Technical Memorandum

To: Marvin Hora, Doug Hall and Mark Tomasek, Minnesota Pollution Control Agency

From: Greg Wilson

Subject: Final — Detailed Assessment of Phosphorus Sources to Minnesota Watersheds — Streambank Erosion

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The purpose of this memorandum is to provide a discussion about streambank erosion as a source of phosphorus to Minnesota watersheds. This discussion is based on a review of the available literature, monitoring data and the results of phosphorus loading computations done for each of Minnesota's major watershed basins as part of this study. This memorandum is intended to:

- Provide an overview and introduction to streambank erosion as a source of phosphorus
- Describe the results of the literature search and review of available monitoring data
- Discuss the characteristics of each watershed basin as it pertains to streambank erosion as a source of phosphorus
- Describe the methodology used to complete the phosphorus loading computations and assessments for this study
- Discuss the results of the phosphorus loading computations and assessments
- Discuss the uncertainty of the phosphorus loading computations and assessment
- Provide recommendations for future refinements to phosphorus loading estimates and methods for reducing error terms
- Provide recommendations for lowering phosphorus export from streambank erosion

Overview and Introduction to Streambank Erosion as a Source of Phosphorus

The stability of stream channels is a complex issue that is highly influenced by the dynamics of natural and anthropogenic disturbances. Under natural conditions, the processes of erosion and deposition result in imperceptible morphologic changes to streams over long periods of time. The banks of unstable streams typically undergo erosion, both in the form of particle detachment from hydrodynamic drag and mass failure following erosion of the bank toe (FEMA, 1999). These adjustments to unstable stream channels can involve small time (days) and spatial scales (a reach) or a longer time (hundred or more years) and extent (entire systems), depending on the magnitude and scale of disturbance (Simon, 1994). Simon and Rinaldi (2000) determined that human disturbances to floodplains and upland areas in the loess area of the midwestern U.S., beginning around 1910, have resulted in accelerated channel erosion, degradation and property damages over the next 80 years. In Minnesota, this loess area covers all of the Lower Mississippi, Cedar and Missouri River Basins, along with a portion of the Minnesota River Basin (Simon and Rinaldi, 2000; Luttenegger, 1987). Adjustments occur in unstable streams until the distribution of particle sizes in each section of the stream reaches equilibrium (FISRWG, 2001).

Lane (1955) completed some of the early work of defining how alluvial channels become unstable and adjust to changes in order to re-establish equilibrium and offset the effects of the imposed changes. The general expression, presented by Lane (1995), shows that the product of the bed-material sediment load and median grain size should balance the product of the water discharge and channel slope. If any of these four variables are altered, it indicates that proportional changes in one or more of the other variables must take place to re-establish equilibrium in the stream.

Simon and Hupp (1986) developed a six-stage, semi-quantitative model of channel evolution in disturbed channels, for bed-level trends, that qualitatively recognizes bank slope development (as illustrated in Figure 1). Stages III and IV represent stream degradation, characterized by the lowering of the channel bed and basal erosion, with a subsequent increase in bank heights and slopes, leading to mass-wasting from slab, pop-out and deep-seated rotational failures (Simon and Hupp, 1986). The critical bank height (h_c) is the height of the bank, above which, the stream bank experiences mass wasting or slab failures. The degradation stage (Stage III) ends, and Stage IV begins, when the critical height of the bank material is reached (Simon and Hupp, 1986). This model of channel evolution is somewhat qualitative and requires a clear understanding of when the bank height has shifted to properly identify the stage class. Stage VI represents re-stabilization of the stream to the present watershed land use and altered hydrologic regimes (Simon and Rinaldi, 2000). Stage I represents a natural or "reference" condition for areas with minimal disturbance, while Stage VI represents a reference (or re-stabilized equilibrium) target for areas following significant disturbance (Simon et al., 2001).

The total suspended sediment load in streams includes the wash load (portion of the sediment load comprised of particle sizes finer than those present in the streambed, primarily derived from the

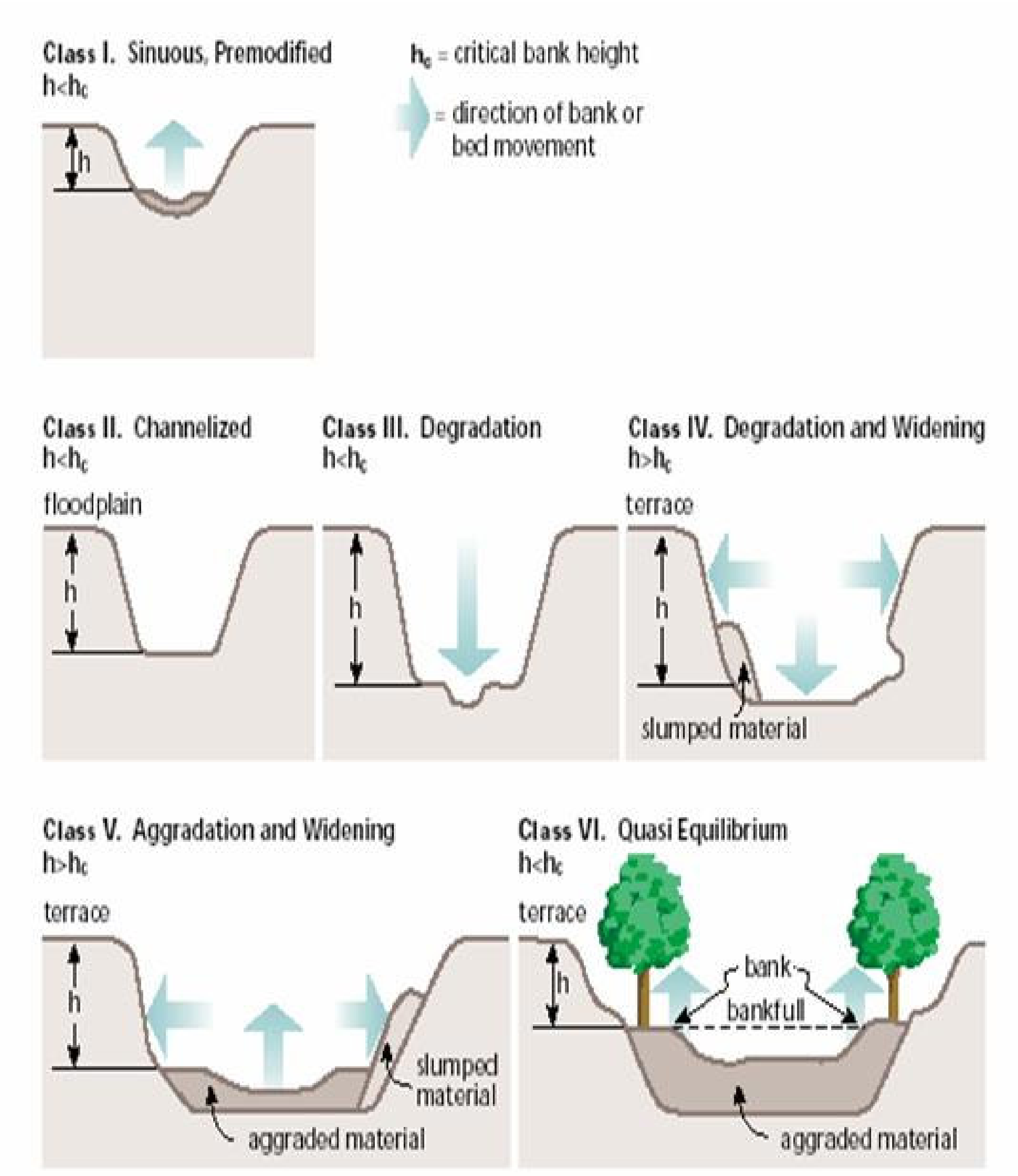


Figure 1
Six Stages of Channel Evolution (from Simon and Hupp, 1986)

watershed) and suspended bed material load or the portion of the total sediment load that is suspended by turbulent fluctuations of flowing water (FISRWG, 2001). The amount of sediment discharged at a given stream cross-section depends on the following (Colby, 1964):

- Depth, width, velocity, energy gradient, temperature, and turbulence of the flowing water
- Size, density, shape, and cohesiveness of particles in the banks and beds at the cross-section and in upstream channels
- Geology, meteorology, topography, soils, subsoils, and vegetal cover of the drainage area

Several researchers have determined that the stream sediment load is proportional to stream discharge (Lane, 1955; Glysson, 1987; Tornes, 1986; Kuhnle and Simon, 2000; Syvitski et al., 2000). Glysson (1987) provided methods for the development and interpretation of sediment-transport curves. Instantaneous flow and sediment transport data are used to develop sediment-transport rating curves based on the following regression relationship:

$$Q_S = a * Q^b \quad \text{or} \quad \log Q_S = \log a + b * \log Q$$

where: Q_S = sediment discharge, in tons per day

Q = stream discharge, in cubic-feet per second

a = constant, or intercept solved by regression

b = constant, slope of linear regression for log-log suspended-sediment rating relationship

Figure 2 provides an example of sediment-transport curves with two different slopes (based on Glysson, 1987). In some cases, two or three linear segments may be needed to adequately represent the sediment discharge at the various intervals of stream discharge (Glysson, 1987; Tornes, 1986; Simon, 1989; Simon et al., 2003). A steep regressed slope (as per Figure 2) to the rating relationship indicates both high sediment availability and high transport capacity. By multiplying the sediment concentration from the resulting rating relation by the discharge and percent occurrence for each discharge class, Simon et al. (2003) determined the discharge class contributing the highest sediment load, which is defined as the effective (or channel forming) discharge. This supported the work of Wolman and Miller (1960). The effective discharge is considered the discharge that shapes the channel, or performs the most geomorphic work, and may be analogous to the bankfull discharge in

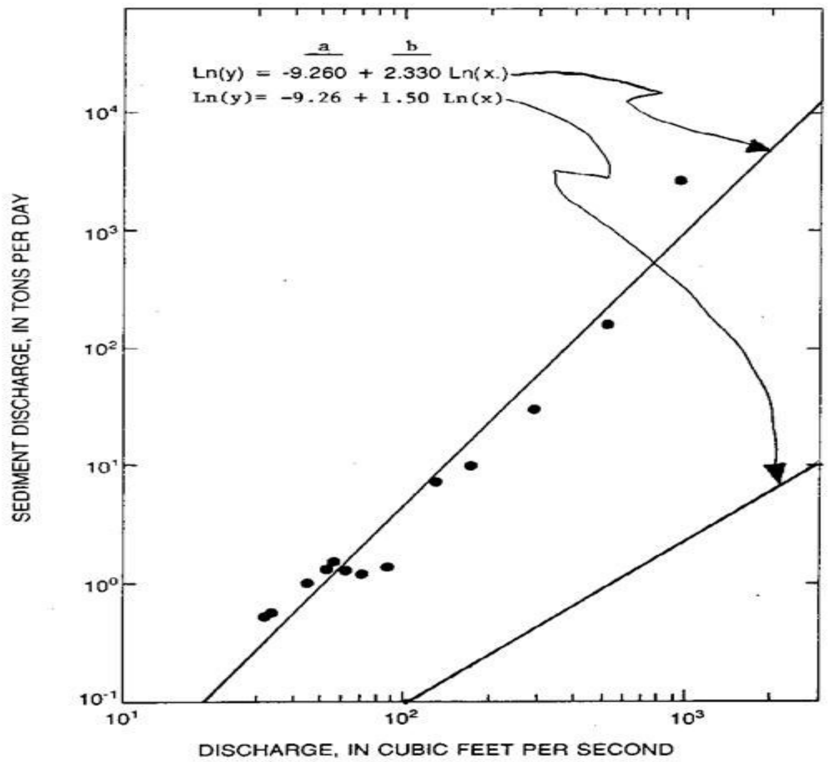


Figure 2 --Sediment-transport curve based on log-linear regression analysis. (Based on Glysson, 1987)

stable streams (Simon et al., 2001). The slope of the suspended-sediment rating relationship (b, from the above expression) varies (Simon, 1989a; Simon et al., 2003), depending upon the stage of channel evolution shown in Figure 1. Figure 3 shows that the highest slope of the suspended-sediment rating relationship corresponds to the stream stages (III and IV) that are undergoing the highest degree of degradation (Simon, 1989a), as previously described above. Migration of knickpoints (or vertical step-changes in bed surface elevation) up tributary streams during Stage III, and bank failures by mass wasting during Stage IV, both serve to significantly increase sediment yield (Simon, 1989a). For re-stabilized streams (Stage VI), Figure 3 shows the slope of the suspended-sediment rating relation is approximately 1.5, as opposed to 1.0 for "natural" streams (Stage I).

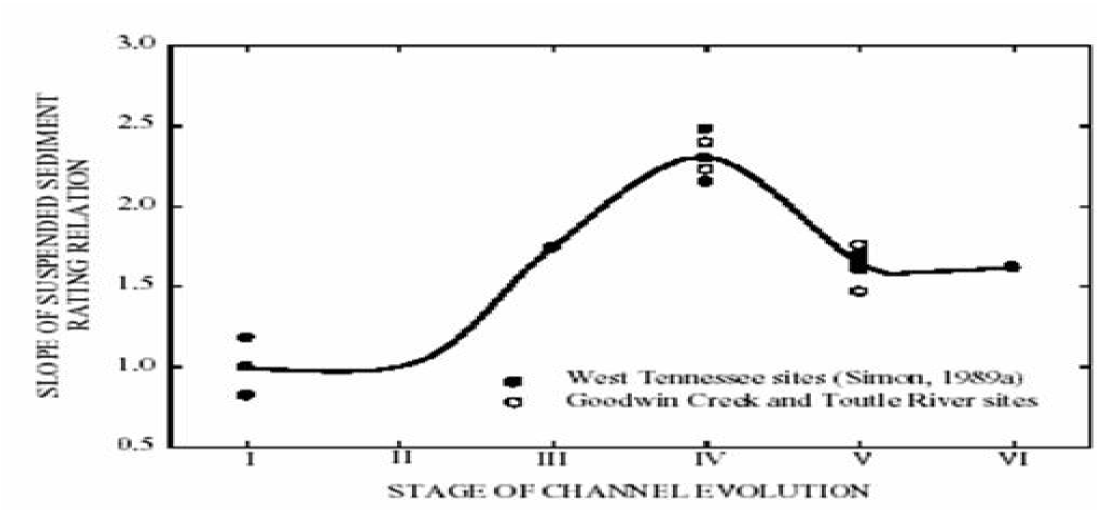


Figure 3
Relationship Between Stage of Channel Evolution and Suspended Sediment Transport (from Simon, 1989a)

The phosphorus attached to eroded streambank material is immediately delivered to the receiving water where it may ultimately become available for biologic uptake, re-deposited downstream, or transported with the flow out of the system. The approach for this assessment will utilize the data and techniques from the literature to estimate total phosphorus loadings to the surface waters within each of the ten major basins in Minnesota.

Results of Literature Search and Review of Available Monitoring Data

The literature search and review of available monitoring data involved a compilation of streambank erosion studies completed within Minnesota, along with an evaluation of the literature pertaining to sediment yield from Minnesota watersheds, to define the contribution of streambank erosion to the total phosphorus budget. Wherever possible, streambank erosion studies completed for Minnesota streams were used to determine the phosphorus load under low, average and high flow conditions for the respective basins. Sediment yield literature specific to the various regions of the state was consulted to develop an approach and assist with the assessment of the remaining unstudied watersheds.

In addition to the literature search, the following sources were consulted for streambank erosion studies or data compiled for Minnesota streams:

- The University of Minnesota Department of Soil, Water and Climate, Department of Forest Resources, Saint Anthony Falls Hydraulics Laboratory, Soil and Landscape Analysis Laboratory, and Water Resources Center
- Natural Resource Conservation Service (NRCS) and County Soil & Water Conservation Districts
- U. S. Geological Survey
- U.S. Forest Service
- U. S. Army Corps of Engineers
- Minnesota Pollution Control Agency
- Minnesota Department of Natural Resources
- Iowa State Water Resources Research Institute
- USDA-ARS National Sedimentation Laboratory

Literature and Monitoring Data Specific to Streambank Erosion in Minnesota Basins

Table 1 presents the results of the literature search and monitoring data specific to streambank erosion within Minnesota watersheds. Five published studies were found that specifically addressed streambank erosion for streams that originate in Minnesota. Wherever possible, average annual streambank sediment erosion, average annual erosion per stream mile, slope of suspended sediment rating relation, sediment erosion as a percentage of observed downstream suspended solids loading, and EPA Level III Ecoregion were expressed for each stream studied. Most of the estimates of streambank sediment erosion were the result of stream channel surveys (including aerial photos) to evaluate streambank retreat (or migration) and eroding bank area to determine the average annual volume of material eroded. The EPA Level III Ecoregion numbers refer to the areas shown in Figure 4. Each ecoregion is discussed in more detail in the following section “Watershed Basin Characteristics”.

Table 1 shows that the average annual erosion rate per stream mile for the Iowa streams is significantly higher than the remaining studies. Also, the slope of the suspended sediment rating relations for the Iowa streams is indicative of degraded streams (Simon, 1989a). However, the erosion rates per stream mile for the Des Moines and Cedar Rivers are based on data collected down to the southern portion of Iowa (Odgaard, 1984). As a result, these erosion rates are probably not as indicative of erosion from the respective streams in Minnesota. The estimated erosion rates for the Rock and Upper Iowa Rivers should be more indicative of the respective streams in Minnesota, as the downstream portions of these watersheds are very close to the Minnesota border. The Cedar, Rock, and Upper Iowa River erosion estimates in Table 1 are a result of modeling (Odgaard, 1984). With the exception of the Upper Iowa River, 90 percent, or more, of the eroded stream channel material remains in suspension as it flows downstream.

Skunk, Deer, and Elim Creeks are smaller streams within the Nemadji River watershed which drains into Wisconsin before discharging to Lake Superior. Channel incision into deposits of lacustrine red clay, combined with forest harvesting and land use conversion, have made this basin susceptible to streambank erosion (Riedel et al., 2002; NRCS & USFS, 1998a). Table 1 shows that approximately 98 percent of the eroded stream channel material is delivered to Lake Superior as suspended sediment. Riedel et al. (2002) noted that channel incision and mass wasting account for more than 95% of the annual sediment load in the Nemadji River basin. The authors also found that stream evolution within this basin was consistent with the model identified by Simon and Hupp (1986).

The Blue Earth River also produces significant streambank erosion, accounting for 31 to 44 percent of the sediment in the flow that discharges to the Minnesota River (Sekely et al., 2002). Sekely et al. (2002) also estimated that streambank slumping accounts for 7 to 10 percent of the annual contributions to total phosphorus load in the Blue Earth River. Bauer (1998) estimated that streambank slumping accounted for 36 to 84 percent of the total suspended solids load in the Blue Earth River. Sekely et al. (2002) also produced a probability plot of annual streambank erosion rates which indicates that erosion rate for the 10% flow rate exceedance probability is 374% higher than the erosion rate for the 50% exceedance probability, while the erosion rate for the 90% exceedance probability is 20% of the erosion rate for the 50% exceedance probability (see Figure 5). Water quality modeling, calibrated for major watersheds within the Minnesota River basin, indicates that bank and bluff erosion should account for 40% of the modeled total sediment load in the Blue Earth River watershed, approximately 35% for the Cottonwood and LeSueur River watersheds, 20 to 25% for the Watonwan and Redwood River watersheds, and 2% of the Yellow Medicine River watershed for the 1986-1992 time period (TetraTech, 2002).

Table 1
Literature and Monitoring Data Specific to Studies of Minnesota Basins

Stream(s)	Average Streambank Sediment Erosion (tons/yr)	Average Erosion (tons/yr/stream mile)	Slope of Suspended Sediment Rating Relation	Sediment Erosion as a Percentage of Observed TSS Loading	EPA Level III Ecoregion	Reference
Des Moines River, Iowa		17,000	2	90	47	Odgaard, 1984
Cedar River, Iowa		5,100	2	100	47	Odgaard, 1984
Rock River, Iowa		8,400	2	93	46	Odgaard, 1984
Upper Iowa River, Iowa		1,180	3	17	52	Odgaard, 1984
Nemadji River	117,000	351	2	98	50	NRCS & USFS, 1998a
Skunk Creek	2,800	190		98	50	NRCS & USFS, 1998a
Deer Creek	4,800	516		98	50	NRCS & USFS, 1998a
Elim Creek	230	256		98	50	NRCS & USFS, 1998a
Blue Earth River	100,292			31 - 44	47	Sekely et al., 2002
Whitewater River, Beaver Creek	142,000	609		80	47/52	NRCS, USFS & MPCA, 1996
Bear Creek	2,200	440			52	NRCS & USFS, 1998b

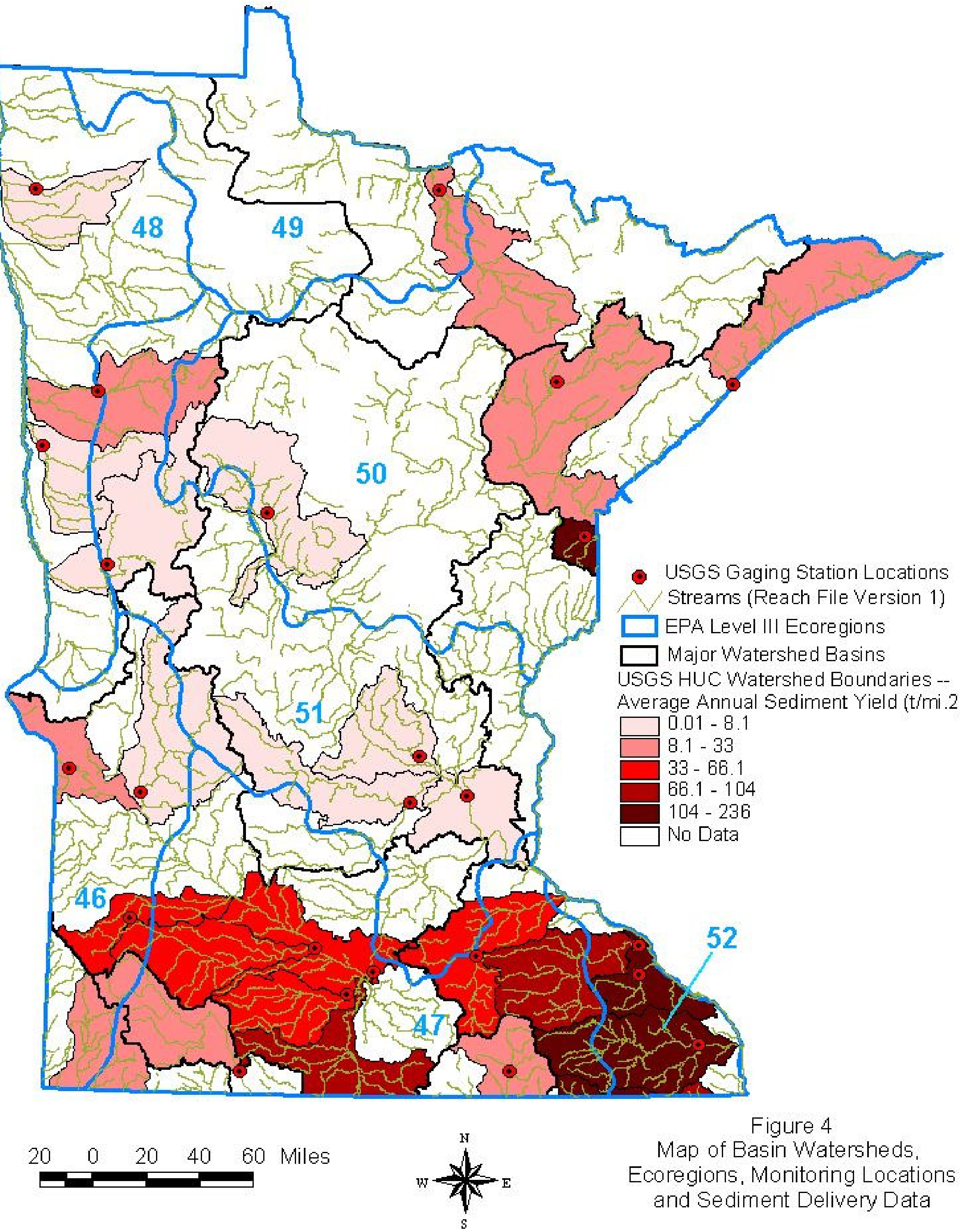


Figure 4
Map of Basin Watersheds,
Ecoregions, Monitoring Locations
and Sediment Delivery Data

Figure 5 (from Sekely et al., 2002)
Probability plot of streambank erosion rates.

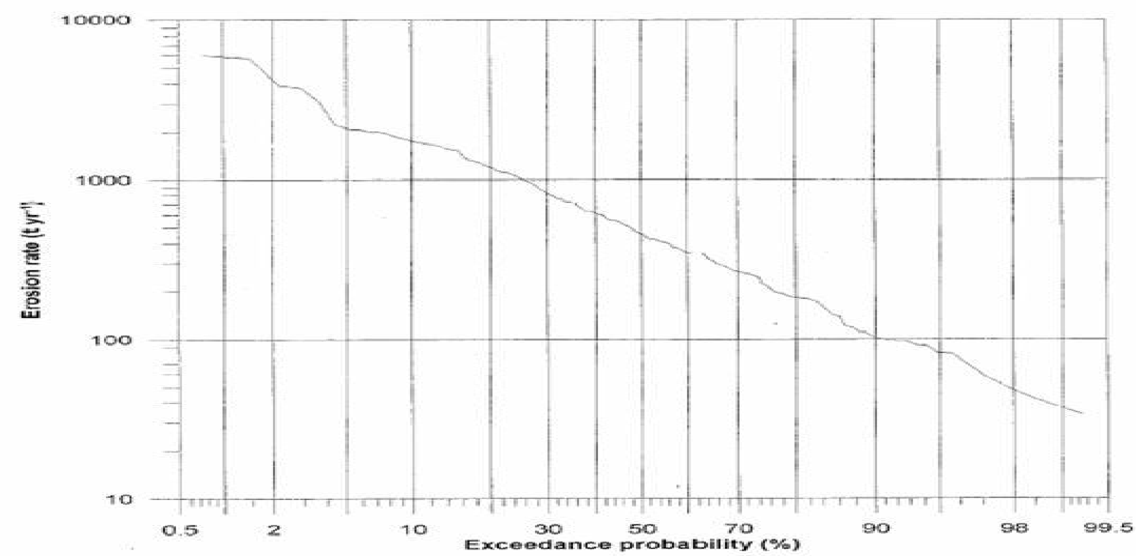


Table 1 shows that the Whitewater River, Beaver and Bear Creek watersheds produce some of the highest rates of streambank erosion in the state. A large part of the Bear Creek watershed is located in Iowa (NRCS & USFS, 1998b). Streambank erosion in the Whitewater River system also accounts for 80 percent of the suspended solids loading that moves downstream (NRCS & USFS, 1998b).

Regional Sediment Yield Literature

In addition to the streambank sediment erosion studies (described above), two regional studies have been completed involving sediment yield data for Minnesota watersheds (Tornes, 1986; Simon et al., 2003). Tornes (1986) analyzed the average annual sediment yield data for 33 USGS gaging stations, in or adjacent to Minnesota, while Simon et al. (2003) determined sediment yield, on the basis of the 1.5-year recurrence interval flow rate, for each of the EPA Level III Ecoregions. Figure 4 shows the locations of the 24 gaging stations utilized for this study, along with the corresponding watersheds, based on the associated USGS Hydrologic Unit Code (HUC). The difference between the 33 USGS gaging locations used by Tornes (1986) and the 24 gaging station sediment yield watersheds utilized for this study is due to the fact that some of the gaging stations were further upstream within monitored watersheds or were not located in Minnesota.

Tornes (1986) determined the average annual sediment yield for each of the gaging stations by developing sediment-transport curves for each of the stations and applying the relationships to flow-duration curves to calculate and sum the sediment loadings at each interval. Most of the sediment-transport curves were best represented by two linear segments. Tornes (1986) solved for and reported the slope and intercept for each segment of the sediment-transport curves for each station.

Tornes (1986) notes that, at extreme high flow, maximum daily sediment yields may nearly double the average annual sediment yield at several stations in southern Minnesota. During these extremely high flows, the normal sediment load for two years may be observed at the sampling station in slightly more than one day.

The recurrence interval of the effective discharge for sediment loading is typically 1.5 years (Wolman and Miller, 1960; Simon et al., 2003). Simon et al. (2003) determined sediment yield quartiles, minimum, and maximum yields, on the basis of the 1.5-year recurrence interval flow rate, for each of the EPA Level III Ecoregions shown in Figure 4. This analysis involved some of the same data and USGS gage locations used by Tornes (1986), but would have included data from other gages, outside of Minnesota, that were within the same ecoregions. This is primarily due to the fact that the USGS has developed a suspended-sediment database containing matching suspended-sediment sample results and instantaneous flow discharge measurements throughout the country (Turcios and Gray, 2001). Most of the Lake Agassiz Plain and all of the Northern Minnesota Wetlands Ecoregions are contained within Minnesota, while the remaining ecoregions generally possess half of their area outside of Minnesota. The difference between the 75^{th} and 25^{th} percent quartiles for sediment yields varied among the ecoregions. There was an order of magnitude difference for Ecoregions 46, 51 and 52; two orders of magnitude difference for Ecoregions 47 and 50; and less than an order of magnitude difference for Ecoregions 48 and 49. Finally, suspended sediment yields from stable streams in eight ecoregions were used by Simon et al. (2003) to determine "background" or "reference" conditions for sediment transport. Within a given ecoregion, the median value for stable sites is approximately one order of magnitude lower than for nonstable sites. None of the seven ecoregions used in this analysis were located in the upper Midwest.

Other literature sources reviewed for this analysis, but not cited, are listed at the end of this memorandum.

Watershed Basin Characteristics

As discussed previously, the large range in observed sediment yields throughout the state (shown in Figure 4) can be attributed to the variability of the geology, topography, land use and climatology of each region. As a result, the following sections discuss the variability associated with the seven EPA Level III ecoregions that cover the state (shown in Figure 4).

Northern Glaciated Plains Ecoregion (No. 46)

Located in the southwest portion of the state, this ecoregion consists of relatively flat agricultural land with loess, clay and sandy soils and low annual precipitation. Tornes (1986) notes that the clay and loess soils, combined with cultivation, result in average suspended solids concentrations above 50 mg/L.

Western Corn Belt Plains Ecoregion (No. 47)

Occupying most of the southern portion of the state, this ecoregion is predominantly agricultural lands with variable topography, clayey and loess soils, and higher precipitation from west to east. Tornes (1986) notes that average suspended solids concentrations in the Minnesota River basin were near 100 mg/L, but it was not uncommon for the maximum concentrations to exceed 2,000 mg/L. The wide fluctuations are presumably due to erosion of the fine-grained soils exposed by heavy cultivation (Tornes, 1986).

Lake Agassiz Plain and Northern Minnesota Wetlands Ecoregions (Nos. 48 and 49)

Located in the north and west portion of the state, these ecoregions consist of relatively flat land, with peat and clayey soils, and low annual precipitation. Tornes (1986) notes that most of the suspended solids concentrations measured in these ecoregions were below 50 mg/L, primarily due to the low precipitation and flat topography.

Northern Lakes and Forests Ecoregion (No. 50)

Located in the northeast portion of the state, this forested ecoregion consists of relatively hilly topography with rock, sand, and peat soils and higher annual precipitation. Most of the average suspended solids concentrations were below 50 mg/L, presumably due to the combination of rocky and sandy soils with forested land use (Tornes, 1986). The Nemadji River basin, with its highly erodible clay soils and high runoff volumes, is a notable exception within this ecoregion.

Northern Central Hardwood Forests Ecoregion (No. 51)

Located in the central portion of the state, this ecoregion with mixed landuse, consists of variable topography, with sand and clay soils, and higher annual precipitation. Tornes (1986) notes that the area drains predominantly sandy soils which is not as easily carried as suspended sediment. This land is not as heavily cultivated as the south portion of the state.

Driftless Area Ecoregion (No. 52)

Located in the southeast portion of the state, this ecoregion with mixed landuse, consists of hilly topography with highly erodible loess and rock or sandy soils, and high annual precipitation. Tornes (1986) notes that tillage of the loessial soils, combined with high runoff from the steep topography, result in average suspended solids concentrations above 50 mg/L, and maximum concentrations exceeding 5,000 mg/L at several monitoring stations.

Approach and Methodology for Phosphorus Loading Computations

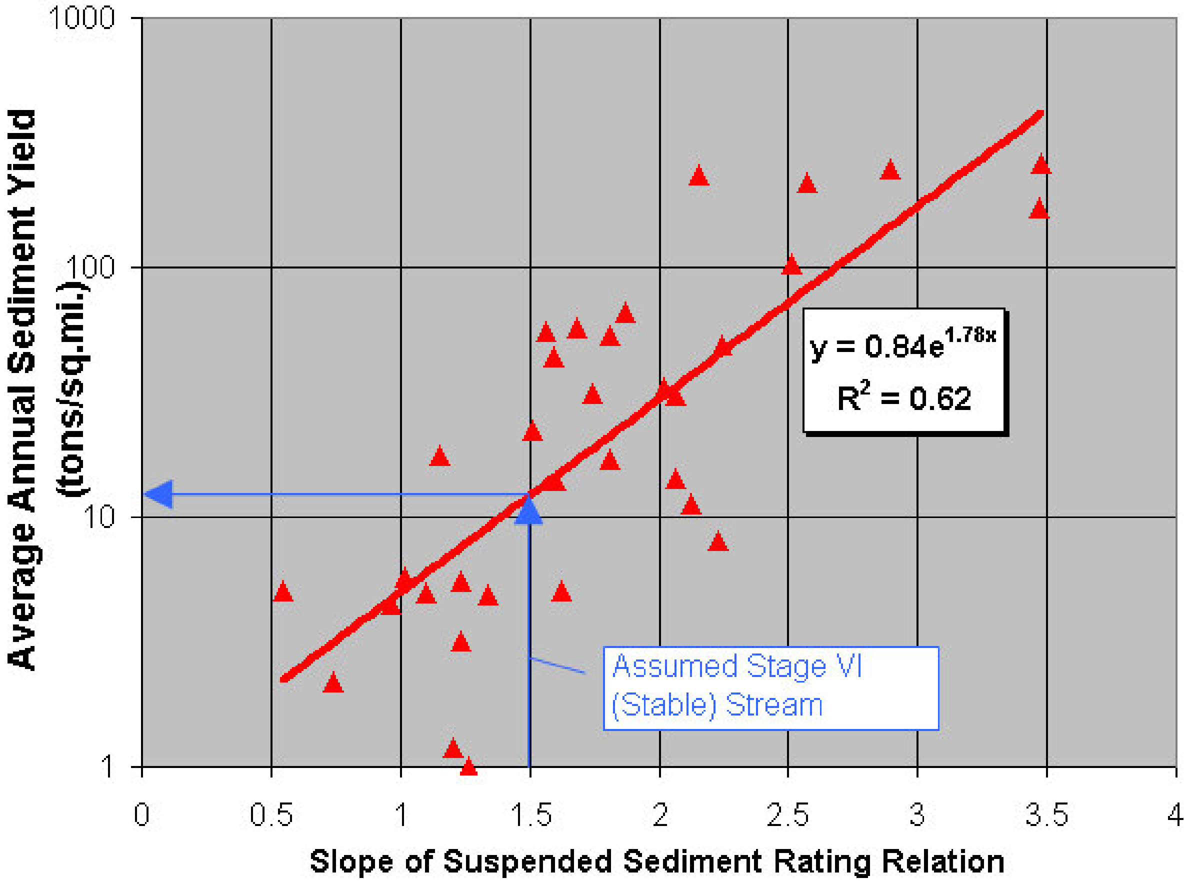
The approach for determining phosphorus loading from streambank erosion generally involves the following steps:

- Convert published streambank erosion estimates from Table 1 into average annual sediment yield
- Using the published sediment-transport curves from Tornes (1986), determine the relationship between average annual sediment yield and the slope of the sediment-transport curve segment containing the 1.5-year recurrence interval flow rate, as a surrogate for the effective discharge
- Apply average annual sediment yields from published streambank erosion estimates and Tornes (1986) to respective watershed units in GIS and determine average annual area-weighted monitored sediment yield for each of the EPA Level III Ecoregions in Minnesota
- Compare average annual monitored sediment yield for each of the EPA Level III Ecoregions in Minnesota to the effective discharge rate sediment yields published by Simon et al. (2003) for the same ecoregions and make adjustments, if necessary
- Assume that we can apply average annual sediment yield for each of the EPA Level III Ecoregions to the unmonitored portions of the state and estimate streambank sediment erosion component based on difference between average annual sediment yield for ecoregion and estimated annual sediment yield for stable (Stage VI) stream, with slope of suspended sediment rating relation equal to 1.5 (per Simon, 1989a)
- Estimate annual streambank sediment erosion for all watersheds under low and high flow conditions, based on the probability plot relationship (taken from Sekely et al., 2002) of annual streambank erosion rates, which indicates that the erosion rate for the 10% exceedance probability is 374% higher than the erosion rate for the 50% exceedance probability, and the erosion rate for the 90% exceedance probability is 20% of the erosion rate for the 50% exceedance probability
- Combine the streambank erosion sediment loadings associated with each watershed with the average soil test phosphorus concentration of 441 ppm (based on 16 surface samples collected from Blue Earth River escarpments, as described in Sekely et al., 2002) to calculate the total

phosphorus load associated with sediment loading estimated from streambank erosion in each basin for each flow condition

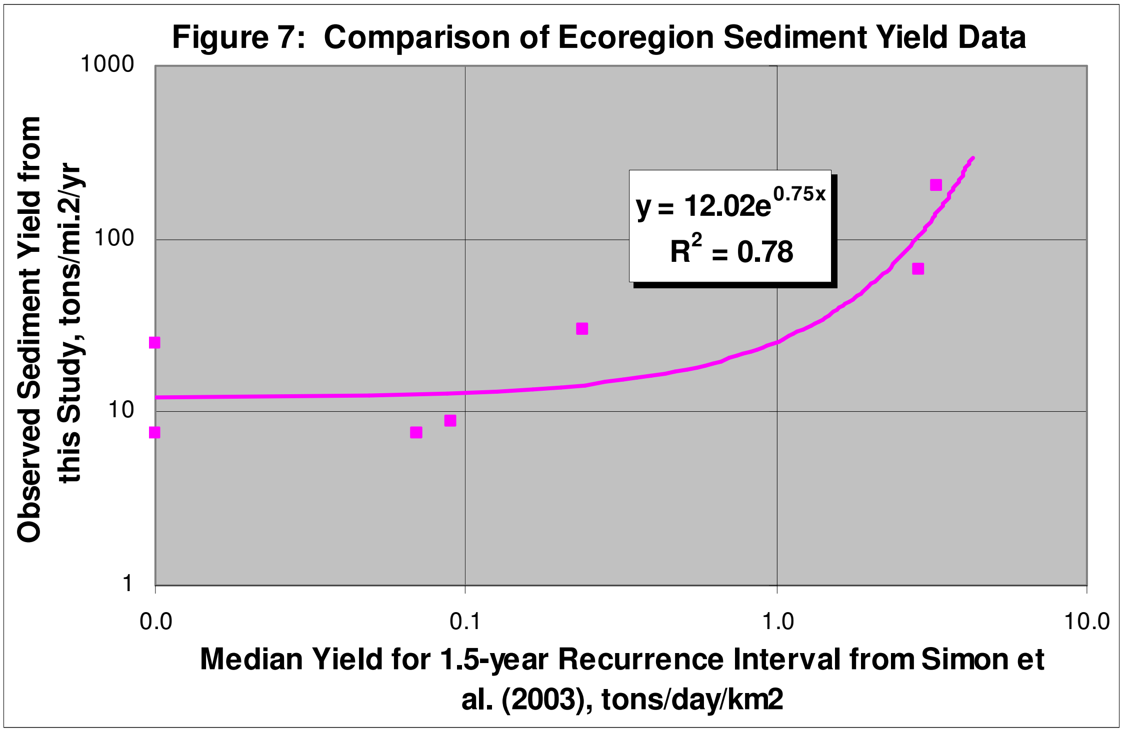
With the exception of the Iowa streams (Odgaard, 1987), the published streambank erosion estimates from Table 1 were converted into average annual sediment yield. Using the published sediment-transport curves from Tornes (1986), the slope of the sediment-transport curve segment containing the 1.5-year recurrence interval flow rate, which is comparable to the effective discharge (Simon et al., 2003), was estimated and tabulated in Excel, along with average annual sediment yield for each watershed. The relationship between average annual sediment yield and the slope of the sediment-transport curve is shown in Figure 6. This graph also shows that the linear regression done on the log-transformed data was significant, with an r^2 of 0.62.

Figure 6: Sediment Yield vs. Slope of Rating Curve



Average annual sediment yields from the published streambank erosion estimates and Tornes (1986) were applied to their respective USGS HUC watershed areas in ArcView (GIS). The coverage of watershed areas representing published average annual sediment yields was intercepted with the coverage representing the EPA Level III Ecoregion areas. By area-weighting the watershed areas with the published sediment yields within each ecoregion, the average annual sediment yield was determined for each of the EPA Level III Ecoregions in Minnesota.

The average annual sediment yield determined for each of the EPA Level III Ecoregions in Minnesota was tabulated in Excel, along with the effective discharge rate sediment yields published by Simon et al. (2003) for each ecoregion. Both datasets were graphed as a means of verifying that the relative differences between the estimated annual sediment yield determined for each ecoregion corresponded well with the larger dataset developed by Simon et al. (2003). The relative difference and ranking of ecoregion sediment yields estimated for each dataset agreed well, with the exception of the Northern Minnesota Wetlands (No. 49 in Figure 4) Ecoregion, which had an average annual sediment yield of 33 tons per square mile. The estimated yield for this ecoregion is more than four times higher than the estimated yield for the nearby Lake Agassiz Plain ecoregion, at 7.59 tons per square mile. Simon et al. (2003) determined that the median sediment yield for the Northern Minnesota Wetlands ecoregion should be comparable to that of the Northern Glaciated Plains (No. 46) or the Lake Agassiz Plain (No. 48) ecoregions. In addition, there was only one data point for this analysis (the Little Fork River sediment yield) and only three data points in the analysis done by Simon et al. (2003) for the Northern Minnesota Wetlands ecoregion. No other published streambank erosion or sediment loading data could be found for this ecoregion. Tornes (1986) noted that the Little Fork River at Littlefork had a higher sediment yield than other sites in the area. As a result, the sediment yield used in this analysis for the Northern Minnesota Wetlands ecoregion was assumed to be the same as the calculated yield for the nearby Lake Agassiz Plain ecoregion. Following this adjustment, the relationship between average annual sediment yield and the effective discharge rate sediment yield for each ecoregion was developed, as shown in Figure 7. This graph also shows that the linear regression done on the log-transformed data was significant, with an r^2 of 0.78.



The average annual sediment yield determined for each of the EPA Level III Ecoregions was applied to the unmonitored watersheds within each ecoregion, based on the area of the respective ecoregions within each watershed area using ArcView. The estimated average annual sediment yield for each of the watersheds was then used to estimate the streambank sediment erosion component based on difference between its average annual sediment yield and the estimated annual sediment yield for a stable (Stage VI) stream, with a slope of the suspended sediment rating relation equal to 1.5 (per Simon, 1989a). The regression equation from Figure 6 shows that the suspended-sediment rating relation slope of 1.5 translates to an average annual sediment yield of 12.13 tons per square mile. As a result, it was assumed for this analysis that if the estimated average annual sediment yield was greater than 12.13 tons per square mile, then the difference in sediment yield was a result of streambank erosion under average flow conditions. With the exception of the observed streambank erosion sediment loadings from Table 1, streambank erosion sediment loadings were estimated for the remaining watersheds in the State, based on the difference between the estimated sediment yield and the average annual sediment yield of 12.13 tons per square mile. It was assumed that there was no streambank erosion occurring in watersheds with average annual sediment yields below 12.13 tons per square mile.

The annual streambank sediment yield for all watersheds under low and high flow conditions was then estimated, based on the probability plot relationship (see Figure 5; from Sekely et al., 2002). The probability plot of annual streambank erosion rates indicated that erosion rate for the 10% exceedance probability is 374% higher than the erosion rate for the 50% exceedance probability, while the erosion rate for the 90% exceedance probability is 20% of the erosion rate for the 50% exceedance probability (Sekely et al., 2002). For this analysis, the proportion of 10% and 90% exceedance probabilities to the 50% exceedance probability was assumed to represent the proportional difference between streambank sediment yield during average flow conditions and the high and low flow conditions, respectively. These relationships were then utilized to estimate the streambank sediment erosion loadings under low and high flow conditions.

Sekely et al. (2002) estimated streambank slumping phosphorus loadings based on an average soil total phosphorus concentration of 441 ppm, resulting from 16 surface samples collected from Blue Earth River escarpments. No other data for total phosphorus content in other escarpments, throughout the state, could be located in the literature. As a result, the total phosphorus load associated with sediment loading estimated from streambank erosion in each basin, for each flow condition, was estimated for this analysis based on an assumed soil total phosphorus concentration of 441 ppm.

Results of Phosphorus Loading Computations and Assessments

Table 2 presents the results of the phosphorus loading computations and assessments for each flow condition, by watershed basin and the entire state. Table 3 compares the phosphorus yield associated with streambank erosion for each flow condition, by watershed basin and the entire state. Table 2 shows that the estimated streambank erosion total phosphorus loadings under low flow conditions are approximately an order of magnitude lower than average flow conditions, while the streambank erosion estimates under high flow conditions are about a half an order of magnitude higher than average flow conditions.

Table 2
Summary of Total Phosphorus Loading Estimates for Streambank Erosion (kg/year)

Basin	Low Flow Conditions	Average Flow Conditions	High Flow Conditions
Cedar River	140	12,200	59,600
Des Moines River	130	7,350	47,900
Lake Superior	4,730	35,100	207,000
Lower Mississippi	45,500	322,000	1,280,000
Minnesota River	9,910	200,000	900,000
Missouri River	1,440	16,100	71,600
Rainy River	0	52,700	318,000
Red River of the North	0	8,840	146,000
St. Croix River	20	15,500	98,000
Upper Mississippi	430	79,900	477,800
Statewide Totals	62,300	750,000	3,606,000

Table 3
Summary of Total Phosphorus Yield Estimates for Streambank Erosion (kg/km^2/year)

Basin	Average Flow Conditions
Cedar River	4.6
Des Moines River	1.9
Lake Superior	2.2
Lower Mississippi	19.7
Minnesota River	5.2
Missouri River	3.5
Rainy River	1.8
Red River of the North	0.2
St. Croix River	1.7
Upper Mississippi	1.5
Statewide Totals	3.4

Table 3 shows that the relative difference between the estimated phosphorus loadings for each basin corresponds well with the variation of observed sediment yields throughout the State (as shown in Figure 4), although sediment yield and streambank erosion loadings would not necessarily be expected to vary the same if other sources of phosphorus and sediment measured in the yield vary significantly. Based on the estimated yield from each basin, the Lower Mississippi River basin loadings are significantly higher than any other basin, followed by the Minnesota and Cedar River basins. This corresponds well with the portion of the State with significant loess deposits, and corresponds with the findings of other researchers (Tornes, 1986; Simon and Rinaldi, 2000; Simon et al., 2003). For each flow condition, the Lower Mississippi River basin streambank erosion estimates from Table 2 account for more than a third of the total loading estimated for the State. Under the low flow condition, the Lower Mississippi River basin streambank erosion estimates accounts for more than 70 percent of the total loading estimated for the State.

Phosphorus Loading Variability and Uncertainty

The variability and uncertainty of the phosphorus loading computations done for this analysis is the result of each of the following sources of error:

- The natural variability associated with the published streambank erosion and sediment yield data
- the uncertainty that is introduced in this analysis as a result of extrapolating the monitored sediment yield data to the unmonitored areas for each ecoregion
- the variation in sediment yield within each ecoregion
- the assumptions that the Simon and Hupp (1986) model of channel evolution applied to Minnesota streams and the slope of the suspended-sediment rating relationship could be used to characterize stable versus unstable streams, based on data published in Simon (1989a)
- the standard error in the regression between the slope of the suspended-sediment rating relationship and the sediment yield
- the assumption that the probability plot of Blue Earth River streambank erosion rates from Sekely et al. (2002) could be utilized to estimate the variation of streambank erosion during low and high flow conditions for the remaining streams in the state
- the variation in the total phosphorus concentration of the sediment eroding from streambank escarpments throughout the state

Tornes (1986) reported coefficients of variation for the sediment-transport curves, used to estimate sediment discharge for each USGS gage site, in tons per day. Based on the sediment-transport curve segments used for this analysis, the median coefficient of variation was 13 percent, with most of the coefficients of variation below 33 percent (Tornes, 1986).

As previously mentioned, the difference between the 75^{th} and 25^{th} percent quartiles for sediment yields varied among the ecoregions (Simon et al., 2003). There was an order of magnitude difference for Ecoregions 46, 51 and 52; two orders of magnitude difference for Ecoregions 47 and 50; and less than an order of magnitude difference for Ecoregions 48 and 49. This variation in sediment yield for each of the ecoregions indicates that the sediment yield can vary significantly, within each ecoregion. As a result, it may not be unexpected for the error of the streambank erosion estimates to approach an order of magnitude when comparing the observed loadings against the estimates for an average annual condition. A semi-quantitative study, completed by the NRCS (1996), estimated streambank sediment erosion in the Thief and Red Lake River basins based on assessments of 30 to 40 percent of the streambanks along each river. This study provided an opportunity to compare the sediment erosion estimates from this study with the estimates obtained by the NRCS (1996). The NRCS (1996) estimated that the long-term average annual streambank sediment erosion should be 31,200 tons per year for both river basins. Using the approach from this study, applied to the Thief and Red Lake River basins, the estimated streambank sediment erosion was 24,700 tons per year, under high flow conditions. This estimate is 20 percent less than the NRCS estimate for both basins, combined.

The Simon and Hupp (1986) model of channel evolution assume that channelization occurs during certain stages of the process. This should be a good assumption for many of the southern and western streams in Minnesota, with the exception of southeastern Minnesota. As discussed previously, the slope of the suspended-sediment rating relationship has been used to characterize stable versus unstable streams, based on data published in Simon (1989a) and shown in Figure 3. This is probably the most significant assumption made for this analysis since this relationship has not been broadly tested across a variety of climate and watershed conditions and may not apply to all of the streams in Minnesota. The slope of the suspended-sediment transport curves will be influenced by: cohesive versus noncohesive parent material, morphology of the new stream alignment, and extent of vegetative restoration during the last stage of evolution.

The relationship developed between the average annual sediment yield and the slope of the sediment-transport curve introduces some uncertainty into this analysis (as shown in Figure 6). The linear regression done on the log-transformed data explained approximately 62 percent of the observed variance. The primary impact of this regression on the overall analysis is that it both impacts the sediment yield (12.13 tons per square mile) assumed for a stable stream (Figure 3, taken from Simon, 1989a), as well as the magnitude of the estimated sediment yield used to estimate the streambank erosion loadings for the unmonitored portions of the State. Based on the 90 percent confidence intervals for the regression, the lower sediment yield estimate used for a stable stream would be 2.88 tons per square mile, while the higher sediment yield estimate is 51.3 tons per square mile. The linear regression done on the log-transformed data was also done separately on the data from the western and eastern portions of the state, but each of the new relationships did not explain significantly more than 62 percent of the observed variance (as it did with all of the data), nor did it change the average annual sediment yield based on the assumed slope of the sediment-transport curve for a stable stream in each of the new regressions.

As discussed previously, the probability plot of Blue Earth River streambank erosion rates from Sekely et al. (2002) was utilized to estimate the variation of streambank erosion during low and high flow conditions for the remaining streams in the state. As a result, the annual streambank erosion rate under high flow conditions was assumed to be 374 percent higher than the rate under average flow conditions. This assumption should be good for streams located within glacial till plains (such as the Blue Earth River), but the proportion may not be high enough for use in estimating erosion from streambanks located within outwash plains.

The total phosphorus load associated with sediment loading estimated from streambank erosion in each basin, for each flow condition, was estimated for this analysis based on an assumed soil total phosphorus concentration of 441 ppm. Sekely et al. (2002) estimated streambank slumping phosphorus loadings based on an average soil total phosphorus concentration of 441 ppm, resulting from 16 surface samples collected from Blue Earth River escarpments. No other data for total phosphorus content in other escarpments or native soils, throughout the state, could be located in the literature. Most of the total phosphorus concentrations of the sixteen samples collected for the Blue Earth River study varied within 50 to 75 ppm of the median concentration (Thoma, 2003). As a result, variation in the estimated phosphorus load associated with streambank erosion from the Blue Earth River could vary by 10 to 20%, and would be expected to result in significantly more variation in the estimates made for the rest of the state.

Recommendations for Future Refinements

Figure 4 shows that many areas of the State have not been adequately sampled for definition of sediment-transport characteristics. Only a few or no sediment samples (with corresponding discharges) have been collected from most of the streams in northern and central Minnesota, with almost no samples present for the Northern Minnesota Wetlands Ecoregion (Tornes, 1986; Simon et al., 2003). Some rivers in west-central Minnesota, parts of the Red River of the North, the Rock

River, and the Pomme de Terre River drain areas underlain by clayey or loess soils may have sediment yields that are similar to those in the southeast part of the State (Tornes, 1986). In addition, no sediment-transport curves or erosion assessments have been published for streams in the St. Croix River basin. The current lack of sediment-transport data and erosion assessments throughout the state make it difficult to adequately ascertain the impacts of streambank erosion, especially as it pertains to impaired biota. Collecting more data for streambank erosion assessments can be used to further refine this analysis, reduce the current level of uncertainty, and improve the understanding of the linkage between sediment and phosphorus loadings with biological impairments.

The MPCA should install continuous flow monitoring equipment, and begin developing stage-discharge-sediment transport curves, as a means of assessing erosion within some of the existing State milestone monitoring watersheds, that are not currently being monitored by the USGS. Additional streambank erosion assessments, similar to those discussed in Table 1, should be done in conjunction with stream water quality and biological monitoring, and channel evolution stage determinations, to develop and refine empirical models and provide a better understanding of the impacts of streambank erosion throughout the State. One such assessment, recently completed by the MPCA, was done to evaluate the relationship between suspended sediment transport, stream classification and fish index of biological integrity (IBI) scores (Magner et al., 2003).

All of these assessments should also be done to evaluate streambank erosion during low and high flow conditions and address the variability and uncertainty associated with the estimates presented here. Also, more total phosphorus data should be collected from eroding streambanks across the state to further evaluate how much of the phosphorus loading is entering the streams from upland sources versus fluvial processes.

Recommendations for Lowering Phosphorus Export

There is the potential for substantial water quality benefits associated with lowering phosphorus export from streambank erosion, including reduced eutrophication and sedimentation and improved biological habitat within reservoirs, lakes and wetlands, along with the river systems themselves. Land use planning should consider the potential adverse impacts associated with the increased runoff volumes and sediment erosion. Stream road crossings should be designed with consideration to the potential hydrodynamic changes to the system. Exclusion of pastured animals and preservation of riparian vegetation will also assist with maintaining streambank stability.

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