Assessing the Impacts of Hydrologic and Geomorphic Alteration of Minnesota Rivers on Riverine Turtle Habitat

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Background

The wood turtle (*Glyptemys insculpta*) and the smooth softshell turtle (*Apalone mutica)* have become increasingly rare in Minnesota due to harvesting, predation and changes to aquatic and upland habitat. These two river-dependent turtles are classified as Species in Greatest Conservation Need (SGCN) by the Minnesota Department of Natural Resources (DNR), with the wood turtle also listed as threatened and the smooth softshell as special concern species on the state Endangered Species list. To better understand human impacts and environmental change on the aquatic habitat of both of these important species, the MNDNR awarded a State Wildlife Grant to the University of Minnesota to assess the impacts of hydrologic and geomorphic alteration on river turtle habitat.

The wood turtle is found throughout the northeastern United States, parts of the Midwestern United States, and eastern Canada (Figure 1). In Minnesota wood turtle distribution is sparse and focused primarily within the eastern counties (Oldfield and Moriarity 1994, Naber et al. 2010). The preferred habitat of wood turtles can be defined with three main components: coarse-bottom rivers with fairly swift moving currents, partially shaded herbaceous vegetation within the river floodplain, and an abundance of sandy substrate within a few hundred meters of the river (Ewert 1984 and 1985, Walde et al. 2007). Since the wood (and smooth softshell) turtles are riverine species, their habitat, population traits, and distribution are directly linked to fluvial geomorphic and river hydrology characteristics. The types of nesting features used by wood turtles include those areas of bare sand formed by fluvial process (i.e. sandbars and cut-banks) but also anthroprogenic features. The focus of this study did not include the artificial nesting features such as sand/gravel pits that are sometimes used by turtles for nesting.

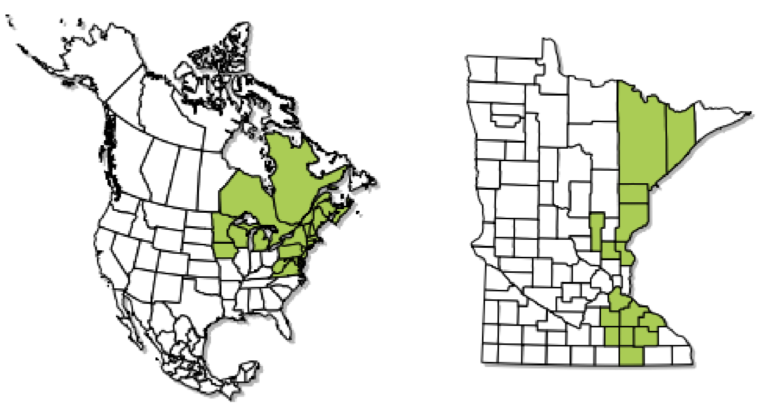

Figure 1. Wood Turtle Range in North America and Minnesota (MNDNR)

The smooth softshell is a riverine turtle found in large river systems (Figure 2). The subspecies found in Minnesota is the midland smooth softshell (*Apalone mutica mutica*). Based on available data, the distribution of this species in Minnesota is limited to the lower St. Croix River, portions of the Minnesota River, and the Mississippi River downstream of the Twin Cities (Moriarity 2004). Smooth softshell turtles prefer large unpolluted rivers with sandy substrates although they can also be found in lakes, ponds and bogs (Ernst and Barbour 1972). In Minnesota, the smooth softshell turtle has been found in large rivers with moderate to fast currents (Oldfield and Moriarty 1994). In terms of bed materials, they prefer sand or mud, without rocky areas or dense vegetation (Pope 1946; Oldfield and Moriarty 1994).

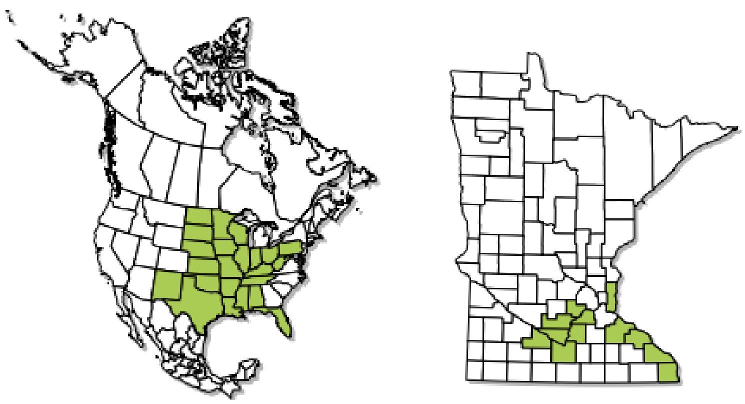

Figure 2. Smooth Softshell Turtle Range in North America and Minnesota (MNDNR 2011)

The primary objectives of this research project included:

1. To quantify hydrologic changes on up to 15 rivers in eastern Minnesota and the consequences of those changes for riverine turtle habitat, particularly wood and softshell turtles.
2. To determine geomorphic impact of the hydrologic changes, particularly the areal extent, duration and timing of sandbar exposure in these selected rivers; and to identify other potential geomorphic impacts that may affect turtle habitat.
3. To provide inventory of wood turtle and softshell turtle nesting and activity within specified river reaches, of the five study rivers in eastern MN (Table 1).
4. To evaluate the relationship between hydrologic changes and river turtles' life cycle in rivers of eastern MN.
5. To provide management recommendations to mitigate the impacts of hydrologic change and human activity on sandbars and the larger river corridor to protect turtles and their habitat

This research will benefit natural resource managers by more clearly identifying hydrologic threats to riverine turtles long-term survival that are currently unknown or poorly understood. Future protection and management of turtles and their habitat will require a greater understanding of how recent hydrologic changes have affected river geomorphology and the life cycles of the turtles (Bodie 2001).

Alteration to Hydrology and Geomorphology in Midwestern Rivers

River systems may respond to watershed hydrologic changes caused by land use, drainage and/or climate changes in a variety of ways. The hydrologic response of rivers may be characterized by changes to runoff magnitude, duration, timing, frequency and variability all of which can alter a river's geomorphologic and riparian characteristics in various ways with subsequent consequences for stream biota (Richter et al. 1996).

The habitat of riverine turtles is directly impacted by hydrologic alteration and artificial or natural changes to stream geomorphology. A typical hydrograph for Minnesota rivers includes a spring peak (April) followed by dropping water levels through the early fall (September). Turtle nesting relies on the falling water level during the summer to avoid flooding of their nests. Although flooding is a widely recognized water management issue, recent research on hydrologic alteration in the upper Midwest has shown that increased low and mean flows may have important impacts on river ecological processes as well. In recent decades the hydrologic regime of many Midwestern streams has shifted, particularly in the agricultural regions of Iowa, southern Minnesota and the eastern Dakotas (Lenhart et al. 2011a). Mean flow has increased by 2 to 3 times in many southern Minnesota rivers although the magnitude of large floods has not changed significantly in many watersheds. While sediment mobilization during high flows and subsequent deposition plays an important role in the formation of sandbars, the effect of water level "drawdown" during low flow is important for sandbar exposure during the nesting season and successful turtle reproduction. Yet, few studies have assessed the consequences of increased low and mean flows on turtle habitat availability and nesting success.

Rivers may respond to flow increases with geomorphic change. While rivers naturally migrate over time across their valley, they go through process of evolution in response to flow changes and related erosional and depositional shifts (Knighton 1998). However the recent stream flow increases in agricultural regions of the Midwest have thrown these rivers out of equilibrium. Channel widening is known to have occurred in numerous Minnesota rivers including the lower Minnesota River, Elm Creek in Martin County, Lac qui Parle in western MN, the upper LeSueur and others (Lenhart et al. 2011b, Nieber et al. 2010).

Effect of Hydrologic Alteration on Turtle Habitat

Bodie (2001) identified eight human alterations that may impact turtle population viability by changing food supply, altering population structure, causing nest inundation or failure, fragmenting populations and reducing or eliminating local populations. These alterations included reduced logjams and woody debris, riparian drainage, channelization, impoundment, flow regulation, reduction of sandbars or beaches, human use of riparian zone and pollution/siltation. In this study reduction of sandbar area and nest inundation from increased streamflow was the major impact of focus.

Sandbar habitat is vital for turtle nesting during late spring and summer. While high flow events may have an impact on potential nesting sites above the bankfull elevation, higher mean to low flows can inundate nesting sites and reduce the duration and frequency of sandbar exposure below the bankfull elevation. Shorter low flow periods reduce the area and the duration of exposed sandbars and delay the timing of egg laying, resulting in a smaller window of opportunity for basking and nesting which is critical to turtle survival. Currently it is unknown if nesting habitat is a major limiting factor in riverine turtle reproduction. However, recent wood turtle nesting site surveys in Minnesota have yielded very few wood turtle nesting sites suggesting that suitable nesting sites could be a limiting factor for that species. Since wood turtles (and other riparian turtles) live almost exclusively in and around rivers, even slight changes to sandbar or other sandy nesting sites could impact the population level.

Hydrologic and geomorphic dynamics in rivers shape the characteristics of sandbars. Sandbars are depositional features formed during the falling limb of the hydrograph (Knighton 1998). Increased flows may mobilize sandbars to a greater extent and/or inundate them longer depending on the type and timing of hydrologic change. The formation of sandbars (and to a lesser extent cutbanks) provides the sandy substratum needed for egg laying, burial and incubation in early summer for smooth softshells and other riverine turtles. A falling hydrograph in June and July is required for egg-laying and incubation. If water level drawdown is delayed until August or September the likelihood of egg laying and hatchling survival is reduced since eggs take 8-12 weeks to hatch. Inundation of nesting sites from streamflow rise during the nesting season lasting more than two days is generally fatal to the eggs.

Wood turtles may use several types of nesting sites. In some cases sand deposits well above bankfull are used following high spring flows and in other cases exposed sand bars are used when decreasing water levels drop below bankfull. In streams containing sandy parent material, flood events may carve into the outer banks of meanders and expose sandy cutbanks that are suitable for nesting. Therefore, increased channel erosion may actually increase the availability of nesting substrates for wood turtles, although this may increase turbidity and affect their feeding ability. Channel widening may also change the frequency and duration of sandbar exposure needed for turtle nesting.

Aside from nesting other turtle life cycle components may be affected by flow increases and related geomorphic response. For example, hatchling emergence and dispersal may be disrupted, reducing survivorship in the 1st year. Hydrologic alteration may change the food base and/or increased flow may increase sediment yield and turbidity making foraging less productive. Basking habitat in the form of large woody debris (LWD) may be increased in the short term by channel widening caused by increased flow (Figure 3). However in the long term wider channels may retain less wood because of the decreased probability of log jams supported by the channel boundaries (Merten 2010). Increased winter flows may reduce overwintering success due to increased mobilization; shear stress; velocity; or stream power that would dislodge turtles burrowing in the mud. Dispersal to upland sites for feeding may be effected by road crossings, agriculture and development (Saumure et al. 2007).

Response of channels to increased flow

Channel evolution may occur in response to streamflow increases or channelization as illustrated in Figure 3 above (Simon and Rinaldi, 2006). Not all rivers follow this model, however. In fact, many of the larger rivers of southern Minnesota, widening (Stage IV-V) has been the primary geomorphic response in recent decades with substantial incision (Lenhart et al. 2011b). When channel widening occurs, a new floodplain surface must be built up (in Stage V) in order for the sandbars to become sub-aerial (above the water surface) and become usable for turtle nesting.

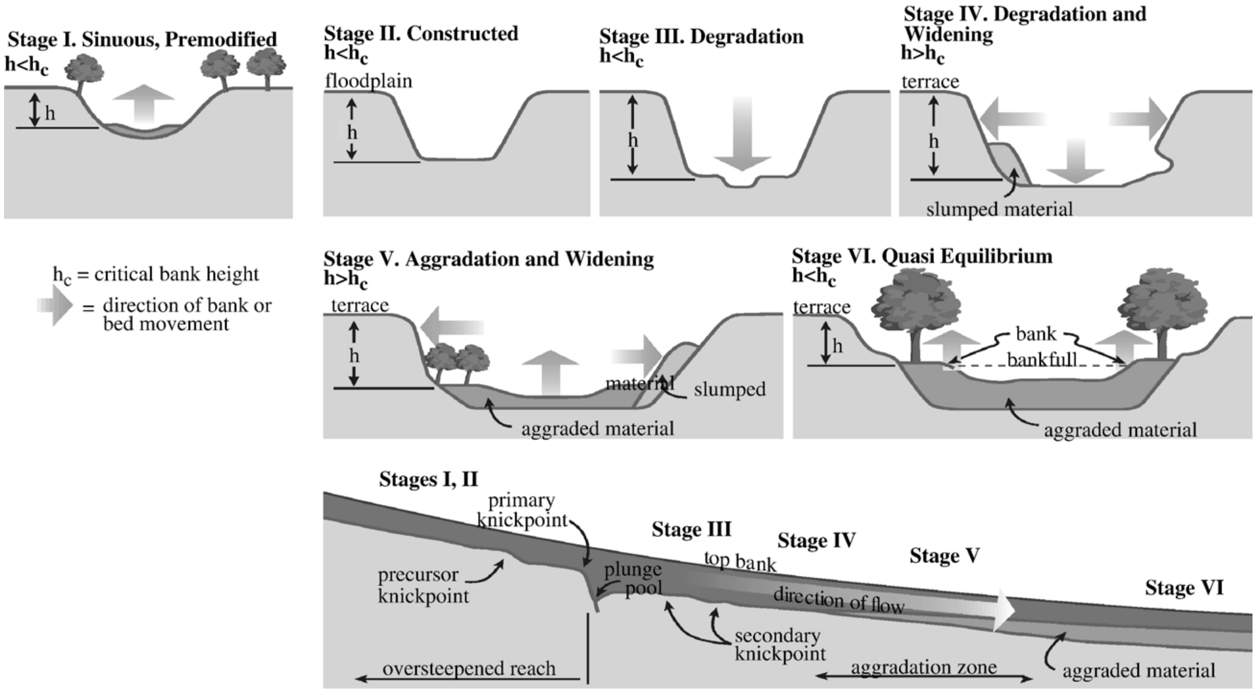

Figure 3. Channel Evolution Model by Simon and Rinaldi (2006) showing channel geomorphic response to increased flow and/or channelization. Not all rivers go through all of the above stages, but the CEM describes the general physical processes at work during different stages of adjustment. Several rivers in southern Minnesota have undergone widening in recent decades, though many northern forested watersheds, such as the Kettle and St. Louis Rivers have been fairly stable.

Methods

A combination of GIS tools, hydrologic statistical analysis and field data collection were utilized to assess the role of altered hydrology on riverine turtle nesting. This approach was used to address the question of how alteration of the hydrologic regime has changed the duration and frequency of suitable nesting sites for riverine turtles (wood and smooth softshell) in eastern Minnesota rivers. The intent of study was to assess the impacts of hydrologic and geomorphic alteration on the ability of the turtles to successfully reproduce and maintain viable populations, as indicated by changes in nesting opportunity. Direct measurement of nesting success was beyond the scope of this study.

The study sites were located in eastern Minnesota in areas of known smooth softshell or wood turtle populations (Figure 4). The smooth softshell is only known to occur on the Minnesota River of the study sites, while the wood turtle range includes all the study rivers except the Minnesota River, at least historically. The sites were selected to include a range of rivers in the south with >67% agricultural land use and northern rivers with >67% forest cover.

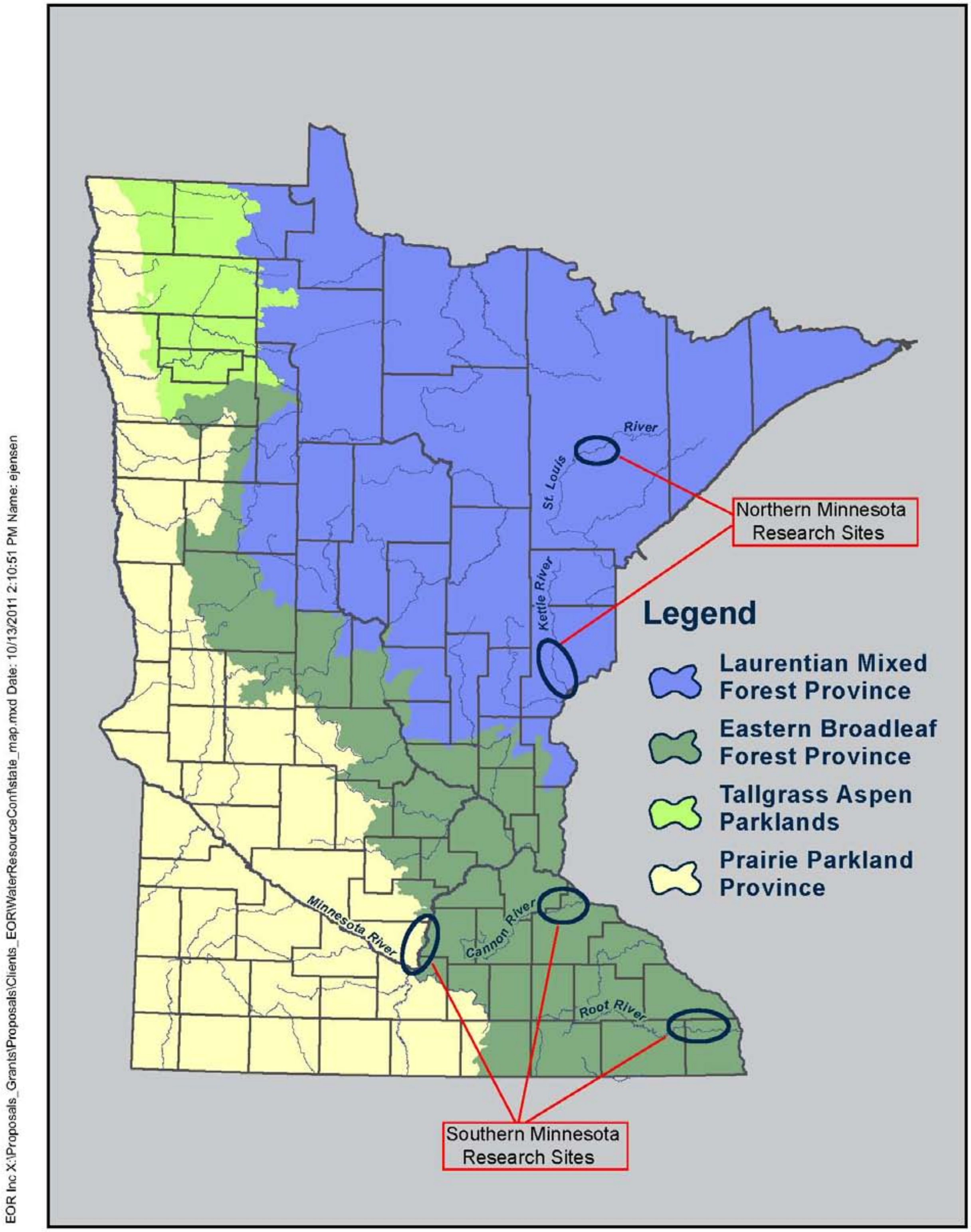

Figure 4. Location of study reaches on five rivers - from north to south: the St. Louis, Kettle, Cannon, Minnesota, and Root Rivers.

Table 1: Characteristics of study reach

River	Study reaches	drainage area at USGS gage	Rosgen channel types and bed substrate in study reaches	Channel Evolution stage	mean annual discharge (cfs) (last 30 years)
Cannon	Welch – Hwy 61		C4-5 (sand, gravel bed)	IV	934
Kettle	Sandstone to river mouth		C3-C5 (cobble, gravel and sand bed)	VI	677
Minnesota	Mankato- St. Peter		C5 (sand bed)	IV	5516
Root	Lanesboro-Houston		C4-5, F4-5 (sand, gravel bed)	IV	1066
St. Louis	Near Makinen		C3-C5 (cobble, gravel and sand bed)	VI	2583

Field collection of data

Sandbars were inventoried and measured between June 2010 and September 2010. We conducted a turtle inventory of species and nest sites observed at 8-20 pointbars within the reaches in Table 1 and Figure 4. Data on the physical properties of sandbars was collected at a subset of these sites and is described below.

Turtle Inventory

An inventory of turtle nesting and activity was conducted noting turtle tracks, nest signs, turtle eggs or shells and other indicators within the study reaches. Potential nesting sites were selected remotely using recent aerial photography and then field surveyed. Physical sandbar characteristics and nesting activity were recorded and tabulated. Turtles were identified to the species level when possible, however it was not possible to distinguish the smooth softshell (*Apalone mutica*) from the more common spiny softshell (*Apalone spinifera*) from a distance of 50 feet or more. Genetic or chemical tests of egg remnants could be utilized to distinguish these two species in future studies.

Physical properties of sandbars

Sandbar properties measured include slope, particle size distribution, temperature and plant coverage and type. Eight to 20 sandbars were surveyed per river with several particle size samples collected per river. Temperature data was recorded at the surface and at 15cm depth (the approximate depth at which turtle eggs are deposited) both on top of the sandbar and at the water's edge. Plant coverage was estimated at each sandbar and was classified as herbaceous or woody.

Hydrologic and geomorphic analysis

The Indicators of Hydrologic Alteration (IHA) statistical software program was used to assess the hydrologic alteration of rivers in Minnesota during the time period of 1980-2009 compared to the previous time period of 1940-1979. A variety of statistical measures of streamflow changed were compared at USGS stream gauge sites with flow records of > 60 years (except the Kettle River which began in the 1960s. The year 1940 was used as the cutoff for the earlier time period since few stream gauges were in operation prior to that time. The 1980 to present time period was used because large streamflow changes were observed in many southern Minnesota Rivers during this time and substantial land-use, tile-drainage and precipitation increases occurred during that time, as summarized in Lenhart et al. (2011a). For consistency in methods we then compared all sites using these time periods for 16 different rivers across Minnesota.

Changes to flow magnitude, duration, frequency and timing were assessed with IHA to better understand the impacts of hydrologic change on the life cycles of turtles. This analysis focused on the duration of flow during the nesting and hatching months of June-August. We also examined the entire historical period of streamflow record to identify the earliest dates available for turtle nesting on each river to determine if nesting has been delayed in the summer from flow increases.

Linking nesting and sandbar exposure /discharge relationships

Since most active sandbars are below the bankfull elevation, increased duration of flows in the low to mean flow range was expected to decrease the time of sandbar exposure. To document changes in sandbar availability we measured the changes in areal extent and duration of sandbar exposure in study reaches of five rivers (Table 1) using aerial photos and GIS. The surface area of exposed sandbar habitat was digitized in aerial photos using GIS from all five rivers dating back to 1938. USGS streamflow data was collected for the same days the aerial photos were taken. Based on 8-12 years of aerial photography with paired discharge data, a relationship between stream discharge and area of exposed sandbars (the *discharge-sandbar area relationship*) was developed. Another approach focused on stream cross-sectional survey data recorded by USGS streamflow gauges to determine the point of sandbar emergence. Due to variability in our calculations we used low, middle and high estimates for the sandbar-submerging flow. Then, the USGS stream gauge record for each site was analyzed to calculate the frequency and duration of exposed sandbars before and after 1980.

The timing and availability of turtle nesting based on flow levels were calculated by identifying the earliest date when flow dropped below the sandbar inundating flow level. If this flow level was later exceeded for two days or more for a period of 75 days between June 1 and August 15 the submerged eggs were assumed to be no longer viable. If sandbar exposure did not occur until after August 15, it was assumed that no successful nesting occurred. Very low nesting success was considered to be August 1-15, marginal nesting success is from July 15 to July 31 and good nesting success from June 1 to July 14. These dates were used as cutoff points for the sake of data analysis. In reality, these time periods may be more variable due to differences in egg development time and susceptibility to flooding as the eggs develop.

Channel Evolution Data

Rivers are not static as sandbars shift over time and channel dimensions may change in response to increased flow. To characterize potential geomorphic responses to altered hydrology (beyond sandbar submergence), the streams were classified using the Rosgen classification system at representative reaches on the five study rivers. Data collected included bed characterization, channel cross-section and profile, estimate of bankfull elevation and entrenchment. To further describe channel stability and the direction of channel evolution, Simon's Channel Evolution Model (CEM) was used to determine the evolution stage of each river and to indicate whether the rivers were aggrading, degrading, widening or at equilibrium. Changes to river width over time were assessed for two rivers with representative land cover and streamflow trends: the St. Louis for northern Minnesota and the Minnesota River for southern Minnesota (see Lenhart et al. 2011b for a description of methods).

Results

Hydrologic alteration statistics

The IHA analysis showed that there were substantial hydrologic changes in southern Minnesota, but not the northern rivers, such as the Kettle and St. Louis (Table 2). In the southern rivers, the duration of medium-high flows has been prolonged until later in the summer, more frequently inundating the sandbars for the entire summer in the post-1980 time period. These changes are likely to impact the smooth softshell more than the wood turtle because its range occurs primarily outside of the southern agricultural watersheds. The northern forested watersheds where most wood turtles occur (including the Kettle and St. Louis) have not experienced great hydrologic changes in recent years.

Mean annual flow increased in most of the southern to western rivers with >67% agricultural land-use and remained relatively unchanged in northern forested (>67% forest) watersheds (Table 2 and Figure 5). The increase in mean annual flow ranged from 42 to 101% in the watersheds with >67% agricultural land cover. However the magnitude of the 2-year and 10-year floods, designated as small and large floods in IHA, did not increase significantly at almost any of the USGS gage sites in the north and south.

Streamflow variability declined at 100% of our research sites in the past three decades as calculated by the coefficient of variation, (c.v.), defined as the standard deviation of all mean daily flows divided by the mean annual flow. For this data set, c.v. values in the 1980-2009 time period ranged from 0.55 and 0.56 at the Mississippi River in Grand Rapids and the St. Croix River at Grantsburg, Wisconsin to 2.4 at the Yellow Medicine River near Granite Falls. The variability decreased because of an increase in low flow at most watersheds. By percentage change, sites ranged from -6% in the Red Lake River to -38% change on the Yellow Medicine River, of southwestern Minnesota. Rivers in western Minnesota naturally have higher variability because of less baseflow than rivers in southeastern Minnesota (such as the Root River) and in north central Minnesota, like the Mississippi at Grand Rapids

Hydrologic changes during the nesting months

Along with mean annual flow, the median monthly flows have increased for a majority of months in the southern agricultural watersheds. Median monthly flow increased in 75-100% of months for southern agricultural watersheds while in the northern forested watersheds, there has been increases only in winter mean flow, despite the fact that the mean annual flow did not change significantly.

The magnitude of the median June and July (turtle nesting months) flow and duration have changed substantially in the Minnesota, Cannon and Root Rivers likely impacting turtle nesting. Change in June and July median flow was greatest in the Cannon River which had 196% and 154% increases in these months, respectively. The Minnesota and the Root River also had significant increases in June and July median flows. The Kettle and St. Louis Rivers did not have significant increases except for the St. Louis River July flow with a 32% increase. Low flow has significantly increased at all three southern rivers, while the northern rivers did not have any significant change (Table 3) in low flow levels.

Table 2. Summary data for the IHA analysis of 16 watersheds in Minnesota, Flow in the 1980–2009 time period was compared to that of the 1940–1979 time period by statistics calculated in IHA. Columns 1-2 describe the USGS stream gage location. Column 3 lists the percentage (%) change in the mean annual flow. Column 4 lists the change in the coefficient of variation (cv) a measure of streamflow variability. Column 5 lists the percentage of the 12 calendar months with a significant change in median flow. Column 6 shows the percentage of months with a significant low-flow change (the lowest mean daily flow for a given month) (Lenhart et al. 2011a).

Gauge Station Location (turtle research sites in bold)	USGS Gauging Station #	Predominant Land Use Category (%)	Change in Mean Annual Flow (%)	Change in Coefficient of Variation (%)	% of 12 Months with a Significant Median Monthly Change	% of 12 Months with a Significant Low-Flow Change
Blue Earth River at Mankato	05320000	> 67 ag	73	−29	83	42
Buffalo River at Hawley	05061000	mixed	42	−7	67	67
Cannon River at Welch	05355200	mixed	101	-36	100	92
Des Moines at Jackson	05476000	> 67 ag	100	−26	83	50
Kettle River at Sandstone	05336700	> 67 forest	-6	-19	0	8
Little Fork River at Little Fork	51315000	> 67 forest	−8	−14	42	42
Minnesota River at Mankato	05325000	> 67 ag	75	−23	92	75
Mississippi River at St. Paul	05331000	mixed	31	−11	50	33
Mississippi at Grand Rapids	05211000	> 67 forest	4	−7	0	0
Pigeon River at Grand Portage	04010500	> 67 forest	−9	−13	33	33
Red River at Grand Forks, ND	05082500	> 67 ag	56	−10	75	33
Red Lake River at Crookston	05079000	> 67 ag	6	−6	17	8
Root River near Houston	05385000	mixed	57	−36	100	83
St. Croix River at Grantsburg, WI	05333500	> 67 forest	−6	−7	0	0
St. Louis River at Scanlon	04024000	> 67 forest	12	-15	42	50
Yellow Medicine River at Granite Falls	05313500	> 67 ag	77	−38	92	58

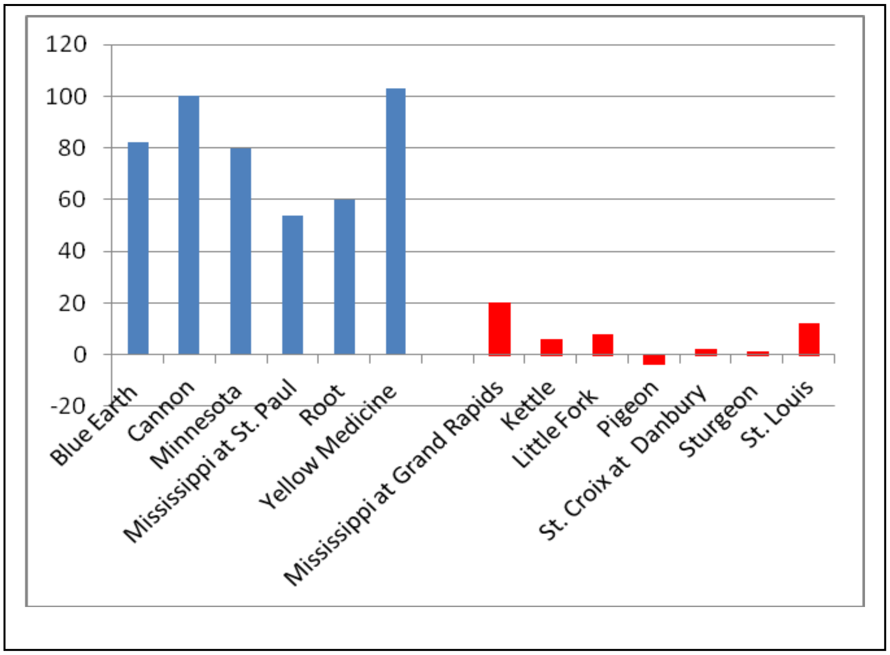

Figure 5. Change in mean annual flow as % change from the pre-1980 time period. Watersheds in southern and western Minnesota with >67% agricultural land-use are shown in red while watersheds in northern Minnesota and Wisconsin with >67% forest cover are shown in blue. The mixed-use watersheds were excluded.

Table 3. Changes to June and July median and low flows at the five study rivers, comparing 1980-2009 to the entire previous period of flow record for each USGS gauge site.

River	month	% change in median monthly flow	Significant change in post-1980 time period ?	% change in monthly low flow	Significant change in post-1980 time period?
Kettle	June	-19%	no	7%	no
Kettle	July	46%	no	28%	no
St. Louis	June	0%	no	5%	no
St. Louis	July	32%	yes	10%	no
Cannon	June	196%	yes	65%	yes
Cannon	July	154%	yes	74%	yes
Minnesota	June	99%	yes	78%	yes
Minnesota	July	162%	yes	141%	yes
Root	June	90%	yes	41%	yes
Root	July	67%	yes	49%	yes

Changes to timing and duration of sandbar exposure during the nesting season

Evaluation of sandbar exposure at different river stages using field data, GIS and USGS streamflow data showed that there were changes to the duration of sandbar exposure during the months of June and July as well as the timing of the exposure.

Frequency and duration of sandbar exposure

The number of June and July months that were suitable for nesting declined in the Minnesota, Root and Cannon Rivers over the 1980-2010 time period were compared to previous decades. At all five sites the sandbar exposure was more frequent in the 1920s-1930s which coincided with the Dust Bowl era drought with very low flow. Maximum mean annual streamflow was reached in the 1990s with the 2000s slightly lower but still frequently submerging the sandbars in the southern rivers (Table 4 and Figure 6). The St. Louis River had less of a downward trend for nesting availability. During the 2000-2009 decade northern Minnesota experienced very low flow, increasing the frequency of years with 75+ days of summer sandbar exposure (Figure 7).

Figure 6. Minnesota River - number of months (June and July) with suitable water levels for riverine turtle nesting on sandbars by decade using mid, low and high estimates for the sandbar-submerging flow level. There was a sharp rise in sandbar availability during the dustbowl era (1930s) due to drought. Nesting availability dropped sharply in the high low period of the 1980s-2000s, particularly in the 1990s when water levels did not drop enough to expose sandbars during the nesting season the entire decade.

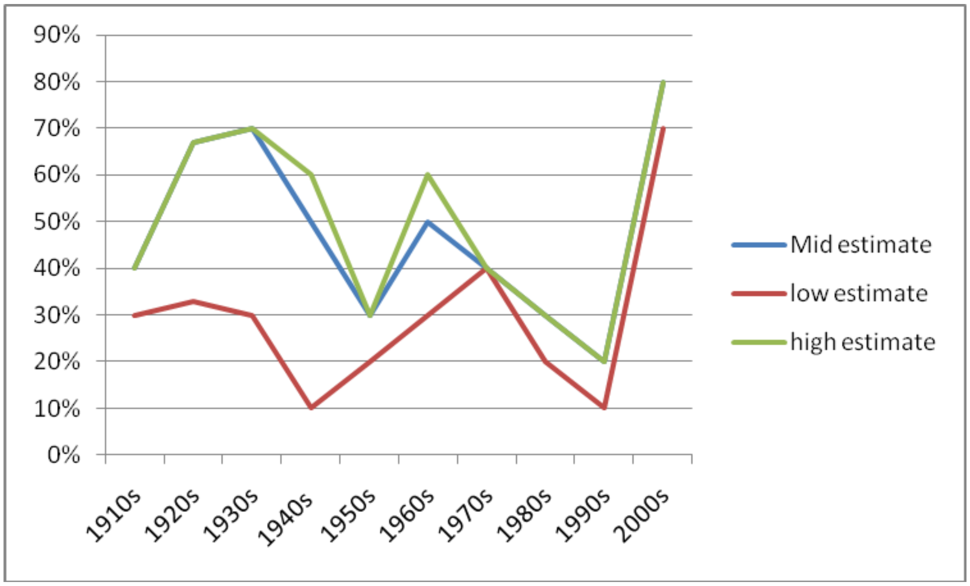

Figure 7. St. Louis River – number of months (June and July) with suitable water levels for riverine turtle nesting on sandbars by decade. There was a sharp rise in sandbar availability during the dustbowl era (1930s) due to drought. Nesting availability dropped early in the 1990s decade, but rebounded sharply in the 2000s during a much drier period with lower streamflow levels.

Table 4. Percentage (%) of years with suitable water levels for riverine turtle nesting on sandbars during June and July by decade. Suitable nesting years had at least 75 consecutive days of non-submerged sandbar conditions for nesting, development and incubation of eggs, starting between June 1 and August 15. Sandbar-submerging flows of 1 day were considered non-lethal, but 2 or more consecutive days above the sandbar level was considered to eliminate successful nesting in a given years.

Decade	Cannon	Kettle	Minnesota	Root	St. Louis
1910s	100%	No data	60%	83%	40%
1920s	Insufficient data	No data	80%	Insufficient data	67%
1930s	78%	No data	90%	70%	70%
1940s	22%	No data	70%	80%	50%
1950s	30%	No data	50%	60%	30%
1960s	70%	50%	40%	90%	50%
1970s	no data	50%	70%	60%	40%
1980s	no data	50%	50%	25%	30%
1990s	0%	20%	10%	33%	20%
2000s	30%	70%	40%	50%	80%

**No data was collected at USGS stream gauges during certain time periods. The Ketle River stream gauge was not installed until the 1960s. The middle flow estimate for sandbar submergence was used in this analysis.*

Along with the frequency of sandbar exposure on an annual basis, the timing of sandbar exposure has been delayed particularly on the Cannon and Minnesota Rivers, where the average date of sandbar exposure was calculated to be 27 days later in the post-1980 time period than before (Table 5 and Figure 8). Sandbar emergence on the Root River was 16 days later in the post-1980 time period, while the Kettle and St. Louis were 4-6 days later compared to the pre-1980 time period.

Table 5. Date of earliest sandbar emergence (using middle flow estimate for sandbar submergence) that would allow nesting to occur. As sandbar exposure is delayed, it may become too late for turtle nesting particularly for wood turtles which generally nest late in May.

River name	Cannon	Kettle	Minnesota	Root	St. Louis
Median pre-1980 date of earliest possible nesting	6/26	6/26	7/1	6/21	6/27
Median post-1980 date of earliest possible nesting	7/23	6/30	7/28	7/6	7/3
Change earliest possible nesting date	+27 days	+4 days	+ 27 days	+16 days	+6 days

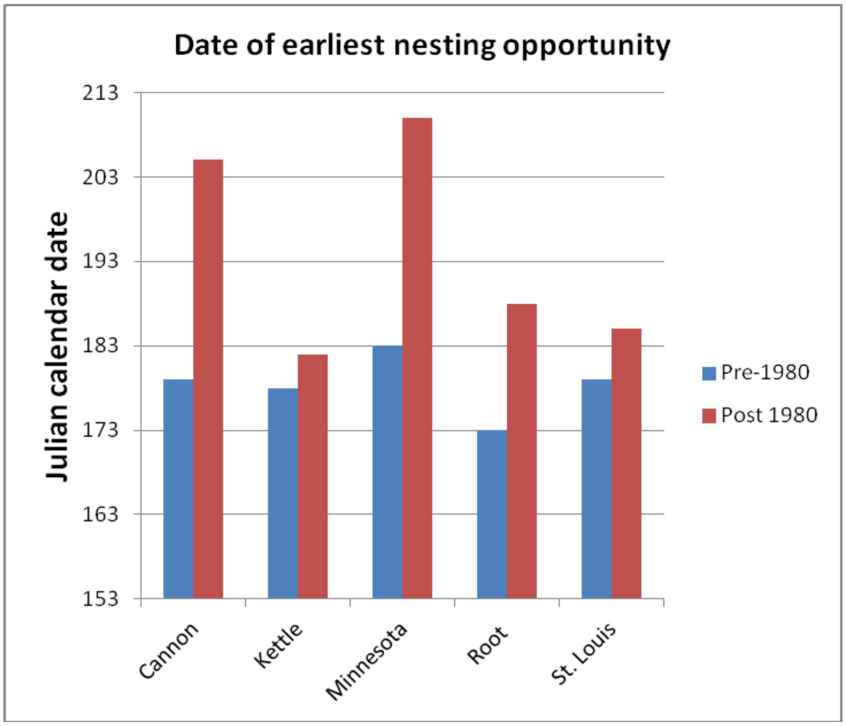

Figure 8. Dates of earliest sandbar emergence allowing nesting to occur in the pre-1980 time period (blue) compared to the post 1980 time period (red) on the five study rivers. The estimated date of earliest sandbar exposure and nesting opportunity was delayed by 27 days on the Cannon and Minnesota Rivers. There was less change on the Root and little change on the Kettle and St. Louis Rivers.

Sandbar characteristics: soil particle size, temperature and plant cover

Data collected on sandbar temperature showed that it is largely controlled by the water level in the stream. Since sand has little capillary fringe (zone of moisture retained by capillary action from water table), little water is held above the water table. Once the water level in the sandbar drops, sand can heat up to high temperatures well in excess of ambient temperatures. A maximum of 42.2˚ C (108˚ F) was observed on the Minnesota River on 8/3/2010 (Table 6). Temperature variability was less by the water edge and at 15cm depth, the approximate depth at which turtle eggs are laid.

Soil particle size data showed that sand and gravel comprised 97-100% the of soil material with some trace amounts of finer sediment. There was much variability in the size of sand and the percent of gravel on the sandbars. The Root River had the highest percentage of fine sand (12%), while the Cannon and Kettle Rivers had the highest cobble and gravel percentage (37-46%) (Table 7).

Table 6. Temperature data on sandbars recorded at top of sandbar and at water edge. At each location, temperature was recorded at the ground surface and at 15cm deep, the approximate depth that turtle eggs are deposited.

Summary	Cannon River	Kettle	MN River	Root	St. Louis
sample date	8/2/2010	9/7/2010	8/3/2010	9/1/2010	9/8/2010
top of sandbar-0 depth (temperature in degrees Celsius)					
mean	30.4	14.0	37.4	29.4	13.7
stand. dev.	6.5	1.8	5.1	5.9	4.1
max	36.1	15.6	42.2	35.6	18.9
min	26.7	13.3	33.3	26.7	11.1
top of sandbar- 15 cm depth					
mean	27.9	15.1	29.0	25.8	13.3
stand. dev.	3.5	1.1	2.9	4.3	1.3
max	30.6	15.6	31.7	27.8	14.4
min	25.6	14.4	26.7	23.9	12.8
by water edge 0- depth					
mean	26.6	13.7	31.2	26.0	12.8
stand. dev.	1.2	3.0	3.6	5.6	2.9
max	27.8	16.7	34.4	30.0	15.0
min	25.6	12.8	28.9	22.8	10.6
by water edge 15 cm depth					
mean	23.7	14.4	25.5	23.6	13.3
stand. dev.	3.0	1.4	3.8	2.9	1.6
max	25.6	15.6	27.8	26.7	14.4
min	21.1	13.3	21.1	22.2	12.2

Channel evolution trends: rates of bank erosion and channel widening.

Though beyond the scope of this study, the increases in flow could be counteracted by channel enlargement via widening or downcutting. The Minnesota River width increased by 50- 100% between St. Paul and Mankato between 1938 and 2009 (Lenhart et al. 2011b). Ongoing data collection on the Minnesota River indicates that the widening is continuing today. However despite the widening, increased flows particularly around the mean annual flow level (Lenhart et al. 2011a) have increased enough that much of the sandbar area remains submerged for much of the summer in most years.

In the other rivers, no data was collected for the Root and Cannon Rivers, though the lower Root River was channelized below Houston in the mid 1900s. The channelization likely led to active channel adjustment over a period of years to decades. In northern Minnesota, preliminary data collected on width of the Kettle and St. Louis rivers showed no significant change in the past 2 decades. In these rivers the sandbars were more stable with a greater percentage of the area covered with perennial riparian vegetation.

Table 7: Particle size data of sandbar soils. (n=3-7)				
Site	**%gravel**	**% med-coarse sand**	**% fine-very fine sand**	**% silt/clay**
Cannon	46%	54%	0%	0%
Kettle	37%	63%	0%	0%
Minnesota	6%	87%	4%	3%
Root	27%	60%	12%	1%
St. Louis	2%	92%	6%	0%

Turtle inventory data

Data collected on turtles observed (identified to species or genus level) and presence of nests showed that there were four to five species observed overall (Table 8). Most were seen basking on logs, particularly the painted and map turtles while most sofsthells (species unknown) were observed on sand bars. There were no confirmed smooth softshell sitings during the surveys and wood turtles were only found on the St. Louis River. Overall, the Kettle River had the highest percentage of sandbars with active turtle nests of any species at 80%, while the Minnesota River had the lowest at 13% (1 of 8 sandbars inspected had evidence of nesting activity).

Table 8. Turtle nesting species observation data on study rivers in summer 2010-2011. Turtle species observations were recorded for the entire study reach while canoeing. A subset of sandbars (n=5-10 per river) was examined more closely for nesting activity.

River	Species observed	% of sandbars surveyed with active turtle nesting (all species)	Notes
Cannon	Map (*Graptemys geographica*), Painted, (*Chrysemys picta*), softshell species, (*Apalone sp*.)	50	No wood turtles observed, site within known range.
Kettle	Painted(*Chrysemys picta*), softshell (*Apalone sp*.)	80	No wood turtles observed, site within known range.
Minnesota	Map (*Graptemys geographica*)	13	Sandbars were submerged for the majority of study period (2010-2011). No softshell turtles observed. The study site is west of the known wood turtle range.
Root	Painted (*Chrysemys picta*), softshell (*Apalone sp*.)	78	No wood turtles observed, site within known range.
St. Louis	Wood (*Glyptemys insculpta)*	25	A number of young wood turtle hatchlings were observed

Discussion

In this study we attempted to determine if there was a change in available nesting habitat caused by increased duration of sandbar submerging flows (approximately equal to the mean annual flow). However, the correlation between reduction in nesting sites and population levels is complex and includes a host of natural and anthropogenic factors that could not all be addressed in this study. Still, many things were learned from this study involving the importance of hydrologic and geomorphic change on turtle habitat.

- In general, natural flow variability in eastern to central Minnesota rivers is such that suitable nesting conditions occur sporadically and not every year.
- Changes in flow around the mean annual level (the 25%-75% flows) may have more impact than changes in peak flows for certain ecological functions such as riverine turtle nesting.
- Increased magnitude and duration of summer flows in the southern rivers (Cannon, Minnesota and Root) have reduced nesting opportunity both in terms of sandbar area exposure and the time available in the summer. The average earliest available nesting date during the 1980-2010 time period has been delayed 16-27 days compared to the pre-1980 streamflow record.

All of these watersheds have experienced human impacts to land-cover since European settlement, although the northern forested watersheds like the St. Louis and Kettle have experienced much less hydrologic change in recent decades. They were logged heavily a century ago, have since reforested and now they are fairly stable, although development and mining impacts may be important in the St. Louis basin. In contrast, flow magnitude, duration and timing have changed greatly in the past 30 years in the southern Minnesota Rivers regardless of any earlier post-European settlement impacts that are still influencing the river (such as channelization). Northern Minnesota, Wisconsin and Michigan have actually undergone a process of watershed stabilization since reduction of the peak logging period in the early to mid 1900s. In contrast southern Minnesota has experienced precipitation increases, land-cover change and increased tile-drainage just in recent decades.

Despite a large increase in the mean annual streamflow in many of the streams in southern and western Minnesota, summer streamflow metrics most directly impact turtle nesting. These nesting-related metrics include the date of earliest sandbar exposure; the duration of continual sandbar emergence and the occurrence of mid-summer hydrograph pulses. In a broader ecological sense, this analysis illustrates the sporadic, cyclical nature of turtle recruitment in rivers that have naturally variable flow levels. Although we did not examine other ecological processes in this study, it is known that many other low-flow functions such as riparian tree colonization and denitrification are similarly variable in time and space.

Smaller rivers and those with more rapid runoff response (such as urban watersheds or those with shallow bedrock as in northeastern Minnesota) would leave river turtles more susceptible to rapid summer rises in water levels that destroy nests. This may be one reason (among many factors) that certain turtle species like the smooth softshell are only found on the larger river systems, such as the Minnesota and Mississippi Rivers. In western Minnesota, rivers are generally more ephemeral which may expose sandbars for longer time periods but limit turtle survival in other ways by eliminating overwintering habitat along rivers or reducing feeding in late summer when the rivers typically go dry. Prolonged periods of lower water levels may also promote vegetative growth which may limit suitable nesting site formation.

Implications for Management

The main implication is that increased low to mean flows (in the 25^{th}-75^{th} percentile range) can reduce turtle nesting success, possibly until channel adjustment returns back to a stable state, which can take as long as decades on larger watersheds. Reduction of late spring and summer flow volume in southern Minnesota (and much of the upper Midwest) would likely benefit turtle nesting success. Improved management and restoration strategies focused on specific components of the turtles' life cycles could benefit turtle populations particularly in larger rivers with existing populations of rare turtles like the Minnesota and St. Louis. Although this study focused on eastern Minnesota, the findings from this study may be applicable to the eastern and southern United States where the range of many turtle species extends (Figures 1 and 2).

Management and restoration recommendations

There are numerous threats to the maintenance of healthy wood and softshell turtle populations. Some problems are universal to all riverine turtles. However, by more clearly identifying threats to riverine turtle habitat, management resources can be targeted more precisely to help stem the decline of these rare turtle species. Based on this analysis it appears that smooth softshells are more susceptible to hydrologic alteration in rivers because they are more aquatic, spending most of their lives in or adjacent to rivers. In contrast, wood turtles are more terrestrial (Oldfield and Moriarity, 1994) and so predation or depredation in uplands maybe may be more of a threat to wood turtles than softshells. However young smooth softshell turtles may face greater risk from avian and aquatic predators than wood turtles.

Other factors that have the potential to affect or alter riparian turtle habitat include: dredging, channel armoring/stabilization, stream channelization, hydrologic and hydraulic manipulations to streams and riparian vegetation alterations. While dredging is not frequently conducted in the rivers we studied, channelization did occur on the lower 20 miles of the Root River greatly reducing the sandbar areas in that reach. While pointbar deposits are forming in the channelized reach, their elevation appears below the water surface at most water levels. Besides predation, other factors that directly affect turtles' reproduction directly include human collection/trapping and anthropogenic hazards such as road crossings.

Restoration and management actions that could be undertaken to increase the viability of turtle populations, include:

- Restore sinuosity in straightened stream channels to re-establish point bar nesting habitat, particularly in lower Root River below Houston.
- Improve connectivity between viable population/habitat areas within suitable riverine corridors (Spradling et al. 2010)
- Expedite channel evolution and process of sandbar vertical growth on smaller rivers
- Clear vegetation above 1 year flood level at highly productive nesting sites to increase exposure to sun, reduce predation and flooding of nests.

- Protect nesting sites from ATVs, human beach parties, camp fires and other disturbance
- Control mesopredator populations at established nest sites, (i.e. trap raccoons, opossums, etc).
- Protect and/restore hydrologic regimes characteristic of the river system (volume, flood peak and timing of flows). In particular, summer high flows need to be reduced.

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- Protect and/restore hydrologic regimes characteristic of the river system (volume, flood peak and timing of flows). In particular, summer high flows need to be reduced in southern Minnesota.
- In northern Minnesota, mitigate activities that cause a large increase in late spring to early summer flow such as mining dewatering that may impact turtle nesting.

Recommendations for future research

Additional observations of nesting timing and predation are needed. This could be done with a motion-activated wildlife camera mounted near sandbars, radiotagging and possibly via trap/mark/recapture studies. The findings of this study indicate that reduced frequency of nesting opportunity and/or delayed nesting in the southern Minnesota Rivers was a consequence of recent hydrologic changes. This finding still needs to be confirmed by actual observations of nesting success, although Spradling et al. (2010) made the same observation in northeastern Iowa rivers.

The impact of altered sediment dynamics on turtle nesting is likely important but little is known about this, particularly in streams undergoing active channel widening that may experience high rates of sandbar deposition. Changes in sandbar particle size and sandbar elevation relative to stream water level are both important for nesting success.

There is also limited information on these species' dispersal after nesting and their range from their nest sites. Even less is known about their overwintering behavior and how hydrologic and geomorphic changes may impact overwintering habits. Does delayed-overwinter emergence occur frequently in Minnesota? Do changes in the supply and removal of large woody debris impact turtles' ability to bask and regulate their temperature? It is not known how the supply and removal practices of large woody debris have changed over time at our study sites.

In terms of species-specific research, it would be useful to develop a genetic or chemical test that the shells of hatched eggs to differentiate the smooth softshell from the spiny softshell turtle since it's difficult to distinguish them in the field. This would enable the identification of nests by species since egg shells persist over years. Since smooth softshell turtles nest close to the water and are highly aquatic, changes to sediment dynamics and sandbar traits may be particularly important for them.

Further wood turtle research should include further field surveys to verify their existing range. Many streams within their geographic range are not known to support wood turtles and it would be useful to know why. It would be helpful to know what the most limiting factors in their life cycles are, whether it is nesting, overwintering, feeding or dispersal and/or juvenile rearing. A better understanding of the reasons for their distribution would be helpful for management as well. For example, if there are innate climatic or geographic factors limiting their range, such as the lack of large, perennial streams, then management resources can be focused on other rivers.

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