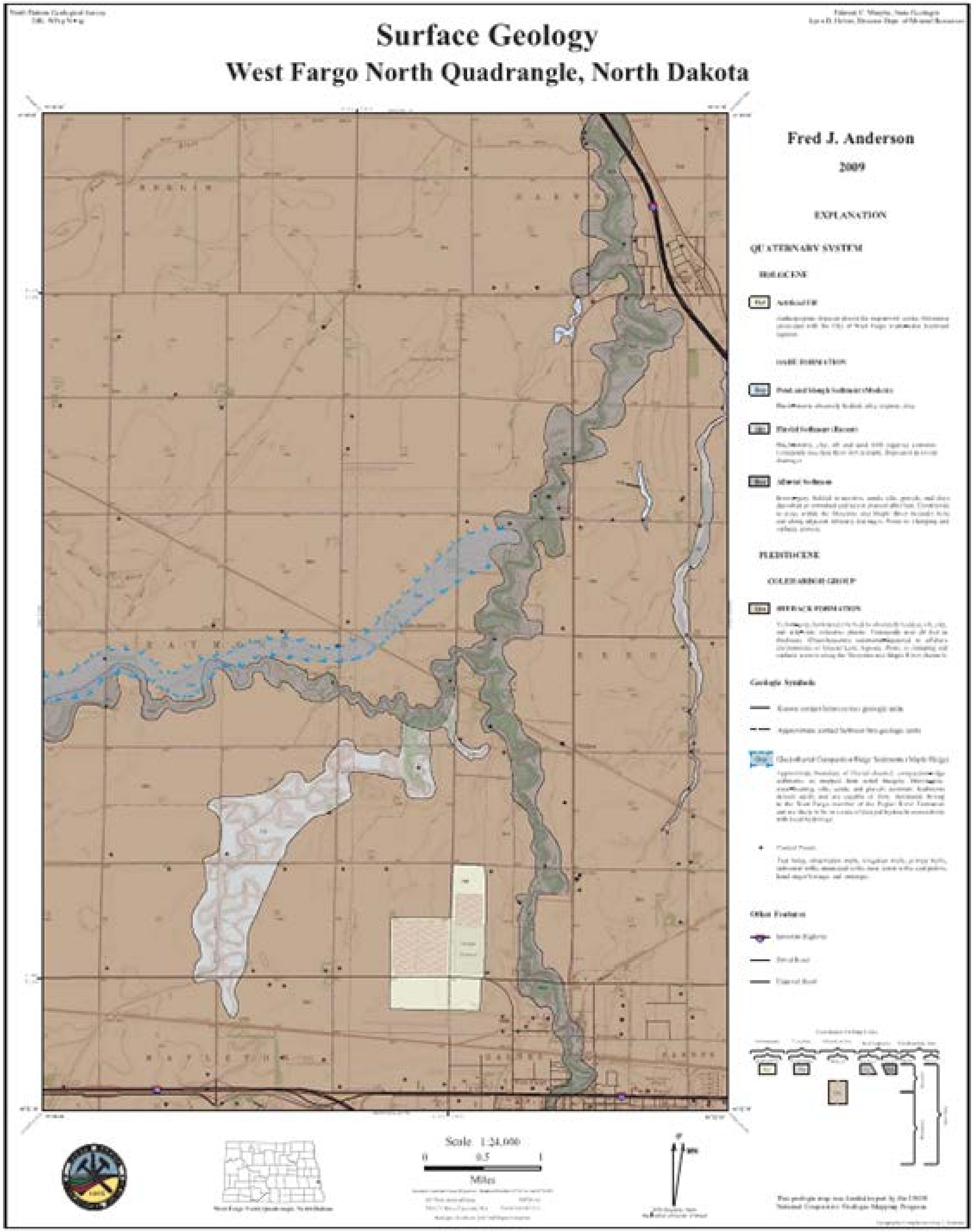


Figure 5. Paleo-channel associated with the Maple River (light blue). Map taken from Anderson (2009).

Slingerland and Smith (2004) noted three distinct type of avulsions, "…(a) avulsion by annexation in which an existing channel is appropriated (if active) or reoccupied (if abandoned); (b) avulsion by incision, where new channels are scoured into the floodplain surface as a direct result of the avulsion; and (c) avulsion by progradation, characterized by extensive deposition and multi-channeled distributive networks." The abandonment of the Grand Marais Creek is a case of annexation avulsion (Brevik, 1994).

West of the Campbell beach ridge near Wheatland, North Dakota lie two abandoned gullies that are oblique to the local slope. The abandonment and different orientation (northeast compared to the southeast trending streams) of the gullies from the current slope could be a result of differential compaction or inherited subglacial tunnels, although most likely resulted from a change in slope from glacial isostatic adjustment (Lepper et al., 2011).

Paleo-Topography

Isostatic adjustment induced shifts in river courses have affected the shape and discharge of watersheds (Kelley et al., 2011). In Maine, uplift caused Moosehead Lake to drain out of the Kennebec River instead of the Penobscot River. There is now an abandoned channel between Moosehead Lake and the Penobscot River (Kelley et al., 2011). Drainage would flow back into the Penobscot River if uplift was removed and the paleo-topography was restored.

Leverington et al. (2002) created an isobase map, which represents the change in elevation across an area, to create the paleo-topography of a region in the central Canadian Arctic. Leverington et al. (2002) produced an isobase surface for the Canadian Arctic using data from Dyke et al. (1991) by subtracting a raster of elevation changes from the current topography. The result was paleo-topography that is now corrected for isostatic adjustment used for his study.

Random Walk Model

The lattice path random walk model is a stochastic process in which an object starts at a point, travels in a straight path, and then turns a random direction in a grid pattern. The object continues this process *n* number of times (Pearson, 1905). Early works by Leopold and Langbein (1962) investigated the path of rain droplets and of streams on a uniformly sloping surface. The lattice path random walk stream network resembles networks observed in nature. The theoretical paper demonstrates the pattern development of streams without geomorphological constraints (Leopold and Langbein, 1962). Edmonds et al. (2016) used a random walk model to predict where river avulsions would occur along rivers in the Andean and Himalayan foreland basins. The avulsion pattern observed by Edmonds et al. (2016) did not resemble the random walk model created. The results suggested that the direction of avulsion was driven by geomorphological features.

CHAPTER II

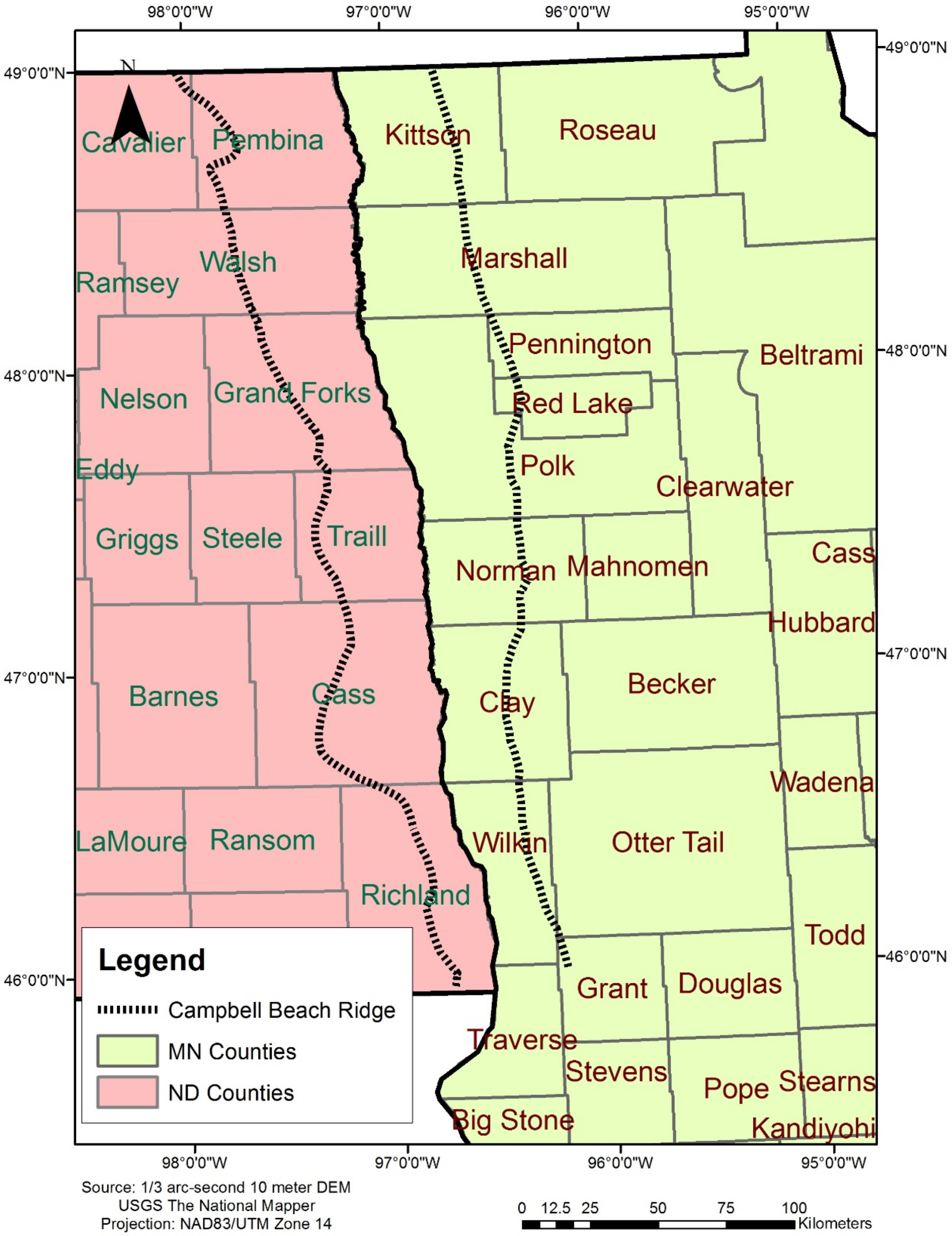
METHODS

The following methods were used to determine if asymmetry is prominent in individual watersheds in the Red River Valley. TTSF and AF values were found for each watershed to reveal the amount of symmetry. The pre-adjustment watersheds were compared to current watersheds to verify if asymmetry is the result of a change in watershed boundaries. Changes in channel courses were used to determine if asymmetry is the result of a shift in river position.

Region of Analysis

The region of analysis only pertains to the portion of the Red River Valley downstream of the Campbell beach ridge (Figure 6). The two main reasons for the boundary are: 1) the topography within is primarily lake plain (Red River Valley Lake Plain) and underlain by nearly homogenous sediments (Stoner et al., 1993) and 2) the Campbell beach ridge is the best preserved, nearly continuous beach ridge that formed during the lower stages of Lake Agassiz. For some of the methods it is necessary to extend analysis beyond the region of analysis.

The Campbell beach ridge was identified using the geological map of North Dakota (Clayton et al., 1980), but the linear features provided were not continuous. Missing segments of the Campbell beach ridge were completed by hand using possible linear features observed on the 1/3 arc-second digital elevation model (DEM) and used as the approximate boundary (Appendix A Section 1). The line representing the beach ridge was drawn down the center of the topographically high beach ridge.



Source: 1/3 arc-second 10 meter DEM
USGS The National Mapper
Projection: NAD83/UTM Zone 14

Figure 6. The region of analysis described in this report are the sections of watersheds downstream of the Campbell Beach Ridge (dotted line). The only exception is that to create the mid-line of the watershed, the entire watershed, both upstream and downstream of the beach ridge were used.

Measuring Effects of Isostatic Adjustment

Basin Asymmetry

The tributaries of the Red River within the Lake Agassiz plain were measured to determine the Transverse Topographic Symmetry Factor (TTSF) (Cox, 1994; Salvany, 2004; Tsodoulos et al., 2008). TTSF is a ratio, represented by D_a/D_d, where the distance (in meters) from the basin midline to the main active stream (D_a) is divided by the distance (in meters) from the basin midline to the basin edge (D_d) (Figure 7).

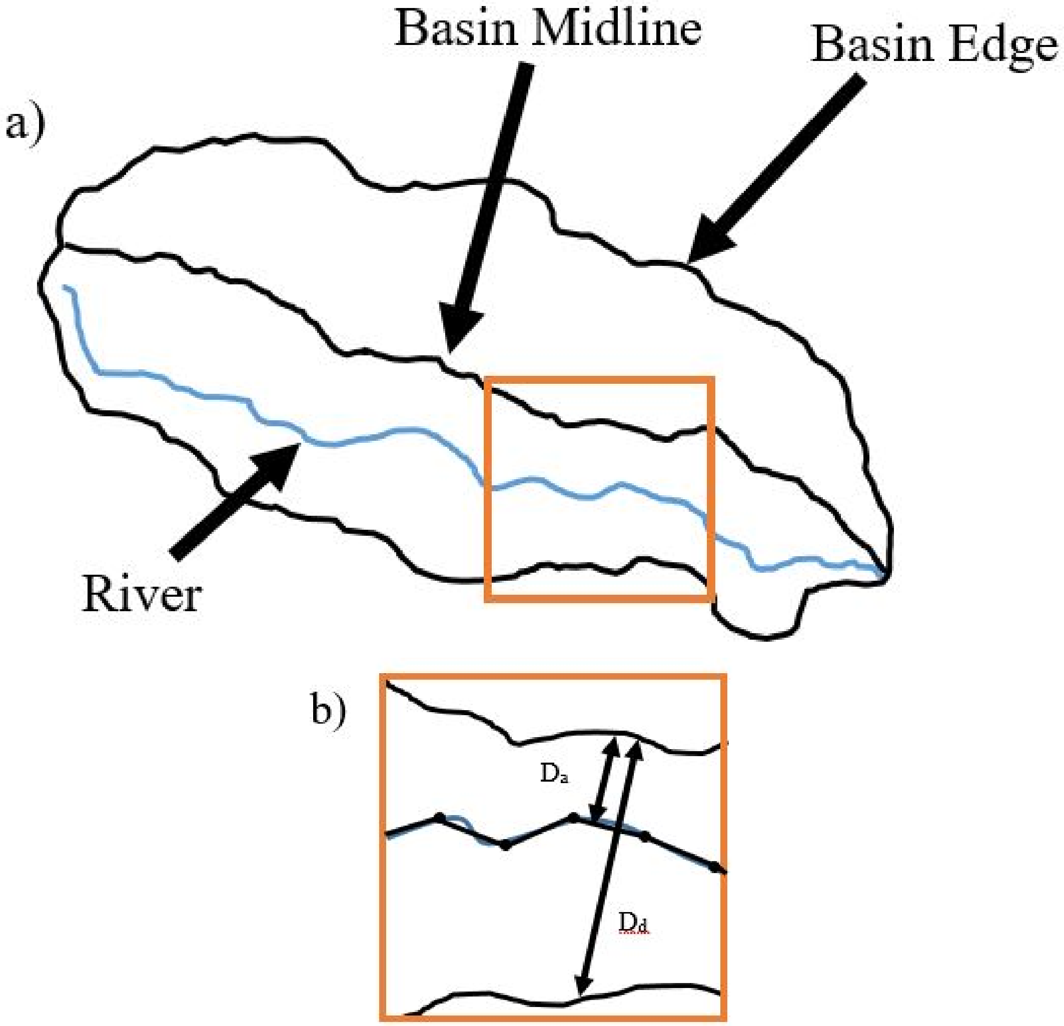


Figure 7. a) A hypothetical basin with the river in the southern portion; b) D_a and D_d distance values used to calculate the TTSF value

Cox (1994) designates a TTSF value that approaches 0 as perfectly symmetrical, and as the value approaches 1 as more asymmetric. This study modifies that concept with expounding on the value of 1 assigned to asymmetry. The modified values are that a value between 0 and 1 signifies that asymmetry is the result of the river being south of the mid-line, while a value between -1 and 0 would signify that the river is north of the mid-line. The resulting value not only indicates the amount of asymmetry but also the direction, being above or below the mid-line. This modification is only applicable if the mid-line is near perpendicular to the slope of adjustment (Figure 8). The midline was created from polygons which have an edge that is perpendicular to a line drawn between two points. (Figure 9). These Thiessen polygons are created for points spaced every 10 meters (Figure 9). The Thiessen polygons were simplified and the edges perpendicular to the points for each polygon were merged into a single mid-line.

The mid-line was created for the watershed both upstream and downstream of the Campbell beach ridge to assess the symmetry attributes of the watershed. Although the mid-line was created for the entire watershed, TTSF and AF analysis was applied to the portion downstream of the Campbell beach ridge. If the mid-line was created for just the watershed downstream of the Campbell beach ridge it would not reflect the actual mid-line for the whole watershed.

Red River tributaries were divided into two-kilometer segments, which is roughly twice the width of the average active meander belts of the tributaries. Cox (1994) suggests for the TTSF analysis to use river segments twice the width of the average active meander belt of all the rivers, which is the zone of migration in a river valley. From the center of each two-kilometer segment, a line was drawn at a right angle first toward the basin midline, then to the basin edge. There are tools within ArcMap that can simplify high sinuosity lines automatically, but the tool

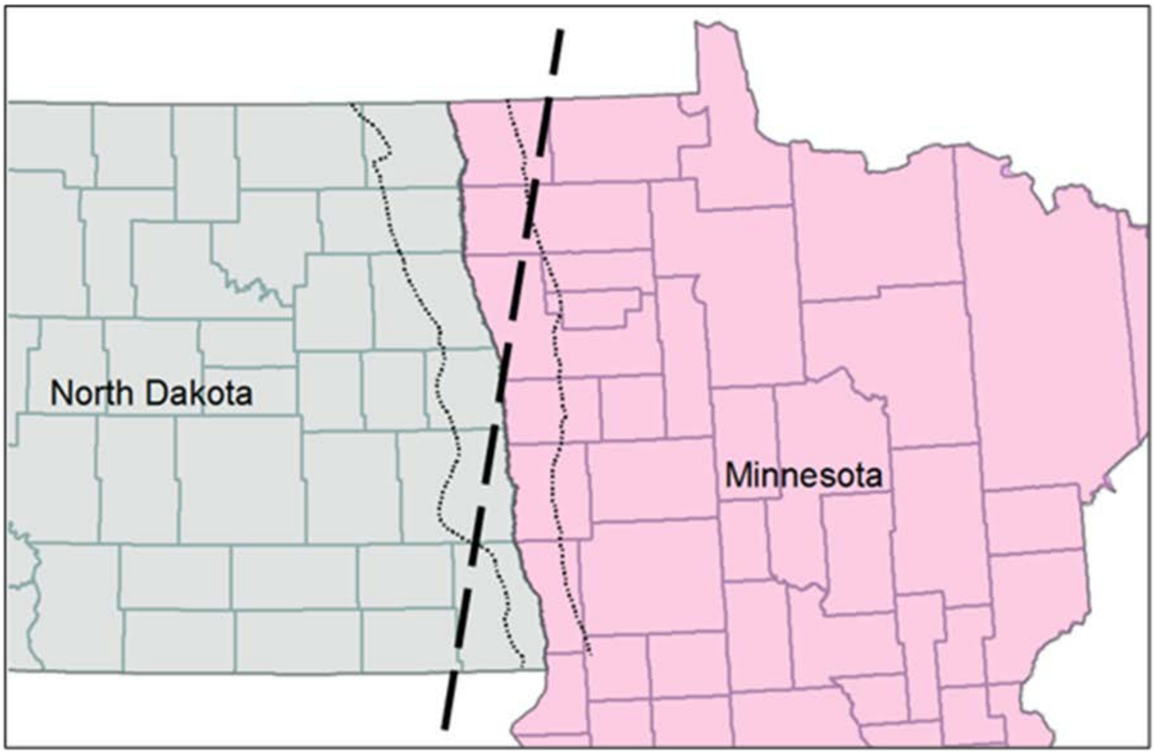


Figure 8. Glacial ice was thicker and resided longer towards the northeast which resulted in faster rates of uplift towards the northeast. The hypothetical line is perpendicular to the equipotential lines (Figure 4) of adjustment and is parallel to the slope of adjustment as seen in.

generates line segments of unequal lengths (Appendix A Section 3). The tool results were compared to the two-kilometer segment river created and were visually similar.

The value associated with the AF is found by dividing the area south of the river (A_s) by the total area (in square meters) of the drainage basin (A_t). After dividing and multiplying by 100, it results in $AF=100(A_s/A_t)$ (Figure 10). Values below 50 in the Red River Valley suggest tilting because the river would be farther south resulting in more watershed area north of the river than south of the river (Hare and Gardner, 1985).

Pre-Adjustment Watersheds

Ten meter DEM data were combined into one large raster that encompassed the entire Red River Valley. To identify the change in watershed boundaries due to isostatic adjustment,

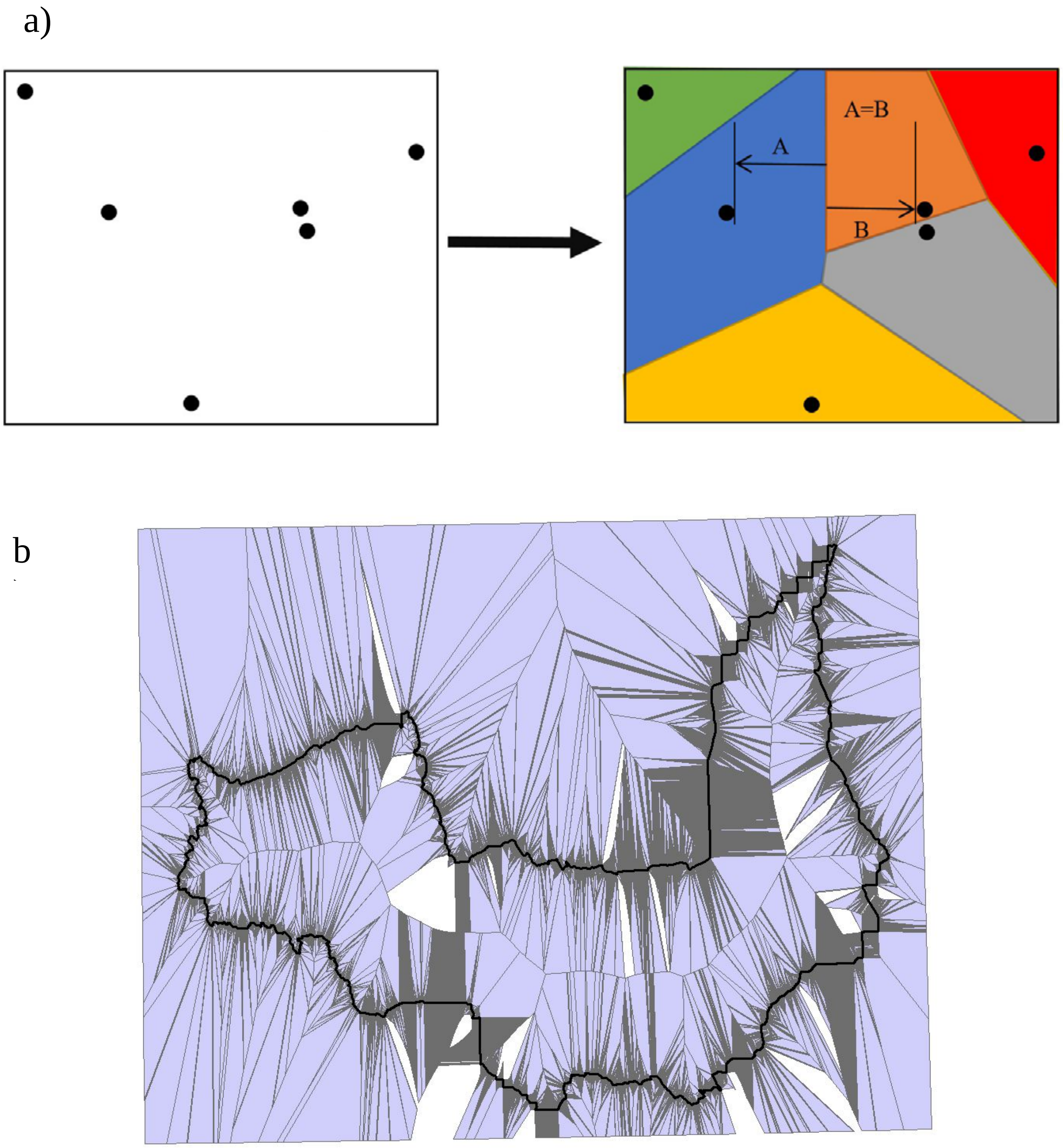


Figure 9. a) Thiessen polygons created with polygon boundary equal distance between two points (Modified from ESRI ArcGIS Desktop, 2017); b) Turtle River watershed after “Create Skeleton” has been executed, but before “Trim Skeleton” was applied. Polygon to Centerline (Dilts, 2011) creates Thiessen Polygons between many points along the perimeter of the watershed. After “Trim Skeleton” is applied the output would be the centerline highlighted in orange in the above image.

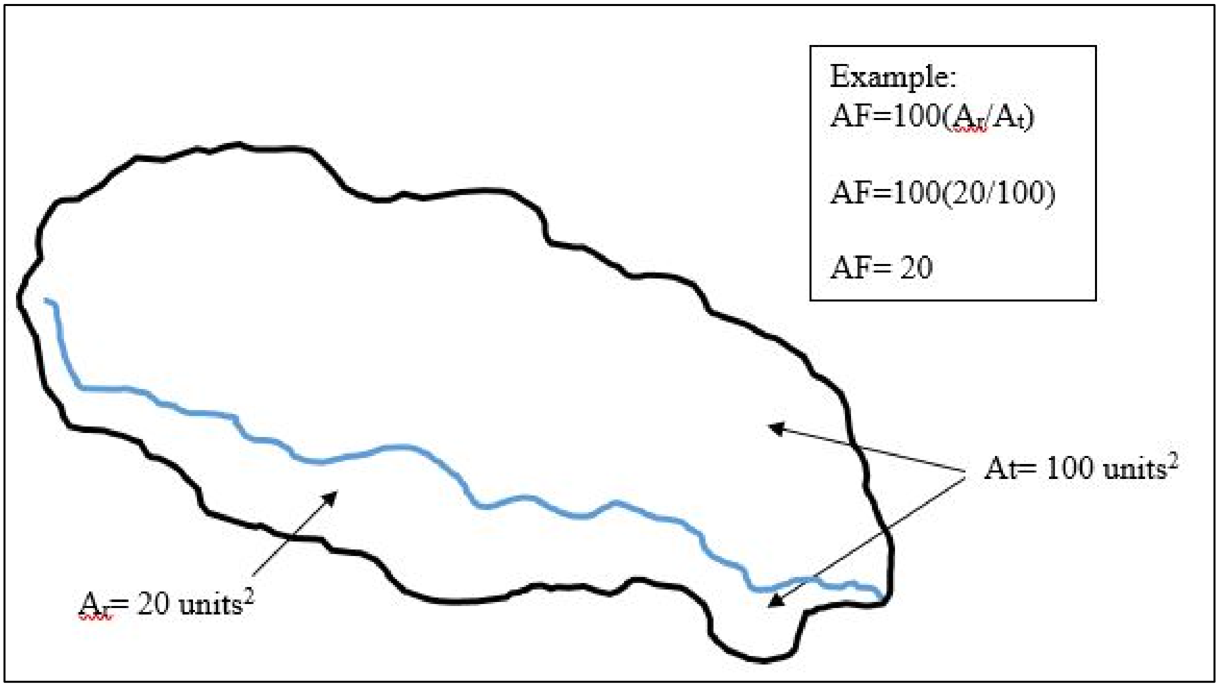


Figure 10. Hypothetical basin from Figure 7 with a value of 20. Values below 50 indicate that tilting has occurred.

the difference between the current and pre-adjustment watershed profiles was calculated. Watersheds were created following the steps outlined by Cooley (2016). Outlet points for the tributaries were selected at the tributary's confluence with the Red River and at the U.S.-Canadian border. To determine the pre-adjustment watersheds, the same steps are repeated on a DEM corrected for isostatic adjustment (Leverington et al., 2002; Oakley and Boothroyd, 2012). To correct for adjustment, a raster representing adjustment is subtracted from the current DEM (Figure 11). The resulting DEM likely resembles the topography of the Red River Valley before adjustment.

To create the raster that represents adjustment, a 1st order polynomial trend (Figure 12) was created using the adjustment elevations indicated by the Herman beach ridge. Beach ridges are deposited along the lake edge at a uniform elevation. Any variation in elevation of the beach

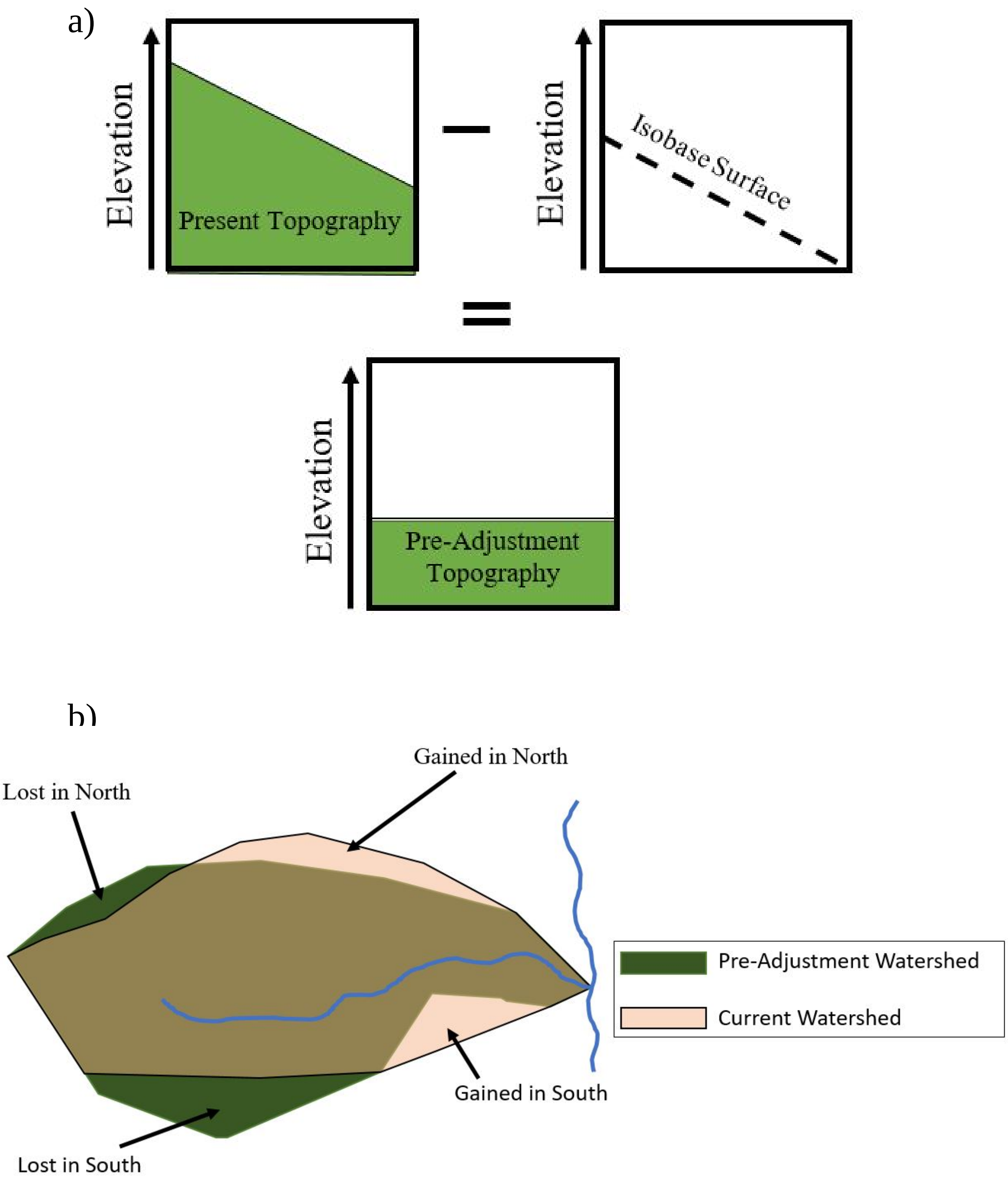
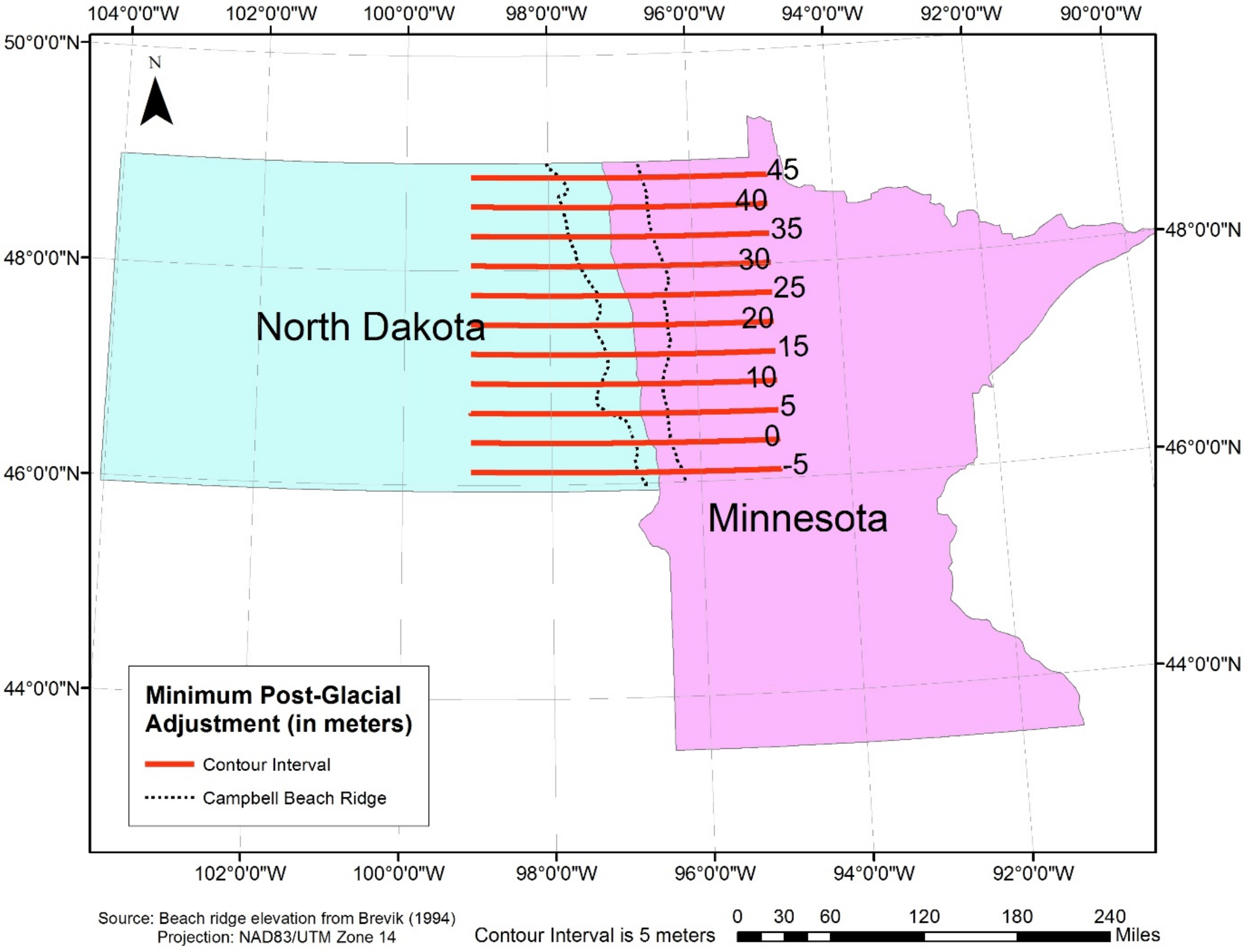


Figure 11. a) Hypothetical pre-adjustment topography was generated by subtracting the isobase surface from the present topography; b) Hypothetical current and pre-adjustment watersheds. The current watershed location is caused by the pre-adjustment watershed shifting north because of isostatic adjustment. Area lost or gained from this shift are used to find the net change in area of the watershed from pre-adjustment boundaries to current boundaries.



Source: Beach ridge elevation from Brevik (1994)
Projection: NAD83/UTM Zone 14

Figure 12. Minimum post-glacial adjustment in meters displayed as contour lines for the region of analysis. Five meter contour interval lines are drawn from adjustment raster which was subtracted from current DEM to create pre-adjustment topography. Adjustment values were generated from elevations recorded by Brevik (1994).

ridge from one location to another is likely a result of isostatic adjustment (Brevik, 1994). Brevik (1994) recorded the elevation of the Herman beach ridge at various locations in North Dakota which were read from a USGS 7.5 minute topographic map with an error of +/- 1 meter. Within this study, a trendline of adjustment in the Red River Valley was created from those elevation points (Table 1).

The watershed boundaries were created for the entire reach of the river, but only the portion of the watershed downstream of the Campbell beach ridge was analyzed. The difference in area between the pre-adjustment watershed and current watershed were separated into changes north and south of the main river channel (Figure 11). The net change south of the river channel was subtracted from the net change north of the river channel to get the total net change in area of the watershed. A positive total net change means that the watershed gained more area north of the river channel, while a negative total net change means that the watershed gained more area south of the river channel.

Channel Avulsion and Paleo-Channels

Abandoned and possible pirated channels were located using DEM patterns. Old channels were identified above the flood plain of the current channel. Paleo-rivers, an ancestral channel to current rivers, were identified by examining where the current channel entered the Lake Agassiz plain downstream of the Campbell beach ridge (Figure 6). The paleo-channels should originate from the same location as the current channel. No paleo-river compaction ridges should exist beyond the Lake Agassiz beach ridges since the terrain was never inundated by Lake Agassiz and therefore never covered by lacustrine sediment.

Long raised mounds, or compaction ridges that are parallel to the current rivers were identified as probable paleo-channels (Figure 13). All compaction ridges were traced digitally in the Red River Valley. Paleo-channels were associated with current channels based on if they originated at the same location along the beach ridge and were determined if the individual paleo-channels lie to the north or south of their corresponding current river.

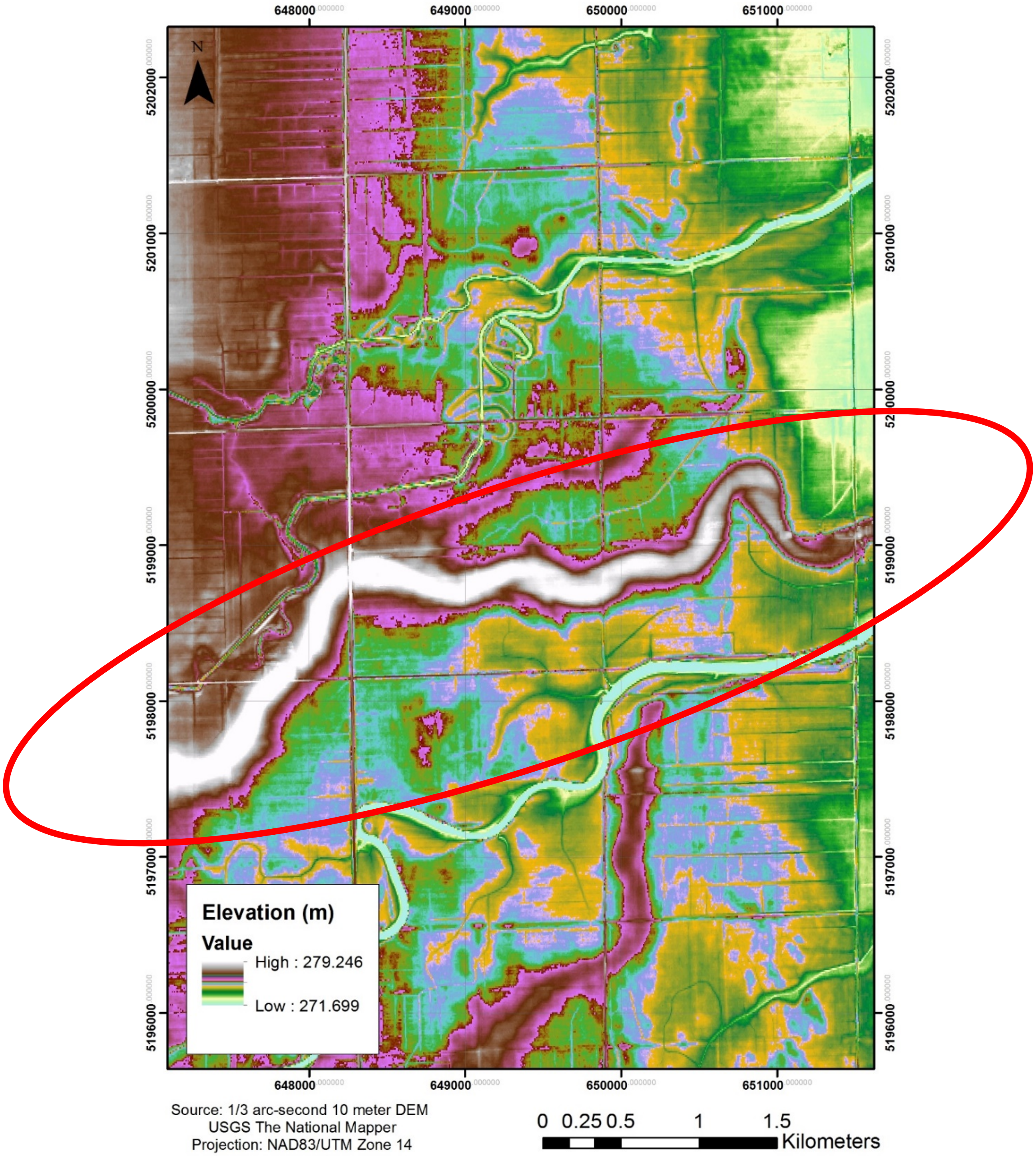
Table 1. Raster values for points used to generate isostatic adjustment trend.

QUADRANGLE	LOCATION	ELEVATION (M)	ELEVATION INCREASE (M)	TREND RASTER VALUE (M)
LA MARS, ND-SD	Sec 32&33, T129N R48W	327.8	0	-7.9
EMBDEN, ND	Sec 3, T138N R54W	331.5	4	7.5
AYR NW, ND	Sec 7, T143N R53W	334.4	7	15.2
INKSTER, ND	Sec 16, T145N R55W	354.3	26	32.2
EDINBURG, ND	Sec 26, T158N R56W	371.4	44	38
VANG, ND	Sec 32, T164N R57W	379.7	52	47.2

Random Walk Model

This statistical model coded and executed in Python (see Appendix C for code) demonstrated if a change in slope would affect channel position. The model uses an arbitrary 100 by 100 matrix with each cell designated as either a channel or non-channel. There are 20 initial channel cells originating along the left side in five-cell increments starting at zero and ending at 95 along the y-axis (Figure 14). Channels, generated at the 20 initial channel cells, transverse the grid from left to right; from 0 to 100 along the x-axis. Two channels that converge, in the matrix of randomly created channels, will merge to form a single channel. The model represents 20 low order streams at the cell origin and fewer, higher order streams at the right edge of the grid.

The random walk model was generated to simulate west to east rivers flowing into the



Source: 1/3 arc-second 10 meter DEM
USGS The National Mapper
Projection: NAD83/UTM Zone 14

Figure 13. Paleo-channel ridge located west of Fargo, North Dakota. This feature is named Maple Ridge on county geological reports.

Red River. Two different models were created. The first represents a level terrain with the rivers entering from the west and flowing east. To simulate the level terrain, the probability of the channel to move northeast, east, or southeast is all equal. The second model simulates drainage probability of movement directly related to adjustment that has occurred in the Red River Valley from the Canadian border to the South Dakota border. Points originating closer to 100 along the y-axis represent channels originating from regions that have experienced greater adjustment. Adjustment rates for the Herman beach ridge resulted in nearly 16 meters of uplift near the North Dakota/Canadian border, and near zero meters of uplift near the North Dakota/South Dakota border (Brevik, 1994). The two models were compared with a standard created by plotting the starting position against itself meaning that a channel will start and end at the same y-axis location (Figure 15).

Values that intersect the boundary of the 100 by 100 grid will either be assigned a value of 100 when the river moves above 100 on the y-axis, or a value of zero when the value moves below zero on the y-axis. The average ending position for each of the five unit increments, which is where the river intersects the main channel on the right side of the grid, was plotted on the y-axis against its starting location, which was plotted on the x-axis. Leopold and Langbein (1962) stated that not many trials of each model were needed to attain the accuracy wanted which confirmed the randomness of the model. The model will be executed 10 times, unless the statistical significant p-value is below 0.005, then further runs will be generated until the value is reached.

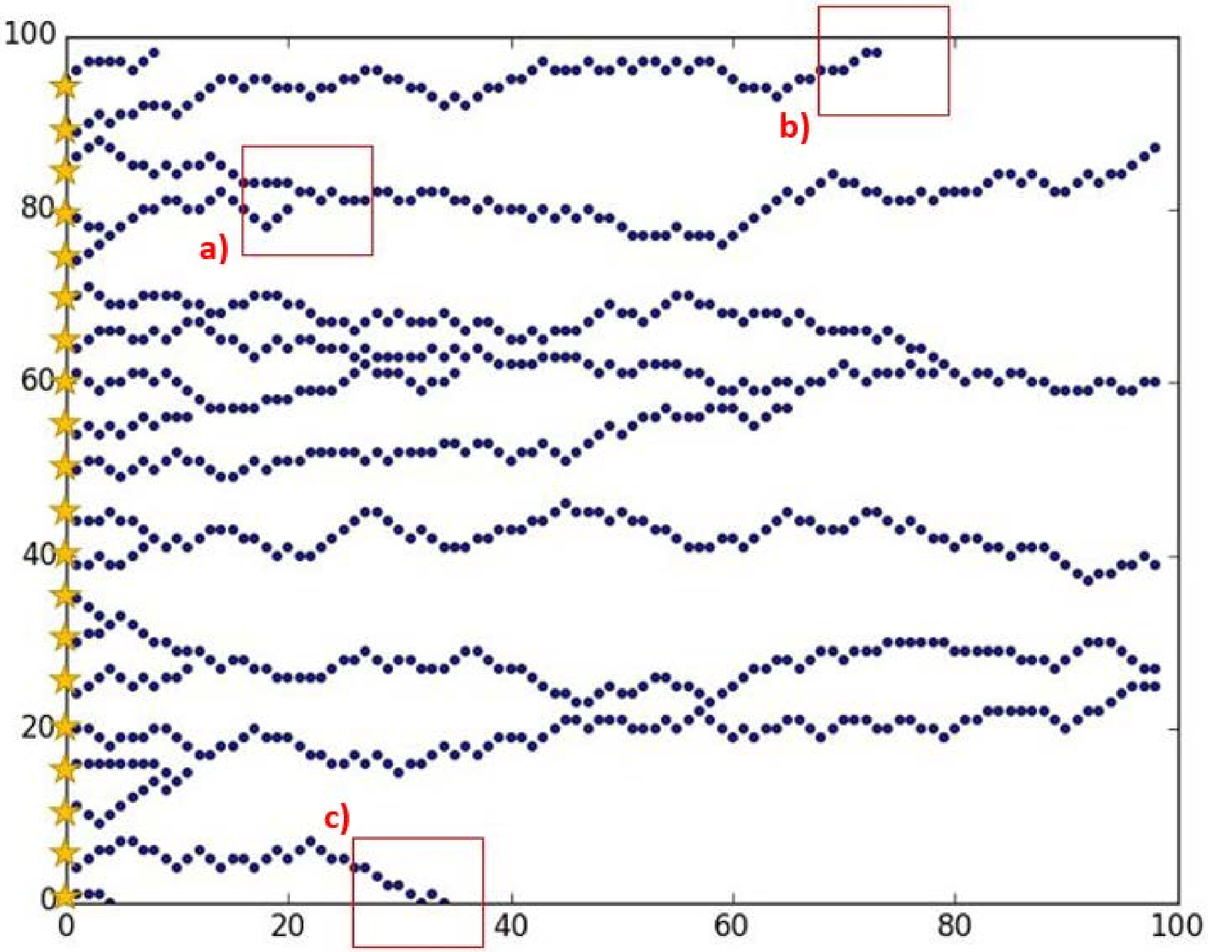


Figure 14. A 100 by 100 grid random walk model with channels having equal probability of propagation to the east, southeast, or northeast. Twenty simulated river seeds are represented by stars along the left side. a) When two paths meet, they merge into one path, b) when the path reaches 100 along the y-axis, the end location is given a value of 100, c) when the path reaches 0 along the y-axis, the end location is given a value of 0. (See text for explanation)

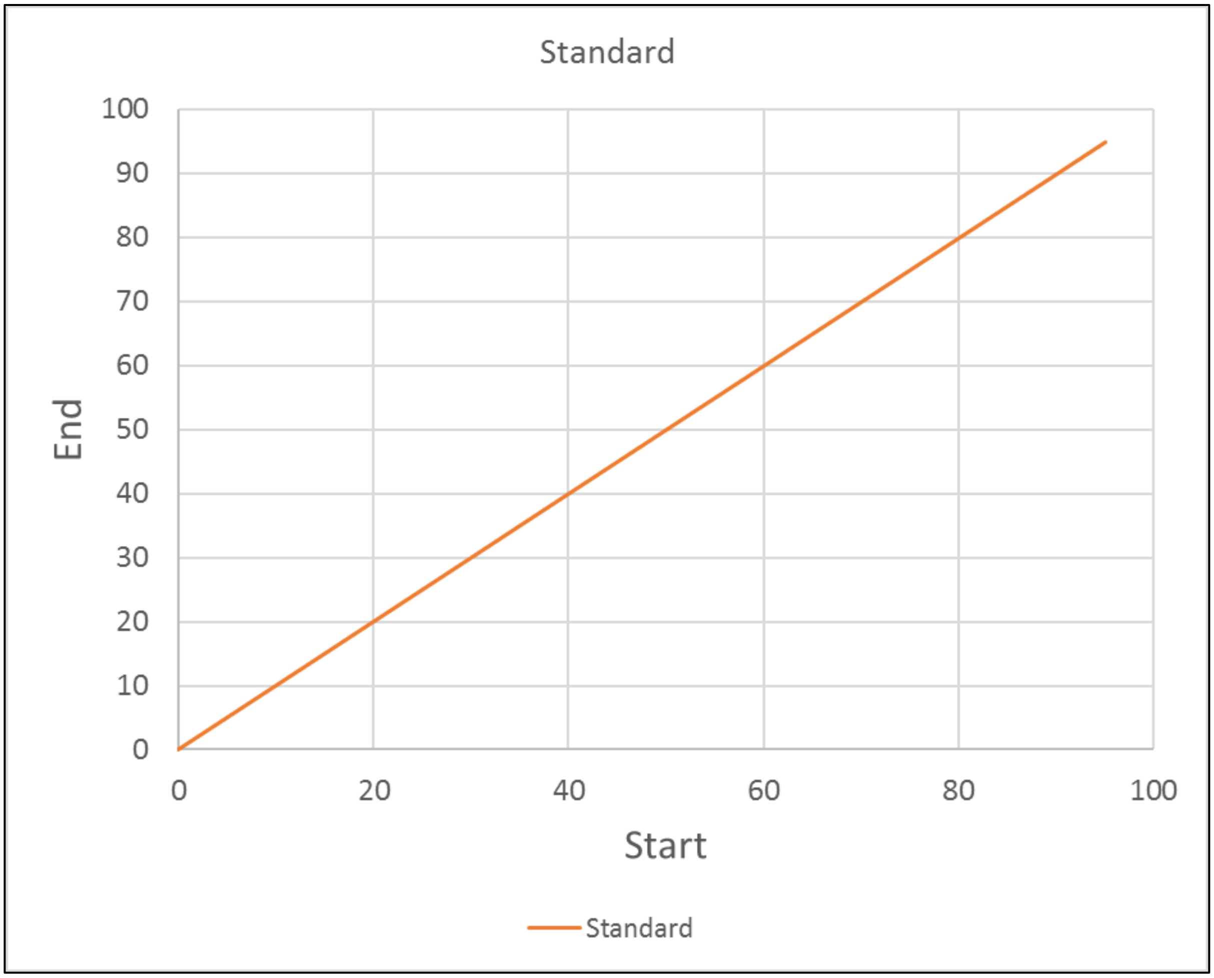


Figure 15. The standard flat terrain and pre-adjustment trend are compared to is the starting location plotted against the end, which is the starting positing plotted against itself.

CHAPTER III

RESULTS

The calculated TTSF and AF values from the basin asymmetry portion of the methods are assigned to each selected watershed along with the values of the pre-adjustment watersheds. Paleo-channels were identified and are named for the current channels that originate from the same location on the Red River Valley lake plain.

Basin Asymmetry

The Transverse Topographic Symmetry Factor and Asymmetry Factor were both measured for channel segments downstream from the Campbell beach ridge. Rivers downstream of the Campbell beach ridge could migrate across the lake plain and avulse more easily than outside the lake plain. Based on the TTSF and AF results, watersheds in the north show more asymmetry than in the south (Table 2).

Transverse Topographic Symmetry Factor

TTSF values range from -0.24 to 0.77 in the watersheds measured (Figure 16). Four of the watersheds (in decreasing value) have TTSF values below zero: Buffalo, Maple, Wild Rice, and Red Lake. The remaining watersheds all have values above zero that signifies that the river is south of the mid-line. The four watersheds with the highest value are (in increasing value): Park, western Wild Rice, Tamarac, and Otter Tail. The Park and Tamarac of two of the watersheds farthest north while the western Wild Rice and Otter Tail are the two farthest south watersheds. A graph displaying the TTSF value of each watershed plotted against the location in

Table 2. Average direction, TTSF, and AF values for selected watersheds in the Red River Valley.

River	**Direction**	**TTSF Value**	**AF**
Buffalo	**195.5**	**-0.087**	**70.07**
Forest	**187.8**	**0.270**	**43.57**
Goose	**189.3**	**0.349**	**28.28**
Maple	**245.6**	**-0.178**	**53.44**
Otter Tail	**197.5**	**0.767**	**13.41**
Park	**262.8**	**0.632**	**13.53**
Red Lake	**157.3**	**-0.243**	**57.49**
Rush	**179.4**	**0.002**	**54.58**
Sandhill	**180.6**	**0.061**	**46.44**
Snake	**186.6**	**0.542**	**25.85**
Tamarac	**194.7**	**0.757**	**13.77**
Turtle	**153.2**	**0.111**	**57.59**
Two Rivers	**188.0**	**0.550**	**17.16**
Western Rice	**101.8**	**0.654**	**39.66**
Wild Rice	**181.9**	**-0.183**	**73.71**

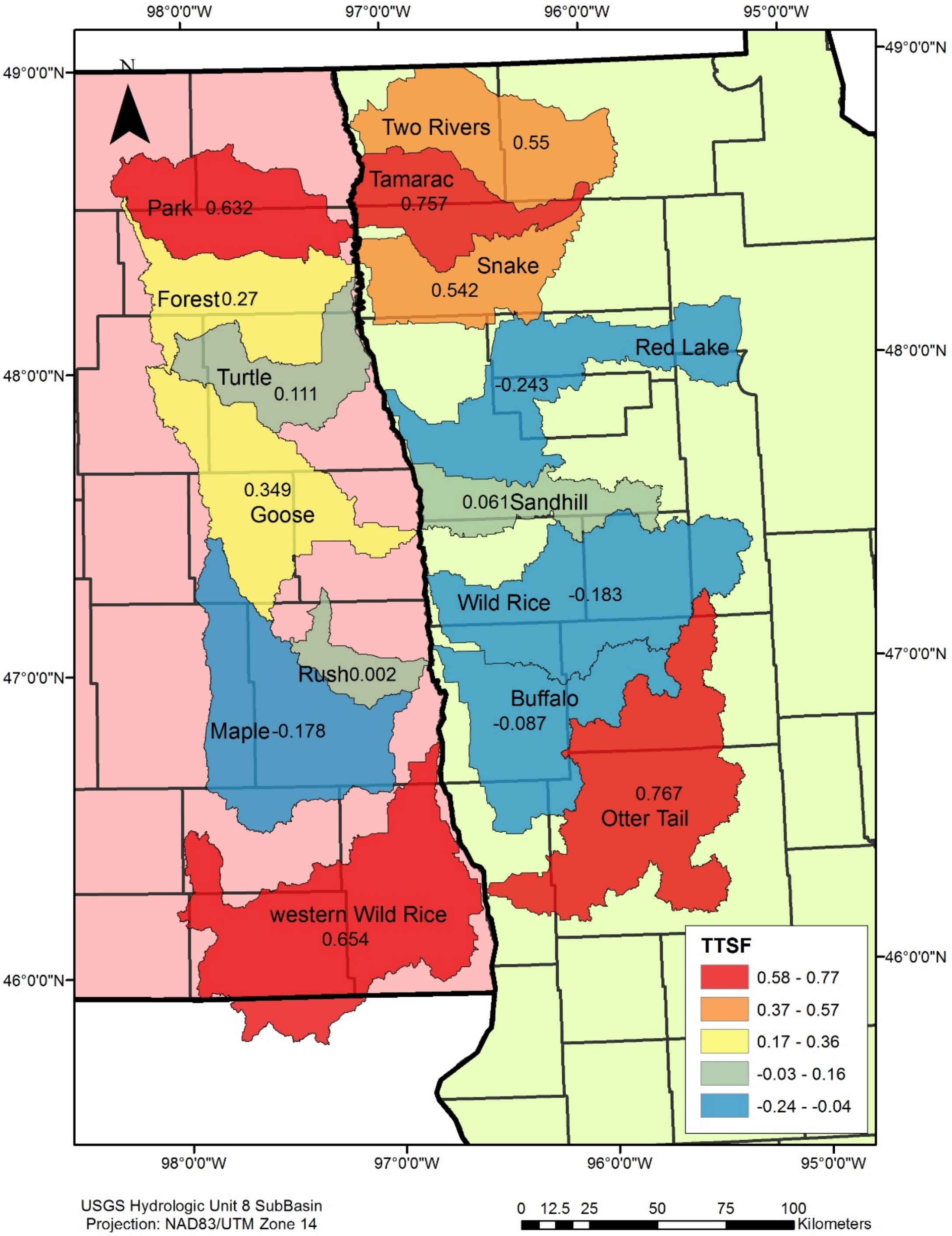


Figure 16. TTSF values for selected watersheds in the Red River Valley. Larger values indicate more asymmetry.

meters (northing) of where the tributary enters the Red River displays a very poorly fitting trend with an R^2 of 0.0424 (Figure 17). Omitting the two watersheds that do not follow the trend, the western Wild Rice and Otter Tail, the shows an R^2 value of 0.5712 (Figure 17).

Asymmetry Factor

AF values assigned to the same watersheds at the TTSF values range from 13.4 to 73.7 (Figure 18). The four watersheds with the lowest values, lower values indicating more asymmetry, are the Park, Two Rivers, Tamarac, and Otter Tail. The Park, Two Rivers, and Tamarac watersheds are the farthest north watersheds while the Otter Tail is the farthest south. The two watersheds with the highest AF values were the Buffalo and Wild Rice. Both watersheds are closer to the South Dakota border than the Canadian border. A graph displaying the AF value of each watershed plotted against the location in meters (northing) of where the tributary enters the Red River shows a possible trend with an R^2 of 0.0979 (Figure 19). Even with omitting the two watersheds that do not follow the trend, the western Wild Rice and Otter Tail, the trend shows an R^2 value of 0.4844. TTSF values were plotted against AF values and there was a trend with an R^2 value of 0.8174. Higher TTSF values usually had a low AF value associated with it (Figure 20).

Watershed Changes

Two sets of watersheds were created representing current watershed and pre-isostatic adjustment boundaries. For each watershed, a positive percentage means that the net gain is in the northern portion of the watershed, while a negative percentage means the net change is in the southern portion of the watershed (Table 3 and Figure 11). The difference in area of the pre-isostatic adjustment watersheds and current watersheds, downstream of the Campbell beach ridge, was also plotted against the location of the tributaries confluence with the Red River

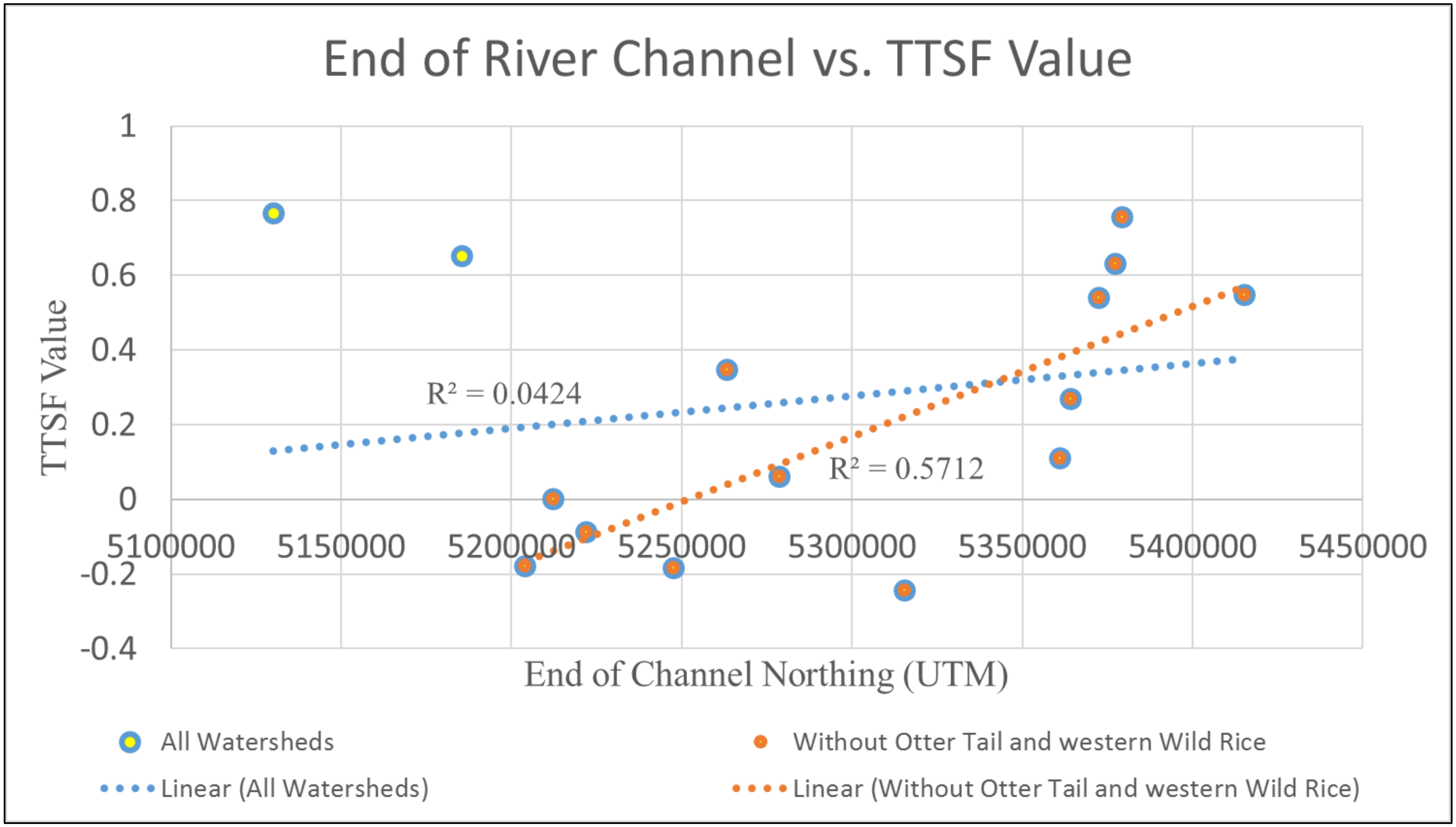


Figure 17. Confluence of current rivers with the Red River plotted against the TTSF value for select watersheds in the Red River Valley.

(Figure 22). The only watershed with a negative percent net change is the Buffalo watershed which gained 8% of its pre-adjustment watershed area in the south. The remaining watersheds all have a positive percent net gain (Figure 22), the highest being the Tamarac watershed which gained 233% of the pre-adjustment watershed area in the north. The trend of the watershed percent net gain in relation to the end of the tributary channel has a trend with an R^2 value of 0.1269. The distance between the eastern and western Campbell beach ridge which is the east and west shore of Lake Agassiz) is larger farther north. Thus, the portions of the watershed analyzed is also larger farther north.

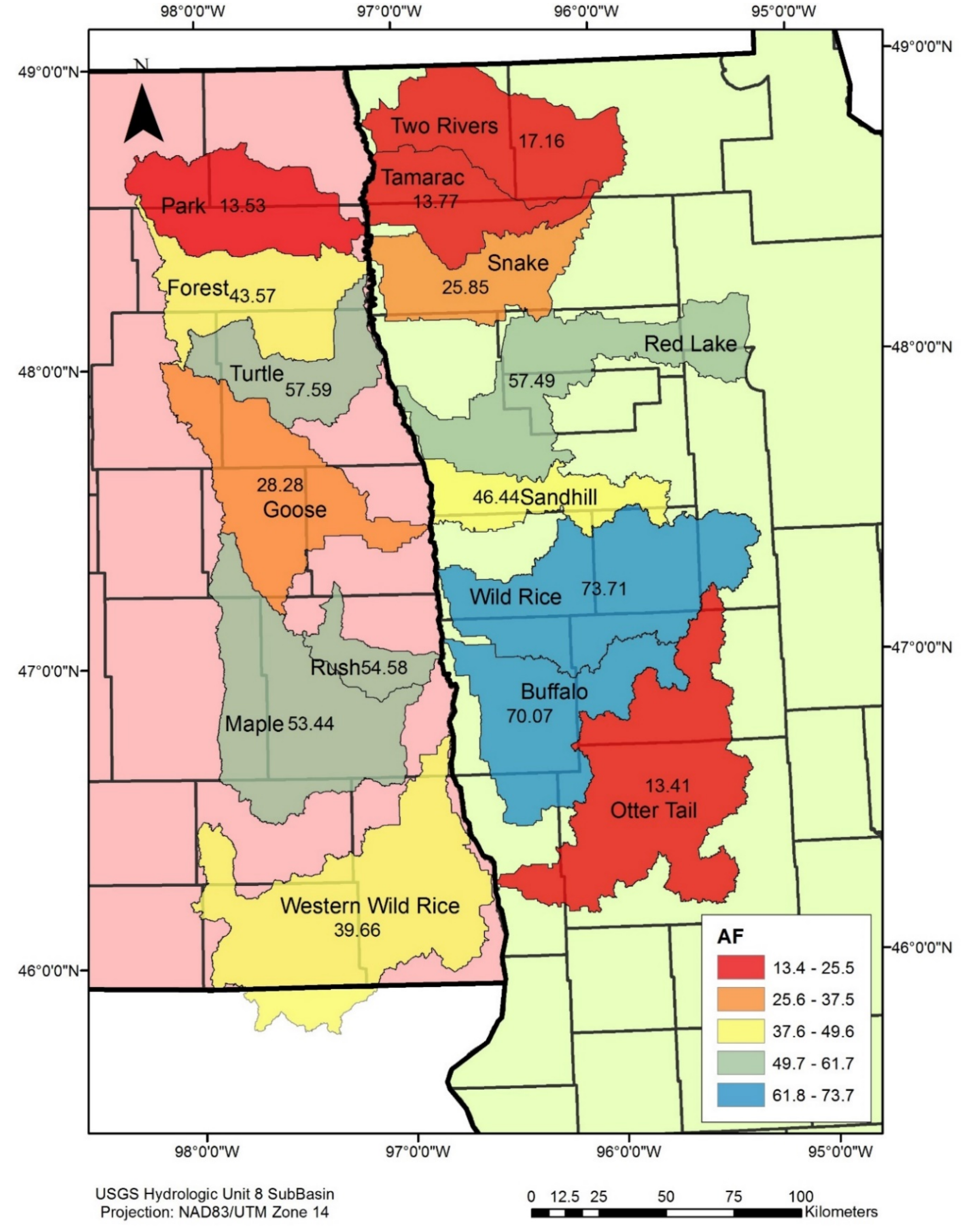
Paleo-Channels

Compaction ridges were identified within the Red River Valley, all of which were found downstream of the Campbell beach ridges (Figure 23). Within the Red River Valley, there were seven main paleo-channels identified associated with an existing channel. Many associated paleo-channel compaction ridges originating at the same location as current channel are continuous from entrance into the valley all the way to paleo-Red River. Major paleo-channels are associated with the current Turtle, Elm, Sand Hill, Buffalo, western Wild Rice, Sheyenne, and Maple Rivers (Figure 24). Six of the seven paleo-channels in this study are partially or entirely north of their respective current channel and have confluences along the paleo-Red River which parallels the current Red River (Figure 25). Many smaller streams have compaction ridges associated with them, such as the compaction ridges associated with the upper and lower Rush River and Buffalo Creek. These smaller streams also have the paleo-channel situated north of the current stream.

A subtle palimpsest channel of the Red River begins at the confluence of the western Wild Rice and Sheyenne paleo-river and is hereafter referred to as the paleo-Red River (Figure

Table 3. Change in watersheds in square meters. Values acquired by subtracting the pre-adjustment watershed from the current watershed.

		NORTH	NORTH	SOUTH	SOUTH		(GAINED-LOST) /(TOTAL AREA)	(GAINED-LOST) /(TOTAL AREA)	(NORTH CHANGE) -(SOUTH CHANGE)
END OF RIVER (M)	**River**	**Gained (m^2)**	**Lost (m^2)**	**Gained (m^2)**	**Lost (m^2)**	**Total Area (m^2)**	**North Percent Net Change**	**South Percent Net Change**	**Total Percent Net Change**
5221823	Buffalo	4.17E+07		1.18E+08	4.69E+06	8.42E+08	5%	13%	-8%
5364222	Forest	4.11E+08			1.02E+07	9.81E+08	42%	-1%	43%
5263257	Goose	8.32E+07			1.50E+07	3.47E+08	24%	-4%	28%
5203884	Maple	6.73E+07			4.36E+06	7.55E+08	9%	-1%	9%
5130066	Otter Tail	3.13E+07			4.88E+06	1.36E+08	23%	-4%	27%
5377081	Park	1.50E+08			1.47E+08	1.40E+09	11%	-10%	21%
5315486	Red Lake	3.76E+07		7.26E+07	8.87E+07	1.09E+09	3%	-1%	5%
5278656	Sandhill	8.91E+07	1.32E+07		1.66E+08	6.55E+08	12%	-25%	37%
5372358	Snake	3.35E+08			3.43E+08	1.82E+09	18%	-19%	37%
5379145	Tamarac	4.37E+08			2.09E+08	2.77E+08	158%	-75%	233%
5360889	Turtle	1.10E+07			9.03E+07	4.96E+08	2%	-18%	20%
5415022	Two Rivers	3.35E+07	6.65E+07		1.39E+08	8.04E+08	-4%	-17%	13%
5185311	Western Wild Rice	1.71E+07			1.65E+07	1.12E+09	2%	-1%	3%
5247382	Wild Rice	1.82E+07			1.46E+07	8.96E+08	2%	-2%	4%



USGS Hydrologic Unit 8 SubBasin
Projection: NAD83/UTM Zone 14

Figure 18. AF values for selected watersheds in the Red River Valley. Values below 50 indicate significant asymmetry

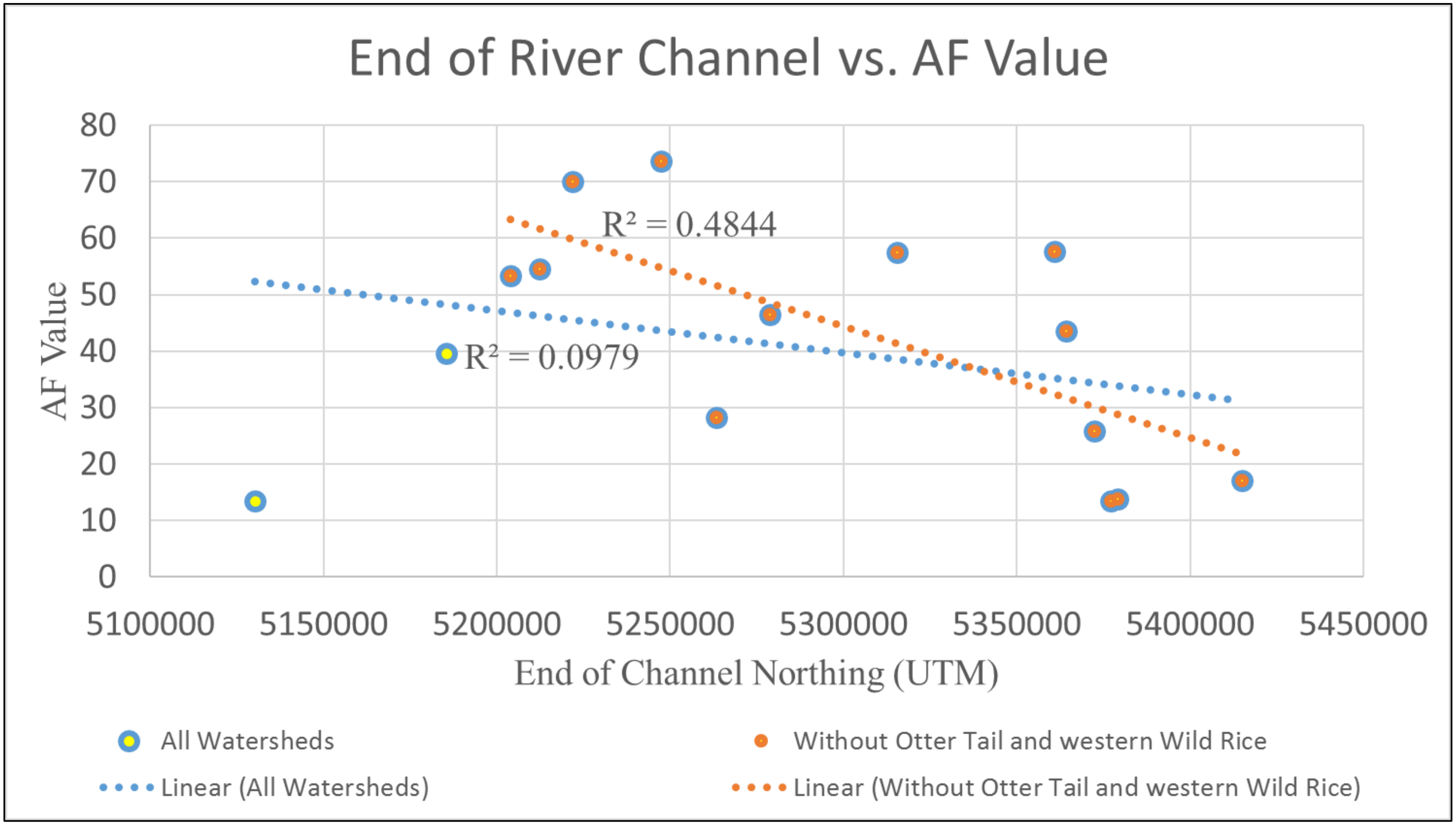


Figure 19. Confluence of current rivers with the Red River plotted against the AF value for select watersheds in the Red River Valley.

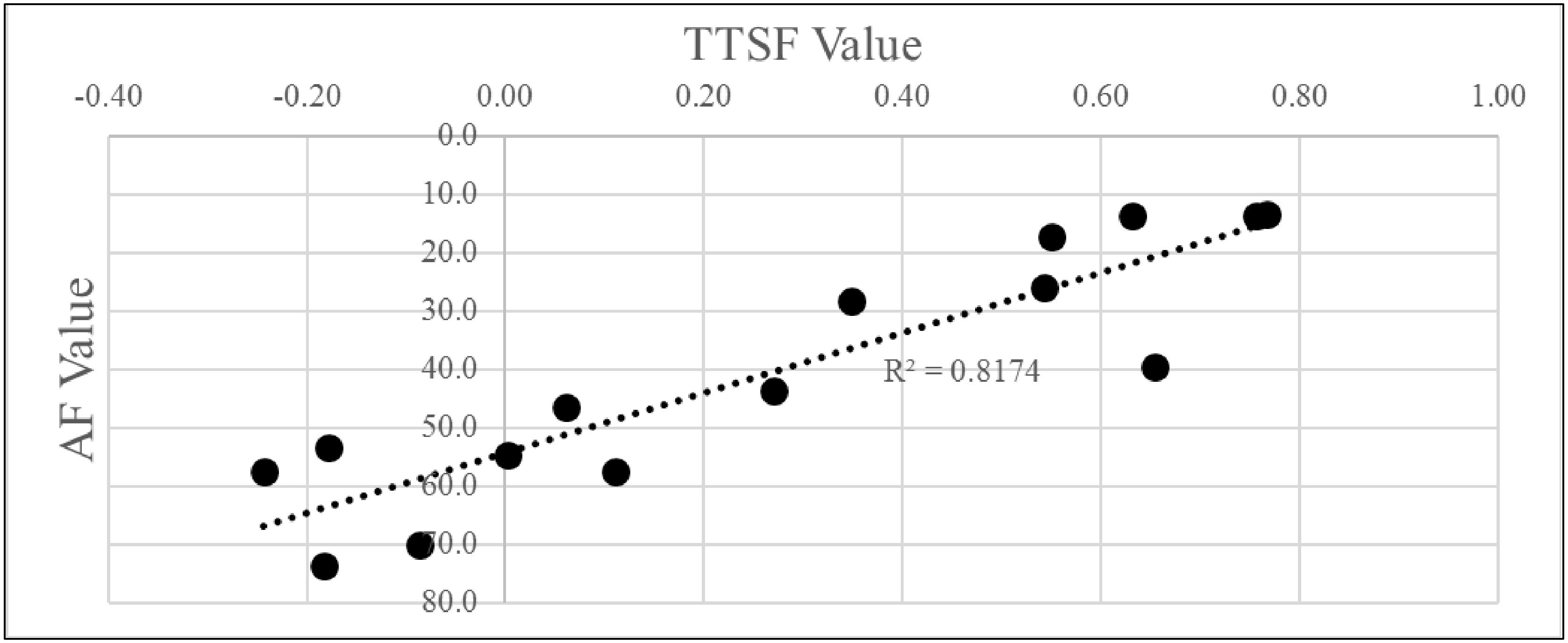


Figure 20. TTSF values plotted against AF values for select watersheds in the Red River Valley.

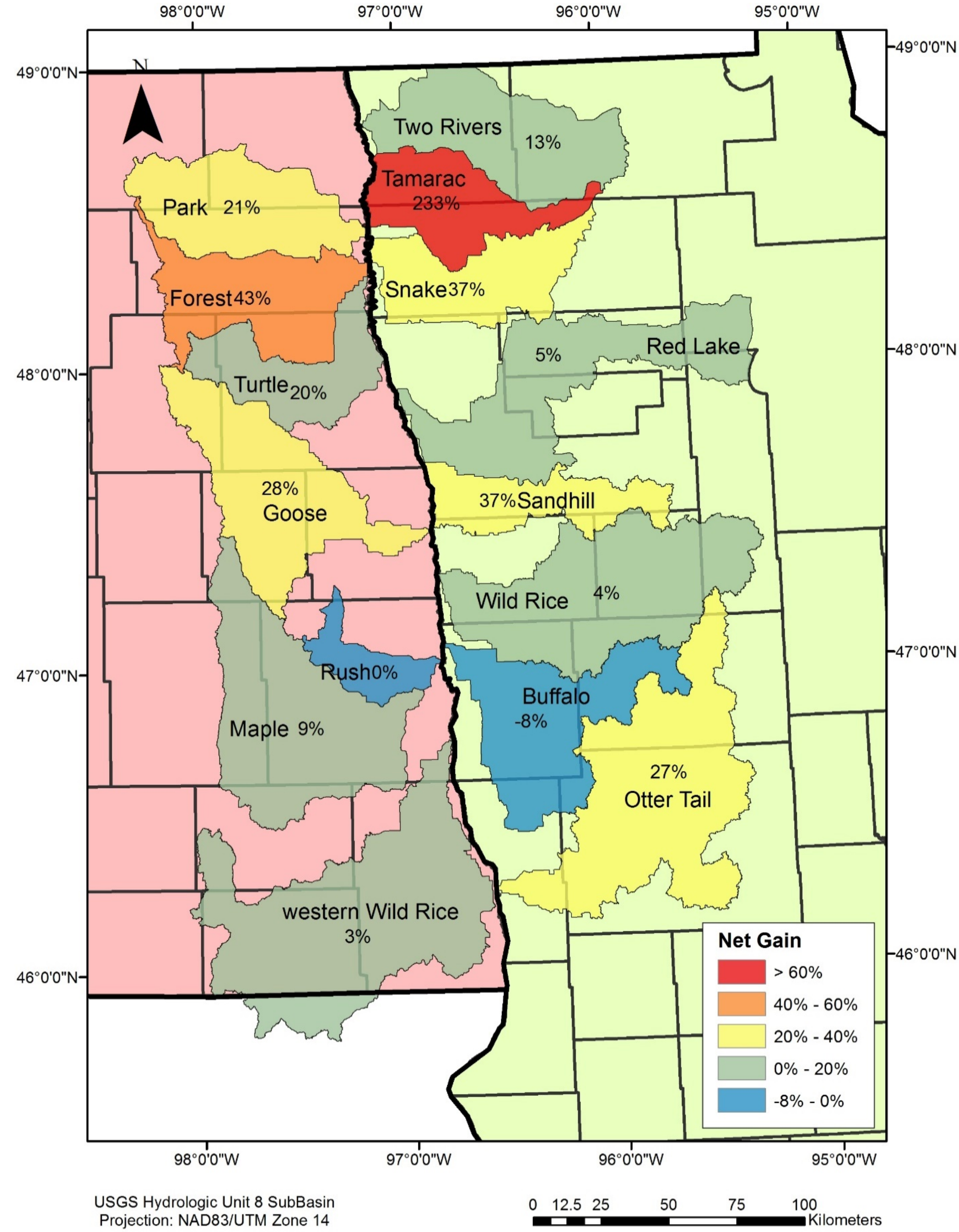


Figure 21. Percent net gain of watershed area for select watersheds in the Red River Valley.

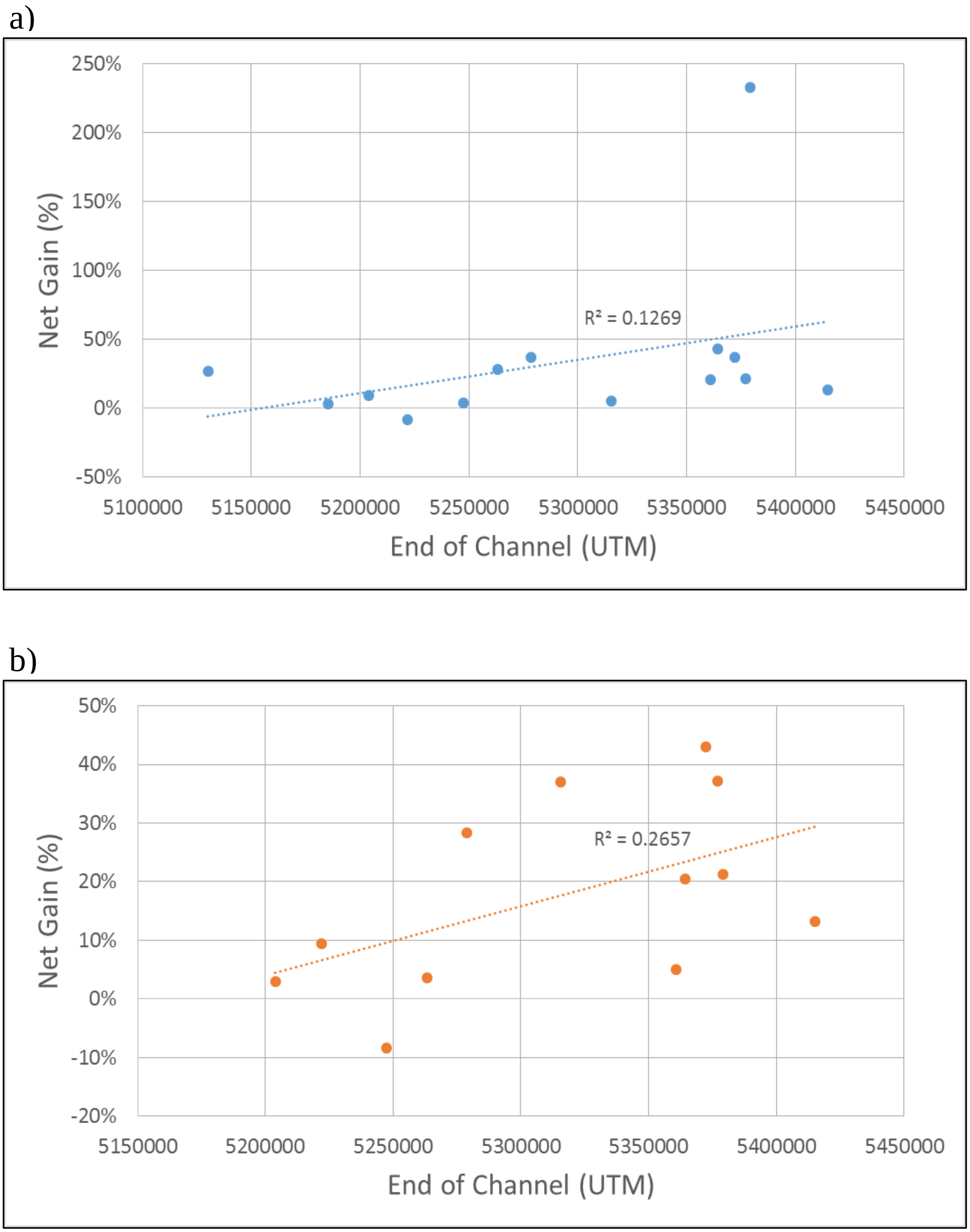


Figure 22. a) Trend of percent net gain of watershed area for selected watersheds in the Red River Valley omitting the Tamarac and Otter Tail watersheds; b) Trend of percent net gain of watershed area for selected watersheds in the Red River Valley.

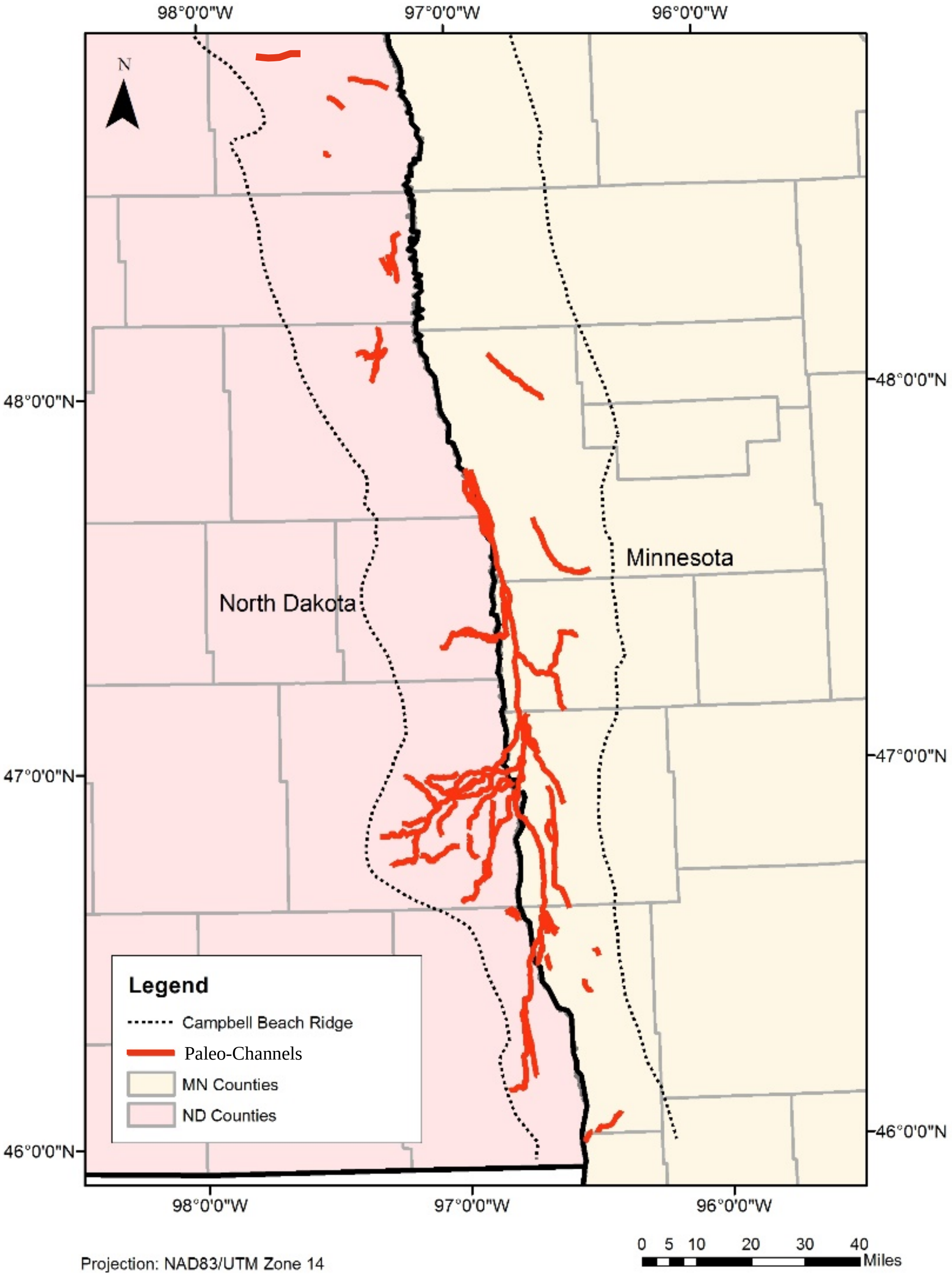


Figure 23. Paleo-channels located from 10 meter DEM. Locating of paleo-channels was extended upstream of the beach ridge, but no paleo-channels were located.

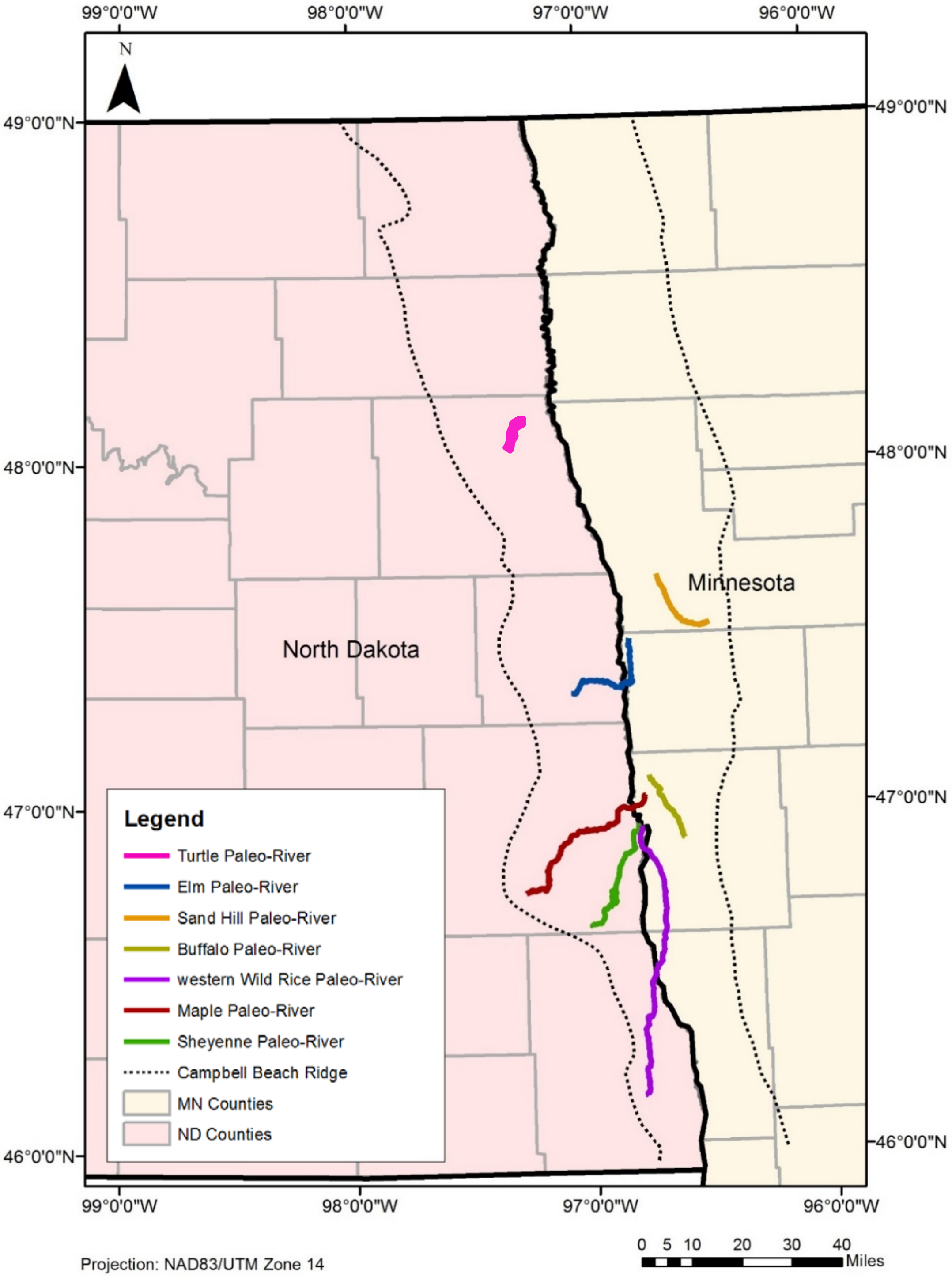


Figure 24. Seven major paleo-channel channel: Turtle (pink), Elm (blue), Sandhill (beige), Maple (red), Buffalo (yellow), Sheyenne (green), and Wild Rice (purple).

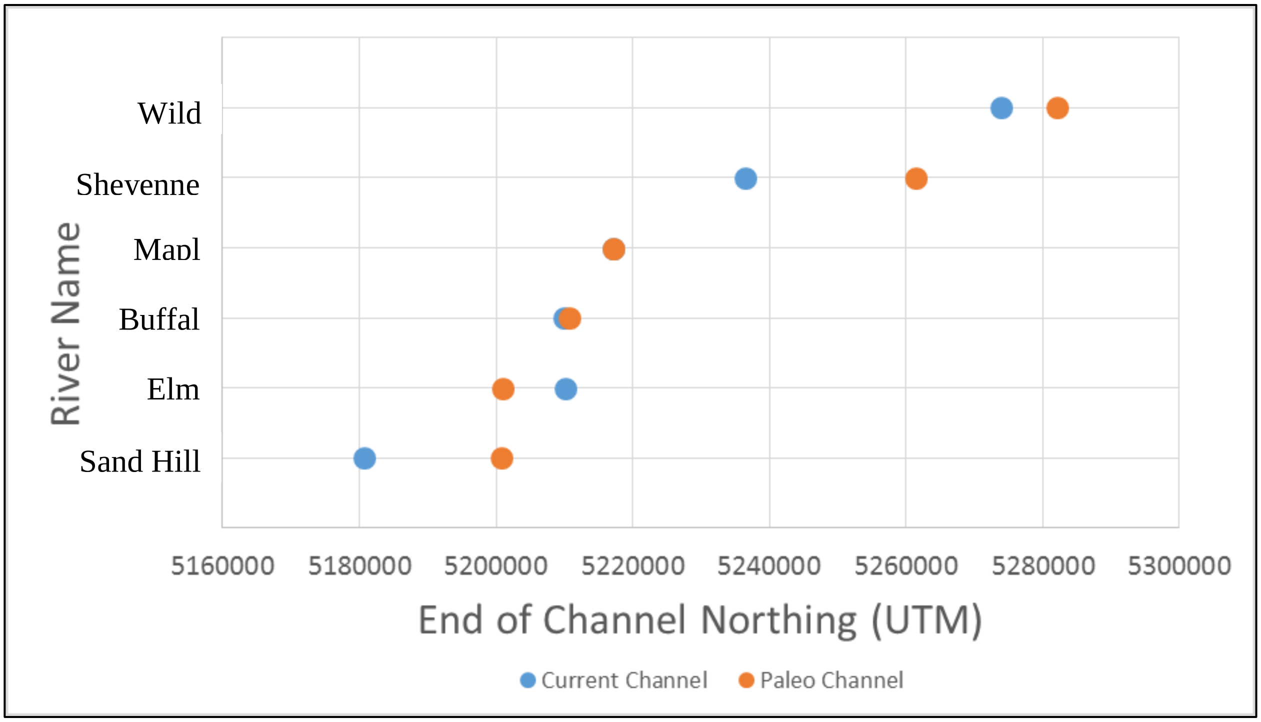


Figure 25. Confluences of the current/Red River and paleo-channel/paleo-Red River.

26). The paleo-Red River is not labeled in any county or geological reports, but is named thus because it is the widest of the compaction ridges (nearly 500 meters) and parallels the current Red River on average 4km to the east. Paleo-channels identified are associated with the western Wild Rice, Sheyenne, Maple, Turtle, Buffalo, Sand Hill and Elm rivers.

Western Wild Rice

Although the current and paleo-channel for the western Wild Rice rivers originate at the same location, they do not follow the same course (Figure 27). Both the current and paleo-channels are north-south trending within the Red River Valley. The current and paleo-channels of the western Wild Rice are parallel while entering the valley with the current channel to the east of the paleo-channel. About 25km downstream of the Campbell beach ridge the paleo-channel crosses the current channel and is now to the east of the current channel. The paleo-western Wild Rice River enters the paleo-Red River 20km north of where the current western Wild Rice River enters the current Red River.

3.3.2 Sheyenne and Maple

The Sheyenne paleo-channel is almost entirely to the south of the current channel and enters the paleo-Red River almost 10km north of the current Sheyenne-Red River confluence (Figure 28). The Maple paleo-channel lies almost entirely north of its current channel, and extends farther east than the current channel to connect with the paleo-Red River (Figure 29). The paleo-Maple and current Maple River have confluences at the same latitude.

Both the Maple and Sheyenne rivers have more recently abandoned channels associated with them that are not compaction ridges. 15km downstream of the Campbell beach ridge, an abandoned 30km channel diverts to the north from the current Sheyenne River. This channel has a higher sinuosity than the compaction ridge and lies north of the Sheyenne River. The Maple River also has an abandoned 6km channel north of its current channel approximately 5km downstream of the beach ridge. This abandoned channel is much smaller than that of the one associated with the Sheyenne River.

Turtle

The Turtle paleo-channel is situated north of its current Turtle River where it also has a paleo-channel network with other paleo-channels coming from the west (Figure 30). Besides the paleo-Turtle River compaction ridge, there is a more recently abandoned channel that lies between the compaction ridge and the current channel.

Buffalo

The Buffalo paleo-channel which is first identified along the current Buffalo River about 10km downstream of the Campbell beach ridge (Figure 31). The paleo-channel is consistently north of the current river and enters the paleo-Red River at approximately the same latitude as the current Buffalo River entering the current Red River. Two kilometers downstream from the beach ridge along the current river is a more recently abandoned 10km channel that is to the south of the Buffalo River.

Sand Hill

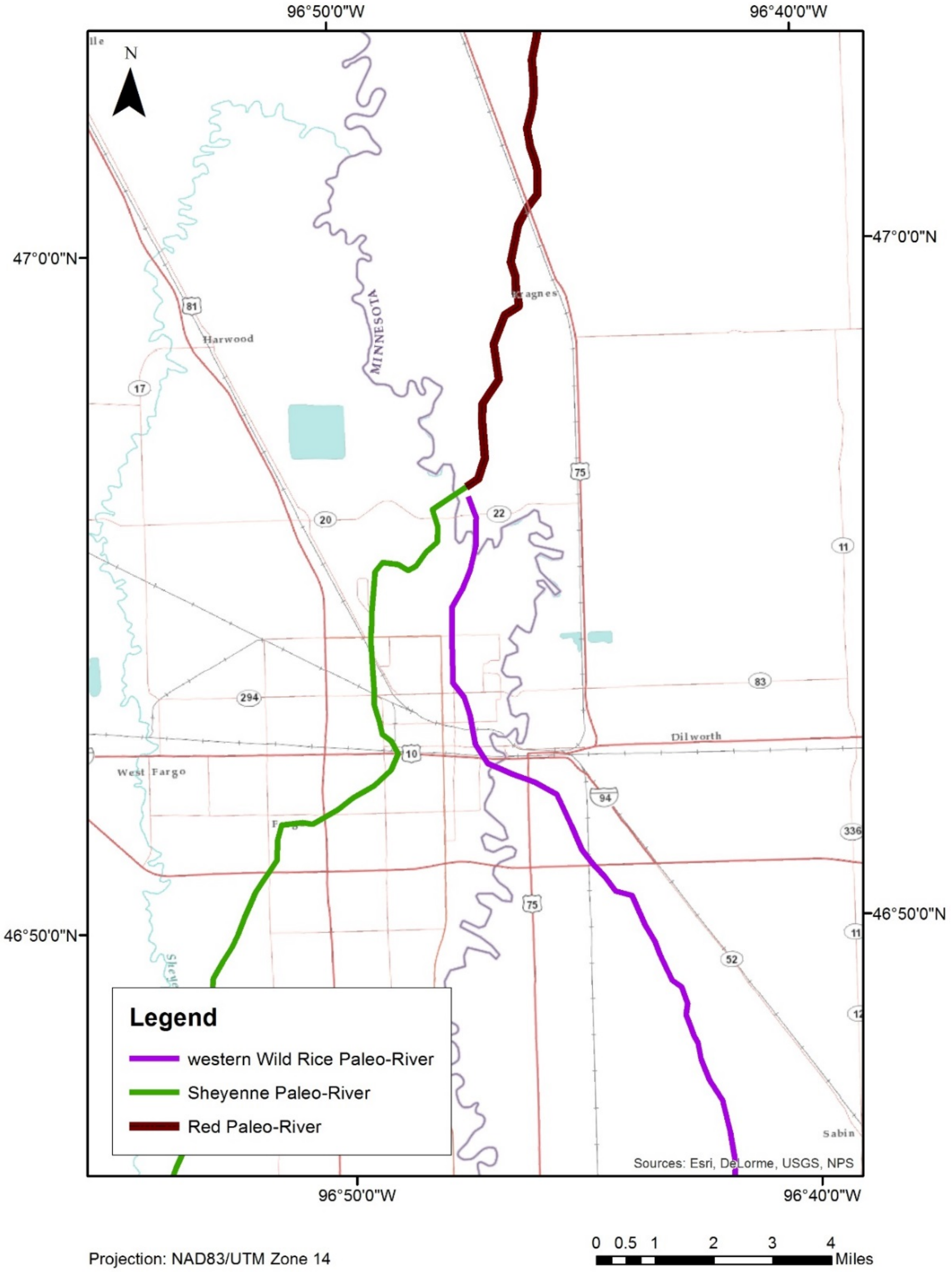
The Sand Hill paleo-channel which is first identified 7km downstream of the Campbell beach ridge 300m south of the current Sand Hill River (Figure 32). The paleo-channel is positioned south of the current river and then crosses the current river 10km downstream of the beach ridge. After the intersection, the paleo-channel continues north at a 45-degree angle and continues north until the channel can no longer be identified.

Elm

The Elm paleo-channel is first identified 25km downstream of the current Elm River (Figure 33). Besides the first kilometer stretch of the paleo-channel the remaining channel lies to the north of the current Elm River. The paleo-channel remains roughly parallel to the current channel until 15km downstream of the paleo-channel where it continues due north until its confluence with the paleo-Red River 25km north of the current Elm and Red River confluence.

Random Walk Model

Not many trials of each model were required to attain the accuracy needed to confirm the randomness of the model (Leopold and Langbein, 1962). The stochastic random walk model (10 trials) of equal channel migration probability produced a linear trendline almost identical with the standard (Figure 34). The linear trendline of the flat terrain results had an R^2 value of 0.9962, and correlated with the standard with a correlation value of 0.9981. The linear trendline with an R^2 value of 0.9915 representing the pre-adjustment probability resulted in the river ending at least five cells farther north than if the channel moved straight across on flat terrain (Figure 35).



Sources: Esri, DeLorme, USGS, NPS

Figure 26. Paleo-rivers and the position of current rivers surrounding Fargo, North Dakota. The paleo-Red River begins at the confluence of the paleo-western Wild Rice and paleo-Sheyenne River.

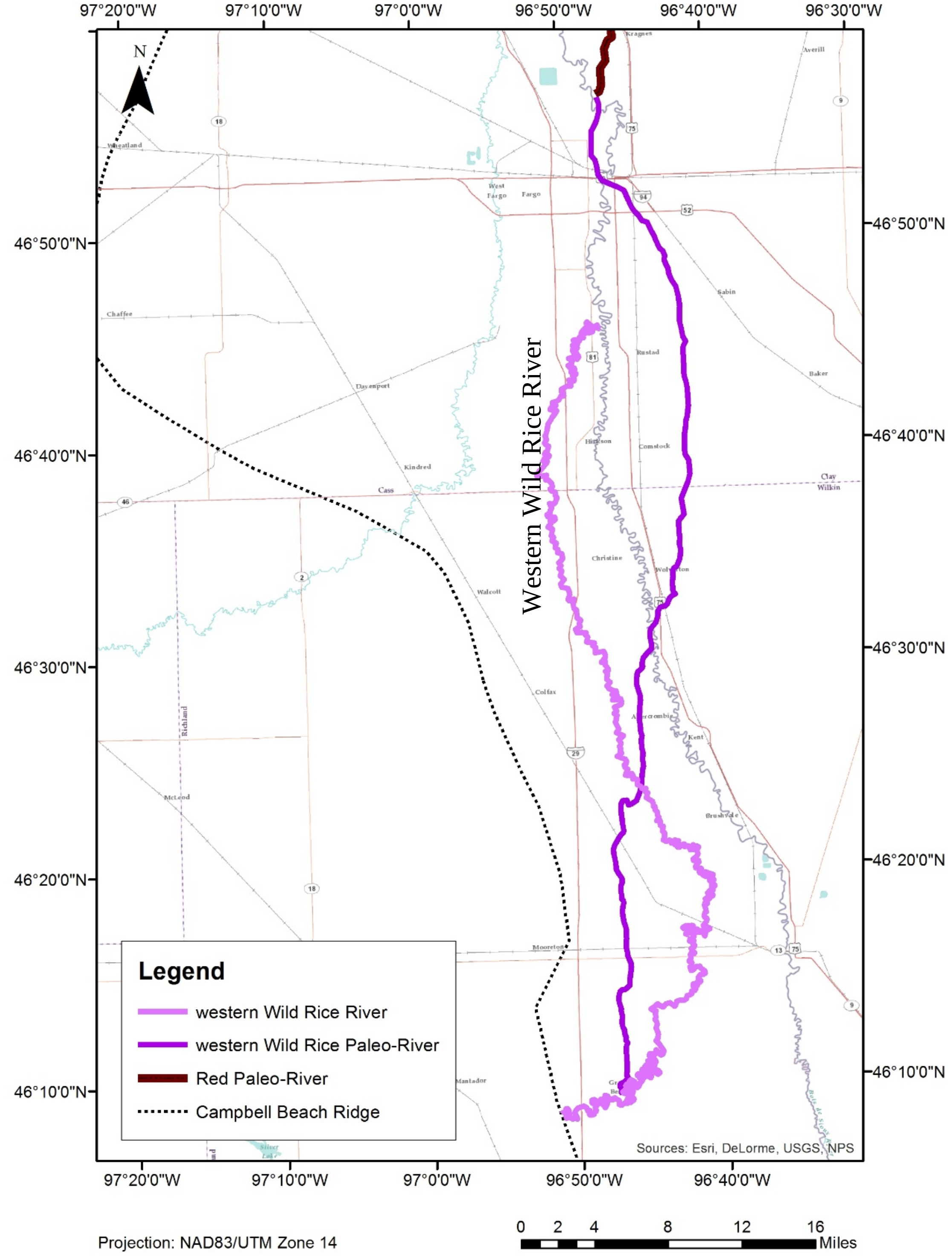


Figure 27. Paleo and current western Wild Rice River; both have confluences near Fargo, ND.

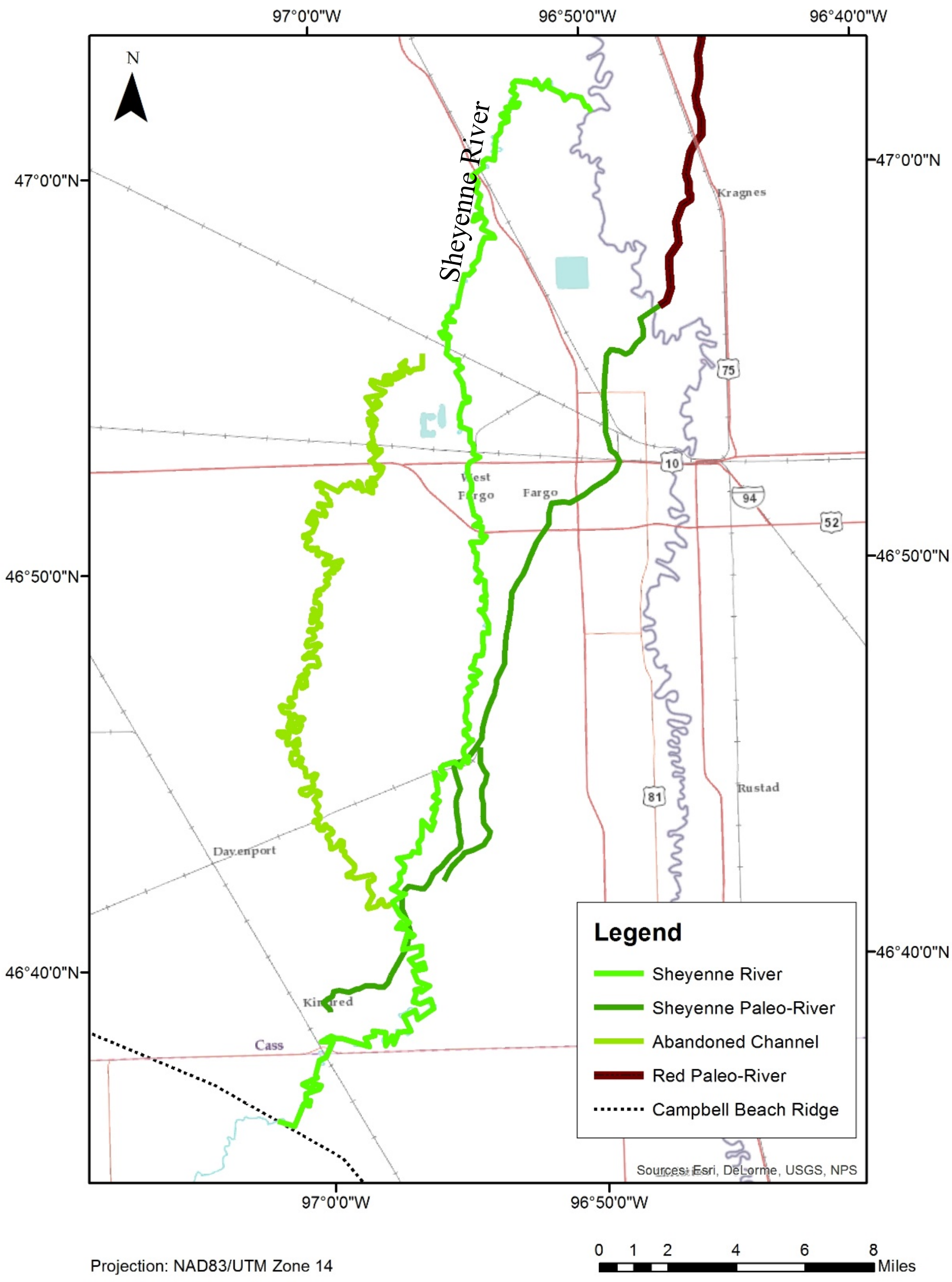


Figure 28. Paleo and current Sheyenne river; both have confluences near Fargo, ND. There is also and abandoned channel which is incised into the lake plain and has no flowing water. The abandoned channel once flowed into the Maple River rather than the Maple River flowing into the Sheyenne River.

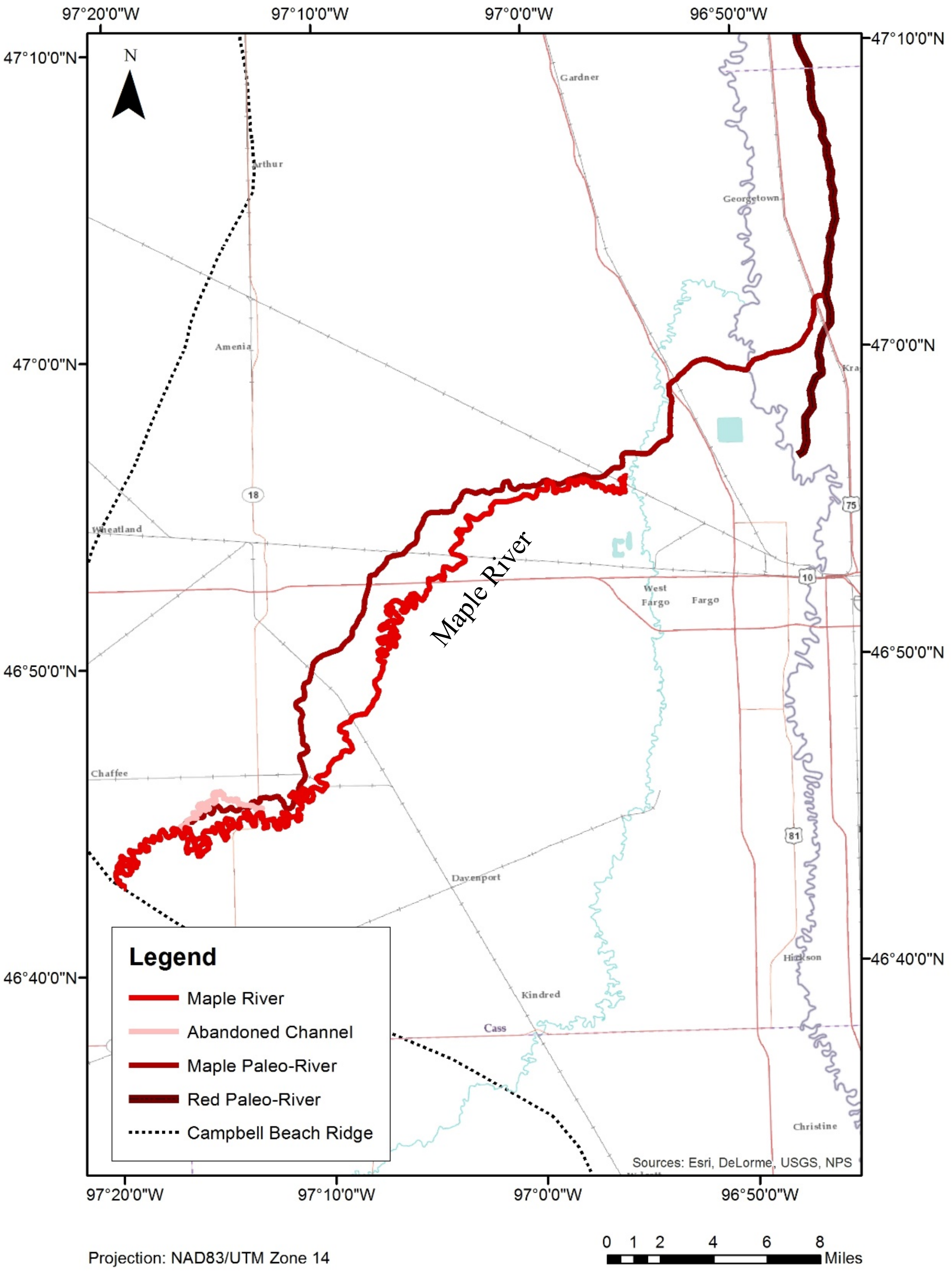


Figure 29. Paleo and current Maple River. The current Maple River flows into the current Sheyenne River. An abandoned 6km channel is located 5km downstream of the Campbell beach ridge.

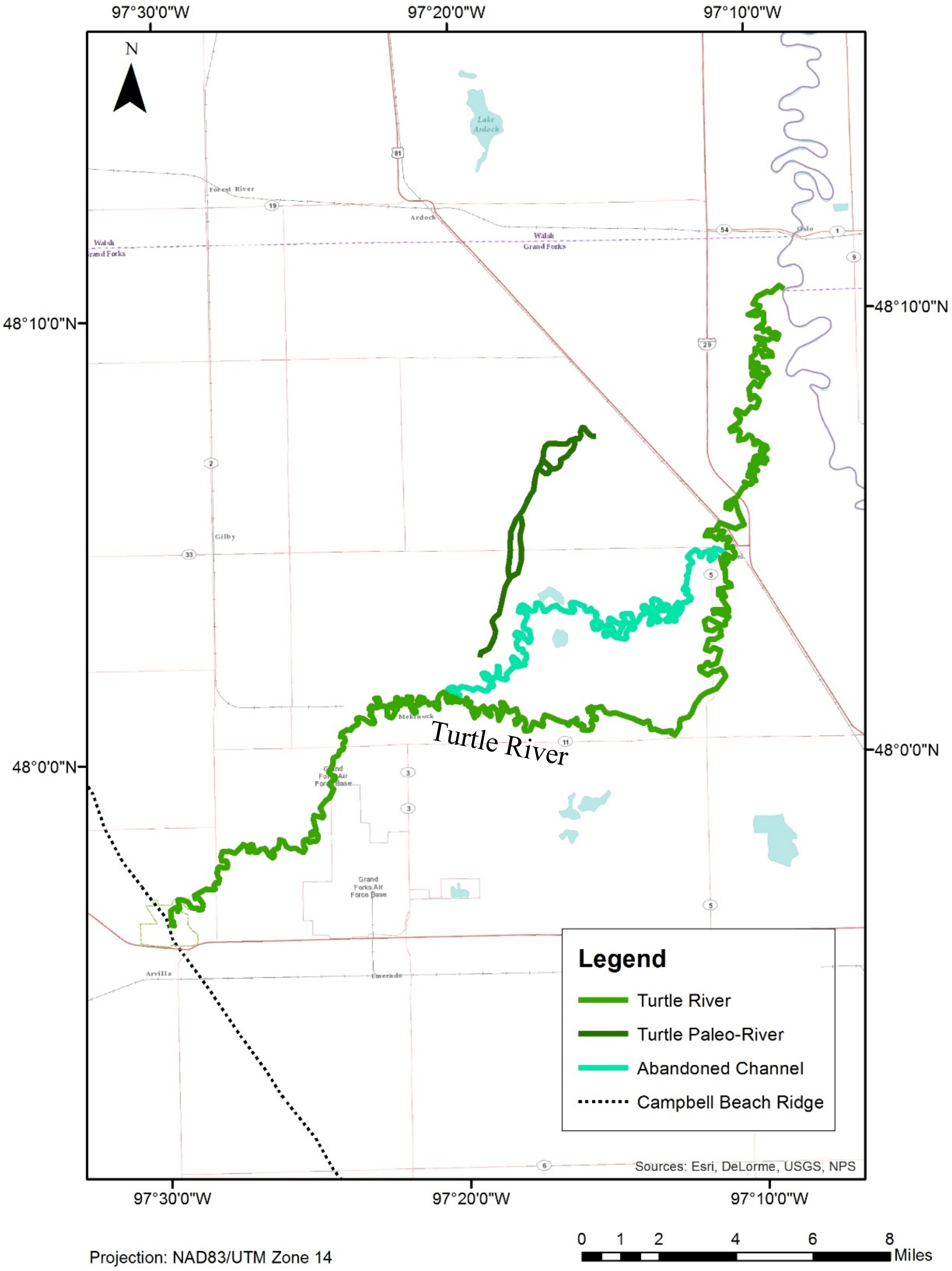


Figure 30. Both the current and abandoned Turtle River flow near or through the Kelly Slough. The paleo channel associated with the Turtle River is north of Kelly Slough.

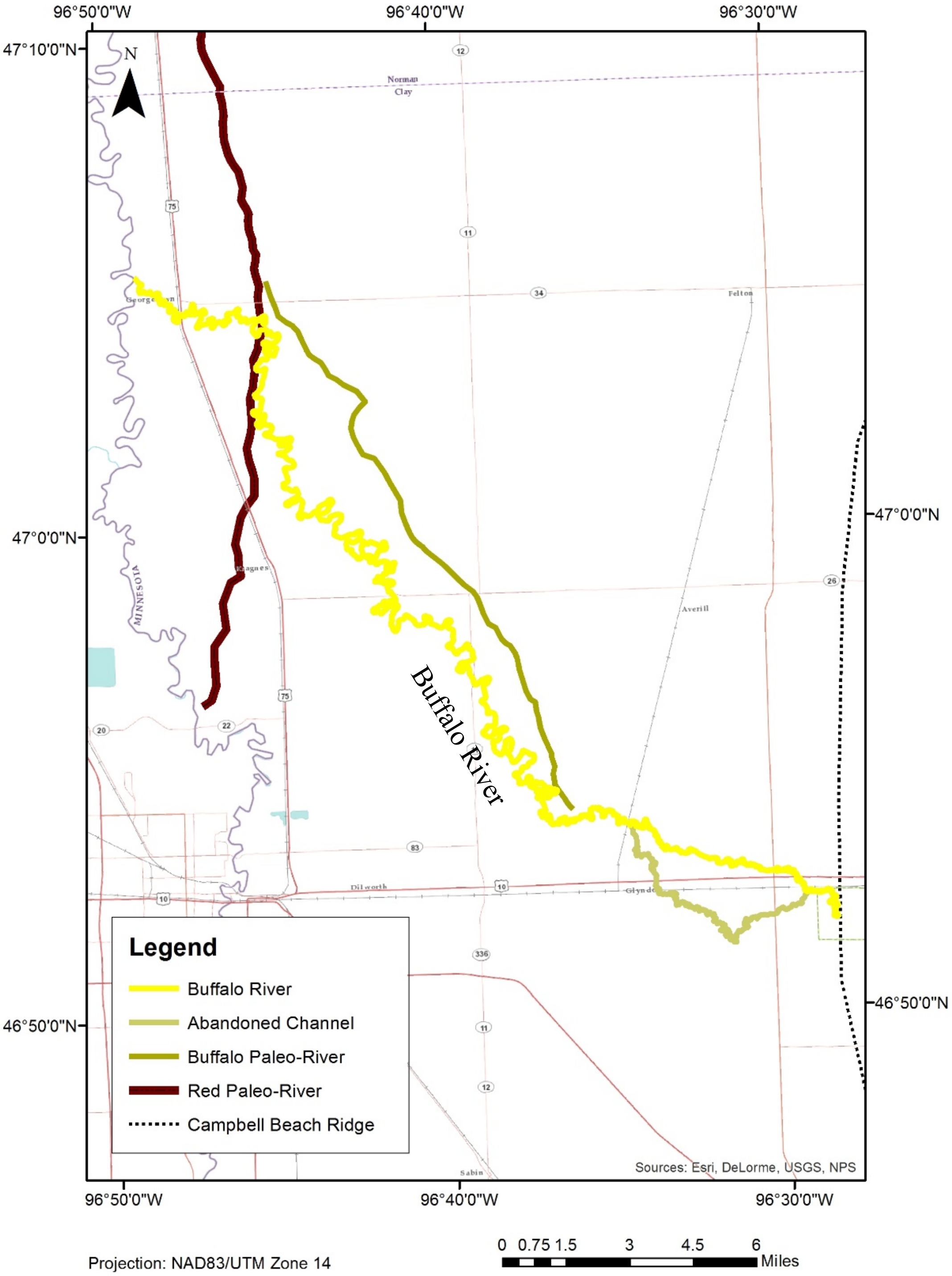


Figure 31. The confluence of the current Buffalo River and current Red River is about the same latitude as the paleo-Buffalo and Red River. Two kilometers downstream of the Campbell beach ridge is a 10km recently abandoned channel that is incised into lake plain.

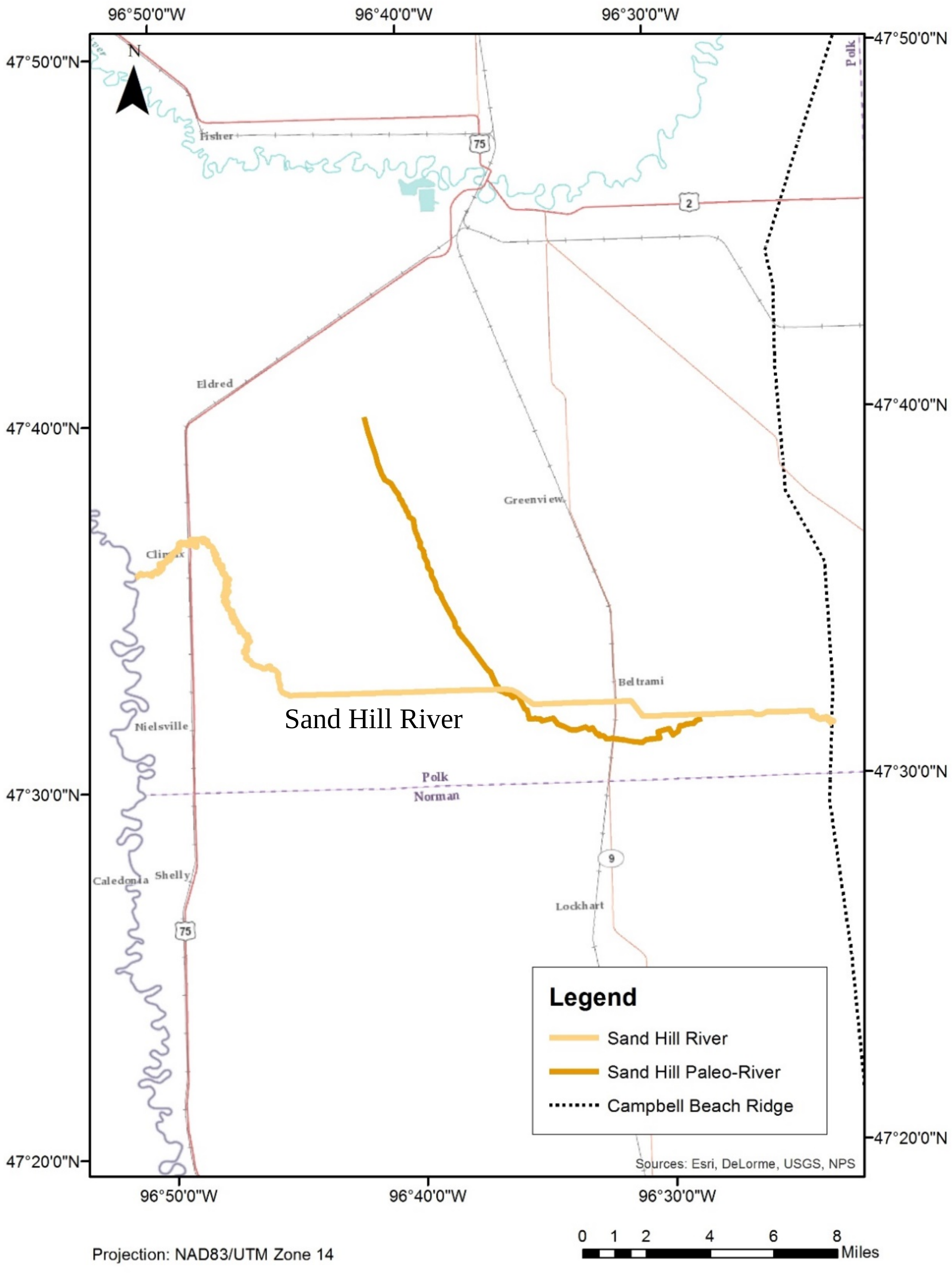


Figure 32. The paleo-Sand Hill River begins south of the current Sand Hill River, but intersects the current Sand Hill River at a 45-degree angle about 10km downstream of the Campbell beach ridge.

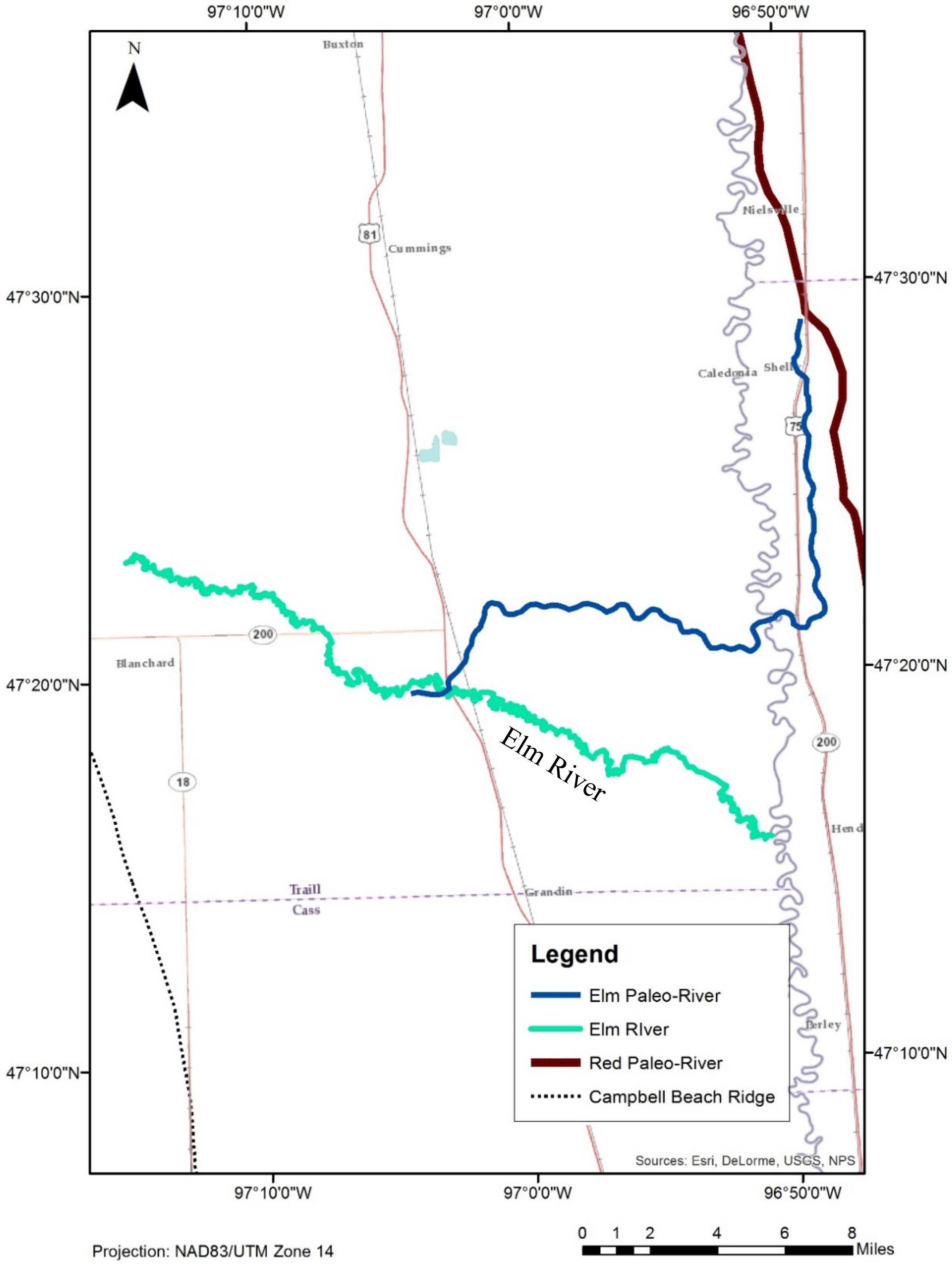


Figure 33. The pale-Elm River has a confluence with the paleo-Red River 25km north of the current Elm and Red River confluence.

The R^2 values for the two models are statistically significant. The pre-adjustment model had a p-value of 0.0002 and the flat terrain model had a p-value of 0.0172.

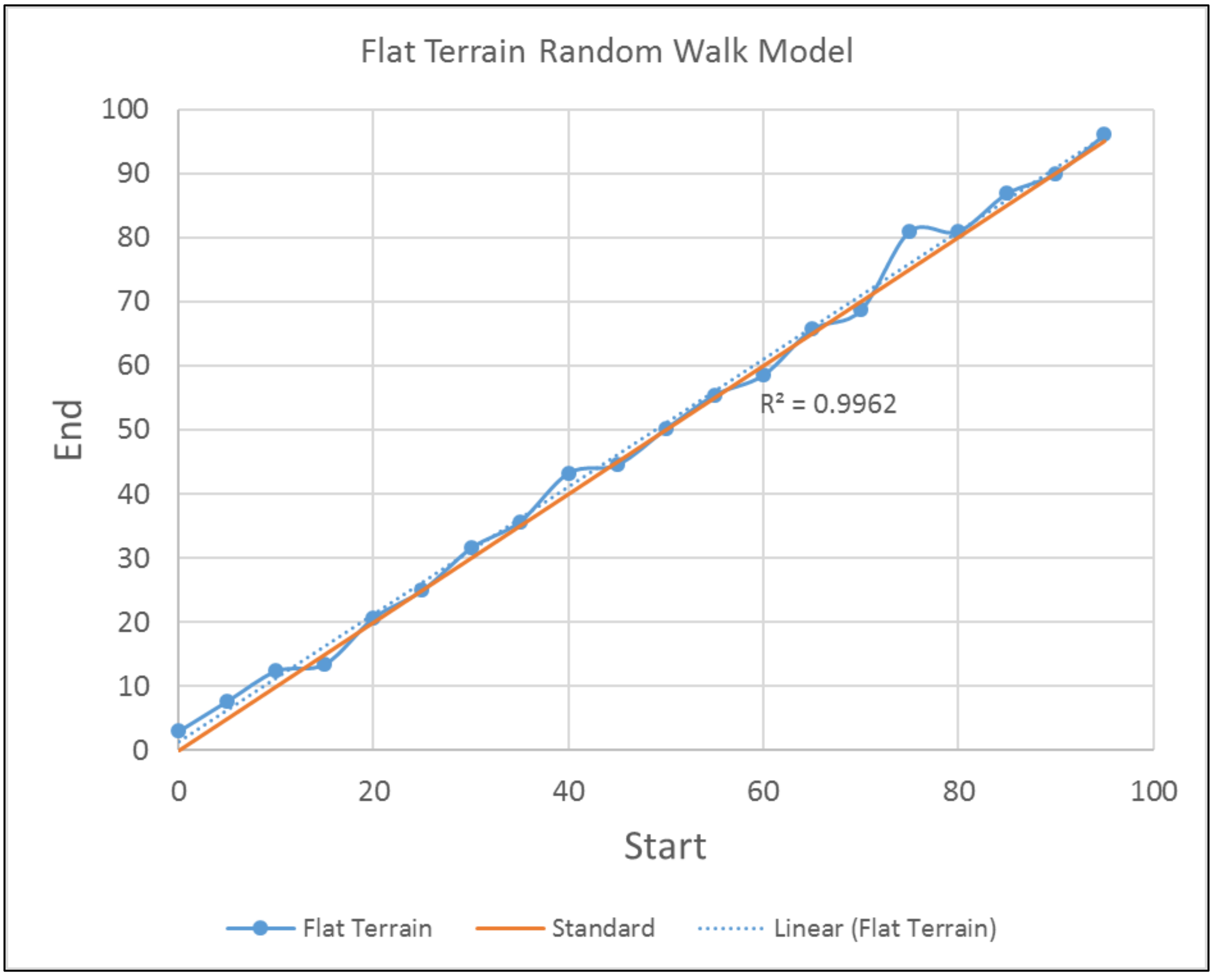


Figure 34. Ending locations along y-axis (End) plotted against starting seed position (Start). This is the result of simulating flat terrain with equal probability for a propagating channel moving east, southeast, or northeast to the next cell. The values for the flat terrain and standard are similar with a correlation value of 0.9981.

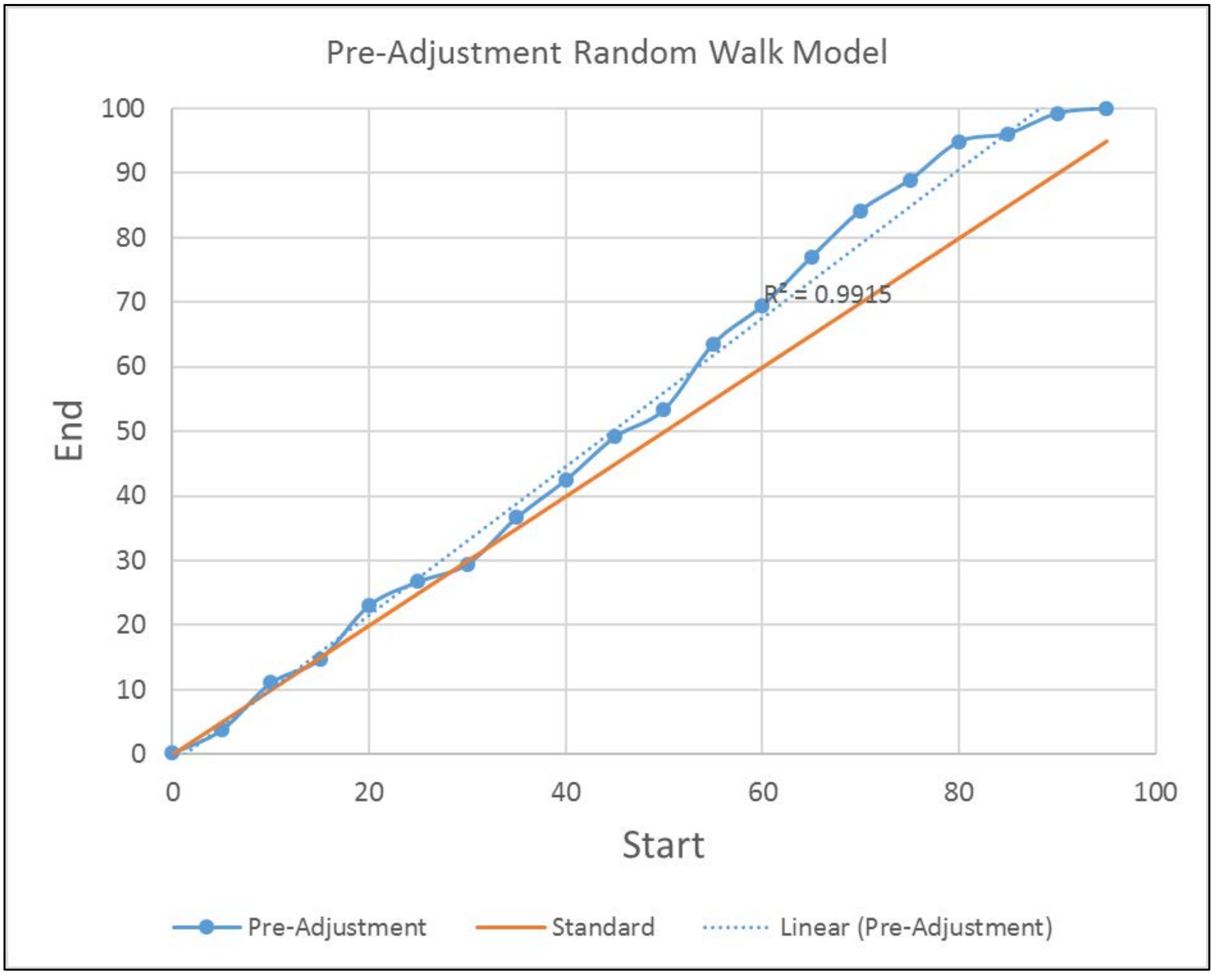


Figure 35. Ending locations along y-axis (End) plotted against starting seed position (Start). Probability of propagation to the east, southeast, or northeast reflect isostatic adjustment rates.

CHAPTER IV

DISCUSSION

This chapter discusses watershed asymmetry and paleo-channel results to determine if asymmetry is the result of 1) a changing watershed, 2) a shift in river position, or 3) both. The TTSF and AF indicate whether there is a strong tectonic influence on the watersheds (Tsodoulos et al., 2008). The basin asymmetry values do not indicate if the asymmetry is the result of a changing watershed or a changing river, but rather addresses if there is in fact asymmetry or not. Delineating the pre-adjustment watersheds and comparing them with the present watersheds helps establish if asymmetry is a result of a changing watershed. Finding the paleo-channels and their relation to current channels addresses if asymmetry is a result of a shift in river position. Lastly, the stochastic channel-development model will be used to display that randomly generated rivers shift with varying adjustment rates.

Other authors work regarding drainage changes from tilting have focused on local occurrences such as faulting or geologic domain changes. This direction of research addresses the effect that continental scale neotectonic forces has on drainage patterns. Faulting can create a sudden change in slope and there might be multiple fault blocks within a single watershed (Cox, 1994; Salvany, 2004; Tsodoulos et al., 2008; Ibanez et al., 2014). TTSF and AF indicate tilting and the change in TTSF and AF values for each watershed reveals the magnitude of tilting (Tsodoulos et al., 2008). The amount of uplift in the Red River Valley has already been proposed (Brevik, 1994) yet there is no research on how varying amounts of uplift effect individual watersheds in the valley. It is already shown that river channels will change to adjust to isostatic adjustment (Clark et al., 2012). The results display that the change in watershed and channel position resembles the adjustment rates experienced in the Red River Valley.

Random Walk Model

The results from the lattice random walk model which simulated pre-adjustment slope generated tributaries that entered the simulated main channel farther north (Figure 35) compared with the modeled flat terrain (Figure 34). A perfectly flat terrain would allow for a drainage pattern to develop in complete randomness, while a sloped terrain, though still considered a random drainage pattern, and would have some influence on the direction of channel propagation. With no geomorphic controls, the simulated pre-adjustment tributaries would enter the main channel farther north than would the perfectly flat terrain tributaries. A similar pattern would be expected in nature if there were no geomorphic controls and no influence from outside forces. In nature, rivers development is influenced by pre-existing conditions including geomorphic features, climate and stratigraphic relations (Leopold and Langbein, 1962). Further modeling of the relationship between changing adjustment rates and drainage pattern evolution would lead to some interesting results. Rather than modeling the effect of the slope during one instance (adjustment based on differences in elevation along the Herman beach ridge), stream development could be compared during every beach stage to determine if it correlates statistically to current river positions and orientations.

Basin Asymmetry

The TTSF values of the watersheds increase toward the Canadian border. The western Wild Rice and the Otter Tail are outliers to trend and omitting these watersheds creates a pattern with stronger evidence (an R^2 value of 0.0424 with the two watersheds and 0.5712 without them) that more uplift resulted in more asymmetry (Figure 17). The western Wild Rice and Otter Tail watersheds might have other factors affecting their values. The western Wild Rice River runs parallel, north-south, to the Red River/ Bois de Sioux River and near parallel with the slope of adjustment while the other rivers are perpendicular to the long axis. The Otter Tail watershed drains the Alexandria Moraine (Lusardi, 1997) and the course of the river flows through many lakes, which may strongly influence the course and thus position of the river within its watershed.

Like TTSF, AF values also indicate greater amounts of tilting toward the Canadian border. The more northern watersheds have lower AF values, indicating greater asymmetry. The Otter Tail watershed also has an AF value that does not fit this pattern (Figure 19). The course of the Otter Tail River through the lake basins and moraine likely affects its AF value also.

Both the TTSF and AF depend on river location, which means that if the river has not reacted to the effects of isostatic adjustment or have other geomorphic controls, then the values will not follow the adjustment trend, which is greater uplift in the north than in the south. All but the western Wild Rice and Otter Tail fit this pattern by showing more asymmetry toward the Canadian border and greater symmetry near the South Dakota border. The results indicate that glacial isostatic adjustment influences the symmetry of the watersheds. Understanding the tectonic history of the region is important (Tsodoulos et al., 2008) in assessing the changes observed in river channels and watersheds. TTSF and AF values can help in understanding the tectonic history of the Red River Valley. Tsodoulos et al. (2008) used TTSF and AF values and other tools to indicate the asymmetry of watersheds resulting from active faults. Tsodoulos et al. (2008) concluded that increasing values correspond to an increasing magnitude and indicate the direction of tilting. Likewise, TTSF and AF values (Figure 17 and Figure 19) correlate to the magnitude of tilting in the Red River Valley.

Pre-Adjustment Watersheds Boundaries

Watershed boundary changes occurred both north and south of the watershed. The percent net change, either positive or negative, of the watershed was used to indicate the amount of change that has occurred. The trend in the pre-adjustment watershed boundary changes is similar to the TTSF and AF trends in that it also has a positive trend. All watersheds except the Buffalo experienced a positive northward boundary change. The consistent northward change can be associated with isostatic adjustment affecting the entire region. The Tamarac and Forest watersheds have the highest values and lie near the northern portion of the Red River Valley. A case could be made that the Tamarac and Forest watersheds in the north, having high positive net changes and the Buffalo watershed in the south having negative net change, supports that the greater uplift in the north has created more asymmetrical watersheds, but the percent net change values do not show a strong trend (R^2=0.2762) (Figure 22). The Tamarac River watershed may not have been suitable for this analysis because of extensive excavated drains, including the creation of its main channel. There is also no paleo-channel associated with the Tamarac which suggests that it was not a developed channel between Lake Agassiz stages. For these reasons, the watershed's anomalous value (233%) (Figure 22) should not be considered in the overall analysis. The distance between Campbell beach ridge to the east and west of the Red River lessens and the region of watershed analysis decreases farther south in the Red River Valley. As a result, the area of the Otter Tail watershed analyzed is very small and unlikely to be representative and comparable to the other watersheds. Changes in the watershed area of the Otter Tail would not be on the same scale as changes in the other watersheds analyzed (Figure 22).

Paleo-Channel

The trend of the paleo-channels will be discussed individually for the Red, western Wild Rice, and Sheyenne paleo-channels. The remaining paleo-channels will be discussed as a group since they have similar characteristics. Generally, the paleo-channels either fully or partially located north of the current river with which it is associated, suggesting that river locations have shifted southward to accommodate the post-glacial uplift (Arndt, 1975; Brevik, 1994; Clark et al., 2012).

Red

With almost the entire paleo-Red River lying east of the current Red River (Figure 23), this relationship might indicate that the slope of adjustment was not parallel with Red River Valley. This is possible since the equipotential rates of adjustment are not perpendicular to the Red River (Figure 4 and Figure 8). Lake Agassiz did not just occupy the 75km wide valley, but also the region to the northeast near Lake of the Woods and Red Lake. The weight of the glacier and subsequent lake may have created a slope of adjustment that is not parallel the Red River Valley (Figure 8).

Western Wild Rice

The western Wild Rice paleo-channel, similar to the paleo-Red River, runs parallel to the slope of adjustment (Figure 27). Thus, the migration of the original western Wild Rice may be caused by the oblique slope of adjustment. Like the paleo-Red River, the paleo-western Wild Rice River is also to the east of the current channel. A slope of adjustment that is not parallel to the Red River could have influenced this difference in channel position.

Sheyenne

Similar to the western Wild Rice, much of the Sheyenne River and paleo-Sheyenne are oriented north-south and are nearly parallel with the slope of adjustment (Figure 8). The current and former rivers also display the two channels crossing, similar to the western Wild Rice (Figure 28). With the channels' north-south orientation, the current channels' relationship to the paleo-channel may exist because the channels are more sensitive to adjustment, being parallel to the slope of adjustment. The more recently abandoned channel to the west of the current Sheyenne River may indicate adjustment is somewhat southward, analogous to other channels that are perpendicular to the slope of adjustment (Figure 8).

Remaining Paleo-Channels

Although the western Wild Rice and Sheyenne are parallel to the slope of adjustment, the remaining paleo-channels are closer to perpendicular and therefore perhaps easier to interpret. The current Turtle, Sand Hill, Elm, Buffalo, and Maple Rivers have paleo-channels that lie to the north of the current channel. The Maple (Figure 29) (flowing into the Sheyenne River) and Buffalo (Figure 30) current and paleo-channels enter the Red and paleo-Red Rivers at approximately the same latitude. In contrast, the remaining three paleo-channels reveal confluences that all lie north of the current confluence. The Elm paleo-channel (Figure 33) enters the paleo-Red River 25km north of the current Elm and Red River confluence. The Sand Hill River paleo-channel (Figure 32) could not be identified all the way to the confluence with the paleo-Red River. If the paleo-channel ridge was complete, based on its current location and orientation, however, the confluence of the Sand Hill paleo-channel with the paleo-Red River would likely be roughly 20km farther north than the current channel. Paleo-channels farther north do not flow into the paleo-Red River because a lower stage Lake Agassiz was still present (Arndt, 1975; Thorleifson, 1996). The lake did not completely recede north of the Canadian border before stage rose again. The Turtle River paleo-channel (Figure 30) likely flowed into the low-water Moorhead stage of Lake Agassiz (Arndt, 1975; Thorleifson, 1996) and not into the paleo-Red River. However, the reach of river between the lake and the Campbell beach ridge can be affected by isostatic adjustment. The Turtle River shows evidence of an abandoned channel that appears to have migrated southward through time, based on depth of incision (Figure 30). Laird (1944) and Gerla (2004) suggest that groundwater sapping of glacial lake sediments occurred in vicinity of Kellys Slough, an area of seeps and shallow valleys that extends northward to the current location of the Turtle River channel. Thus, this may have influenced, or even caused, the southward avulsion of the river rather than migration responding to isostatic adjustment.

CHAPTER V

CONCLUSION

The purpose of this project was to recognize how glacial isostatic adjustment has affected the asymmetry of the watersheds and rivers in the Red River Valley. Through the process of isostatic adjustment, the northern watersheds show greater asymmetry. After omitting the western Wild Rice and Otter Tail watersheds, both the Transverse Topographic Symmetry Factor (TTSF) and Asymmetry Factor (AF) indicate that there is a trend of increasing asymmetry in watersheds farther north. The course of the major rivers in the Red River Valley such as the western Wild Rice, Sheyenne, Maple, Turtle, Buffalo, Sand Hill and Elm rivers have not always occupied their current channel.

A change in watershed boundary is not likely to be the sole cause of asymmetry of each watershed. Change in river location as the main contributor to asymmetry in the watersheds was supported by the location of the paleo-channels found within the Red River Valley. At least three (and possibly five) major paleo-channels addressed in this report, which were deposited during stages of Lake Agassiz, enter the paleo-Red River farther north than their respective current rivers. There are also segments of the current channels that have avulsed and shifted southward. The shift in river location due to isostatic adjustment was modeled with a simple stochastic model. Greater amounts of adjustment were equated with a higher probability of the pre-adjustment channels to move in a northeastern course opposed to due east.

These results would suggest that the asymmetry identified using the TTSF and AF values would be the result of a shifting river rather than a shifting watershed. This does not imply that a shift in watershed did not take place. The shift in watersheds that might have occurred and discussed previously were not enough to create the amount of asymmetry observed currently. The hypothesis states that this regional tectonic force of isostatic adjustment has created the asymmetry we observe today because of a 1) changing watershed, and/or a result of a 2) shift in river position. By the observations made in this study, asymmetry in the current watersheds of the tributaries to the Red River are mainly influenced by the shift in river position, and less so by a shift in the watershed boundary.

Shifts that have occurred in the river position and watershed boundary might not be entirely the result of isostatic adjustment. The influence that Kellys Slough might have on the Turtle River is one example. There might be other controlling factors that affect the shifts observed in the rivers and watersheds such as the heterogeneity of the soil and local topographic highs. Asymmetry values of the observed watersheds did not reflect perfectly isostatic adjustment, but there was a general trend of increasing asymmetry farther north. Each watershed might have unique controlling factors affecting the shift rather than isostatic adjustment alone.

Methods in this report are not specific to the Lake Agassiz region, but could be applied to other regions which are 1) relatively flat and are underlain by homogenous sediments and 2) have been influenced tectonic tilting which can be measured. Other watersheds surrounding the northern United States boarder and much of Canada and Europe are affected by isostatic adjustment and could also have a hydrology that has not acclimated to the adjustment. The combination of TTSF and AF values, pre-adjustment watershed net change, and location of paleo-channels could aid in quantifying the relationship between continental scale neotectonic forces and watershed and drainage pattern development.

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