Environ Monit Assess (2010) 165:435–447
DOI 10.1007/s10661-009-0957-y

Spatial and temporal variation in suspended sediment, organic matter, and turbidity in a Minnesota prairie river: implications for TMDLs

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Received: 16 July 2008 / Accepted: 18 April 2009 / Published online: 13 May 2009

Abstract The Minnesota River Basin (MRB), situated in the prairie pothole region of the Upper Midwest, contributes excessive sediment and nutrient loads to the Upper Mississippi River. Over 330 stream channels in the MRB are listed as impaired by the Minnesota Pollution Control Agency, with turbidity levels exceeding water quality standards in much of the basin. Addressing turbidity impairment requires an understanding of pollutant sources that drive turbidity, which was the focus of this study. Suspended volatile solids (SVS), total suspended solids (TSS), and turbidity were measured over two sampling seasons at ten monitoring stations in Elm Creek, a turbidity impaired tributary in the MRB. Turbidity levels exceeded the Minnesota standard of 25 nephelometric units in 73% of Elm Creek samples. Turbidity and TSS were correlated ($r^2 = 0.76$), yet they varied with discharge and season. High levels of turbidity occurred during periods of high stream flow (May–June) because of excessive suspended inorganic sediment from watershed runoff, stream bank, and channel contributions. Both turbidity and TSS increased exponentially downstream with increasing stream power, bank height, and bluff erosion. However, organic matter discharged from wetlands and eutrophic lakes elevated SVS levels and stream turbidity in late summer when flows were low. SVS concentrations reached maxima at lake outlets (50 mg/l) in August. Relying on turbidity measurements alone fails to identify the cause of water quality impairment whether from suspended inorganic sediment or organic matter. Therefore, developing mitigation measures requires monitoring of both TSS and SVS from upstream to downstream reaches.

Keywords Suspended sediment · Turbidity · Organic matter · Prairie pothole region · Monitoring

Introduction

The Minnesota River Basin (MRB), reported to be one of the 20 most polluted waterways in

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the USA (American Rivers Council 1997), contributes some of the highest levels of sediment and nutrients to the Upper Mississippi River (Magner et al. 2004) and ultimately to hypoxia in the Gulf of Mexico (Goolsby 2000). Over 92% of the MRB is in agricultural land use, primarily row crop cultivation, with corn–soybean as the most widely planted crops (Almendinger 1999), with corn production expanding because of the rising demand for ethanol production. Intensive agriculture in the Blue Earth River Basin (BERB) is the major contributor of nutrients and sediment to the MRB (Minnesota Pollution Control Agency (MPCA) 1994; Quade 2000; Magner et al. 2004) and is listed as impaired for nutrients and turbidity by the MPCA (2008). Reducing turbidity levels is important, not only to meet water quality standards but also to improve habitat of fish and aquatic organisms and to enhance aesthetic and recreational values (Newcombe and Jensen 1996; Zimmerman et al. 2003).

An impaired water body is one that fails to meet water quality standards. Nationwide, the Clean Water Act (CWA) requires a total maximum daily load (TMDL) to be developed when water bodies fail to meet water quality standards. Section 303(d) of the CWA requires that mitigative strategies be developed to reduce pollutant loads to levels that will meet water quality standards. To mitigate turbidity impairment, the causes of turbidity must be allocated to sources such as upland erosion, channel erosion, and organic matter discharge from wetlands or lakes. In Minnesota and several other states, sediment loading must be controlled to meet the state's numeric water quality standard for turbidity.

There are fundamental problems with Minnesota's numeric turbidity water quality standard. Turbidity impairment for class 2B waters, defined as >25 nephelometric units (NTU), does not distinguish between organic matter and inorganic sediment, yet both affect turbidity (Waters 1995). In addition, turbidity is influenced by color, temperature, and the shape of the suspended minerals (Packman et al. 1999). Although organic matter typically comprises a much smaller percentage of the annual load of total suspended solids (TSS), the organic fraction, defined in this paper as suspended volatile solids (SVS), is important because it influences turbidity differently than inorganic sediment via increased light scattering (Henley et al. 2000). Furthermore, turbidity is not a measurement of mass, and therefore, a loading rate of turbidity (mass per unit area divided by time) cannot be directly established for the development of load allocations in a TMDL. Turbidity was promulgated as a Minnesota water quality standard several decades ago before the 1972 amendments to the CWA because it was easy and relatively inexpensive to measure (Johnson et al. 2007).

This study was undertaken to determine sources of turbidity, seasonal changes, and changes associated with stream flow and location as defined by basin scale. Recognizing that organic matter and inorganic sediment contribute to turbidity, both SVS and non-volatile suspended solids (NVSS) were measured concurrently with turbidity. NVSS is equivalent to suspended sediment, the more widely used term for inorganic sediment suspended in water.

The relative contributions of organic and inorganic matter to turbidity vary by area, for example urban watersheds tend to have less organic matter than agricultural watersheds. In the prairie pothole region (particularly southwestern Minnesota and northwestern Iowa), eutrophic wetlands and shallow lakes receive nutrient-rich runoff and drainage from agricultural croplands. They act as sinks and processors of sediments and nutrients from the watershed, transforming nutrients into large quantities of algae and aquatic vegetation (Lenhart 2008). Lakes and wetlands can reduce inorganic sediment discharge to streams but can potentially contribute high organic loads, which can increase in-stream turbidity, particularly during late summer.

Both TSS and SVS vary seasonally with primary productivity and flow fluctuations (Chapman 1996). TSS concentrations have been shown to be strongly correlated with stream discharge, with most of the sediment load transported during peak flow events (Allan 1995; Doyle et al. 2005; Leopold et al. 1964). Historically, the largest peak flows in the MRB occur in April, May, and June with corresponding high suspended sediment concentrations. While the relationship between flow and suspended sediment is fairly well established, the relationship between stream flow and SVS is less well understood. There is also a much uncertainty about how much of the sediment contributing to turbidity is from upland surface erosion versus channel sources, such as unstable stream banks and bluffs that are common in the BERB.

SVS levels have been reported to be correlated to high nutrient levels in waterbodies, particularly phosphorous, which have resulted in widespread eutrophication in the region (Allan 1995; Carpenter et al. 1998; Heiskary et al. 1987). SVS levels may increase during snow melt/soil thaw from flushing of organic matter accumulated throughout the October to May low-flow period (Allan 1995). However, organic matter production peaks in late summer when long-term average stream flow is near its lowest (Lenhart 2008). When determining causes of turbidity, and eventually developing methods to mitigate turbidity impairment through the TMDL process, it is, therefore important to discern how SVS varies with season and discharge, as well as how TSS and turbidity respond spatially, moving from upstream tributaries to downstream channels. To date, considerable TMDL monitoring has been conducted at sites dispersed across Minnesota, but they tend to focus on the river mouth and do not address variation in streamflow or watershed and stream conditions. This study considered how turbidity, as related to TSS and SVS, vary seasonally, with discharge and spatially from upstream to downstream.

According to current stream ecological theories, turbidity and suspended sediment are thought to increase with increasing stream size, stream order, and drainage area because of the accumulation of sediment and nutrients from the watershed and streambanks (Thorp et al. 2006). Therefore, we expected TSS and turbidity to increase approximately linearly with drainage area. Lake outlets were expected to decrease river turbidity by dilution with clear water, although much detritus and other forms of organic matter were expected to be added to the stream flow.

Meeting turbidity reduction goals in the BERB and MRB requires a better understanding of the origins and sources of turbidity than what currently exists. Sampling stations were located to characterize the changes to turbidity, TSS, and organic matter (SVS) moving in the downstream direction.

The objectives of this study were to (1) improve the understanding of spatial and temporal variability of turbidity, TSS, and SVS for improved TMDL assessment and load allocation between organic and inorganic sources of turbidity, (2) determine the importance of sampling design on results obtained from single station, river mouth sampling versus spatially dispersed sampling at multiple sites from upstream reaches to the mouth of the stream, (3) determine the importance of organic matter contributions to turbidity from eutrophic lakes/wetlands discharging into the main channel of Elm Creek, and (4) determine the importance of stream channel stability on turbidity levels in Elm Creek.

Study area

Elm Creek (Fig. 1) is a tributary of the Blue Earth River within the MRB located in Martin and Jackson Counties of southwestern Minnesota. Encompassing 700 km^2, the watershed is 86% corn/soybean agriculture. Wetlands cover less than 2% of the watershed, although, historically, this prairie pothole landscape had greater than 50% wetland coverage (Leach and Magner 1992; Quade 2000). Drainage of wetlands and lakes has lead to increased runoff and sediment delivery to streams (Miller 1999).

Geologically, Elm Creek was carved through the high-clay content glacial till plain of the Des Moines Lobe with slightly steeper terrain in the Altamont stagnation moraine located in the western portion of the watershed (Ojakangas and Matsch 2004). Elm Creek has a water surface slope ranging from 0.002 to 0.0003 m/m. The watershed is mostly flat with some steeper slopes in the highly erodible stream valleys and in the western part of the watershed in the Altamont Moraine. Soil erosion of primarily fine-textured loamy soils is estimated at 3–4 tons ha^{-1} year^{-1} (Quade 2000).

In testing turbidity responses, we considered the hypotheses that: (1) turbidity increases proportionally (linearly) with drainage area, (2) lakes

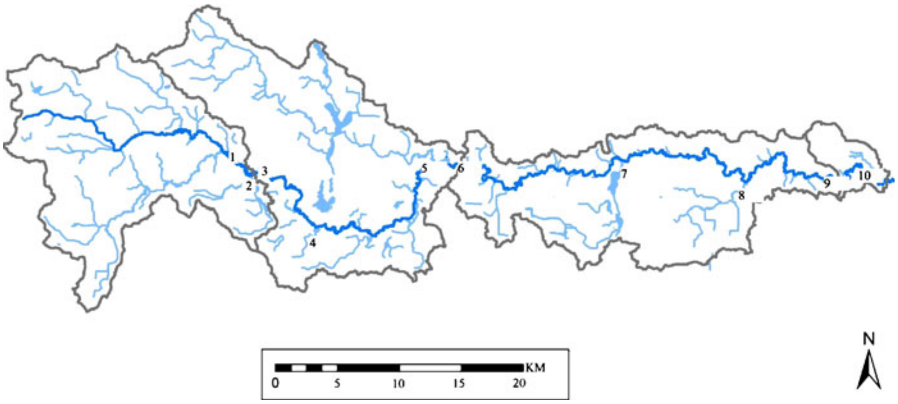

Fig. 1 Location of monitoring stations in Elm Creek Watershed, Minnesota. Elm Creek mainstem sites are *numbered in bold* (1, 3, 5, 6, 9, and 10), while tributaries and lake outlets are in *smaller, non-bold font* (2, 4, 7, and 8). Elm Creek enters the Blue Earth River east of station 10

discharging into Elm Creek would reduce turbidity because of diluted TSS concentrations, and (3) SVS would constitute a large portion of the TSS load in Elm Creek in late summer when primary productivity is at a maximum.

Methods

We further hypothesized that turbidity increases with increasing TSS and SVS and that turbidity, TSS, and SVS vary with discharge, season, watershed position, and channel stability.

Sampling procedures

Sixteen stations were sampled for TSS and turbidity on reconnaissance trips in September to October of 2004 and March 2005 to identify suitable sites for the study. We selected ten long-term monitoring sites from among the original, with watershed areas ranging from 15 to 700 km^2. Six stations were located along the main stem of Elm Creek (Fig. 1), the details of which are presented in Table 1.

TSS and SVS were sampled using a DH-48 depth-integrated sediment sampler (Leopold et al. 1964). The sampler was hung from a bridge to obtain samples at high flows. At low flows (below

Table 1 Monitoring site characteristics from upstream to downstream

Site	Basin area (km^2)	River distance (km)	Channel slope (m/m)	Cross sectional area (m^2)	Stream order	Site type
1. North and south fork merger of Elm Creek	207	35.3	0.0010	9.8	3	Main stem
2. Watkins Lake	26	39.3	0.0012	2.5	2	Lake outlet
3. Upper Elm Creek mainstem	241	39.7	0.00083	8.5	3	Main stem
4. Ditch 37 outlet	16	53.4	0.0011	3.1	2	Tributary
5. Elm Creek above Creek Lake	347	63.8	0.00008	32.9	3	Main stem
6. Elm Creek below Creek Lake	496	67.3	0.0005	19.4	4	Main stem
7. Martin Lake	49	89.7	0.00036	Culvert—not applicable	2	Lake outlet
8. Ditch 3 outlet	44	107.1	0.0015	4.6	2	Tributary
9. Lower Elm Creek	674	116.1	0.0008	22.4	4	Main stem
10. Elm Creek mouth	700	125	0.001	25.2	4	Main stem

Data from Lenhart (2008)

0.5-m depth), grab samples were taken to avoid stirring up bottom sediments. Turbidity was measured in NTU using a YSI 6820 multi-parameter probe in the thalweg of the channel. Turbidity data were collected over 20 times between March 2005 and December 2006; TSS was measured on 16 of those dates, while SVS was also sampled on eight of those dates in 2006. Water samples for TSS and SVS were analyzed at a commercial laboratory following standard procedures (Eaton et al. 1995).

Stream discharge was determined from stage–discharge relationships at each of the ten sites. A continuous stream flow record was available from a Minnesota Pollution Control Agency (MPCA) gage located at site 9, near the mouth of Elm Creek. The MPCA flow record was used to calibrate the stage–discharge rating curves at the six main-stem Elm Creek sites. Stage measurements were collected with each TSS and SVS sample, and flow velocity was measured in a subset of those samples.

Stream channel morphology was surveyed at 18 sites across the Elm Creek basin, including all of the TSS, turbidity, and SVS sampling sites (except site 7, the Martin Lake outlet, which consisted of three culverts). Data were collected on streambed materials (particle size and depth of fine sediment), cross-sectional dimensions, longitudinal profiles of the river bed, including a water surface measurement and plan view measurements to calculate sinuosity. From these basic geomorphic measurements, parameters related to sediment transport and bank stability were calculated (Lenhart 2008). The relationships between, stream power, entrenchment, bank height, and bank stability indices (such as the Bank Erosion Hazard Index) were examined in relation to turbidity, TSS, and SVS.

Data analysis

Summary statistics (mean, median, range, and variance) were used to characterize the spatial and temporal variability of TSS, SVS, and turbidity. Differences between individual sites and categories of sites were assessed for significance using *t* tests at an $\alpha = 0.05$ level (as samples collected on the same date were paired). The variability of TSS and SVS both longitudinally (upstream–downstream) and seasonally was examined with repeated measurements from March 2005 to December 2006. In assessing spatial variability, we focused on key transition points such as tributary junctions and lake outlets because these were the locations where the greatest changes in TSS and SVS were observed.

Relationships between TSS, SVS, and stream flow (Q) and their variability were assessed using regression analysis. The correlation between turbidity and TSS and Q and between TSS and SVS were determined using linear regression. We focused on turbidity data for the longitudinal assessment of trends because there was a larger sample size for turbidity than either TSS or SVS, due to ease and cost of measurement. Downstream trends in turbidity, TSS, and SVS were examined using both linear and non-linear regression. Finally, the significance of upstream–downstream trends were assessed by testing the hypothesis that the slope of the line $(\beta) = 0$. If the slope of the line was significantly different than 0, then the trend was significant.

Results

TSS and turbidity were more strongly correlated than SVS and turbidity in Elm Creek. Linear regression analysis between log-transformed TSS and turbidity data yielded an r^2 of 0.76 ($n = 119$)

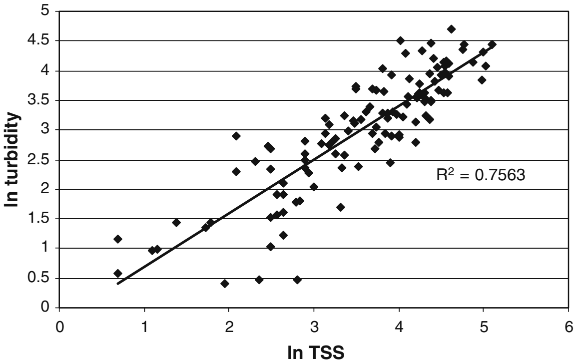

Fig. 2 Turbidity–total suspended solids (TSS) relationship in Elm Creek. Turbidity units are nephelometric units (NTU) and TSS units are milligram per liter on a natural log scale (ln)

(Fig. 2). In comparison, the correlation of SVS to turbidity yielded an r^2 of 0.58 ($n = 80$).

In the Elm Creek, the correlation between TSS–turbidity fell within the range found by previous researchers in the MRB, where r^2 values ranged from 0.56 to 0.87 (Campbell 2008), although correlations were stronger in the lower Mississippi watershed in Minnesota (Ganske 2004).

Influence of stream flow discharge

TSS, SVS, and turbidity were highly variable with stream flow. TSS and turbidity generally increased with stream flow. At high flows (>10 m^3/s), turbidity maxima increased dramatically downstream of Creek Lake (site 6) on the main branch of Elm Creek (Fig. 3). However, turbidity behaved differently at low to medium flows (<0.28 m^3/s), with the highest median turbidity measured near Creek Lake (sites 5 and 6) (Fig. 3). During low flows, turbidity appeared to increase from upstream sites (1 and 3) to middle reaches (5 and 6); however, there was no overall relationship from upstream to the mouth of Elm Creek (β was not significantly different than 0; $r^2 = 0.44$).

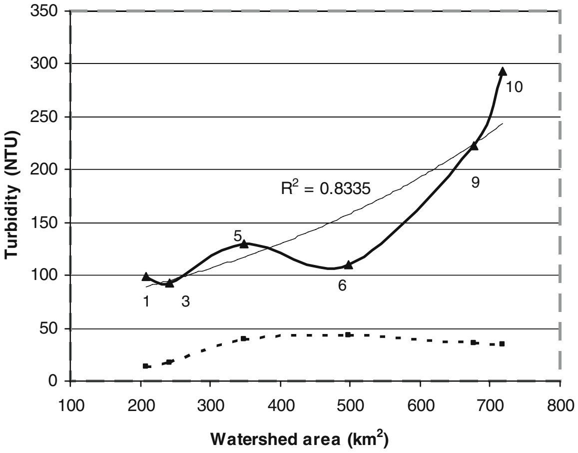

Fig. 3 Longitudinal turbidity trends in Elm Creek. Regression of watershed area vs. turbidity maxima using a power function yielded an r^2 of 0.8335. Elm Creek main stem sites are shown below (site numbers 1, 3, 5, 6, 9 and 10). Median turbidity values are shown by the *dashed line located below the solid line*

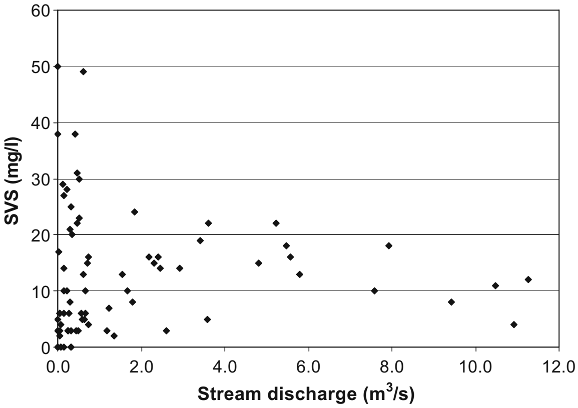

Fig. 4 Variation in suspended volatile solids (SVS) with stream flow. Data was collected at ten Elm Creek monitoring stations between May and August of 2006. Stream flow at time of sampling is shown on *x*-axis in cubic meter per second (cms)

Turbidity at low flows (<0.28 m^3/s) was influenced by lake inputs of organic matter comprised mostly of algae (Fig. 3). Sites 5 and 6 had about three times the mean turbidity (mean, 50 NTU) of Elm Creek main-stem sites (mean, 17 NTU) and seven times that found in the tributary ditches (mean, 7 NTU). Turbidity at the lake outlets was double (>50 NTU) the Minnesota impairment level at low flows.

In contrast to TSS, SVS was not correlated with stream flow ($r^2 = 0.00001$). The maximum SVS concentrations (up to 50 mg/l) occurred at low flows (Fig. 4).

Seasonal effects on turbidity and SVS

Spring snowmelt runoff events from March to early April in the BERB often had substantially lower TSS per volume of discharge (flow-weighted mean concentration) than rainfall runoff events in May or June. During May and June, TSS values increased with maximum values recorded following a large June storm.

Turbidity declined throughout the summer of 2005 following the large storm event of June 21, 2005. Turbidity did not predict TSS very well during late summer. The correlation of turbidity and TSS decreased in the late summer with an r^2 of 0.15 in August compared to an r^2 of 0.59 in April. This relationship was attributed to

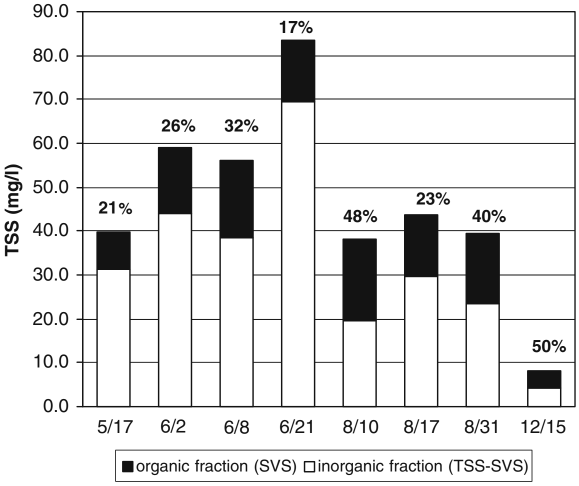

Fig. 5 Variation in organic matter (SVS) concentration by season in 2006 on Elm Creek. The percentages are the fraction of SVS/TSS; an average of all ten sites for each date that data was collected

the positive correlation between TSS and stream flow ($p < 0.005$), although the relationship varied considerably by season and site. Similarly to turbidity, TSS values generally increased downstream with increasing flow and drainage area (Lenhart 2008).

The percentage of SVS of TSS and how it varied by season is shown for all ten sites in Fig. 5. SVS from the lake outlets varied more widely than the river sites, ranging from 18% to 70% of TSS. In the late summer, the SVS percentage increased as primary productivity was augmented by rising temperature and nutrient availability. SVS comprised a greater percentage of the TSS during late summer (August) than May and June 2005 (Fig. 5). Early season SVS transport appeared to be composed of more highly decomposed organic matter (detritus), while late season SVS consisted primarily of algal material. The late summer external loading of SVS from lakes and wetlands increased turbidity levels. Suspended solids become concentrated at low flows particularly in slow-moving channel areas such as site 5, where flow is backed up by Creek Lake.

The percentage of SVS dropped considerably following a storm event on June 21, presumably because of dilution at high flows (Allan 1995). However, by late summer (August), SVS comprised more than 50% of TSS at many sites.

The timing of peak lake discharge to streams occurs weeks after peak stream flow (Fig. 6). The delayed release is caused by a backwater effect that prevents lakes and wetlands from discharging

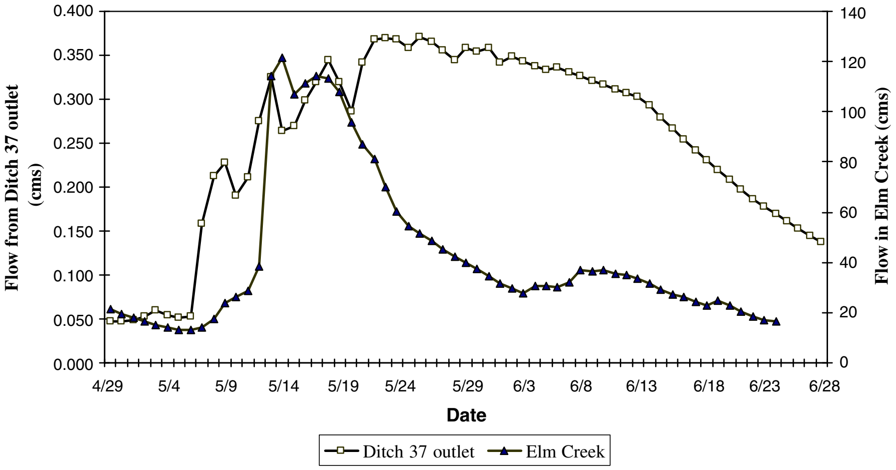

Fig. 6 Timing of discharge from lakes and wetlands. Discharge in cubic meter per second (cms), in Elm Creek compared to large wetland/lake input. The Ditch 37 watershed flow comes mainly from several large upstream lakes and wetlands. High water levels in Elm Creek downstream of lakes and wetlands delays peak discharge from lakes and wetlands. Lake discharge comprises an increasing percentage of stream flow during summer as shown by the high flows from the Ditch 37 watershed in June, while Elm Creek is dropping. Note that scale is different on each *y*-axis; flow for Ditch 37 is shown on the left axis while flow for Elm Creek is shown on the right axis

at the maximum possible rate through outlet pipes until the water level in Elm Creek has dropped. For example the Ditch 37 outlet discharge made up 0.7% of the Elm Creek flow on May 14, 2005 and increased to 4.0% of total stream flow on June 4, 2005 (Fig. 6).

Stream power and channel stability effects

TSS increased in the downstream direction, as with turbidity (during high flows), particularly downstream of Creek Lake where greater stream bank and bluff erosion contributions were observed in geomorphic surveys (Lenhart 2008). The sites influenced by lakes, particularly the Creek Lake stations both had lower TSS at high discharge levels, presumably because lakes induce settling of suspended solids with reduced velocity and shear force (Table 1). For example, Elm Creek above Creek Lake (at site 5) had low sediment transport capacity with the least water surface slope (0.00008 m/m) of all sites and low velocity (about 0.3 m/s). Consequently, about 1 m of fine sediment deposition was found at this site, in data collected by Lenhart (2008).

Variability of turbidity, TSS, and SVS by watershed position

Over all sites, turbidity values ranged from 0 to 385 NTU in the Elm Creek watershed from May 2005 to December 2006. Turbidity exceeded the standard of 25 NTU in 47% of all samples ($n = 189$), but in the middle and lower reaches of Elm Creek (downstream of site 6), 73% of samples exceeded the standard. Upstream of Creek Lake (site 5), only 38% of samples exceeded 25 NTU. Overall, the variability in turbidity and TSS was high both seasonally and spatially. Seasonally, TSS and turbidity measurements were highest during spring peak flows with maxima observed on May 13, 2005.

Turbidity tended to increase downstream with increasing drainage area in a nonlinear pattern on the main branch of Elm Creek (Fig. 3). We found a significant increase in turbidity maxima moving in the downstream direction (the slope of the line, β, was significantly different than 0), but linear regression explained only 68% of the variation ($r^2 = 0.68$). An exponential regression line of turbidity maxima yielded the best fit with an r^2 of 0.83.

A threshold of turbidity appears to have been crossed downstream of the in-stream Creek Lake at site 6 at 496-km^2 drainage area; from this point (Fig. 3), peak turbidity values increased substantially downstream, as indicated by the increasing slope of the line toward the river mouth. At the station upstream of Creek Lake (site 5), we frequently observed a reduction in turbidity due to slow-moving water and lake backwater effects. However, Creek Lake served as both a source and sink of suspended sediment, as turbidity downstream of the lake (site 6) occasionally exceeded upstream values (site 5). SVS generally decreased after site 6 (Fig. 7).

Figure 7 summarizes the SVS data collected in 2006 by site and watershed position ($n = 80$). On the main stem of Elm Creek (sites 1, 3, 5, 6, 9, and10), median SVS values were greater at downstream stations (sites 9 and 10) compared to upstream sites 1 and 3, though the variability was too great to produce statistically significant differences. However, the upstream Elm Creek stations had equal or greater SVS concentration than the downstream reaches in June. Over the entire monitoring period, the highest SVS values on the Elm Creek main stem sites occurred at the Creek Lake stations (site 5 and 6; median of

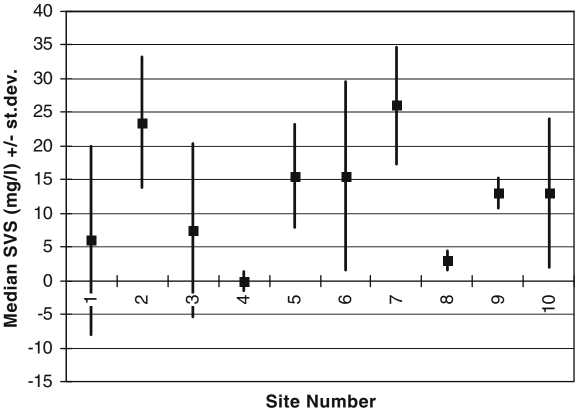

Fig. 7 Summary of SVS data by sampling station. Sites are organized from upstream to downstream from left to right. The site number refers to the sampling stations in Fig. 1 and Table 1

16 mg/l for both with maximum values of 28 and 38 mg/l, respectively).

On tributary sites, the sub-watershed outlets for Martin County Ditch 3 (site 8) and Ditch 37 (site 4) had by far the lowest SVS values, with medians of 0 and 3 mg/l and maximum of 3 and 5 mg/l, respectively. SVS maxima and variability were lower in the two subsurface drainage-dominated tributaries than the lakes or main channel sites (Fig. 7). In contrast to subsurface tile drained tributaries, the outlets for Watkins Lake (site 2) and Martin Lake (site 7) had the highest SVS levels (medians, 24 and 26; maximum, 50 and 31 mg/l) of the ten sites. The maximum SVS concentration of 50 mg/l from Watkins Lake was enough to exceed the turbidity standard of 25 NTU (equal to 42 mg/l) apart from any sediment contributions.

Discussion

Lakes and wetlands play a key role in stream turbidity within the prairie pothole region by contributing allochthonous (material produced outside of the stream itself) organic matter to streams. Although more than 90% of the wetlands have been lost in southern Minnesota, the larger lakes and wetlands now act as sinks and processors of sediment and nutrients delivered from this row-crop-agriculture-dominated landscape. Historically, isolated waterbodies are now interconnected with streams via pipe outlets or ditches, carrying their SVS loads to prairie pothole region streams, as in the case of the Ditch 37 outlet (site 4). The lakes and wetlands delay peak discharge into receiving streams until the stream's peak flow has receded, often by a period of weeks (Fig. 6). The delay is important because lake and wetland flow contributes a greater percentage of the stream flow at low flow levels than at peak spring flows. Secondly, it demonstrates the flood reduction benefits of lakes and wetlands in the region.

Today, many prairie pothole region lakes and wetlands contribute to turbidity in downstream rivers. Yet, before European settlement, many of the prairie pothole lakes and wetlands were hydrologically isolated basins and thus did not contribute their sediment and organic loads to rivers (Winter 1989). Today, most lakes and wetlands in southwestern Minnesota directly (Kuehner 2004; Leach and Magner 1992; MPCA 1994), empty their organic loads into tributaries of the Blue Earth via pipes or ditches. In the Elm Creek watershed, SVS constituted 22% of the annual TSS load in a 1996 diagnostic study (Quade 2000). Although SVS comprises less of the TSS load than sediment, we found that SVS contributes to high turbidity during summer low flow conditions, creating unfavorable conditions for many aquatic organisms.

Sources of organic matter: internal vs. external loading

Larger, wider streams are expected to have greater primary productivity than headwaters (Murphy 2001). In Elm Creek, the channel width-to-depth ratio increases downstream, theoretically exposing a greater percentage of the water column to sunlight, increasing water temperatures and organic matter production. Yet, there was not a statistically significant increase in SVS moving downstream in the Elm Creek. Differences in light availability due to riparian vegetation cover are also known to strongly influence primary production rates in rivers (Allan 1995; Murphy 2001). Increasing forest cover downstream in Elm Creek may have reduced light availability and internal productivity in contrast to the headwaters of Elm Creek, which is mostly bordered by open pasture, row crops, or prairie.

The external (allochthonous) load of organic matter from wetlands and lakes was an important source of SVS in Elm Creek. For example, Martin Lake (site 7), the outlet for a chain of glacial lakes, contributes substantial base flow and SVS loads to Elm Creek. The Martin Lake outflow constitutes a significant portion of Elm Creek's base flow during late summer low flow periods, with lake outflow comparable to Elm Creek discharge at that time (both 0.14 to 0.28 m^3/s in August 2006). A similar effect is shown for another subwatershed in Fig. 7. The lake's large organic load enters the river in the downstream portion of Elm Creek, upstream of site 9. There are no equivalently large lake inputs upstream of Creek Lake, and as a result, the most upstream Elm Creek sites (sites

1 and 3) had the lowest mean SVS values. Lake sources in late summer (external loading of SVS from lakes) drive riverine turbidity.

The loading of SVS, TSS, and turbidity from sources external to the stream is also influenced by watershed land use and hydrology. Extensively subsurface tile-drained watersheds (such as site 8), with almost no lakes or wetlands have low organic matter production compared to lake-rich watersheds, like the Martin Lake sub-watershed (site 7). In contrast, inorganic sediment from watershed erosion and runoff is much greater in spring than late summer. Consequently, TSS and turbidity peaks have corresponding maxima during the high spring flow period. Erosion is greatest in spring because the growth of annual row crops (which cover 86% of the Elm Creek basin), is minimal from April to June, allowing for high rates of surface runoff and erosion and subsequent loading to streams. However, once corn and soybean crops reach full growth and canopy coverage in July or August, soils are stabilized, reducing erosion. Thus, external loading of inorganic sediment is reduced, while loading of organic matter is increased. During summer, plant growth and transpiration decrease runoff and sediment delivery to streams. Increased native plant or perennial crops coverage (woody crops, hay, and grasses) would thus decrease in-stream TSS levels, as increased perennial plant cover reduces sediment loading to streams.

Fertilizer application on farm fields in late spring augments nutrient levels for primary productivity in rivers, wetlands, and lakes as runoff carries excess nutrients to these waterbodies (Randall et al. 1997). Contributing to spring nutrient and sediment loading is the increased rainfall intensity on exposed soils of fields yet to be planted into row crops (Baskfield, P., Hydrologist, Minnesota Pollution Control Agency, personal communication.). In contrast, runoff from summer storms often has reduced TSS as a result of the increased plant cover stabilizing the soil and reducing soil moisture. In July and August, algae and aquatic plant growth are known to increase in response to high nutrient levels and increasing temperatures in shallow eutrophic lakes and wetlands throughout the region (Heiskary et al. 1987). The Elm Creek main-stem sampling stations (sites 1, 3, 5, 6, 9, and 10) also showed increased SVS concentrations but to a lesser extent than the lakes, increasing from 16% in May to 25–32% in August.

In addition to watershed factors, channel morphology influences TSS and turbidity levels. Previous research has shown that channel instability is strongly related to suspended sediment load and that streams in the region contribute substantial amounts of sediment via channel erosion (Bauer 1998; Sekely 2001; Simon and Rinaldi 2000; Simon et al. 2004). Therefore, we hypothesized that increased turbidity downstream of Creek Lake is attributable to increased stream bank height, channel incision, and stream power.

Monitoring issues

The distribution of monitoring stations longitudinally across the length of Elm Creek and tributaries provided important data that would not have been captured by single station monitoring. Typically, monitoring programs will incorporate only one station near the river mouth. However, the non-linear nature of turbidity and organic matter increases would not have been detected without spatially distributed monitoring. The role of lake and wetland inputs would have gone unnoticed with the use of the lake outlet monitoring sites at Martin and Watkins Lake (sites 4 and 7) as well as the Creek Lake (sites 5 and 6) stations, an inline lake connected to Elm Creek. Lakes acted as sources rather than sinks for TSS and SVS during summer months.

Recommendations for TMDL assessment and implementation

A correlation between turbidity and TSS must be established in Minnesota turbidity TMDLs because turbidity is the numeric water quality standard in the state, serving as a surrogate for sediment, which in turn serves as a surrogate for “fishable and swimmable.” High organic content reduces the correlation between turbidity and TSS, since TSS is partially composed of organics. This becomes particularly important in the prairie pothole region and other wetland and lake-rich regions with their high organic loads, compared to regions with few lakes or wetlands, such as the Driftless (unglaciated) region of southeastern Minnesota and western Wisconsin.

To account for the role of organic matter in TMDLs, TSS data should be separated into NVSS and SVS components for the purpose of allocating loads between sediment and organic matter. NVSS and SVS will require appropriate mitigation strategies to reduce turbidity and meet water quality standards. While mitigation strategies to reduce sediment (NVSS) loading from the watershed has been discussed in detail by others (Dalzell et al. 2004; Quade 2000), the need to control organic loading (SVS) from lakes and wetlands to rivers has received less attention. Turbidity-impaired streams in the prairie pothole region (and other lake-rich regions) will require management of lake eutrophication as well as watershed management to reduce sediment loading. A sentinel watershed approach is suggested (Magner and Brooks 2008), in which land use and flow regimes within a watershed can be related to water quality impairment.

Lake and wetland management may call for innovative in-lake management to reduce the export of SVS to streams and rivers, since the issue of organic-loading has not been traditionally addressed in watershed management programs. In-lake management strategies may include water level drawdown, vegetation management, reduction of available phosphorous, and/or biomanipulation to reduce export of SVS. Seasonal control of outflow may help reduce downstream nutrient loading on water bodies with outlet control structures, which include many of the lakes and wetlands in the watershed.

Conclusions

Relying on turbidity alone as a measure of water quality impairment fails to capture the relative importance of sediment vs. organic matter to stream degradation. Fine-grained sediment supply from field and channel sources is abundant, contributing to high TSS and turbidity levels in streams. However, SVS constitutes a significant proportion of the TSS load in the Elm Creek watershed. Therefore, organic matter contributions to turbidity are important and must be addressed along with inorganic sediment to meet water quality standards. Although SVS constitutes less of the total TSS load in Elm Creek than sediment, high summer SVS concentrations have important ecological impacts by prolonging the duration of high turbidity and water quality standard exceedance. This creates physiological stress for fish and aquatic invertebrates, possibly leading to increased mortality rates and decreased biological diversity (Henley et al. 2000; Newcombe and Jensen 1996).

Monitoring the water quality of streams only at the stream mouth may disregard important processes happening at finer scales upstream. A watershed approach using dispersed monitoring stations allowed us to identify important processes concerning the spatial and temporal svariability of organic matter and turbidity. If only one river mouth site were monitored, diagnostic information needed to allocate loads would have been overlooked. In the case of Elm Creek, the influences of channel morphology and inline storage by lakes and wetlands would not have been revealed. Turbidity did not increase linearly with watershed area because of increased sediment transport capacity downstream and sediment supply from increased downstream streambank erosion. By focusing on the sediment load at the mouth of the river, TMDLs tend to discount local impacts and processes occurring upstream of the river mouth. This is problematic if it is important to maintain upstream reaches for recreation, fish habitat, or aesthetics.

Acknowledgements We acknowledge the Minnesota Pollution Control Agency, the Legislative Commission of Minnesota Resources, the University of Minnesota Department of Forest Resources, and Three Rivers Resource Conservation and Development, who provided financial support for this project.

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