Nutrient Dynamics and Budgetary Analysis of the Lower Minnesota River: 2003-2006

Confluence of the Minnesota and Mississippi Rivers
Source: *Minnesota-Wisconsin Boundary Area Commission*

Final Report 2007

8 February, 2008

William F. James
ERDC Eau Galle Aquatic Ecology Laboratory
W. 500 Eau Galle Dam Road
Spring Valley, Wisconsin 54767

TABLE OF CONTENTS

BACKGROUND

The lower Minnesota River, extending from river mile (RM) 39.4 near Jordan, MN, to its confluence with the Mississippi River in Minneapolis, MN, is a critical habitat for migratory waterfowl and other wildlife and represents an important resource for recreation, commercial transportation, and historical features of the State of Minnesota. Concerns over high algal biomass and dissolved oxygen depletion during low flow periods, deposition of nutrient-rich sediment, and excessive loads of nitrogen (as nitrate and ammonium) and phosphorus to the system have led to an assessment of water quality and the development of a eutrophication model for use in establishing goals for load reduction of point and nonpoint sources and evaluation of management scenarios to improve current water quality conditions in the system (http://www.metrocouncil.org/environment/Water/LMRM/index.htm and http://www.metrocouncil.org/environment/Water/LMRM/lmrmReports/Minnesota-River-Model-Project-Description.pdf). The objectives of this portion of the project were to 1) partition inflow (i.e., at RM 39.4) and outflow (i.e., at RM 3.5) nutrient loads into phosphorus (P) fractions that are biologically labile (either directly available for algal uptake or subject to recycling pathways) and refractory (unavailable for uptake and subject to burial) and 2) examine the role of equilibrium and diffusive fluxes of P from both suspended and deposited sediment in order to better assess the magnitude of P availability and its recycling potential to both the lower Minnesota River and downstream reaches of the Upper Mississippi River.

METHODS

Biologically labile and refractory phosphorus pools of suspended sediment

Sampling stations were established on the lower Minnesota River at RM 39.4 (near Jordan, MN) and RM 3.5 (upstream of the confluence with the Mississippi River near Fort Snelling) for determination of concentrations and loading of biologically labile and refractory particulate P (PP) fractions (Fig. 1). Twenty liters of river water were collected at each station via surface grab sampling during periods of high flow (i.e., > 200 $m^3 s^{-1}$) and suspended sediment concentration in 2005 and 2006. In the laboratory, a portion of the sample was filtered onto 0.45 μm membrane filters and dried at 105 ^{o}C to a constant weight for the determination of total suspended solids (TSS; American Public Health Association 1998). Another portion was filtered through a 0.45 μm filter for filtered orthophosphate or soluble reactive P (SRP) determination. Suspended sediment in the remainder of the sample was concentrated by settling and centrifugation at 500 g and preserved with 0.5 mL of 0.1% chloroform and refrigeration at 4 ^{o}C prior to analysis of biologically labile and refractory forms of PP. Analyses were conducted within 2 weeks of sample collection. Sequential fractionation of PP (Table 1) was conducted according to Hjieltjes and Lijklema (1980), Psenner and Puckso (1988), and Nürnberg (1988) for the determination of ammonium-chloride-extractable PP (i.e., loosely-bound PP), bicarbonate dithionite-extractable PP (i.e., iron-bound PP), sodium hydroxide-extractable PP (i.e., aluminum-bound PP), and hydrochloric acid-extractable PP (i.e., calcium-bound PP). A subsample of the sodium hydroxide extract was digested with potassium persulfate to determine nonreactive sodium hydroxide-extractable PP (Psenner and Puckso 1988). Labile organic PP was calculated as the difference between reactive and nonreactive sodium hydroxide-extractable PP. PP remaining after the hydrochloric acid extraction was digested with potassium persulfate and 5 N sulfuric acid for determination of refractory organic PP. Each extraction was adjusted to pH 7 and analyzed for SRP using the ascorbic acid method (APHA 1998).

Phosphorus equilibrium characteristics of suspended sediment

Aliquots (~500 mg L^{-1} dry weight equivalent) of concentrated sediment collected during periods of elevated flow and TSS (primarily May-June, 2005) were subjected to a series of SRP (KH_2PO_4 as SRP) standards ranging from 0 to 1.0 mg L^{-1} for examination of P adsorption and desorption over a twenty-four hour period. Untreated tap water (groundwater) from the laboratory was used as the water medium because it was phosphate-free. Potassium chloride, sodium chloride, and magnesium sulfate were added to the tap water to adjust its ionic composition to more closely approximate water from the Minnesota River (Fang and Brezonik 2002; Table 2). The assay systems, consisting of TSS, amended tap water, and known concentrations of SRP contained in sealed 50 mL centrifuge tubes, were shaken uniformly for 24 hours in a darkened environment then sampled and analyzed for SRP using the ascorbic acid method (APHA 1998). The assay systems were maintained under oxic conditions at a pH of ~ 8.0 to 8.3 and a temperature of ~ 20 ^{o}C during shaking and equilibration process.

The change in SRP mass (i.e., initial SRP - final SRP; mg) over the twenty-four hour period was divided by the dry mass equivalent of TSS used in the experiment to determine the quantity of P desorbed or adsorbed (S; mg P kg^{-1} sediment). These data were plotted as a function of the equilibrium SRP concentration after 24 hours of incubation to determine the linear adsorption coefficient (k_d; L kg^{-1}) and the equilibrium P concentration (EPC; mg P L^{-1}; the point where net sorption is zero; Froelich 1988). The k_d and EPC were calculated via regression analysis from linear relationships between final SRP concentrations and the quantity of P sorbed at low equilibrium concentrations (Pant and Reddy 2001). The EPC was calculated as S_o divided by K_d. Data were also fitted to a two-surface layer Langmuir regression models using a spreadsheet developed by Bolster and Hornberger (2007) to estimate the sorption maximum (S_{max}) of TSS. The general linearized model is

$$\frac{C}{S} = \left[\frac{1}{S_{\max_1} K_1} + \frac{C}{S_{\max_1}}\right] + \left[\frac{1}{S_{\max_2} K_2} + \frac{C}{S_{\max_2}}\right] \qquad 1),$$

where, C equals the equilibrium SRP concentration and K represents the binding strength coefficient (L kg^{-1}). Because P desorption occurred at low equilibrium SRP, the concentration of the exchangeable P pool (mg kg^{-1}) had to be taken into account in S_{max} calculation. The NH_4Cl-extractable loosely-bound and the bicarbonate-dithonite-extractable iron-bound P fractions were chosen as an estimate of this pool. Various extraction and extrapolation techniques have been used to quantify exchangeable P; however, there is uncertainty regarding its estimation and caution needs to be used in interpretation of S_{max} (Aminot and Andrieux 1996; Bolster and Hornberger 2007). The degree of P saturation (DSP) was calculated as extractable loosely-bound and iron-bound P divided by S_{max}.

For kinetic studies, sediment (~500 mg L^{-1} dry weight equivalent) was subjected to water that contained either zero P or 0.750 mg P L^{-1}. Assay systems were uniformly shaken over a period of five days and subsamples for SRP analysis were collected at various time intervals. SRP concentration was plotted as a function of time to examine uptake or release of P due to adsorption or desorption.

Sediment characteristics and diffusive fluxes

Sampling stations were established between RM 0 and RM 26 for collection of sediment cores in late September, 2005, and early October, 2006. Difficulties in navigation prevented sediment core sampling above RM 26. Station selection was based on a survey conducted by the U.S. Geological Survey (USGS) that identified sediment textural (sand-gravel, sand-silt, silt-clay) features between RM 0 and RM 26 using hydroacoustic and ground-truthing techniques. This stretch of the river was divided into upper (i.e., RM 12 to 26) and lower (i.e., RM 0 to 12) sections for sediment sampling purposes. Sampling within each section was further stratified to capture sand-silt sediment in 60% of the cores, silt sediment in 30% of the cores, and sand sediment in 10% of the cores based on general compositional features measured a priori by the USGS. Thus, sediment sampling stations were established randomly within these stratification schemes. Sediment textural distribution maps constructed by the MCES were used to approximately locate an area likely to contain sand-silt, silt, or sand sediment at the randomly assigned river mile.

During each year, two sediment cores (i.e., one for oxic and one for anoxic nutrient release) were collected at each of 12 stations (6 stations in the upper section and 6 stations in the lower section) for determination of rates of ammonium-N and P release from sediments. One additional core was collected at these same stations and at 12 additional stations for determination of sediment compositional characteristics. All sediment cores were collected intact using a Wildco sediment coring device, and preserved on ice for transport. In the laboratory, the cores used for determination of rates of N and P release were drained of overlying water and the upper 10 cm of sediment were extruded to a smaller acrylic core liner (6.5-cm dia and 20-cm ht) using a core remover tool. Water collected from the Minnesota River was filtered through a glass fiber filter (Gelman A-E), with 300 mL then siphoned onto the sediment contained in the small acrylic core liner without causing sediment resuspension. Sediment incubation systems consisted of the upper 10 cm of sediment and filtered overlying water contained in acrylic core liners that were sealed with rubber stoppers. The sediment incubation systems were placed in a darkened environmental chamber and incubated at a constant temperature (20 ^{o}C) for a two week period. The oxidation-reduction environment in each system was controlled by purging with either air (oxic) or nitrogen (anoxic) through an air stone placed just above the sediment surface. Bubbling action ensured complete mixing of the water column but did not disrupt the sediment.

Water samples were collected from the center of each sediment incubation system using an acid-washed syringe and immediately filtered through a 0.45 μm membrane syringe filter. The water volume removed from each system during sampling was replaced by addition of filtered river water preadjusted to the proper oxidation-reduction condition. Sampling was conducted at daily intervals for eight days, then every other day for an additional eight day period. Ammonium-N was measured using the salicylate method and automated analytical techniques (Lachat QuikChem; Hach Environmental;

Loveland, CO). Rates of nutrient release from the sediment (mg m^{-2} d^{-1}) were calculated as the linear change in concentration in the overlying water divided by time and the area of the incubation core liner.

For determination of sediment compositional characteristics, the upper 10 cm of sediment were extruded and homogenized for analysis. Organic matter content was estimated as loss-on-ignition (LOI) by combusting sediment at 500 ^{o}C for twenty-four hours. The percentage of sand (> 63 µ), silt (between 2 µ and 63 µ) and clay (< 2 µ) was determined using a combination of sieving and pipette techniques (Plumb 1981). Total sediment P was analyzed colorimetrically following block digestion with sulfuric acid, potassium sulfate, and red mercuric oxide (Plumb 1981). Sequential fractionation of biologically labile and refractory P was conducted as described above. Exchangeable ammonium-N was determined via extraction with 0.5 N NaCl (Plumb 1981).

Nutrient loading rates and budgetary analysis

Flow and sampling stations for determination of the various point and nonpoint loads entering the lower Minnesota River are shown in Fig. 1 and Table 3. Flow measurements and chemical analyses were conducted by the USGS and the MCES between October, 2003, and September, 2006. The MCES operates long-term river, stream, and effluent monitoring programs which were enhanced during the water years 2004-2006 to support the lower Minnesota River Model: Monitoring Program (http://www.metrocouncil.org/environment/Water/LMRM/lmrmreports/Minnesota-River-Model-Monitoring-Program.pdf). Details on analytical variables and methodology are described in that report. Annual loadings for various constituents (TSS, phaeophytin-corrected chlorophyll, total Kjeldahl N, nitrate nitrite-N, ammonium-N, total P, and SRP) were estimated using the program FLUX (Walker 1996). Net annual constituent retention or export was calculated as the sum of measured inputs to the lower Minnesota River below RM 39.4 minus the output at RM 3.5. A positive annual difference represented net constituent retention while a negative annual difference represented net constituent export to downstream locations.

Phosphorus inputs and outputs were also examined during a period of extended low flow that occurred between 15 July and 30 September, 2006. During this period, additional samples were collected by MCES staff along the longitudinal axis of the lower Minnesota River at miles 25.1, 16.8, 14.3, 10.8, 8.5, 7.2, 5.0, and 0.5 at weekly to biweekly intervals. Because flows were not directly measured at these stations, they were estimated as the sum of measured discharges into the lower Minnesota River upstream of each sampling station. The program FLUX was used to estimate P loading.

RESULTS AND DISCUSSION

Phosphorus Dynamics

Concentrations of TSS and PP were lowest at RM 39.4 and RM 3.5 during extended low-flow periods in winter and late summer and usually increased in conjunction with elevated flows, with peaks occurring on the rising side of the hydrograph (Fig. 2a-c). An exception occurred during a period of snowmelt and high flow in March through late April, 2006, when concentrations were low despite very high flow. Chlorophyll concentrations were lowest during winter months of December through March (Fig. 2d). For other months, it was highest during periods of lower flow and declined as a result of higher flow, flushing, and cellular washout. Chlorophyll and organic matter (expressed as LOI) increased logarithmically as flow declined below ~ 200 $m^3 s^{-1}$, indicating that phytoplankton biomass accounted for majority of TSS and PP under low flow conditions (Fig. 3a and b). As flow increased, TSS composition was dominated by inorganic components of allochthonous origin and phytoplankton biomass indicators declined to an asymptotic minimum (chlorophyll ~ 0.3 mg g^{-1} and LOI ~ 97 mg g^{-1}). PP exhibited a similar logarithmic pattern (Fig. 3c). It was highest under low flow conditions in conjunction with TSS composed of phytoplankton biomass and decreased logarithmically with increasing flow, reaching a minimum of ~ 1.1 mg g^{-1} as flow increased above 200 $m^3 s^{-1}$.

TSS collected during periods of higher flow was composed of equal percentages of extractable biologically labile and refractory PP forms (Table 4). Loosely-bound and iron-bound PP, assumed to approximate the exchangeable PP pool, collectively represented 85% and 43% of the biologically labile and total PP, respectively. Calcium-bound (53%) and refractory organic PP (31%) accounted for most of the refractory PP. Phosphorus desorption from TSS occurred at very low aqueous SRP while adsorption occurred above an EPC of 0.117 mg L^{-1} (Fig. 4). In addition, the EPC was equivalent to the mean ambient SRP in the river determined at the time of TSS collection (Table 2), suggesting equilibrium control of SRP by TSS loads during higher flow periods. The k_d and S_{max} were 332 L kg^{-1} and 608 mg kg^{-1}, respectively. The DSP was high at 69%. Kinetic flux exhibited a biphasic pattern (Fig. 5). At low ambient SRP, phosphorus desorption was linear and rapid during the first 300 mins due to deviation below the EPC. The rate of P desorption declined and was constant between 300 and 7200 mins. Under conditions of high ambient SRP, adsorption was very rapid between zero and 60 mins and lower between 60 and 720 mins.

SRP exhibited a complex seasonal pattern that was related to flow and residence time, relative loading contribution by point and nonpoint sources, equilibrium processes, and phytoplankton dynamics. SRP declined from ~ 0.1 to < 0.01 mg L^{-1} on the falling limb of hydrograph peaks in conjunction with increases in chlorophyll, suggesting phytoplankton uptake of P (Fig. 2e). Examples of these inverse patterns occurred in May, June, and August, 2004, May, June, and October, 2005, and April and May, 2006. The molar TN:TP and DIN:DIP (i.e., dissolved inorganic N and P) ratios were > 50 under these flow conditions, suggesting potential P limitation. Subsequent increases in flow resulted in washout of the phytoplankton community and increases in TSS. SRP concentrations were similar at both stations and near the EPC under these conditions (Fig. 2e). For instance, SRP concentrations averaged 0.115 mg L^{-1} during flow peaks and high TSS loading that occurred in early June, mid-July, mid-August, and late September, 2004. Similar SRP patterns occurred during high flow periods in March, early April, early May, and June, 2005, and April and early June, 2006.

During periods of extended low flow in late summer, 2006, SRP increased to peak concentrations at RM 3.5 versus concentrations near zero at RM 39.4 (Fig. 2e). These patterns reflected inputs of SRP by point sources located below RM 39.4 and changes in the phytoplankton community during transit to the mouth of the lower Minnesota River (see below). During low flow winter months, SRP was 0.20 to > 0.30 mg L^{-1} with similar concentrations at both stations (Fig. 2e). These patterns suggested that SRP inputs originating upstream of RM 39.4 were contributing to the P budget of the river with little transformation to particulate forms due to very low chlorophyll.

Variations between TSS and PP loading versus SRP reflected the outcome of hydrologic, biotic, and abiotic factors regulating P in the lower Minnesota River. During periods of low flow and high phytoplankton biomass, point sources from within the system increasingly dominated P loading, primarily as SRP (Fig. 6a). Under these loading circumstances, SRP tended to decline toward zero (Fig. 7) in conjunction with high chlorophyll (Fig. 6b) due to phytoplankton uptake. As flow and loading increased, TSS and PP were higher in concentration and derived from allochthonous point and nonpoint sources. SRP approached the EPC under these conditions indicating regulation by equilibrium processes. In addition, results suggested that minor P transformation occurred under higher flow and loading while transformation of SRP to PP via phytoplankton uptake usually occurred under lower flow conditions.

Differences in LOI mass concentrations versus flow (Fig. 3) were used to estimate loading of allochthonous material, exchangeable PP (i.e., loosely-bound and iron-bound PP), and equilibrium P flux (i.e., adsorption or desorption) when SRP deviated from the EPC during the summer periods of 2004-2006. It was assumed that an LOI mass concentration endpoint of 400 mg g^{-1} represented phytoplankton biomass while an endpoint of 100 mg g^{-1} reflected allochthonous loading originating upstream of RM 39.4. Mass concentrations lying between these endpoints were assumed to be a mixture of phytoplankton and allochthonous material. These fractions were estimated for each sampling date as;

$$C_{mass} = (X \cdot C_{phyto}) + ((1-X) \cdot C_{alloch}) \qquad 2),$$

where, C_{mass} is the observed mass concentration of LOI, C_{phyto} and C_{alloch} are the mass concentration endpoints for phytoplankton or allochthonous material, respectively, and X is the relative proportion. Daily TSS and PP loadings were partitioned into phytoplankton versus allochthonous loads based on these relative proportions. The exchangeable PP load was estimated as ~ 43% of the allochthonous PP load (e.g., Table 4). Equilibrium PP flux (kg d^{-1}) between the exchangeable PP pool and water was calculated as;

$$[(EPC\text{- } Ambient\ SRP) \cdot k_d] \cdot Allochthonous\ TSS\ Load \qquad 3),$$

where, *EPC* is the equilibrium phosphate concentration (Table 4), *Ambient SRP* is the observed concentration in the river, and k_d is the linear adsorption coefficient. The exchangeable PP load increased in conjunction with elevated flow periods and peaks in total P and SRP loading (Fig. 8). Equilibrium P flux followed a pattern similar to that of chlorophyll, reaching maxima on the falling limb of the hydrograph during spring periods of high flow and exchangeable PP loading (Fig. 8). This pattern also coincided with declines in SRP concentration below the EPC due to phytoplankton uptake. Although net P desorption flux (i.e., positive flux) often exceeded 100 kg d^{-1} during these periods, it was low compared to total P and SRP loading, representing only ~ 1-2 % of these loads. During periods of lower flow in late summer, the exchangeable PP load and equilibrium P flux declined to near zero as most of the PP was phytoplankton biomass. Overall, there was an inverse relationship between chlorophyll, the exchangeable PP load, and P desorption flux due to influences of flow on the residence time of phytoplankton (Fig. 9).

Sediment characteristics and diffusive fluxes

Surface sediments collected in the lower Minnesota River during 2005 and 2006 reflected findings from the USGS hydroacoustic survey as the particle size distribution was dominated primarily by sand and silt; clay accounted for less than 17% of the particle size composition (Fig. 10). The sand content ranged between 4 and 98% and silt content ranged between 2 and 75% over all stations. Moisture content of the sediment was positively related to the silt and clay content while the inverse pattern occurred for sand content (Fig. 10). Sediment density versus particle size distribution relationships were opposite to that of moisture content. Thus, both moisture content and sediment density were good predictors of the particle size distribution of the sediments.

Total P of the sediment varied as a function of sediment physical characteristics. The concentration was positively related to sediment moisture content, silt content, and clay content, and negatively related to sediment density and sand content (Fig. 11). Positive linear relationships and significant correlations also existed between total P and loosely-bound, iron-bound, and the refractory organic P fraction (Table 5). Overall, refractory P (i.e., sum of aluminum-bound, calcium-bound, and residual organic P) constituted the majority of sediment total P and it was dominated by the calcium-bound and refractory organic P fractions (Fig. 12). The iron-bound P fraction accounted for most of the biologically labile sediment P (i.e., sum of loosely-bound, iron-bound, and labile organic P).

Rates of P release from sediment were high under both oxic and anoxic conditions and there was a strong linear relationship between the two variables (Fig. 13). Rates were 3.7 to 4.8 times greater under anoxic conditions versus oxic conditions. Under oxic conditions, rates of P release from sediment ranged between 0.7 and 6.5 mg m^{-2} d^{-1}. The greatest rate under anoxic conditions of 31 mg m^{-2} d^{-1} was measured from sediment collected at RM 7.3 in 2006. Rates under both oxic and anoxic conditions were positively related to iron-bound P during both years, suggesting that Fe-P interactions were important in driving diffusive fluxes of P out of the sediment (Fig. 13). Significant correlations were observed between rates of P release under oxic and anoxic conditions and sediment moisture content, density, sand, silt, and clay content for sediments collected in 2005 (Table 6). However, correlations between rates of P release and sediment physical characteristics were weaker to nonexistent for sediment samples collected in 2006. For instance, statistically significant correlations were not observed between rates of P release and silt content in 2006. However, significant correlations were observed between rates of P release under both oxic and anoxic conditions and sediment moisture content and density. These trends suggested overall linkages between diffusive flux and the occurrence of fine-grained sediment.

To estimate internal P loading via P release from sediment during the summer, hydroacoustic analysis of sediment texture throughout the lower Minnesota River was used in conjunction with regression relationships developed between independently determined sand and silt content, iron-bound P, and rates of P release from sediment (Fig. 14). Means from hydroacoustic data for percent sand-gravel, silt-sand, and silt content of sediment between RM 0.0 and RM 26.5 are shown in Table 7. For budgetary purposes, it was assumed that dissolved oxygen concentrations in the bottom water were above 1 mg L^{-1} and that P release from sediment was regulated by oxic conditions. The mean rate of P release over the lower 26 mile stretch of the Minnesota River was ~4.0 mg m^{-2} d^{-1} under oxic conditions and 21.3 mg m^{-2} d^{-1} under anoxic conditions (Table 7). Extrapolation of the oxic release rate over the entire 39 mile stretch between Jordan and the confluence with the Mississippi River resulted in an estimated sediment P release rate of 23 kg d^{-1} (i.e., area-weighted mean 4.0 mg m^{-2} d^{-1} x 5.77 km^2, approximate surface area between RM 0 and RM 39.4). This rate represented < 1% of the total P load at RM 3.5 for flows > 200 m^3 s^{-1} (Fig. 15). The relative percentage increased logarithmically with decreasing flow but represented < 10% of the total P load even for the lowest summer flows.

Total and exchangeable N was positively related to moisture content, silt, and clay content and negatively related to sediment density and sand content, suggesting that greater total and exchangeable N concentrations were associated with fine-grained, flocculent sediments (Fig. 16-17). Rates of N release from sediment occurred primarily under anoxic conditions due to inhibition of bacterial nitrification (i.e., transformation of ammonium-N to nitrate). Anoxic rates ranged from 2.2 to 41.8 mg m^{-2} d^{-1}. Under oxic conditions, rates of N release from sediment were negligible (not shown), indicating conversion of ammonium-N to nitrate by bacterial nitrification under oxic conditions. Unlike P release from sediment, significant correlations were not detected between anoxic rates of N release and sediment characteristics or exchangeable N concentration.

Inflow-outflow budgetary analysis

Nutrient dynamics during the low-flow period (15 July through 30 September) of 2006. With the exception of a small peak in the hydrograph that occurred on 6-7 August, flows at RM 39.4 and RM 3.5 were less than 3000 $ft^3\ s^{-1}$ between 15 July and 30 September and declined below 1500 $ft^3\ s^{-1}$ between 15 July and 30 September (Fig. 18a). The Minnesota River accounted for 94% of the inflow during the low-flow period (Table 8). Combined inputs from small tributaries and the Blue Lake and Seneca WWTP were < 10% of the hydrological budget. Flow was slightly greater at RM 3.5 versus RM 39.4, reflecting hydrological inputs from point and nonpoint sources entering the Minnesota River downstream of RM 39.4 (Fig. 18a). Overall, hydrological outputs exceeded inputs by ~7% (Table 8). Measured inflow to the Black Dog Generating Plant (GP) averaged 14.6 $m^3\ s^{-1}$, while discharge back to the Minnesota River was 12.4 $m^3\ s^{-1}$, resulting in an apparent net water efflux (118%) from the Minnesota River (Table 8). The inflow-outflow discrepancy for the Black Dog GP largely explained the apparent hydrological imbalance for the lower Minnesota River during the low-flow period. Reasons for the inflow-outflow imbalance are not entirely clear but may be explained by a combination of the following: 1) additional unmeasured discharge from the Black Dog GP to the Minnesota River and 2) some evaporative loss. Inflow to the Black Dog GP represented a mean 37% (range = 14 - 63%) of the estimated flow at RM 8.5 during the low flow period.

Concentrations of TSS were less than 50 mg L^{-1} at RM 39.4 and RM 3.5 during most of the low-flow period (Fig. 18b) and inputs from the Minnesota River at RM 39.4 dominated the TSS budget of the lower Minnesota River (86% of total input; Table 9). Viable chlorophyll concentrations were usually greatest at RM 39.4 versus RM 3.5, often exceeding 100 mg m^{-3} (Fig. 18c). Peaks in viable chlorophyll of > 200 mg L^{-1} occurred at

RM 39.4 in mid-July through mid-August.

Total P concentrations at RM 39.4 were nearly constant (0.141 mg L^{-1}) during most of August through September (Fig. 18d). In contrast, they increased exponentially from 0.163 mg L^{-1} in mid-August to 0.377 mg L^{-1} in late September at RM 3.5 (Fig. 18d), indicating substantial influx from point and nonpoint sources located downstream of RM 39.4. Overall, the lower Minnesota River was a modest sink for total P during the low-flow period, retaining ~9% of the measured inputs (Table 10). Thus, the majority of the total P load influx to the lower Minnesota River was transported downstream.

The Minnesota River at RM 39.4 was the major contributor of total P loading at 52%, followed by the Seneca and Blue Lake WWTP at 18% and 14%, respectively (Table 10). Sand Creek represented 5%, while other small tributary inputs combined accounted for 2% of the total P input. For the Black Dog GP, total P flux was calculated under the assumption that outflow was approximately equal to inflow in order to resolved the hydrological inflow-outflow imbalance. Influx to the Black Dog GP was 18,039 kg total P and efflux back to the Minnesota River was 24,734 kg total P, resulting in a net load of 6,695 kg total P, or 7.6% of the total P input to the lower Minnesota River. P flux from sediment under oxic conditions represented ~ 3% of the total P input during the low flow period.

Efflux of SRP from the lower Minnesota River at RM 3.5 occurred during the low-flow period (Table 11; Fig. 18e). SRP concentrations were usually near detection limits throughout the low-flow period at RM 39.4. In contrast, they increased to a peak of 0.103 mg L^{-1} in early August, declined to near zero in mid-August, and increased linearly to 0.140 mg L^{-1} in late September at RM 3.5. Unlike total P budgetary patterns, SRP loading to the lower Minnesota River was co-dominated by the Blue Lake and Seneca WWTP. Combined input from these sources represented 74% of the SRP budget. SRP input was much lower for the Minnesota River at RM 39.4 (~ 8%) because most of the P load was in particulate form, probably as algal biomass, versus loads from the WWTP's, which were primarily in soluble forms. Estimated sediment P flux accounted for 7.3% of the

SRP input. Net input from the Black Dog GP and other smaller tributaries accounted for 6% and 2%, respectively, of SRP load. There was considerable net retention of SRP loads (35% of measured input), suggesting uptake and transformation to PP as algal biomass.

PP concentrations exhibited a peak at RM 39.4 in July and early August conjunction with small increases in flow and peaks in chlorophyll (Fig. 18f). PP was lower at RM 3.5, suggesting sedimentation of a portion of the load during this period. As flow declined below 50 $m^3 s^{-1}$ in September, PP was greater at RM 3.5 than RM 39.4. Budgetary analysis indicated the occurrence of net PP export, probably as algal biomass (Table 12). The Minnesota River at RM 39.4 contributed the greatest PP load, accounting for 81% of the total input to the system. The Black Dog GP was the second greatest contributor at ~ 8% followed by Sand Creek at 6%.

Phosphorus loading estimates for stations established along the main stem of the river exhibited longitudinal variations between mid-August and September (Fig. 19). Total P loading was relatively constant upstream of RM 25.1 and dominated by the PP fraction; SRP loading was minor. On 14-16 and 21-23 August, net increases in total P loading occurred downstream of RM 8.5 due primarily to increases in PP loading. In late August through September, SRP accounted for most of the increase in total P loading downstream of RM 8.5. In contrast, PP loading declined within this stretch of the river, suggesting possible deposition and/or conversion of PP to soluble P.

Mass balance approaches were used to examine input-output dynamics during the low-flow period for sections of the lower Minnesota River receiving loads that included the Blue Lake WWTP (Section 1, RM 39.4 to RM 14.3), the Black Dog GP (Section 2, RM 14.3 to RM 7.2), and the Seneca WWTP (Section 3, RM 7.2 to RM 3.5, Table 13). The greatest net inputs of total P were observed in Sections 1 and 3 in conjunction with inputs from the Blue Lake WWTP and the Seneca WWTP, respectively (Table 13; Fig. 20). In addition, SRP accounted for ~ 80% of the total P inputs to these sections of the river. Substantial retention (i.e., 74% of the input) of SRP loads in Section 1 probably reflected conversion of SRP to PP via algal assimilation (Table 13) as viable chlorophyll concentrations were generally greatest above RM 14.3 (see below). Export of PP (primarily as algal biomass) from this section of the river suggested transport of assimilated SRP loads to downstream locations (Table 13). The net result was some minor retention of total P loads in Section 1.

Total P inputs were lower in Section 2 relative to the other sections (Table 13; Fig. 20). SRP represented ~ 33%, while PP represented 54%, of the total P inputs. Greatest retention of both total and PP occurred within this section of the river versus other locations. In contrast, only minor net retention of SRP loads was observed, suggesting much less uptake by biota.

The Seneca WWTP was the major contributor of total and SRP loading to Section 3 (Table 13; Fig. 20). In addition, total P, SRP, and PP outputs exceeded measured inputs, resulting in calculated net export of total P from this section of the river (Table 13). By mass balance, unmeasured total P inputs to Section 3 of 2,786 kg represented a flux of 10.9 mg m^{-2} d^{-1}. Several mechanisms might have contributed to this unmeasured flux. First, anoxic conditions could have developed intermittently above the sediment interface in the main stem of Section 3, resulting in greater sediment P flux than allocated for in the mass balance. Second, backwaters, if connected to the main stem in this section, might have contributed additional total P in the form of algal biomass during the low-flow period. Some of this P was exported as PP while another portion was transformed to SRP via senescence during efflux. Third, P derived from sediment P flux in backwaters might have contributed to main stem P dynamics if there was some exchange with backwaters.

Longitudinal patterns in viable chlorophyll, phaeophytin, and phosphorus species in mid-September, 2006, provided insight into possible mechanisms explaining the buildup of SRP concentrations in the lower reaches of the Minnesota River during the low-flow period (Fig. 21). For example, SRP was near zero in the upper reaches in conjunction with chlorophyll exceeding 150 μg L^{-1}. SRP increased between RM 25.1 and 7.2 in conjunction with inputs from the Blue Lake WWTP (RM 20.5) and the Black Dog GP

(RM 10.7 and 7.6), ranging between 0.023 and 0.039 mg L^{-1}. SRP increased to greater than 0.100 mg L^{-1} downstream of RM 7.2 and a peak of 0.115 mg L^{-1} was observed at RM 3.5 (Fig. 20). This trend coincided with point source inputs from the Seneca WWTP at RM 6.7. Chlorophyll declined in a linear pattern from RM 39.4 to RM 0.5 while phaeophytin exhibited the opposite trend. Concentration maxima were observed in the vicinity of the Black Dog GP near RM 7.2 to 10.8. These longitudinal patterns indicated that most of the P was in particulate form as viable algal biomass in the upper reach of the lower Minnesota River. SRP input from the Blue Lake WWTP was probably assimilated by algae for growth as suggested by mass balance (Table 13). During transport to lower reaches, however, algal growth was probably no longer limited by P and had begun to senesce as suggested by longitudinal increases in phaeophytin. Discharge of algal biomass from the Black Dog GP cooling ponds probably contributed to peak phaeophytin concentration near RM 7.2. Thus, SRP loads from the Seneca WWTP were not being assimilated by phytoplankton community, resulting in the buildup of high SRP concentrations downstream of RM 6.7. Phytoplankton senescence in this vicinity may have additionally contributed to the SRP load.

In summary, 87,520 kg total P entered the lower Minnesota River during the low-flow period. The Minnesota River at RM 39.4 contributed greater than 50% of this load to the system, primarily as PP. The Blue Lake and Seneca WWTP accounted for 28% (24,070 kg) of the total P input primarily as SRP. The Black Dog GP accounted for ~ 2% (2,011 kg) of the total P input; 56% was in particulate form while 30% was SRP. P flux from sediment under oxic conditions, as SRP, represented 2% (1837 kg) of the total P input. Overall, SRP accounted for 37% of the total P load. A substantial portion (~35%) of this load was probably transformed to PP via assimilation by algae in the upper reaches (i.e., upstream of RM 7.2), resulting in some net PP export from the system.

The buildup of SRP in the water column downstream of RM 7.2 in late August-September could have been due to a combination of several factors. First, algal growth was probably not P limited in this reach of the river and did not assimilate SRP inputs via the Seneca WWTP. These inputs were not transformed into PP and instead accumulated in the water column. Second, the algal community was crashing during transport, resulting in conversion of PP as algal biomass to soluble forms which contributed to further SRP accumulation in the water column. Peaks in phaeophytin concentration were observed in the vicinity of the Black Dog GP. Since, intake for generator cooling represented a substantial portion of the Minnesota River flow during this period it is conceivable that much of the algal senescence was associated with flow through the GP. More research is needed to test this hypothesis. Mass balances for total P suggested that there might have been an additional unmeasured input to the system downstream of RM 7.2 that was minor relative to other inputs (i.e., ~3% of the gross input). Overall, only about 9% (8,318 kg) of the total P load was retained in the lower Minnesota River system, indicating that most of the P input (79,730 kg) was transported downstream to the Mississippi River during the low flow period.

The lower Minnesota River was a net sink for TKN and a net source for nitrate and ammonium during the low flow period (Figure 18g-i; Tables 14-16). The Minnesota River at RM 39.4 dominated TKN inputs to the system at 91.4%. Loading at RM 39.4 also accounted for greater than 50% of the gross input of nitrate and ammonium. The Blue Lake and Seneca WWTP and Sand Creek each contributed about one third of the TKN inputs to the lower Minnesota River downstream of RM 39.4 (i.e., net input, Table 14). The WWTPs accounted for most of the net inputs of nitrate and ammonium to the system. However, considerable net export of ammonium occurred from the lower Minnesota River during the low flow period that was not accounted for by measured inputs. Flux of ammonium from sediment, determined from laboratory incubation systems, was minor under oxic conditions and could not account for the apparent high net ammonium export. Similar to phosphorus, exported ammonium may have been derived from algal biomass which senesced during the latter part of the low flow period.

The Black Dog GP was a net sink for both TKN and nitrate and a net source of ammonium during the low flow period. TKN was probably retained in the GP ponds via some deposition as algal biomass. A portion of this TKN might have also been converted to ammonium via mineralization or cellular breakup and discharged back to the lower

Minnesota River as ammonium. Finally, the Black Dog GP was a net sink for nitrate, retaining about 47% of the input from the Minnesota River. These results suggested that a portion of the nitrate was denitrified in the pond system, similar to nitrate dynamics occurring in wetland systems.

Annual Budgetary Analysis. For the water years 2004-2006, annual flow income was dominated by the Minnesota River at river mile 39.4 (Table 17). Percentage income from this station varied between 92 and 95%. Despite the extended low flow period in July through September, 2006, annual flows were greatest in 2006, followed by 2005 and 2004. Flow income from the various creeks followed the same inter-annual trend while flows from point sources (primarily the Blue Lake and Seneca WWTPs) were similar in 2004 and 2005 and declined slightly in 2006. Tributary creeks contributed 3.2 to 4.2%, while point sources accounted for 1.5 to 3.8% of the annual flow. Overall, the flow budget was approximately balanced for the 3 year period. The difference between measured inflow and outflow was slightly negative, suggesting possible net export due to groundwater inputs. However, this contribution represented < 2% of the flow budget.

Even though flow income was greatest in 2006, TSS loading from the Minnesota River was highest in 2004 (Table 17) due, primarily, to high rates that occurred during the month of June, 2004 (Fig. 22). Meyer and Schellhaass (2002) indicated that monthly precipitation and rainfall erosivity indices are relatively constant for the Minnesota River watershed in June through August. However, TSS and total P loading generally peak in June due to the lack of row crop canopy coverage. As canopy coverage and evapotransporation rates increase in July and August, loading correspondingly decreases. Peak flows were generally confined to earlier months (April and May) in 2005 and 2006 in conjunction with lower TSS concentration. TSS loading from the Minnesota River at RM 39.4 represented 91.6 to 96.8% of the measured TSS income to the system during the three-year period. Tributary creeks contributed 8.4% of the TSS load in conjunction with higher flows in 2006 and accounted for less than 4% of the annual loading in 2004 and 2005. TSS contributions from point sources were minor in comparison.

The Minnesota River was a sink for TSS loads during the 3 year period. Approximately 40% of the annual TSS load was retained in 2004 versus ~ 22% in 2005 and 2006. The higher retention rate in 2004 was associated with high loading in June of that year and may be related to overbank flows and deposition in the floodplain and backwaters of the lower Minnesota River (Meyer and Schellhaass 2002). Relationships between annual flow and annual TSS loading at RM 3.5 for the years 2004-2006 fell within the range of values reported for this station between 1976 and 1996 (Meyer and Schellhaass 2002).

The Minnesota River at RM 39.4 also dominated annual total P and SRP loads to the lower Minnesota River during the 3 year period (Table 17). SRP accounted for 28 to 33% of the total P loading at this station. Tributary creeks only accounted for 4 to 7% of the annual total P loading and less than 5% of the annual SRP loading to the system. SRP loading represented 18 to 25% of the total P load contributed by tributary creeks. Annual total P loading from point sources was also minor compared to loading from the Minnesota River at RM 39.4 (i.e., ~3 to 4% of the annual total P load). However, inputs from these sources represented a larger percentage of the SRP loading to the system, ranging between ~6 and 13%. In addition, SRP loading accounted for a much larger percentage of the point source total P load. It represented ~ 60% of the point source total P load in 2004 and 2005 and over 90% of the total P load in 2006. The lower Minnesota River was a modest sink for total P and SRP during the three year period, retaining between 5 and 11% and 1 to 13% of the load, respectively. Most of the SRP retention was probably the result of its conversion to PP as algal biomass.

Annual total P loading at RM 39.4 and RM 3.5 were further partitioned into PP and soluble P fractions. It was assumed that biologically labile and refractory particulate P fractions determined for TSS collected during high flows were a constant percentage of the annual PP load. This assumption was reasonable since greater than 70% of the loading occurred for flows > 200 $m^3 s^{-1}$. Over the 3 year period, soluble P (i.e., equivalent to total soluble P), biologically labile PP, and refractory PP each represented about one third of the total P budget (Fig. 23). Thus, combined biologically labile soluble and PP accounted for an average 67% (range = 63 to 72%) of the total P load.

Nitrate was the dominant N form of the annual nitrogen load in the lower Minnesota River (Table 17). Annual nitrate loading increased as a function of increasing annual flow at both RM 39.4 and 3.5. Annual nitrate inputs from tributary creeks and point sources were negligible compared to annual loads from the Minnesota River at RM 39.4. The lower Minnesota River was a minor sink for nitrate in 2006 and a minor source in 2004 and 2005. Annual ammonium loads were low and represented a small fraction of the annual nitrogen load during the three year period (i.e., less than 2%). Considerable net export of ammonium also occurred during each year, suggesting possible conversion of organic N to ammonium as a result of algal senescence. Organic nitrogen (i.e., TKN minus ammonium) represented ~ 15% of the nitrogen load contributed by point sources and the Minnesota River at RM 39.4. In contrast, organic nitrogen accounted for ~ 40% of the tributary creeks nitrogen load. Like nitrate, very little net annual retention or export of TKN occurred during the three year period, suggesting that these constituents were transported through the system with only minor transformation. Annual loading for individual point and nonpoint sources to the lower Minnesota River are shown in Appendix A.

SUMMARY AND CONCLUSIONS

TSS fractionation results suggested that biologically labile PP forms accounted for a substantial portion of the lower Minnesota River P load during higher flow periods. In particular, the loosely-bound and iron-bound PP fraction represented ~ 43% of the PP load, which is in agreement with ranges reported for other agriculturally-managed watersheds (Pacini and Gächter 1999; James et al. 2002; Uusitalo et al. 2003; James and Barko 2005). These extractable PP fractions have been indirectly linked to internal sediment P recycling via diffusive flux under both oxic and anoxic conditions (Bostrom et al. 1982; Nürnberg 1988; Jensen and Thamdrup 1993; Petticrew and Arocena 2001; Søndergaard et al. 2003) and, thus, represent a quantifiable surrogate metric for estimating redox-sensitive PP loading and recycling potential in receiving water bodies.

Transport of redox-sensitive PP derived from the Minnesota River and deposition in navigation pools of the Upper Mississippi River has implications for P dynamics, eutrophication, and recovery of these systems after management of point and nonpoint sources. For instance, Minnesota River TSS loads (20 y mean = 6 x 105 Mg y^{-1}; Meyer and Schellhaass 2002) currently represent > 80% of sediment deposition rate in Lake Pepin of Navigation Pool 4 (1.5 cm y^{-1}; Kelley and Nater 2000). Loosely-bound and iron-bound P transported by the Minnesota River translated into very high potential oxic and anoxic diffusive P fluxes as deposited sediment in Lake Pepin. Intermittent stratification and development of anoxia above the sediment interface occur during periods of low flow in navigation pools of the Upper Mississippi River (James and Barko 2004). In Lake Pepin, sediment diffusive P flux can account for > 30% of the P budget under these conditions (Larson et al. 2002) and is an important factor driving phytoplankton productivity.

Equilibrium P assays demonstrated that P buffering occurred between aqueous and particulate phases resulting in an EPC of ~ 0.10 mg L^{-1}. SRP concentration in the lower Minnesota River converged with the independently measured EPC as TSS concentration or loading increased due to higher flow. The strong correspondence between measured EPC and SRP suggested that equilibrium reactions between TSS of allochthonous origin and aqueous phases were regulating SRP at higher flow and TSS loading. This finding falls in line with other evidence indicating equilibrium control of SRP by suspended particulate material in runoff and turbid river systems (Mayer and Gloss 1980; Froelich 1988; Carignan and Vaithiyanathan 1999; Fang et al. 2002; James et al. 2002; James and Barko 2005). The EPC for lower Minnesota River TSS was high relative to EPC values reported for some other systems (Table 18). The DSP was also high and within ranges reported in Fang et al. (2005) for agricultural soils within the Minnesota River Basin. These observations could be related to management practices that result in a buildup of P in soils, versus unmanaged forested watersheds like Bear Brook, as both the EPC and concentrations of soluble P in runoff have been shown to increase as a function of increasing soil P and DSP for soils of the Minnesota River basin (Fang et al. 2002). However, more information is needed in order to definitively associate source PP contributions to the EPC of TSS loads in large rivers. For instance, sediment erosion in the Minnesota River Basin has been strongly correlated to row crop area, population, and river flow, with row crop area explaining 84% of the variation in sediment loss (Mulla et al. 2000). These relationships support the hypothesis that agricultural land use practice and PP erosion from the landscape is a dominant contributor to Minnesota River loads. However, there is also evidence that stream bank erosion has increased in the past decade and represents a larger proportion of the TSS load than once thought (Sekely et al. 2002).

k_d was moderate but within ranges reported for other river systems, suggesting well buffered conditions (i.e., ~ 0.5 L g^{-1}; Froelich 1988). For instance, Wauchope and McDowell (1984) estimated a k_d of 0.4 L g^{-1} for floodplain sediments of the lower Mississippi River. k_d ranged between 0.25 and 1.38 L g^{-1} for TSS in rivers of South America (Carignan and Vaithiyanathan 1999). Mayer and Gloss (1980) reported a k_d of 0.6 L g^{-1} for TSS of the Colorado River. Higher percentages of fine sand with lower P affinity for loads may have been a factor in lower k_d for TSS of the lower Minnesota River (House 2003).

Interestingly, chlorophyll was usually lowest during periods of higher flow and equilibrium control of SRP due to flushing. There were instances when chlorophyll increased with concomitant declines in SRP on the falling limb of the hydrograph or between flow peaks, suggesting P desorption flux from the allochthonous exchangeable PP load in response to phytoplankton uptake. However, an inverse relationship generally occurred between TSS and chlorophyll due to the influence of flow and residence time on algal growth and washout. Allochthonous TSS was low during periods of extended low flow and higher residence time and SRP dynamics were regulated more by point source P loadings and transformation to phytoplankton PP than by equilibrium reactions with TSS. As flow and loading increased, SRP dynamics was regulated by buffering with allochthonous TSS. Phytoplankton uptake and growth was minimal due to low residence time and cellular washout. Thus, biotic control of SRP and transformation to PP dominated under very low loading while abiotic regulation of SRP and downstream transport occurred under higher loading conditions.

Since point source inputs of primarily SRP were relatively constant during the 3 year period, contributions by WWTP's to the P budget increased as flow and P loading at RM 39.4 decreased, particularly during late summer periods of low flow as observed for 2006. Patterns during the summer low flow period of 2006 suggested that the phytoplankton community assimilated soluble P, originating primarily from the Blue Lake WWTP, for growth in the upper reaches of the system. Phytoplankton growth was apparently not limited by P and perhaps started to senesce during transport downstream in late summer, 2006. Senescence may have been enhanced by circulation through the Black Dog GP, which accounted for an average 37% of the Minnesota River flow at RM 10.8 between mid-July and September, 2006. The buildup of high SRP concentrations near the mouth of the lower Minnesota River was likely due to a combination of the following factors: 1) discharge of SRP loads via the Seneca WWTP, 2) lack of SRP uptake by algae, 3) the onset of algal senescence in this region and conversion of PP to soluble P, and 4) input of additional soluble P from the bottom sediments.

Total sediment P was positively related to sediment moisture content, silt content, and clay content and negatively related to sediment density and sand content, suggesting that the more flocculent sediments composed of finer particles were associated with a higher total sediment P concentration. Refractory P (i.e., sum of aluminum-bound, calcium-bound, and residual organic P) constituted the majority of sediment total P and it was dominated by residual organic P and calcium-bound P. The iron-bound P fraction accounted for most of the biologically labile sediment P (i.e., sum of loosely-bound, iron-bound, and labile organic P) and concentrations were positively correlated with rates of P release from sediment under both oxic and anoxic conditions. These patterns coupled with higher rates of P release under anoxic conditions suggested that Fe-P interactions were important in P flux from sediments. Although the release rate was high under both oxic and anoxic conditions, relative contributions from sediment flux to the P budget were minor in relation to the much larger inputs from other point and nonpoint sources.

On an annual basis, loading of TSS and P species was dominated by point and nonpoint source inputs located upstream of RM 39.4. Substantial net TSS retention (22 to 39% of the TSS load) occurred within the lower Minnesota River system downstream of RM 39.4 during 3 year period, suggesting deposition. However, budgetary analysis could not differentiate between deposition in the river channel versus in the adjoining floodplain. It is likely that storage of TSS in the floodplain occurred as a result of high flow and overbanking. In contrast, annual inputs and outputs of total P, SRP, TKN, and nitrate to the lower Minnesota River were similar, suggesting minor retention and transformation.

ACKNOWLEGMENTS

Karen Jensen, Catherine Larson, Scott Shellhaass, and staff of MCES, are gratefully acknowledged for data base compilation, sampling, and chemical analyses of river water samples. Harry Eakin and Laura Pommier of the Engineer Research and Development Center Eau Galle Aquatic Ecology Laboratory participated in field sediment core sampling and laboratory sediment nutrient release analyses. Catherine Larson of MCES was the principal manager and Terry Zien of the USACE District, St. Paul, was the Section 22 coordinator for the lower Minnesota River Project. Funding for this research was provided by MCES and USACE District, St. Paul.

REFERENCES

Aminot, A., and Andrieux, F. (1996). Concept and determination of exchangeable phosphate in aquatic sediments. Wat. Res. 30:2805-2811.

APHA (American Public Health Association). (1998). Standard Methods for the Examination of Water and Wastewater. 20th ed. American Public Health Association, American Water Works Association, Water Environment Federation.

Bolster, C.H. and Hornberger, G.M. (2007). On the use of linearized Langmuir equations. Soil Sci. Soc. Am. J. 71:1796-1806.

Boström, B., Jansson, M., and Forsberg, C. (1982). Phosphorus release from lake sediments. Arch. Hydrobiol. Beih. Ergebn. Limnol. 18:5-59.

Carignan, R., and Vaithiyanathan, P. (1999). Phosphorus availability in the Paraná lakes (Argentina): Influence of pH and phosphate buffering by fluvial sediments. Limnol. Oceanogr. 44:1540-1548.

Chang-Ying F., Fang T., and Sheng Deng, N. (2006). The research of phosphorus of Xiangxi River nearby Three Gorges, China. Environ. Geol. 49:923-928.

Fang, F., and Brezonik, P.L. (2002). Phosphorus retention by river suspended sediment in the Minnesota-Mississippi Rivers system. Thesis submitted to the University of Minnesota.

Fang, F., Brezonik, P.L., Mulla, D.J., and Hatch, L.K. (2002). Estimating runoff phosphorus losses from calcareous soils in the Minnesota River Basin. J. Environ. Qual. 31:1918-1929.

Fang, F., Brezonik, P.L., Mulla, D.J., Hatch, L.K. (2005). Characterization of soil algal bioavailable phosphorus in the Minnesota River Basin. Soil Sci. Soc. Am. J. 69:1016-1025.

Froelich, P.N. (1988). Kinetic control of dissolved phosphate in natural rivers and estuaries: A primer on the phosphate buffer mechanism. Limnol. Oceanogr. 33:649-668.

Hjieltjes, A.H., and Lijklema, L. (1980). Fractionation of inorganic phosphorus in calcareous sediments. J. Environ. Qual. 8, 130-132.

House, W.A. (2003). Geochemical cycling of phosphorus in rivers. Appl. Geochem. 18:739-748.

James, W.F., Barko, J.W., Eakin, H.L. (2002). Labile and refractory forms of phosphorus in runoff of the Redwood River Basin, Minnesota. J. Freshwat. Ecol. 17:297-304.

James, W.F., and Barko, J.W. (2004). Diffusive fluxes and equilibrium processes in relation to phosphorus dynamics in the Upper Mississippi River. River Res. Applic. 20:473-484.

James, W.F., and Barko, J.W. (2005). Biologically labile and refractory phosphorus loads from the agriculturally-managed Upper Eau Galle River watershed, Wisconsin. Lake Res. Manage. 21:165-173.

Jensen, H.S., and Thamdrup, B. (1993). Iron-bound phosphorus in marine sediments as measured by bicarbonate-dithionite extraction. Hydrobiologia 253:47-59.

Kelley, D.W., and Nater, E.A. (2000). Historical sediment flux from three watersheds into Lake Pepin, Minnesota, USA. J. Environ. Quality 29:561-568.

Klotz, R.L. (1985). Factors controlling phosphorus limitation in stream sediments. Limnol. Oceanogr. 30:543-553.

Larson C.E., Johnson, D.K., Flood, R.J., Meyer, M.L., O'Dea, T.J., Schellhaass, S.M. (2002). Lake Pepin phosphorus study, 1994-1998. Effects of phosphorus loads on the water quality of the Upper Mississippi River, Lock and Dam 1 through Lake Pepin. Final report Metropolitan Council Environmental Services, St. Paul, MN USA

Mayer, L.M., and Gloss, S.P. (1980). Buffering of silica and phosphate in a turbid river. Limnol. Oceanogr. 25:12-22.

Meyer, J.L. (1979). The role of sediments and bryophytes in phosphorus dynamics in a headwater stream ecosystem. Limnol. Oceanogr. 24:365-375.

Meyer, M.L., and Schellhaass, S.M. (2002) Sources of phosphorus, chlorophyll, and sediment to the Mississippi River upstream of Lake Pepin: 1976-1996. Metropolitan Council Environmental Services, St Paul, MN.

Mulla, D.J., Sekely, A., Wheeler, D., Bell, J.C. (2000). Historical trends affecting accumulation of sediment and phosphorus in Lake Pepin. University of Minnesota, Dept Soil, Water, and Climate, St. Paul MN

Nürnberg, G.K. (1988). Prediction of phosphorus release rates from total and reductant-soluble phosphorus in anoxic lake sediments. Can. J. Fish. Aquat. Sci. 45:453-462.

Pacini, N, and Gächter, R. (1999). Speciation of riverine particulate phosphorus during rain events. Biogeochemistry 47:87-109.

Pant, H.K., and Reddy, K.R. (2001). Phosphorus sorption characteristics of estuarine sediments under different redox conditions. Journal of Environmental Quality 30:1474-1480.

Petticrew, E.L., and Arocena, J.M. (2001). Evaluation of iron-phosphate as a source of internal lake phosphorus loadings. Sci. Tot. Env. 266:87-93.

Plumb, R.H. (1981). Procedures for handling and chemical analysis of sediment and water samples. Technical Report EPA/CE-81-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Psenner, R., and Puckso, R. (1988). Phosphorus fractionation: Advantages and limits of the method for the study of sediment P origins and interactions. Arch. Hydrobiol. Biel. Erg. Limnol. 30:43-59.

Søndergaard, M., Jensen, J.P., and Jeppesen, E. (2003). Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia 506-509:135-145.

Uusitalo, R., Turtola, E., Puustinen, M., Paasonen-Kivekäs, M., and Uusi-Kämppä. (2003). Contribution of particulate phosphorus to runoff phosphorus bioavailability. J. Environ. Qual. 32:2007-2016.

Walker, W.W. (1996). Simplified procedures for eutrophication assessment and prediction: User manual. Instruction Report W-96-2, September, 1996, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, USA

Wauchope, R.D., and McDowell, L.L. (1984) Adsorption of phosphate, arsenate, methancarsonate and cacodylate by lake and stream sediments: Comparisons with soils. J. Environ. Qual. 13:499-504.

TABLES

Table 1. Operationally-defined particulate phosphorus (PP) fractions. Biologically labile = Subject to recycling pathways. Biologically refractory = Low recycling potential and subject to burial.

Variable	Extractant	Recycling Potential
Loosely-bound PP	1 M ammonium chloride	Biologically labile; can be recycled via eH and pH reactions and equilibrium processes.
Iron-bound PP	0.11 M sodium bicarbonate-dithionate	Biologically labile; can be recycled via eH and pH reactions and equilibrium processes.
Labile organic/ polyphosphate PP	Persulfate digestion of the NaOH extraction	Biologically labile; recycled via bacterial mineralization of organic P and mobilization of polyphosphates stored in cells.
Aluminum-bound PP	0.1 N sodium hydroxide	Biologically refractory; generally unavailable for biological use and subject to burial.
Calcium-bound PP	0.5 N hydrochloric acid	Biologically refractory; generally unavailable for biological use and subject to burial.
Refractory organic PP	Persulfate digestion of remaining particulate P	Biologically refractory; generally unavailable for biological use and subject to burial.

Table 2. Comparison of ionic concentration between Minnesota River water, tap water, and adjusted tap water used for P equilibrium assays.

Ion (mM)	Minnesota River[1]	Tap water	Adjusted tap water
Ca	2.46	1.42	1.42
Mg	1.74	1.148	1.74
K	0.133	0.02	0.133
Na	1.31	0.074	1.31
Cl	0.947	0	1.349
SO_4	1.64	0.229	0.812
HCO_3	5.33	3.278	3.278

[1] Fang and Brezonik (2002)

Table 3. Point and nonpoint source monitoring stations and confluence along the lower Minnesota River.

Source	Confluence (River mile)	Period of record (year)
Bevens Creek	41.4	2003-2006
Sand Creek	33.5	2003-2006
Carver Creek	32.1	2003-2006
Chaska Creek	30.0	2003-2006
Bluff Creek	22.5	2003-2006
Riley Creek	22.3	2003-2005
Blue Lake Wastewater Treatment Plant	20.5	2003-2006
Purgatory Creek	18.3	2003-2006
Eagle Creek	15.8	2003-2006
Credit Creek	13.4	2003-2006
Nine Mile Creek	11.0 & 12.5	2003-2006
Willow Creek	11.1	2003-2006
Seneca Wastewater Treatment Plant	6.7	2003-2006
Black Dog Generating Plant	7.6 & 10.1	2006
MSP International Airport	3.0, 3.8, & 4.1	2003-2006

Table 4. Mean (n=10 to 20) concentrations of ambient soluble reactive phosphorus (SRP), equilibrium phosphate concentration (EPC), linear adsorption coefficient (k_d), Langmuir sorption capacity (S_{max}), and P fractions for allochthonous TSS of the lower Minnesota River.

Variable	Mean	SE	Percent
Ambient SRP (mg L^{-1})	0.116	0.003	
EPC (mg L^{-1})	0.117	0.012	
k_d (L kg^{-1})	332	31	
S_{max} (mg kg^{-1})	608	16	
Loosely-bound P (mg kg^{-1})	138	7	18.2
Iron-bound P (mg kg^{-1})	186	6	24.5
Labile organic P (mg kg^{-1})	56	4	7.4
Aluminum-bound P (mg kg^{-1})	59	3	7.8
Calcium-bound P (mg kg^{-1})	203	14	26.8
Refractory organic P (mg kg^{-1})	116	18	15.3

Table 5. Correlation coefficients (r) between various constituents for sediments collected in the lower Minnesota River in 2005 and 2006. Red fonts represent biologically labile sediment phosphorus fractions and blue fonts represent refractory sediment phosphorus fractions. NS = not significant (P > 0.05).

2005	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
1) Moisture content (%)	1.00											
2) Density (g/mL)	-0.90	1.00										
3) Sand content (%)	-0.93	0.84	1.00									
4) Silt content (%)	0.93	-0.84	-0.99	1.00								
5) Clay content (%)	0.81	-0.73	-0.90	0.85	1.00							
6) Total P (mg/g)	0.86	-0.81	-0.94	0.93	0.86	1.00						
7) Loosely-bound P (mg/g)	0.66	-0.59	-0.69	0.72	0.49	0.67	1.00					
8) Iron-bound P (mg/g)	0.76	-0.74	-0.79	0.79	0.69	0.84	0.69	1.00				
9) Labile organic P (mg/g)	0.42	-0.39	NS	NS	NS	NS	NS	NS	1.00			
10) Aluminum-bound P (mg/g)	0.47	-0.47	-0.46	0.50	NS	0.56	0.66	0.76	NS	1.00		
11) Calcium-bound P (mg/g)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	1.00	
12) Residual organic P (mg/g)	NS	NS	-0.45	0.44	0.48	0.46	NS	NS	NS	NS	-0.74	1.00

2006	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
1) Moisture content (%)	1.00											
2) Density (g/mL)	-0.99	1.00										
3) Sand content (%)	-0.84	0.82	1.00									
4) Silt content (%)	0.86	-0.85	-0.99	1.00								
5) Clay content (%)	0.62	-0.60	-0.88	0.81	1.00							
6) Total P (mg/g)	0.63	-0.59	-0.76	0.74	0.71	1.00						
7) Loosely-bound P (mg/g)	0.41	NS	NS	NS	NS	0.59	1.00					
8) Iron-bound P (mg/g)	0.89	-0.85	-0.74	0.75	0.60	0.62	NS	1.00				
9) Labile organic P (mg/g)	0.52	-0.54	NS	NS	NS	NS	NS	0.46	1.00			
10) Aluminum-bound P (mg/g)	0.58	-0.57	NS	0.39	NS	NS	NS	0.53	0.44	1.00		
11) Calcium-bound P (mg/g)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	1.00	
12) Residual organic P (mg/g)	NS	NS	-0.48	0.47	0.43	0.71	0.43	NS	NS	NS	-0.49	1.00

Table 6. Correlation coefficients for rates of phosphorus (P) release from sediment under oxic and anoxic conditions versus sediment characteristics. NS = not significant at the 5% level or less. Red fonts represent biologically labile sediment phosphorus fractions and blue fonts represent refractory sediment phosphorus fractions. NS = not significant (P > 0.05).

2005	Oxic P release	Anoxic P release
	(mg m^{-2} d^{-1})	
1) Moisture content (%)	0.54	0.53
2) Density (g/mL)	-0.55	-0.54
3) Sand content (%)	-0.37	-0.36
4) Silt content (%)	0.38	0.38
5) Clay content (%)	0.33	0.23
6) Total P (mg/g)	0.36	0.33
7) Loosely-bound P (mg/g)	NS	NS
8) Iron-bound P (mg/g)	0.72	0.66
9) Labile organic P (mg/g)	NS	NS
10) Aluminum-bound P (mg/g)	0.20	NS
11) Calcium-bound P (mg/g)	0.41	0.33
12) Residual organic P (mg/g)	-0.40	-0.29

2006	Oxic P release	Anoxic P release
	(mg m^{-2} d^{-1})	
1) Moisture content (%)	0.30	0.44
2) Density (g/mL)	-0.28	-0.44
3) Sand content (%)	0.26	NS
4) Silt content (%)	NS	NS
5) Clay content (%)	-0.44	-0.33
6) Total P (mg/g)	NS	NS
7) Loosely-bound P (mg/g)	NS	0.26
8) Iron-bound P (mg/g)	0.49	0.61
9) Labile organic P (mg/g)	NS	NS
10) Aluminum-bound P (mg/g)	NS	0.25
11) Calcium-bound P (mg/g)	-0.36	NS
12) Residual organic P (mg/g)	NS	-0.24

Table 7. Predicted concentrations of iron-bound phosphorus (P) in the sediment and rates of P release under oxic and anoxic conditions for river mile sections of the lower Minnesota River. Sediment textural categories determined by the U.S. Geological Survey (T. Winterstein, unpublished data) were used in conjunction with regression relationships developed between sand or silt content versus iron-bound P and iron-bound P versus rates of P release under oxic or anoxic conditions (Figure 12).

River Mile	Sediment Texture		Sand-gravel			Sand-Silt		
	Sand-Gravel (%)	Sand-Silt (%)	Iron-bound P (mg/g)	Oxic P Release ($\mathrm{mg\ m^{-2}\ d^{-1}}$)	Anoxic P Release ($\mathrm{mg\ m^{-2}\ d^{-1}}$)	Iron-bound P (mg/g)	Oxic P Release ($\mathrm{mg\ m^{-2}\ d^{-1}}$)	Anoxic P Release ($\mathrm{mg\ m^{-2}\ d^{-1}}$)
0.5	69	31	0.119	2.5	13.4	0.127	2.7	14.6
1.5	39	62	0.161	3.5	19.1	0.181	4.0	21.8
2.5	21	78	0.186	4.2	22.5	0.208	4.7	25.5
3.5	29	71	0.175	3.9	21.0	0.196	4.4	23.9
4.5	32	68	0.170	3.8	20.4	0.191	4.3	23.2
5.5	28	72	0.176	3.9	21.1	0.198	4.4	24.1
6.5	38	62	0.162	3.6	19.3	0.181	4.0	21.8
7.5	74	26	0.112	2.4	12.5	0.119	2.5	13.4
8.5	44	47	0.154	3.4	18.1	0.155	3.4	18.3
9.5	60	28	0.131	2.8	15.1	0.122	2.6	13.9
10.5	51	48	0.144	3.1	16.8	0.156	3.4	18.5
11.5	20	80	0.187	4.2	22.7	0.212	4.8	25.9
12.5	25	75	0.180	4.0	21.7	0.203	4.6	24.8
13.5	22	77	0.184	4.1	22.3	0.206	4.6	25.3
14.5	36	64	0.165	3.6	19.6	0.184	4.1	22.2
15.5	61	39	0.130	2.8	14.9	0.141	3.1	16.4
16.5	27	72	0.177	3.9	21.3	0.198	4.4	24.1
17.5	25	75	0.180	4.0	21.7	0.203	4.6	24.8
18.5	20	80	0.187	4.2	22.7	0.212	4.8	25.9
19.5	46	54	0.151	3.3	17.7	0.167	3.7	19.9
20.5	57	43	0.135	2.9	15.7	0.148	3.2	17.3
21.5	6	95	0.207	4.7	25.3	0.237	5.4	29.4
22.5	23	77	0.183	4.1	22.1	0.206	4.6	25.3
23.5	15	85	0.194	4.4	23.6	0.220	5.0	27.1
24.5	0	100	0.215	4.9	26.4	0.246	5.6	30.6
25.5	23	77	0.183	4.1	22.1	0.206	4.6	25.3
26.25	27	73	0.177	3.9	21.3	0.200	4.5	24.3
Average (1 SE)	34 (3.6)	65 (3.8)	0.168 (0.005)	3.7 (0.1)	20.0 (0.7)	0.186 (0.006)	4.2 (0.2)	22.5 (0.9)

Table 8. Measured input flows from point and nonpoint sources and output flow for the low-flow period of 2006. Net retention represents a positive value while net export represents a negative value.

Low-flow 2006 Loads 15 JUL - 30 SEP		Station	Flow (m^3 s^{-1})	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	41.77	94.2
		Bluff Creek	0.06	0.1
		Carver Creek	0.33	0.8
		Chaska Creek	0.10	0.2
		Credit Creek	0.24	0.6
		Eagle Creek	0.25	0.6
		Nine-Mile Creek	0.56	1.3
		Purgatory Creek	0.24	0.5
		Sand Creek	0.61	1.4
		Willow Creek	0.13	0.3
		Subtotal	44.30	
	Point sources	Blue Lake WWTP	1.22	2.7
		Seneca WWTP	1.04	2.4
		Black Dog (Net Input = 436.19 cfs outflow - 514.74 cfs inflow)	-2.22	-5.0
		Subtotal	0.04	
		Total	91.73	
Output		Minnesota River at river mile 3.5	47.43	
Net retention or export			**-3.08**	**107.0**

Table 9. Measured total suspended solids (TSS) loads from point and nonpoint sources and TSS loading output for the low-flow period of 2006. Gross input includes loading from the Minnesota River at RM 39.4 while net input represents all loads entering the lower Minnesota River below RM 39.4. Net retention represents a positive value while net export represents a negative value.

Low-Flow 2006 Loads 15 JUL - 30 SEP		Station	TSS (kg)	TSS (mg/L)	CV	Gross Input (%)	Net Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	21439600	76.2	0.06	85.7	
		Bluff Creek	51	0.1	0.16	0.0	0.0
		Carver Creek	50660	22.6	0.24	0.2	1.4
		Chaska Creek	3426	5.0	0.21	0.0	0.1
		Credit Creek	68476	41.6	0.75	0.3	1.9
		Eagle Creek	8986	5.3	0.24	0.0	0.3
		Nine-Mile Creek	61860	16.4	0.37	0.3	1.7
		Purgatory Creek	47296	29.7	0.48	0.2	1.3
		Sand Creek	1959967	473.8	0.44	7.8	54.6
		Willow Creek	17891	20.0	0.03	0.1	0.5
		Subtotal	23658213				
	Point sources	Blue Lake WWTP	10785	13.2	0.06	0.0	0.3
		Seneca WWTP	15641	2.2	0.08	0.1	0.4
		Black Dog (Net Input = 5907257 kg TSS outflow - 4559937 kg TSS inflow)	1347320			5.4	37.5
		Subtotal	1373746				
		Total	25031959				
Output		Minnesota River at river mile 3.5	15827680	49.5	0.07		
Net retention or export			**9204279**			36.8	

Table 10. Measured total phosphorus (P) loads from point and nonpoint sources and total P loading output for the low-flow period of 2006. Gross input includes loading from the Minnesota River at RM 39.4 while net input represents all loads entering the lower Minnesota River below RM 39.4. Net retention represents a positive value while net export represents a negative value.

Low-Flow 2006 Loads 15 JUL - 30 SEP		Station	Total P (kg)	Total P (mg/L)	CV	Gross Input (%)	Net Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	45519	0.162	0.08	52.0	
		Bluff Creek	104	0.258	0.43	0.1	0.3
		Carver Creek	414	0.185	0.08	0.5	1.0
		Chaska Creek	61	0.089	0.03	0.1	0.2
		Credit Creek	362	0.219	0.11	0.4	0.9
		Eagle Creek	68	0.040	0.20	0.1	0.2
		Nine-Mile Creek	484	0.128	0.27	0.6	1.2
		Purgatory Creek	308	0.193	0.10	0.4	0.7
		Sand Creek	4078	0.986	0.20	4.7	9.7
		Willow Creek	139	0.155	0.17	0.2	0.3
		Sediment P Flux	1856			2.1	4.4
		Subtotal	53393				
	Point sources	Blue Lake WWTP	11841	1.445	0.22	13.5	28.2
		Seneca WWTP	15592	2.216	0.06	17.8	37.1
		Black Dog (Net Input = 24,734 kg P outflow - 18,039 kg P inflow)	6695	0.267	0.03	7.7	15.9
		Subtotal	34128				
		Total	87521				
Output		Minnesota River at river mile 3.5	79730	0.249	0.06		
Net retention or export			7791			8.9	

Table 11. Measured soluble reactive phosphorus (SRP) loads from point and nonpoint sources and SRP loading output for the low-flow period of 2006. Gross input includes loading from the Minnesota River at RM 39.4 while net input represents all loads entering the lower Minnesota River below RM 39.4. Total P (%) represents the percentage of the total P load that is SRP. Net retention represents a positive value while net export represents a negative value.

Low-Flow 2006 Loads 15 JUL - 30 SEP		Station	SRP (kg)	SRP (mg/L)	CV	Gross Input (%)	Net Input (%)	Total P (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	2669	0.010	0.45	8.3		5.9
		Bluff Creek	51	0.126	0.16	0.2	0.2	49.0
		Carver Creek	166	0.074	0.02	0.5	0.6	40.1
		Chaska Creek	56	0.082	0.21	0.2	0.2	91.8
		Credit Creek	171	0.104	0.14	0.5	0.6	47.2
		Eagle Creek	23	0.014	0.12	0.1	0.1	34.0
		Nine-Mile Creek	81	0.021	0.19	0.3	0.3	16.7
		Purgatory Creek	34	0.022	0.39	0.1	0.1	11.0
		Sand Creek	942	0.228	0.08	2.9	3.2	23.1
		Willow Creek	25	0.028	0.07	0.1	0.1	18.0
		Sediment P Flux	1856			5.8	6.3	100.0
		Subtotal	6074					
	Point sources	Blue Lake WWTP	11841	1.445	0.22	36.8	40.2	100.0
		Seneca WWTP	12229	1.738	0.17	38.0	41.5	78.4
		Black Dog (Net Input = 3750 kg P outflow - 1739 kg P inflow)	2011	0.042	0.23	6.3	6.8	30.0
		Subtotal	26081					
		Total	32155					
Output		Minnesota River at river mile 3.5	21300	0.067	0.16			26.7
Net retention or export			10855			33.8		

Table 12. Measured particulate phosphorus (PP) loads from point and nonpoint sources and PP loading output for the low-flow period of 2006. Gross input includes loading from the Minnesota River at RM 39.4 while net input represents all loads entering the lower Minnesota River below RM 39.4. Total P (%) represents the percentage of the total P load that is PP. Net retention represents a positive value while net export represents a negative value.

Low-flow 2006 Loads 15 JUL - 30 SEP		Station	PP (kg)	PP (mg/L)	CV	Gross Input (%)	Net Input (%)	Total P (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	39812	0.141	0.05	80.8		87.5
		Bluff Creek				0.0	0.0	0.0
		Carver Creek	168	0.075	0.15	0.3	1.8	40.6
		Chaska Creek	79	0.116	0.73	0.2	0.8	100.0
		Credit Creek	183	0.111	0.26	0.4	1.9	50.6
		Eagle Creek	42	0.025	0.31	0.1	0.4	62.1
		Nine-Mile Creek	241	0.064	0.64	0.5	2.6	49.8
		Purgatory Creek	167	0.105	0.37	0.3	1.8	54.2
		Sand Creek	3146	0.760	0.28	6.4	33.3	77.1
		Willow Creek	139	0.155	0.17	0.3	1.5	100.0
		Subtotal	43977					
	Point sources	Blue Lake WWTP	587	0.072	0.35	1.2	6.2	5.0
		Seneca WWTP	963	0.137	0.17	2.0	10.2	6.2
		Black Dog (Net Input = 19542 kg P outflow - 15800 kg P inflo	3742	0.042	0.23	7.6	39.6	55.9
		Subtotal	5292					
		Total	49269					
Output		Minnesota River at river mile 3.5	51489	0.161	0.05			64.6
Net retention or export			-2220			-4.5		

Table 13. Phosphorus (P) mass balances for 3 sections of the lower Minnesota River during a period of low flow between 15 July and 30 September, 2006. Gross input includes the load entering the section from upstream as well as inputs from within the section. Net input represents loading sources from within the section. Total P (%) represents the percentage of the total P load that is either particulate P or soluble reactive P.

Section	River Mile	Sources	Total P				
			Gross Input	Net Input	Output	Retention	
			(kg)	(kg)	(kg)	(kg)	(% Input)
	>39.4	Boundary Conditions			45,519		
1	39.4 - 14.3	Minnesota River @ RM 39.4, Sand, Carver, Chaska, Bluff, Purgatory, Riley, and Eagle Creek, Blue Lake WWTP, Sediment P flux	63,703	18,184	60,131	3,572	5.6%
2	14.3 - 7.2	Minnesota River @ RM 14.3, Credit, Nine Mile, and Willow Creek, Black Dog GP, Sediment P Flux	68,139	8,008	61,135	7,004	10.3%
3	7.2 - 3.5	Minnesota River @ RM 7.2, Seneca Lake WWTP, MSP Airport, Sediment P flux	76,944	15,809	79,730	-2,786	-3.6%
Total	<39.4 to 3.5		87,520	42,001	79,730	7,790	8.9%

Section	River Mile	Sources	Soluble Reactive P							
			Gross Input		Net Input		Output		Retention	
			(kg)	(% TP)	(kg)	(% TP)	(kg)	(% TP)	(kg)	(% Input)
0	>39.4	Boundary Conditions					2669	5.9%		
1	39.4 - 14.3	Minnesota River @ RM 39.4, Sand, Carver, Chaska, Bluff, Purgatory, Riley, and Eagle Creek, Blue Lake WWTP, Sediment P flux	17092	26.8%	14423	79.3%	4470	7.4%	12622	73.8%
2	14.3 - 7.2	Minnesota River @ RM 14.3, Credit, Nine Mile, and Willow Creek, Black Dog GP, Sediment P Flux	7086	10.4%	2616	32.7%	6617	10.8%	469	6.6%
3	7.2 - 3.5	Minnesota River @ RM 7.2, Seneca WWTP, MSP Airport, Sediment P flux	19063	24.8%	12446	78.7%	21300	26.7%	-2237	-11.7%
Total	<39.4 to 3.5		32,154		29,485		21,300		10854	33.8%

Section	River Mile	Sources	Particulate P							
			Gross Input		Net Input		Output		Retention	
			(kg)	(% TP)	(kg)	(% TP)	(kg)	(% TP)	(kg)	(% Input)
0	>39.4	Boundary Conditions					39812	87.5%		
1	39.4 - 14.3	Minnesota River, Sand, Carver, Chaska, Bluff, Purgatory, Riley, and Eagle Creek, Blue Lake WWTP	44001	69.1%	4189	23.0%	53380	88.8%	-9379	-21.3%
2	14.3 - 7.2	Minnesota River, Credit, Nine Mile, and Willow Creek, Black Dog GP	57685	84.7%	4305	53.8%	49386	80.8%	8299	14.4%
3	7.2 - 3.5	Minnesota River, Seneca WWTP, MSP Airport	50349	65.4%	963	6.1%	51489	64.6%	-1140	-2.3%
Total	<39.4 to 3.5		49,269		9,457		51,489		-2220	-4.5%

Table 14. Measured total kjeldahl nitrogen (TKN) loads from point and nonpoint sources and TKN loading output for the low-flow period of 2006. Gross input includes loading from the Minnesota River at RM 39.4 while net input represents all loads entering the lower Minnesota River below RM 39.4. Net retention represents a positive value while net export represents a negative value.

Low-Flow 2006 Loads 15 JUL - 30 SEP		Station	TKN (kg)	TKN (mg/L)	CV	Gross Input (%)	Net Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	485532	1.725	0.05	91.4	
		Bluff Creek	356	0.880	0.63	0.1	0.8
		Carver Creek	3471	1.552	0.11	0.7	7.6
		Chaska Creek	586	0.859	0.31	0.1	1.3
		Credit Creek	1681	1.022	0.14	0.3	3.7
		Eagle Creek	439	0.259	0.12	0.1	1.0
		Nine-Mile Creek	4055	1.072	0.18	0.8	8.9
		Purgatory Creek	2754	1.727	0.19	0.5	6.0
		Sand Creek	14922	3.607	0.20	2.8	32.6
		Willow Creek	850	0.867	0.31	0.2	1.9
						0.0	0.0
		Subtotal	514646				
	Point sources	Blue Lake WWTP	16476	2.010	0.03	3.1	36.0
		Seneca WWTP	15976	2.270	0.02	3.0	34.9
		Black Dog (Net Input = 131282 kg N outflow - 147037 kg N inflow)	-15755	1.577	0.06	-3.0	-34.4
		Subtotal	16697				
		Total	531343				
Output		Minnesota River at river mile 3.5	465282	1.456	0.07		
Net retention or export			66061			12.4	

Table 15. Measured nitrate+nitrite nitrogen (N) loads from point and nonpoint sources and nitrate+nitrite N loading output for the low-flow period of 2006. Gross input includes loading from the Minnesota River at RM 39.4 while net input represents all loads entering the lower Minnesota River below RM 39.4. Net retention represents a positive value while net export represents a negative value.

Low-Flow 2006 Loads 15 JUL - 30 SEP		Station	Nitrate (kg)	Nitrate (mg/L)	CV	Gross Input (%)	Net Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	312150	1.109	0.47	64.6	
		Bluff Creek	116	0.286	0.33	0.0	0.1
		Carver Creek	722	0.314	0.36	0.2	0.4
		Chaska Creek	1190	1.746	0.22	0.3	0.7
		Credit Creek	992	0.603	0.01	0.2	0.6
		Eagle Creek	348	0.205	0.10	0.1	0.2
		Nine-Mile Creek	584	0.154	0.07	0.1	0.3
		Purgatory Creek	413	0.259	0.39	0.1	0.2
		Sand Creek	4796	1.159	0.14	1.0	2.8
		Willow Creek	291	0.324	0.07	0.1	0.2
						0.0	0.0
		Subtotal	321602				
	Point sources	Blue Lake WWTP	102281	12.480	0.01	21.2	59.8
		Seneca WWTP	117722	16.729	0.01	24.4	68.9
		Black Dog (Net Input = 50934 kg N outflow - 109400 kg N inflow)	-58466	0.611	0.30	-12.1	-34.2
		Subtotal	161537				
		Total	483139				
Output		Minnesota River at river mile 3.5	504973	1.114	0.32		
Net retention or export			-21834			104.5	

Table 16. Measured ammonium nitrogen (N) loads from point and nonpoint sources and ammonium N loading output for the low-flow period of 2006. Gross input includes loading from the Minnesota River at RM 39.4 while net input represents all loads entering the lower Minnesota River below RM 39.4. Net retention represents a positive value while net export represents a negative value.

Low-Flow 2006 Loads 15 JUL - 30 SEP		Station	Ammonium (kg)	Ammonium (mg/L)	CV	Gross Input (%)	Net Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	5630	0.020	0.01	65.7	
		Bluff Creek	8	0.020	0.01	0.1	0.3
		Carver Creek	45	0.020	0.01	0.5	1.5
		Chaska Creek	23	0.033	0.28	0.3	0.8
		Credit Creek	43	0.026	0.15	0.5	1.5
		Eagle Creek	37	0.022	0.09	0.4	1.3
		Nine-Mile Creek	76	0.020	0.01	0.9	2.6
		Purgatory Creek	159	0.100	0.52	1.9	5.4
		Sand Creek	386	0.093	0.36	4.5	13.1
		Willow Creek	64	0.074	0.55	0.8	2.2
						0.0	0.0
		Subtotal	6471				
	Point sources	Blue Lake WWTP	1668	0.203	0.06	19.5	56.7
		Seneca WWTP	1262	0.179	0.13	14.7	42.9
		Black Dog (Net Input = 6617 kg N outflow - 7444 kg N inflow)	-827	0.079	0.30	-9.7	-28.1
		Subtotal	2103				
		Total	8574				
Output		Minnesota River at river mile 3.5	31329	0.098	0.19		
Net retention or export			-22755			365.4	

Table 17. Annual measured inputs and output of flow and various constituents in the lower Minnesota River for the water years 2004-2006.

2004 Loads		Flow		TSS		TKN		Nitrate nitrite-N		Ammonium-N		Total P		SRP	
		(ft^3/s)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)
Inputs	Minnesota River at river mile 39.4	4075	92.0	1119044000	95.9	6001984	90.8	30040550	95.4	183248	84.1	1362796	92.2	389698	89.9
	Creeks	185	4.2	47044270	4.0	446348	6.8	615649	2.0	15506	7.1	74058	5.0	18417	4.2
	Point sources	168	3.8	376932	0.0	163995	2.5	823582	2.6	19107	8.8	40464	2.7	25422	5.9
Outputs	Minnesota River at river mile 3.5	4462		708883300		6918528		32682110		327041		1405095		412217	
Retention or export		-33	100.8	457581902	39.2	-306201	104.6	-1202329	103.8	-109180	150.1	72222	4.9	21320	4.9

2005 Loads		Flow		TSS		TKN		Nitrate nitrite-N		Ammonium-N		Total P		SRP	
		(ft^3/s)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)
Inputs	Minnesota River at river mile 39.4	5830	94.1	859606300	96.8	7225342	92.4	45373490	97.4	208142	71.1	1402904	91.3	461762	88.7
	Creeks	198	3.2	28001126	3.2	376891	4.8	427700	0.9	13802	4.7	66869	4.4	19835	3.8
	Point sources	169	2.7	393769	0.0	213287	2.7	776383	1.7	70744	24.2	66776	4.3	39205	7.5
Outputs	Minnesota River at river mile 3.5	6303		694589300		7579811		48654140		373428		1381346		513897	
Retention or export		-106	101.7	193411895	21.8	235709	3.0	-2076567	104.5	-80740	127.6	155203	10.1	6905	1.3

2006 Loads		Flow		TSS		TKN		Nitrate nitrite-N		Ammonium-N		Total P		SRP	
		(ft^3/s)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)	(kg/y)	(%)
Inputs	Minnesota River at river mile 39.4	7864	95.0	980185000	91.6	9365269	92.9	60955770	97.3	205120	89.1	1505394	88.4	427398	82.9
	Creeks	296	3.6	89467707	8.4	556868	5.5	761145	1.2	15333	6.7	125661	7.4	22813	4.4
	Point sources	121	1.5	262770	0.0	160753	1.6	908895	1.5	9666	4.2	71890	4.2	65583	12.7
Outputs	Minnesota River at river mile 3.5	8370		834103500		9715084		60166680		329577		1517663		450477	
Retention or export		-90	101.1	235811977	22.0	367806	3.6	2459130	3.9	-99458	143.2	185282	10.9	65317	12.7

Table 18. Comparison of equilibrium phosphate concentration (EPC) for suspended and deposited sediments of various rivers.

System	EPC (mg L^{-1})	Reference
lower Minnesota River (USA)	0.117	Present study
Lake Pepin sediment (USA)	0.155	James and Barko (2004)
Redwood River (USA)	0.070	James et al. (2002)
Eau Galle River (USA)	0.129	James and Barko (2005)
Colorado River (USA)	0.040	Mayer and Gloss (1980)
Bermejo River (Argentina)	0.060	Carignan and Vaithiyanathan (1999)
Paraguay River (Argentina)	0.020-0.090	Carignan and Vaithiyanathan (1999)
Paraná River (Argentina)	0.005-0.021	Carignan and Vaithiyanathan (1999)
Bear Brook (USA)	0.002	Meyer (1979)
NY wooded streams (USA)	<0.002	Klotz (1985)
Lower Missisippi River (USA)	0.108	Wauchope and McDowell (1984)
Xiangxi River (China)	0.100	Chang-ying et al. (2006)

FIGURES

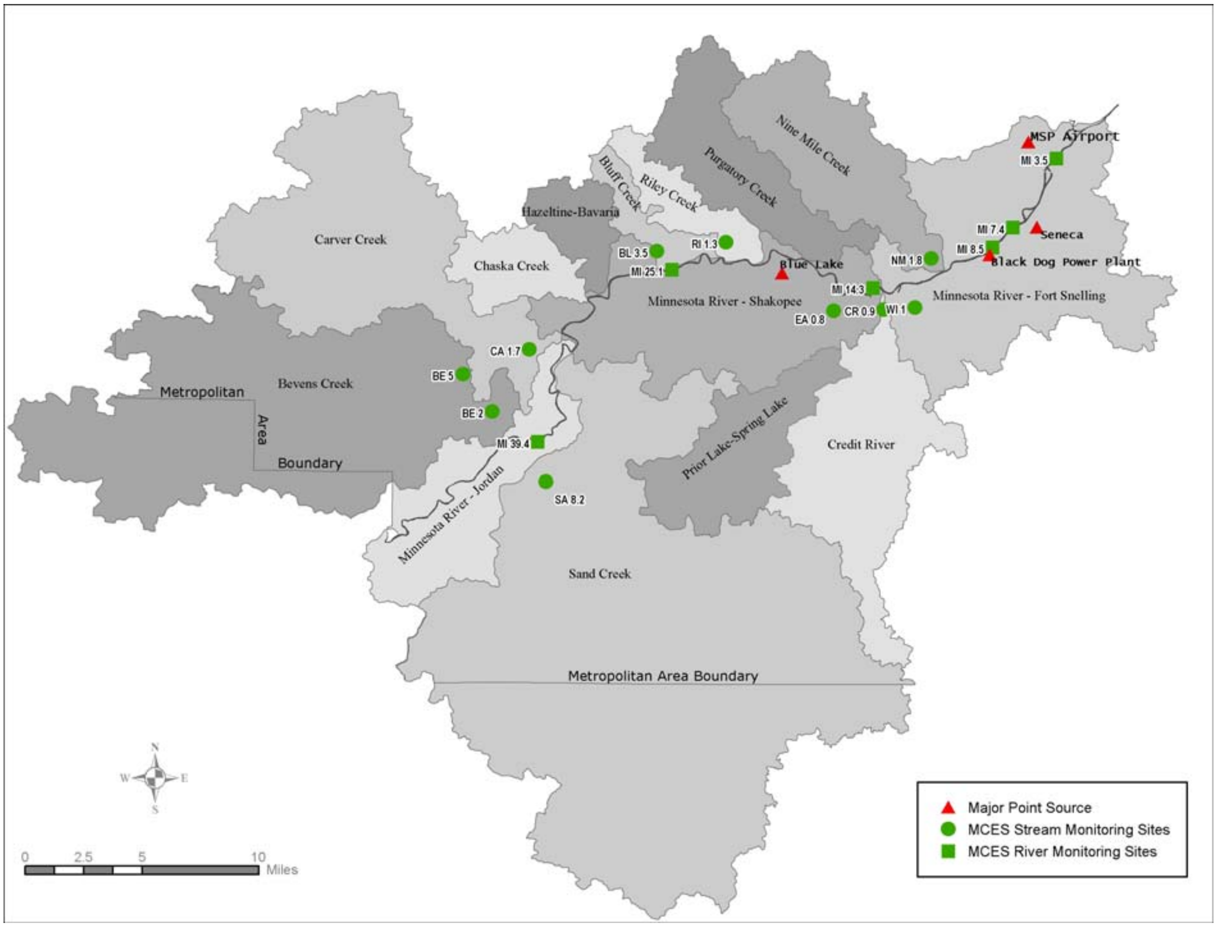


Figure 1. Map of minor watersheds, major point sources, and MCES monitoring stations in the study area (Matthew McGuire, MCES).

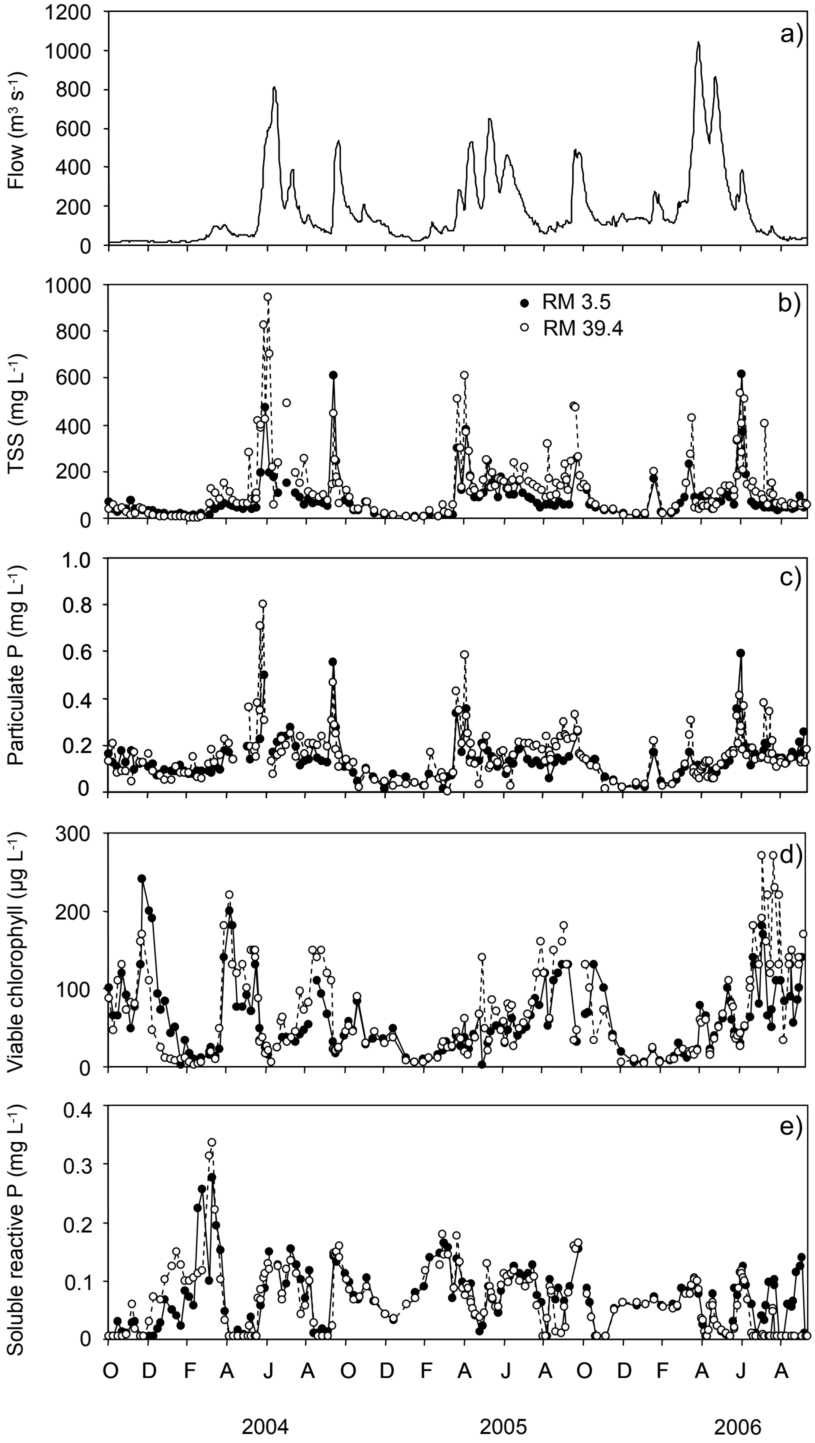


Figure 2. Variations in (a) flow, (b) total suspended sediment (TSS), (c) particulate phosphorus (P), (d) viable chlorophyll, and (e) soluble reactive P.

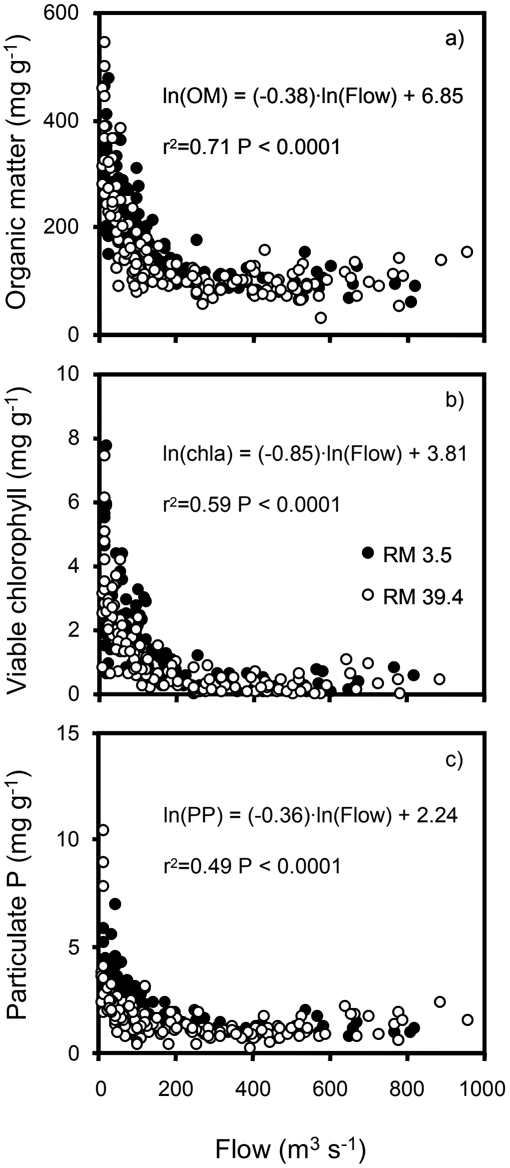


Figure 3. Relationships between flow and (a) organic matter (as loss on ignition; OM), (b) viable chlorophyll (CHLA) mass concentration, and (c) particulate P (PP) concentration for the April through November period, 2004-2006.

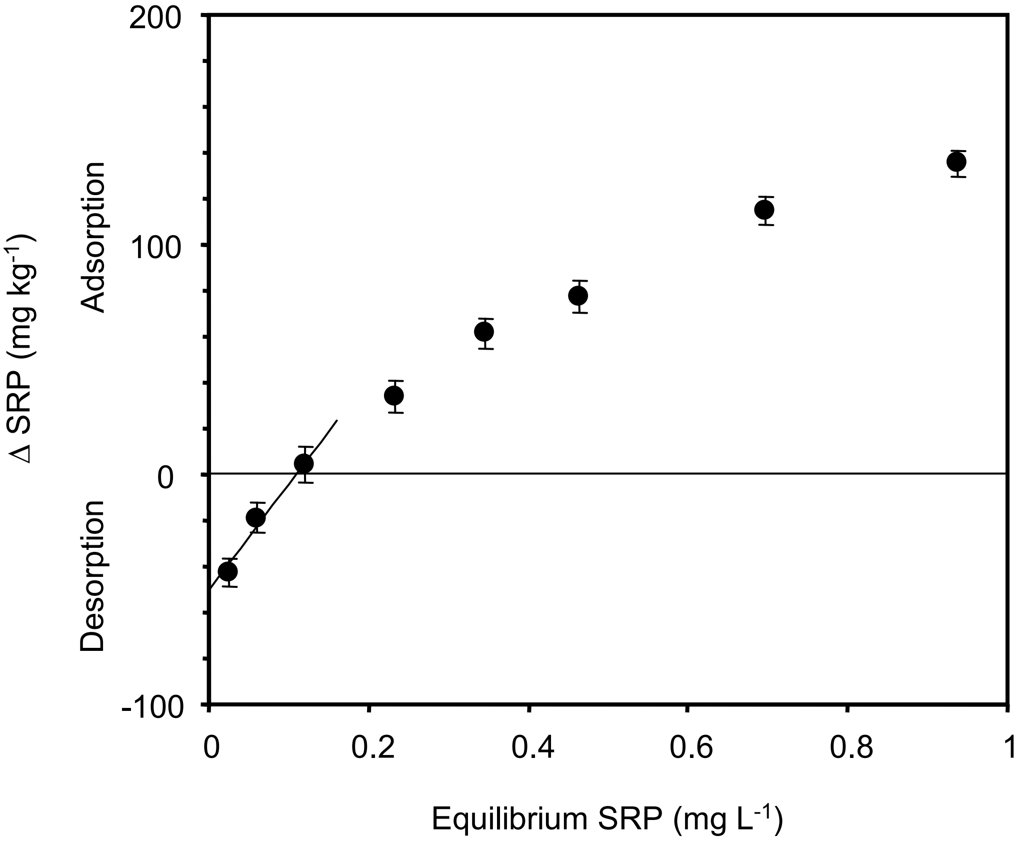


Figure 4. Means (± 1 SE; n=10) for soluble reactive phosphorus (SRP) desorption or adsorption versus equilibrium SRP. The sloped line represents the region on the curve used to estimate the equilibrium phosphate concentration (EPC) and linear adsorption coefficient (k_d).

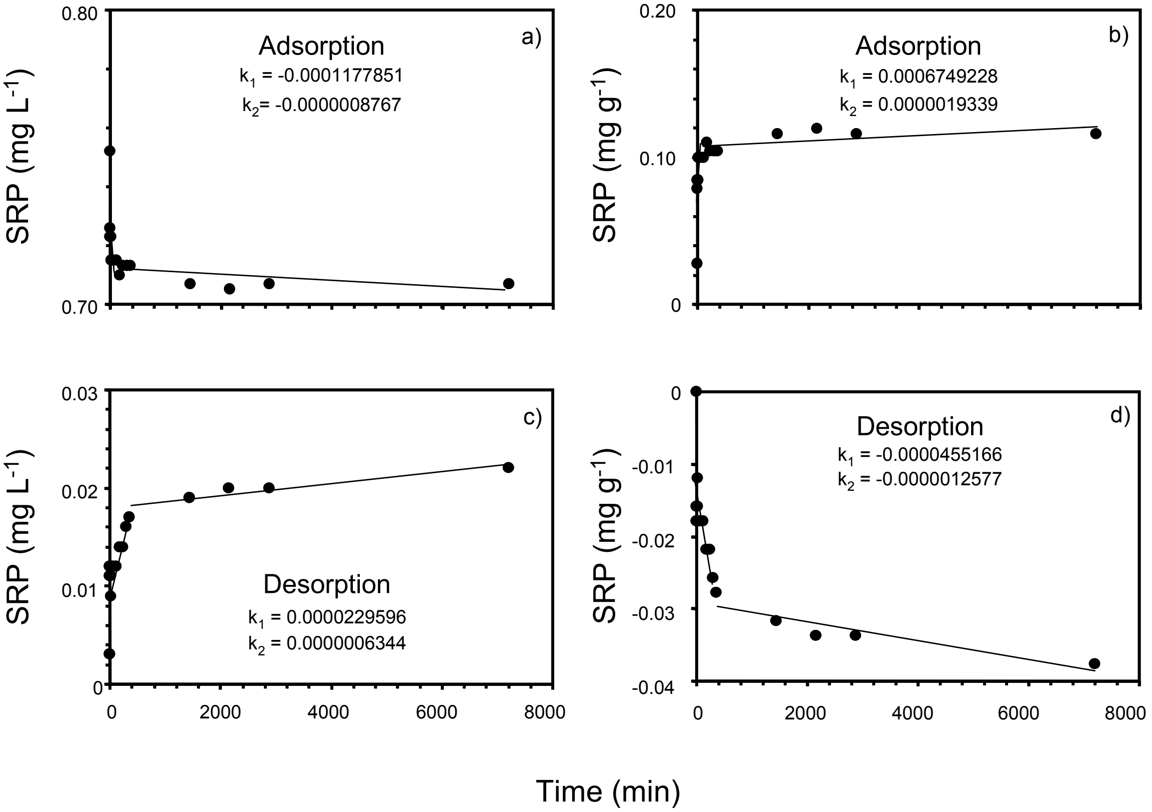


Figure 5. Variations in adsorption (panels 1 and b) and desorption (panels c and d) of soluble reactive phosphorus (SRP) as a function of time for suspended sediment collected at RM 3.5 in May, 2005. k_1 represents rapid kinetics; k_2 represents slow kinetics.

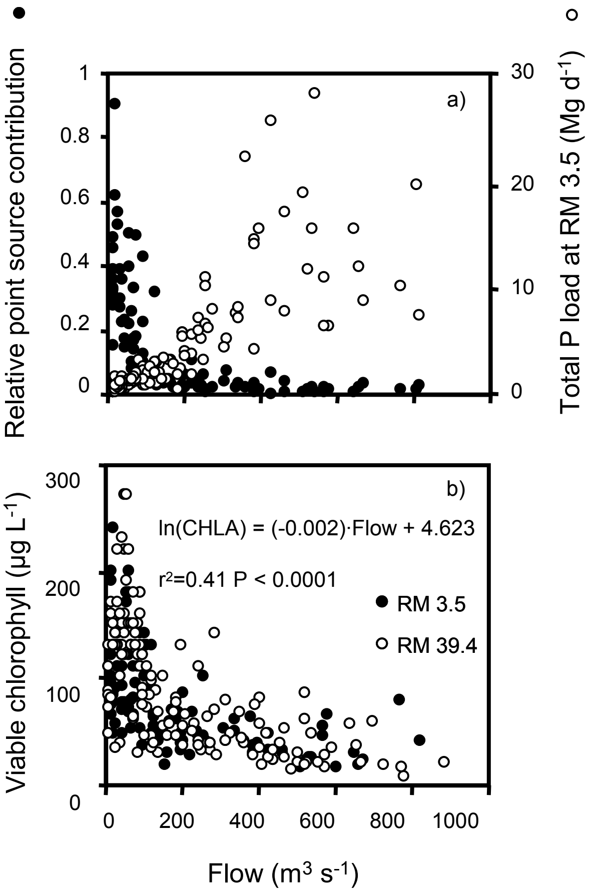


Figure 6. Relationships between flow and a) relative point source contribution (solid circles; Blue Lake and Seneca WWTP) or total phosphorus (P) load (open circles) for the Minnesota River at river mile (RM) 3.5 and b) viable chlorophyll concentration for the April through November period, 2004-2006.

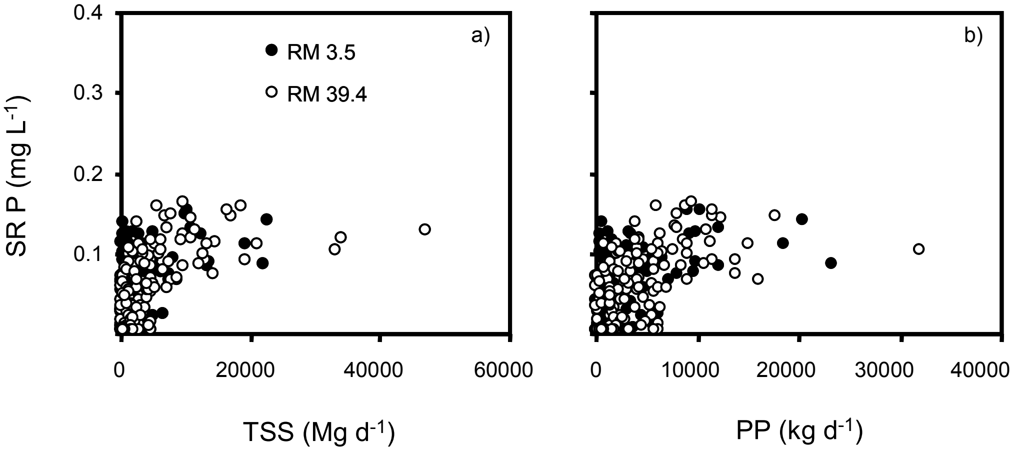


Figure 7. Relationships between soluble reactive phosphorus (SRP) concentration and a) total suspended solids (TSS) and b) particulate phosphorus (PP) for the April through November period, 2004-2006.

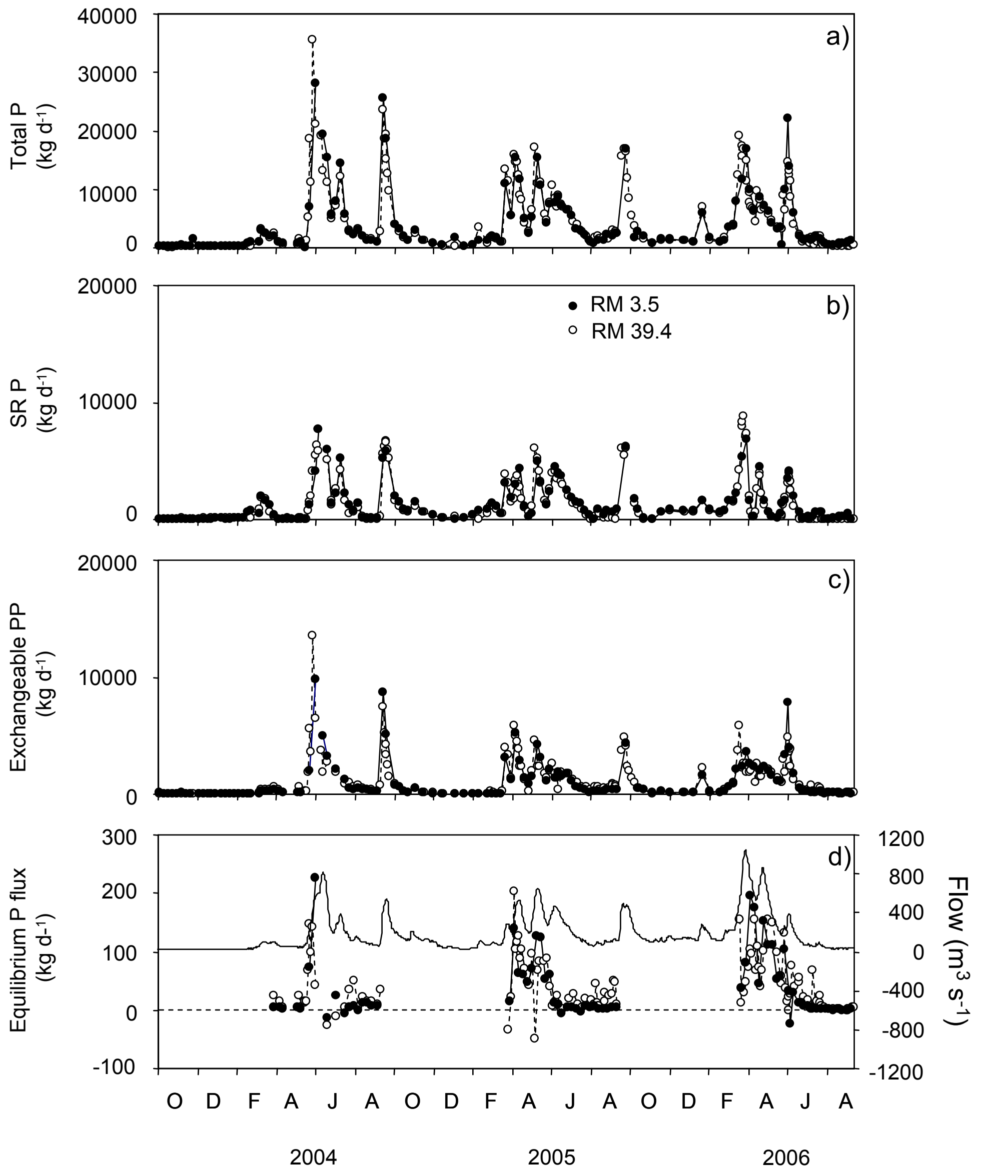


Figure 8. Variations in (a) total phosphorus (P) loading, (b) soluble reactive P (SRP) loading, (c) exchangeable particulate P (PP) loading (i.e., loosely-bound and iron-bound PP), and (d) flow and equilibrium P flux between particulate and aqueous phases. A positive equilibrium P flux represents desorption from exchangeable PP to the water column while a negative flux represents adsorption of P onto the exchangeable PP pool.

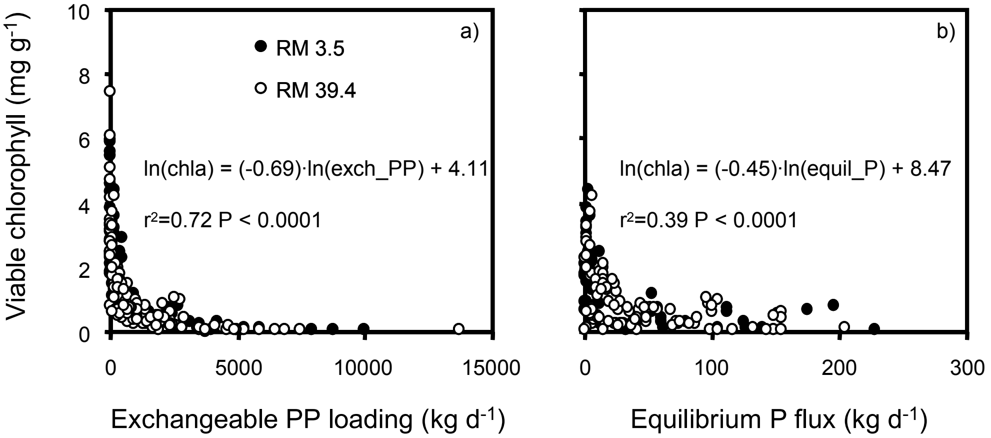


Figure 9. Relationships between viable chlorophyll mass concentration and a) exchangeable particulate P (PP) loading (i.e., loosely-bound and iron-bound PP) and b) equilibrium P flux (as desorption of P from particulate to aqueous phases) for the April through November period, 2004-2006.

.

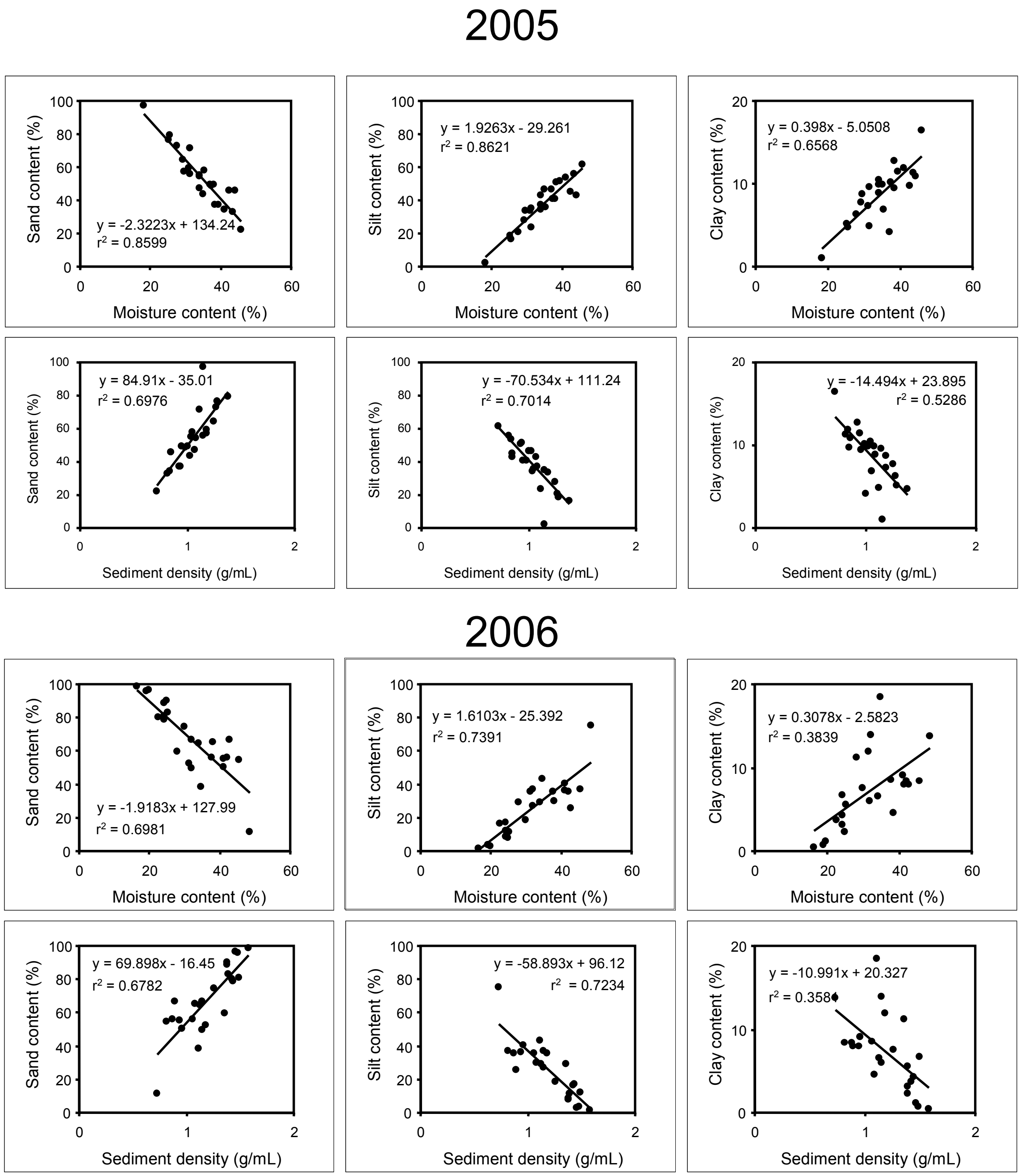


Figure 10. Linear relationships between particle size, moisture content, and sediment density for the upper 10 cm of bottom sediment collected in the lower Minnesota River in 2005 and 2006.

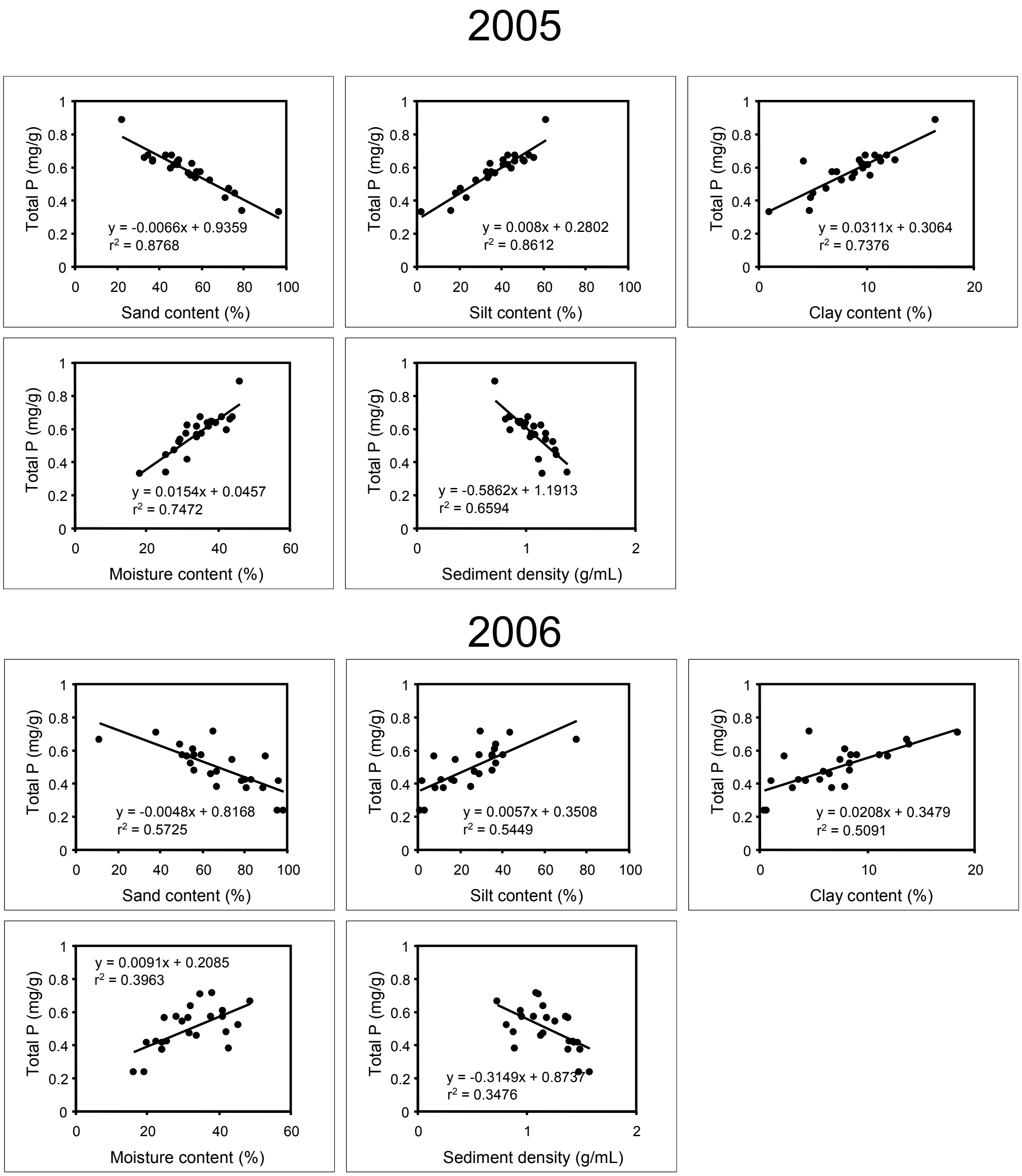


Figure 11. Linear relationships between particle size, moisture content, and sediment density versus total phosphorus (P) for the upper 10 cm of bottom sediment collected in the lower Minnesota River in 2005 and 2006.

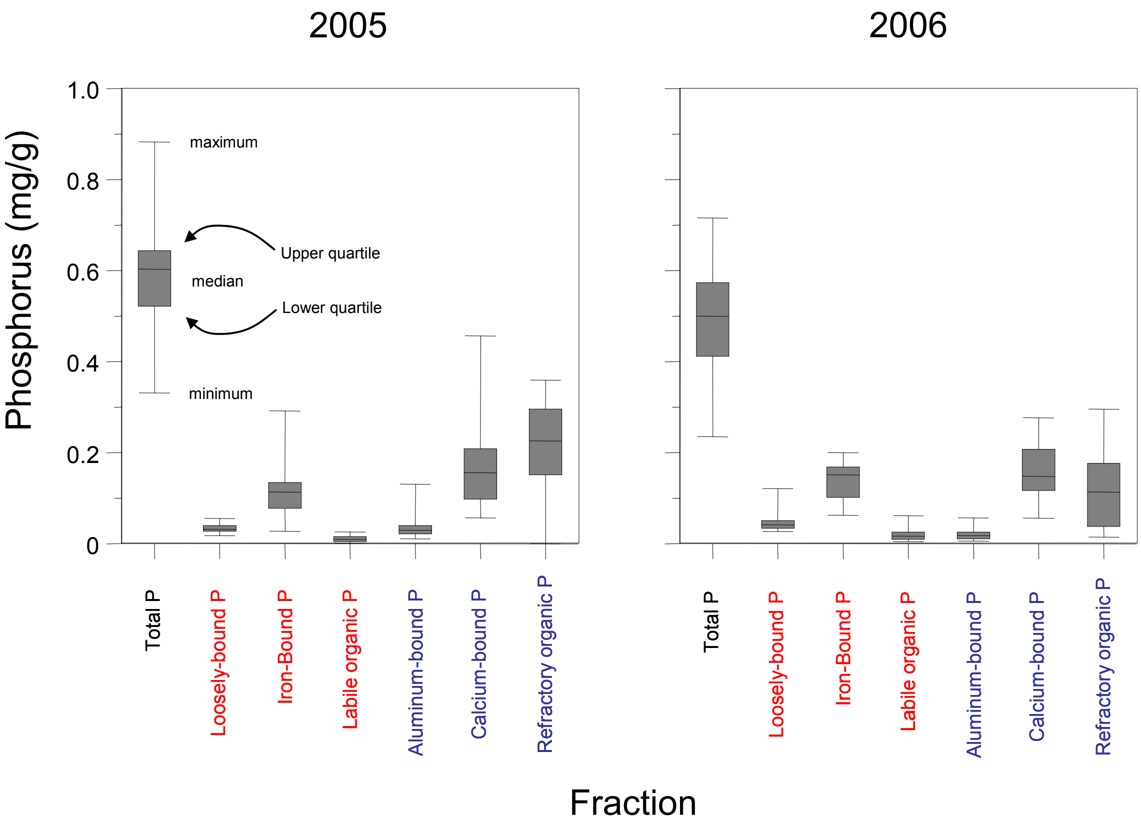


Figure 12. Box and whisker plots of total sediment phosphorus (P), biologically available (red fonts) P, and refractory P for the upper 10 cm of bottom sediment collected in the lower Minnesota River in 2005 and 2006.

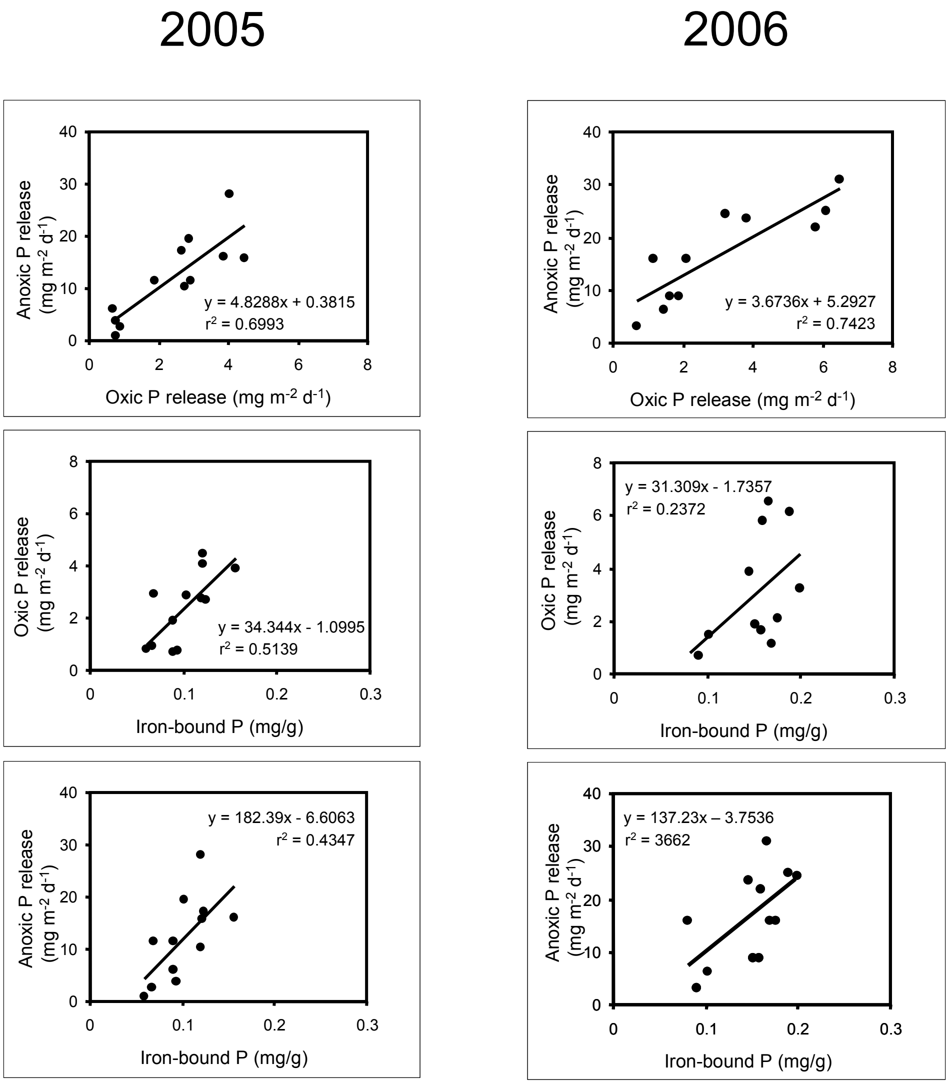


Figure 13. Linear relationships between rates of phosphorus (P) release from sediment under oxic versus anoxic conditions (upper panels) and the iron-bound sediment P concentration versus rates of P release from sediment under oxic and anoxic conditions (middle and lower panels).

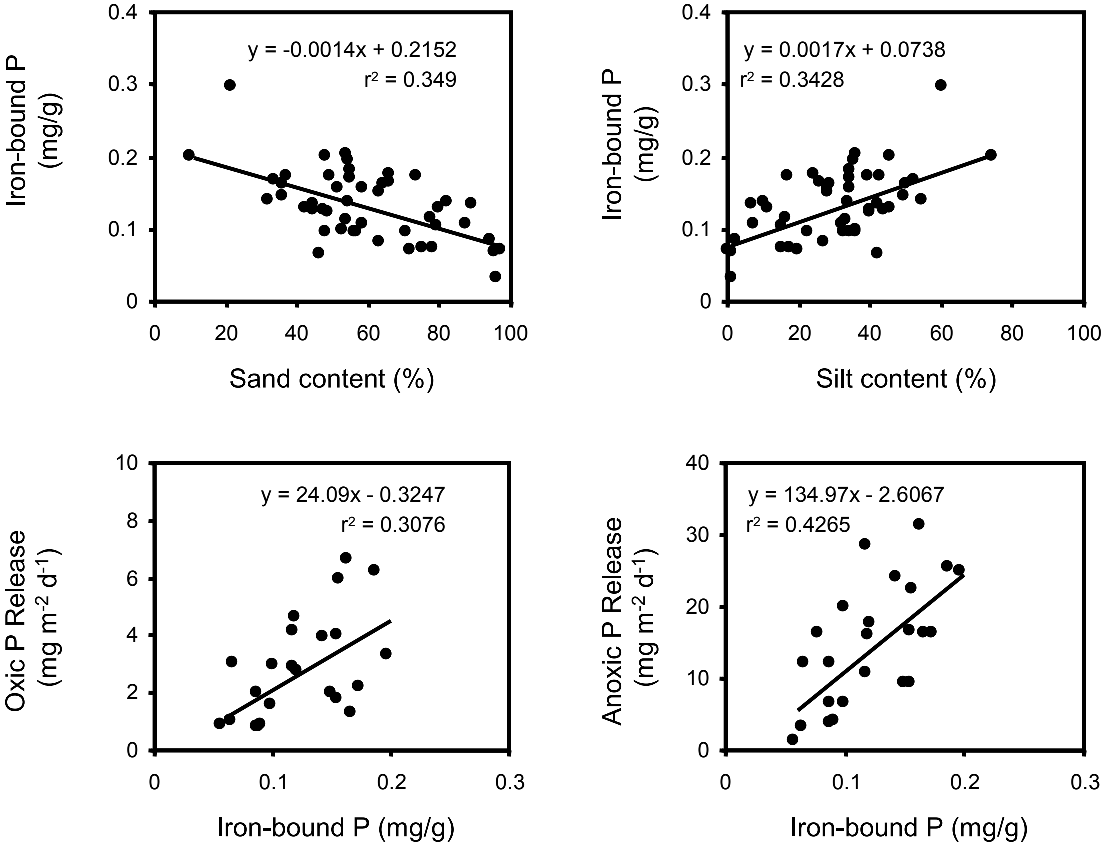


Figure 14. Relationships between sand or silt content and iron-bound P (upper panels) and iron-bound P versus phosphorus (P) release from sediments (lower panels).

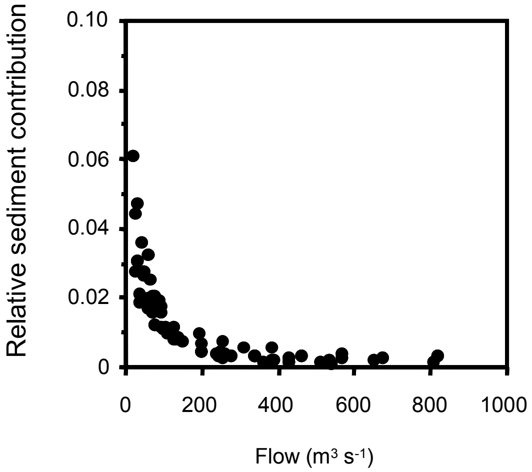


Figure 15. The relative contribution of phosphorus (P) release from sediment under oxic conditions to the P budget of the lower Minnesota River versus flow. The relative sediment P contribution was calculated as the system-wide rate of P release divided by total P loading at RM 3.5.

2006

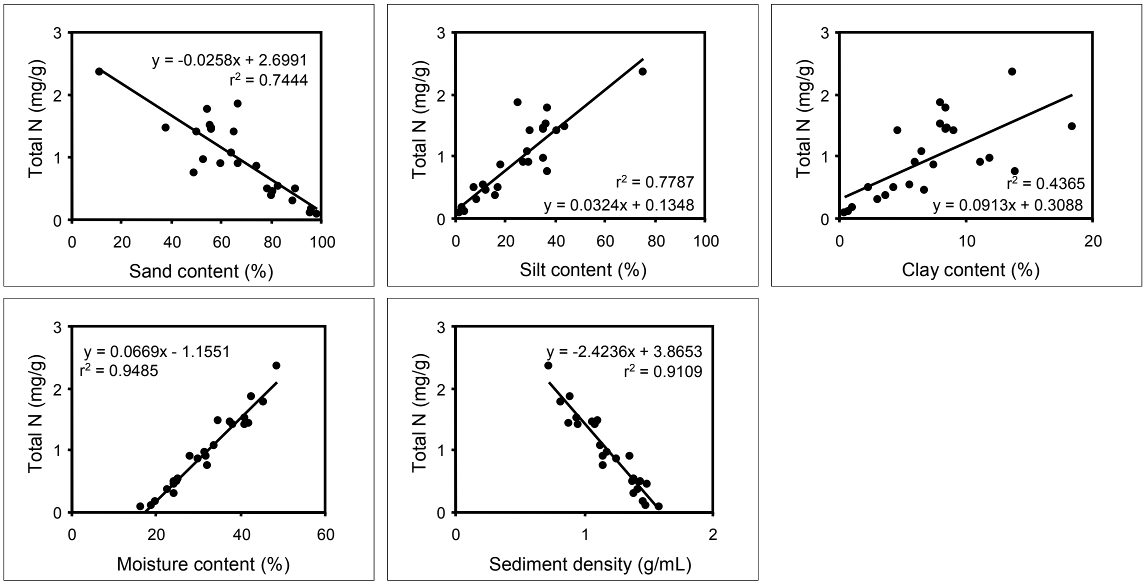
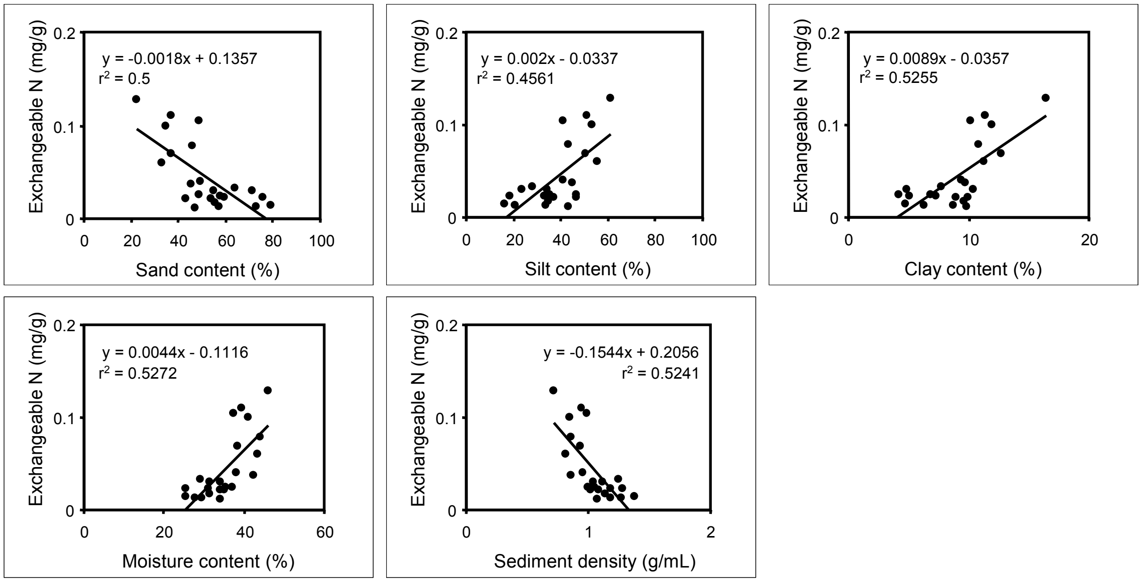


Figure 16. Linear relationships between sediment physical characteristics and total sediment nitrogen (N) concentrations.

2005



2006

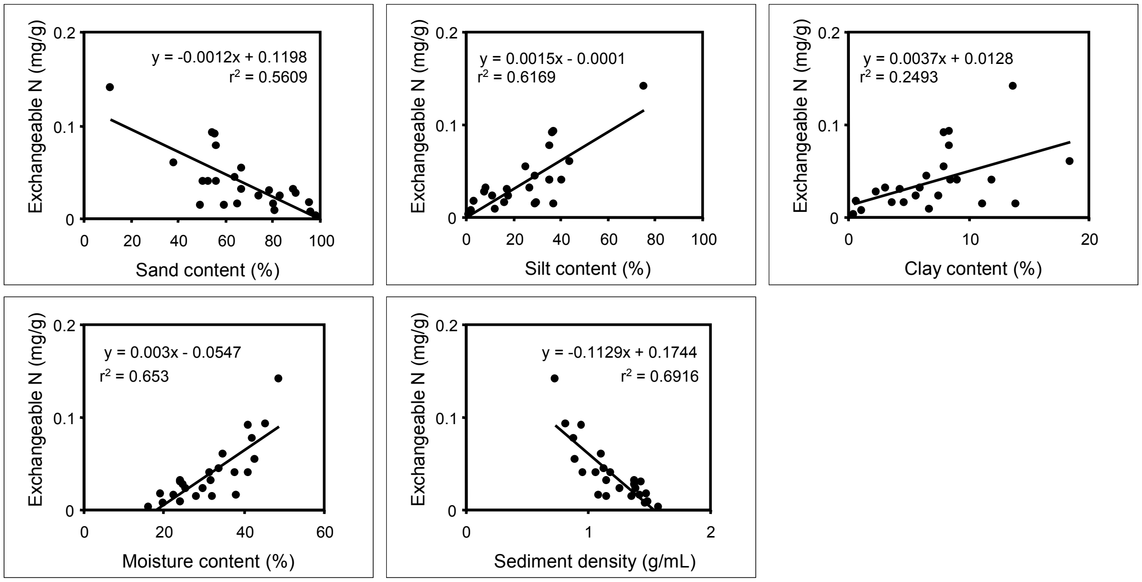


Figure 17. Linear relationships between sediment exchangeable ammonium (N) and sediment physical characteristics.

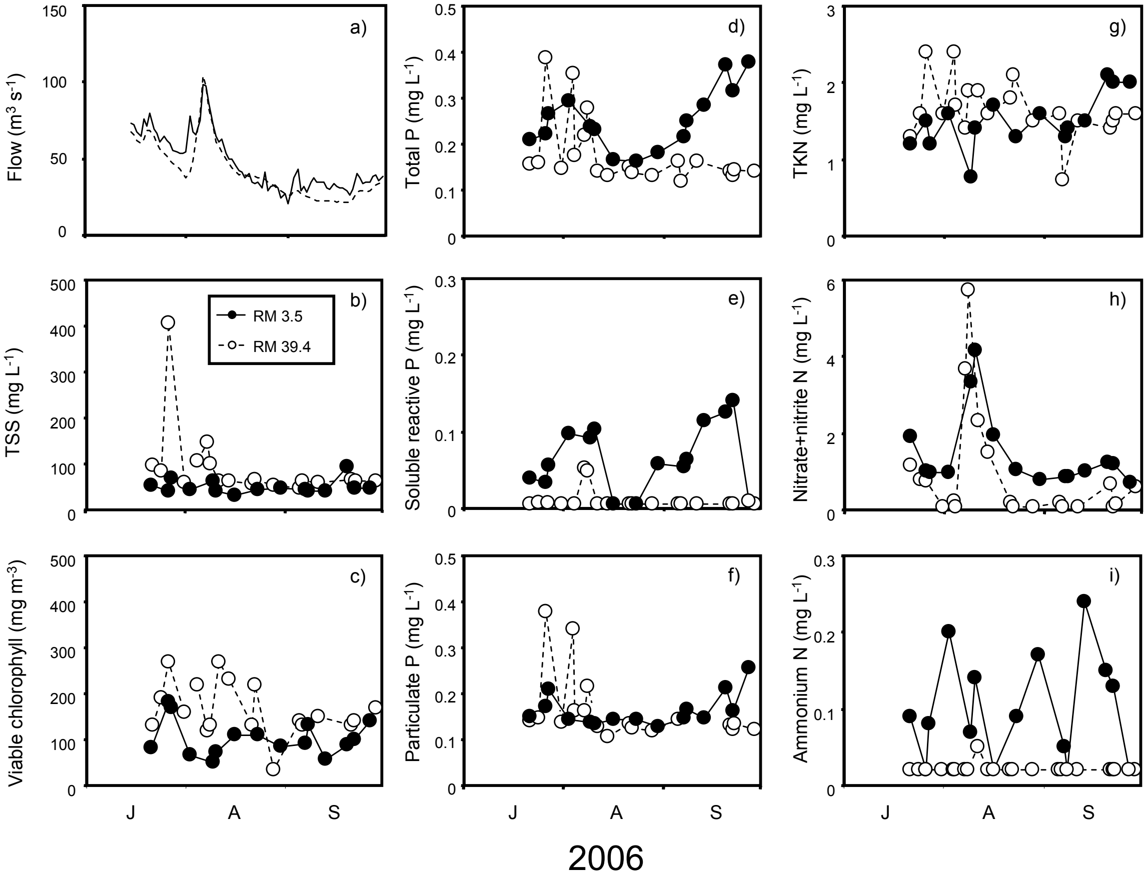


Figure 18. Variations in flow, total suspended solids (TSS), viable chlorophyll, phosphorus (P), and nitrogen (N) species during a period of very low flow between July and September, 2006.

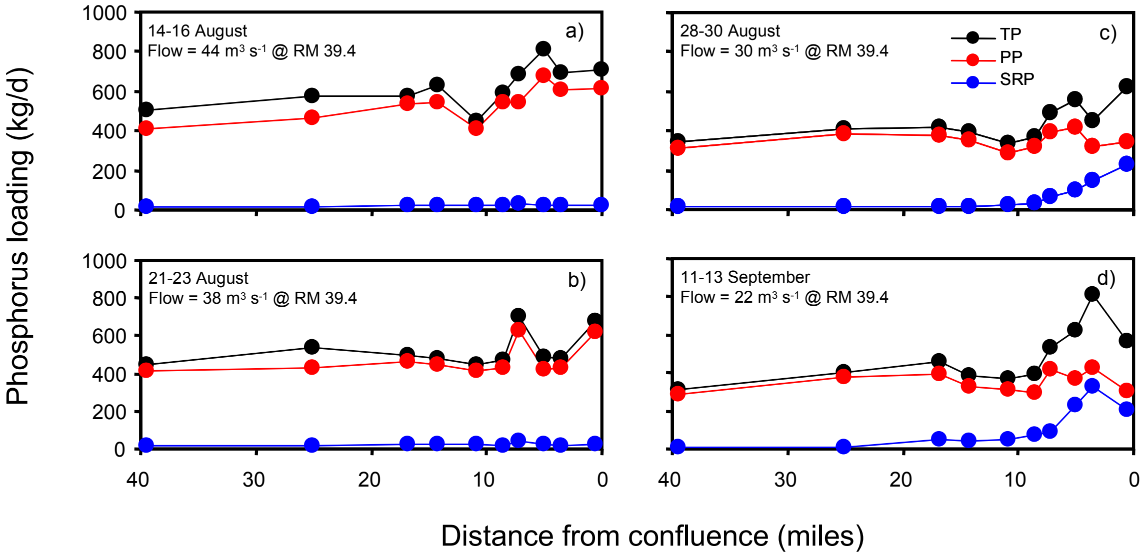


Figure 19. Estimated total (TP), particulate (PP), and soluble reactive P (SRP) loading along the longitudinal axis of the lower Minnesota River on four dates during the low flow period of 2006.

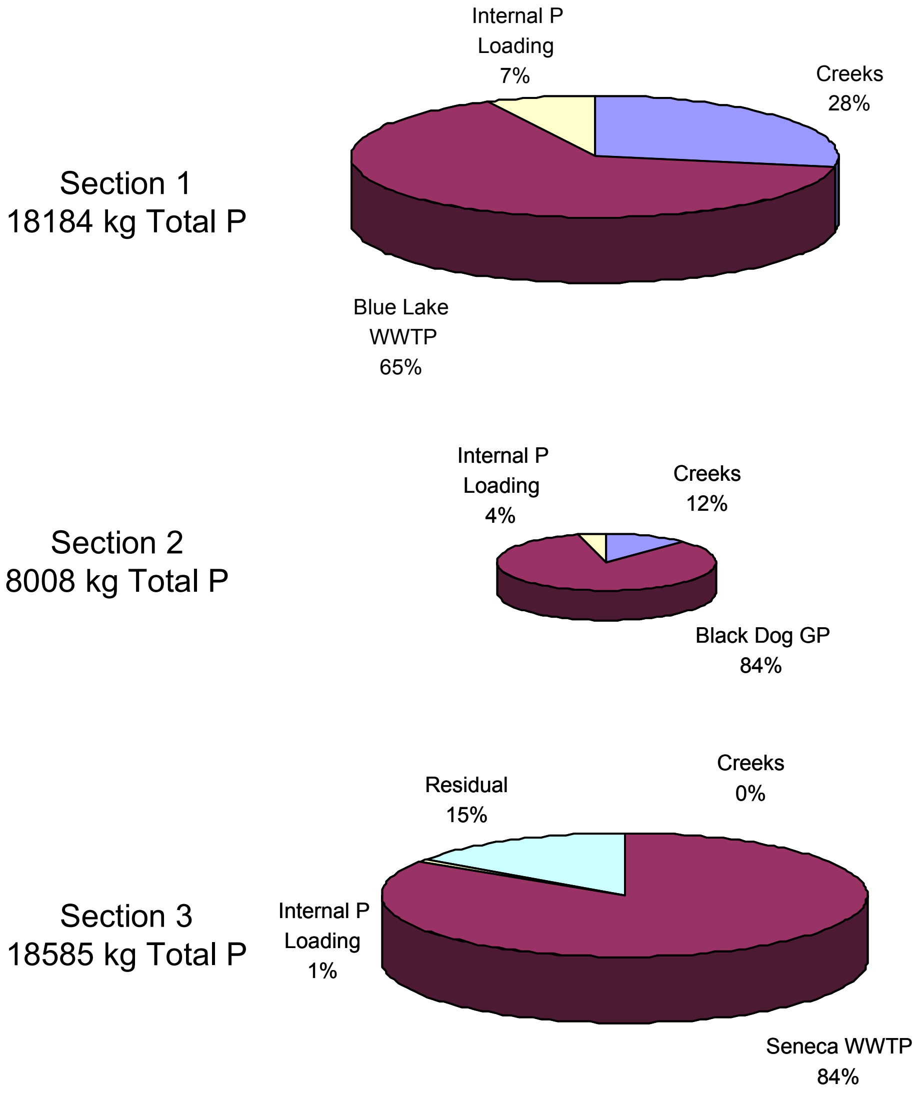


Figure 20. Contributions of various point and nonpoint source total phosphorus (P) inputs to the lower Minnesota River downstream of river mile (RM) 39.4. Section 1 = RM 39.4 to RM 14.3; Section 2 = RM 14.3 to RM 7.2; Section 3 = RM 7.2 to RM 3.5. Residual P inputs shown for Section 3 represent unmeasured P inputs estimated by difference. WWTP = wastewater treatment plant; Black Dog GP = Black Dog Generating Plant.

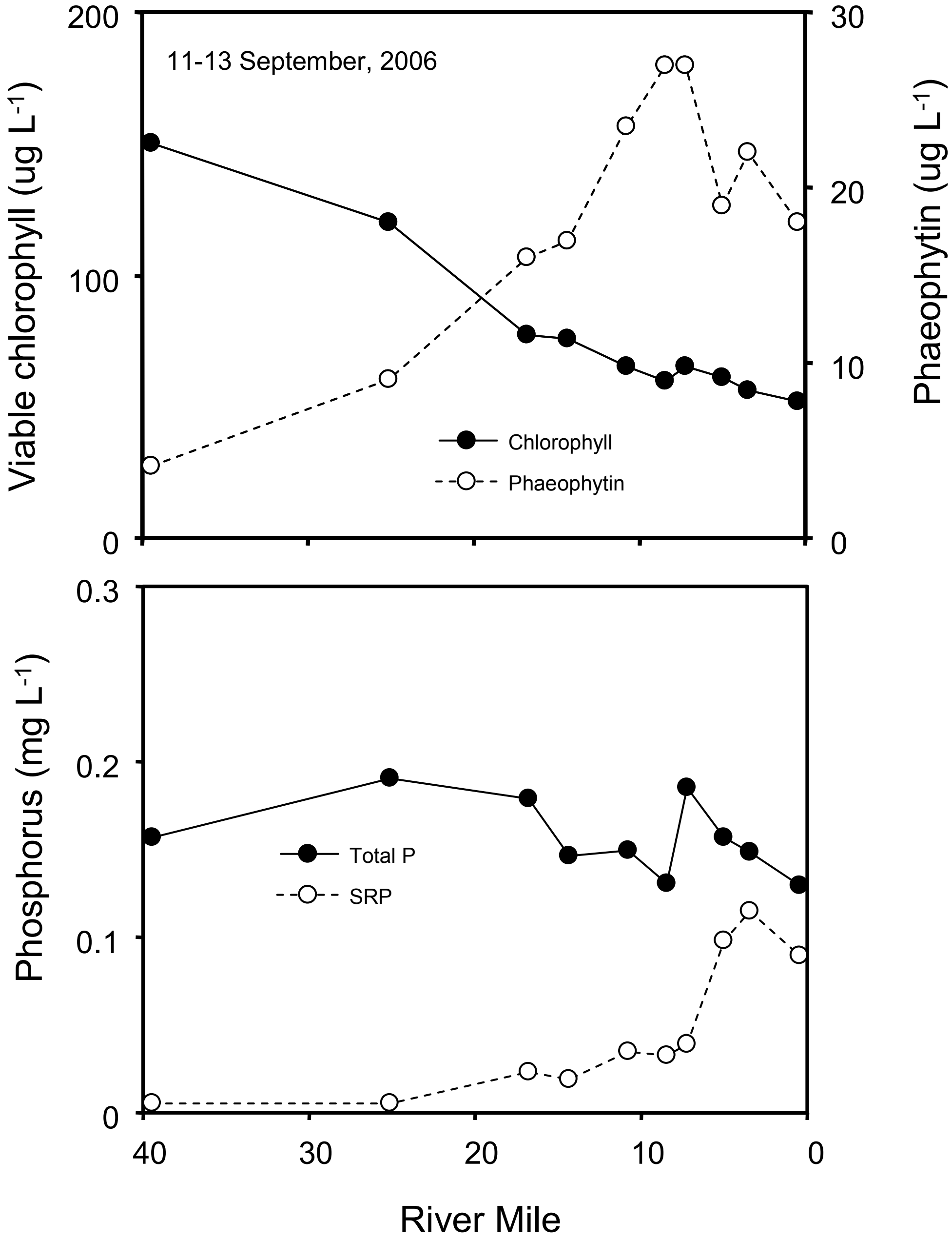
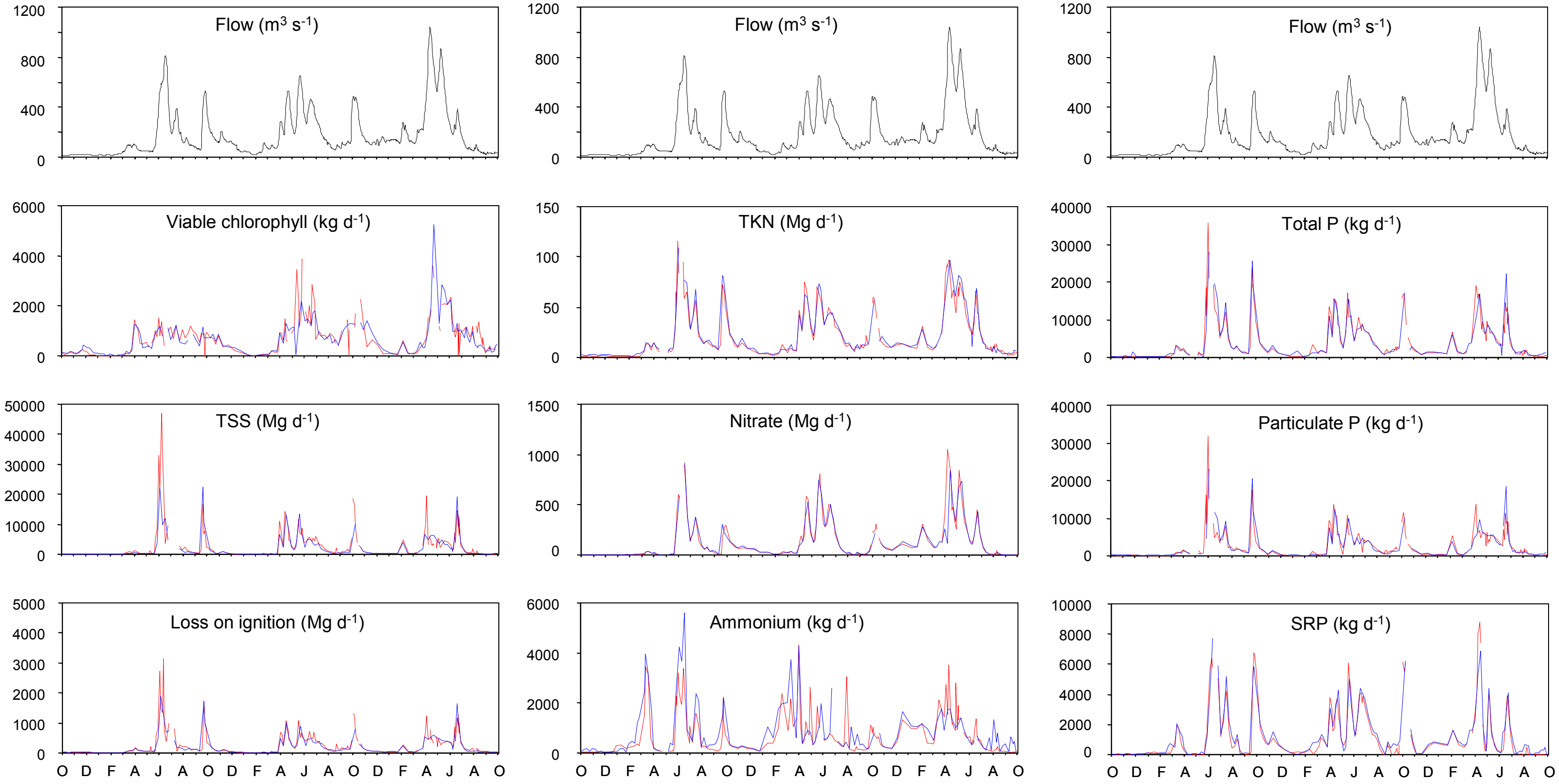


Figure 21. Longitudinal variations in viable chlorophyll, pheaophytin, total phosphorus (P), and soluble reactive P (SRP) during 11-13 September, 2006.



2003 - 2006

Figure 22. Variations in flow and constituent loading at river mile 39.4 (red lines) and 3.5 (blue lines) between October, 2003 and October, 2006.

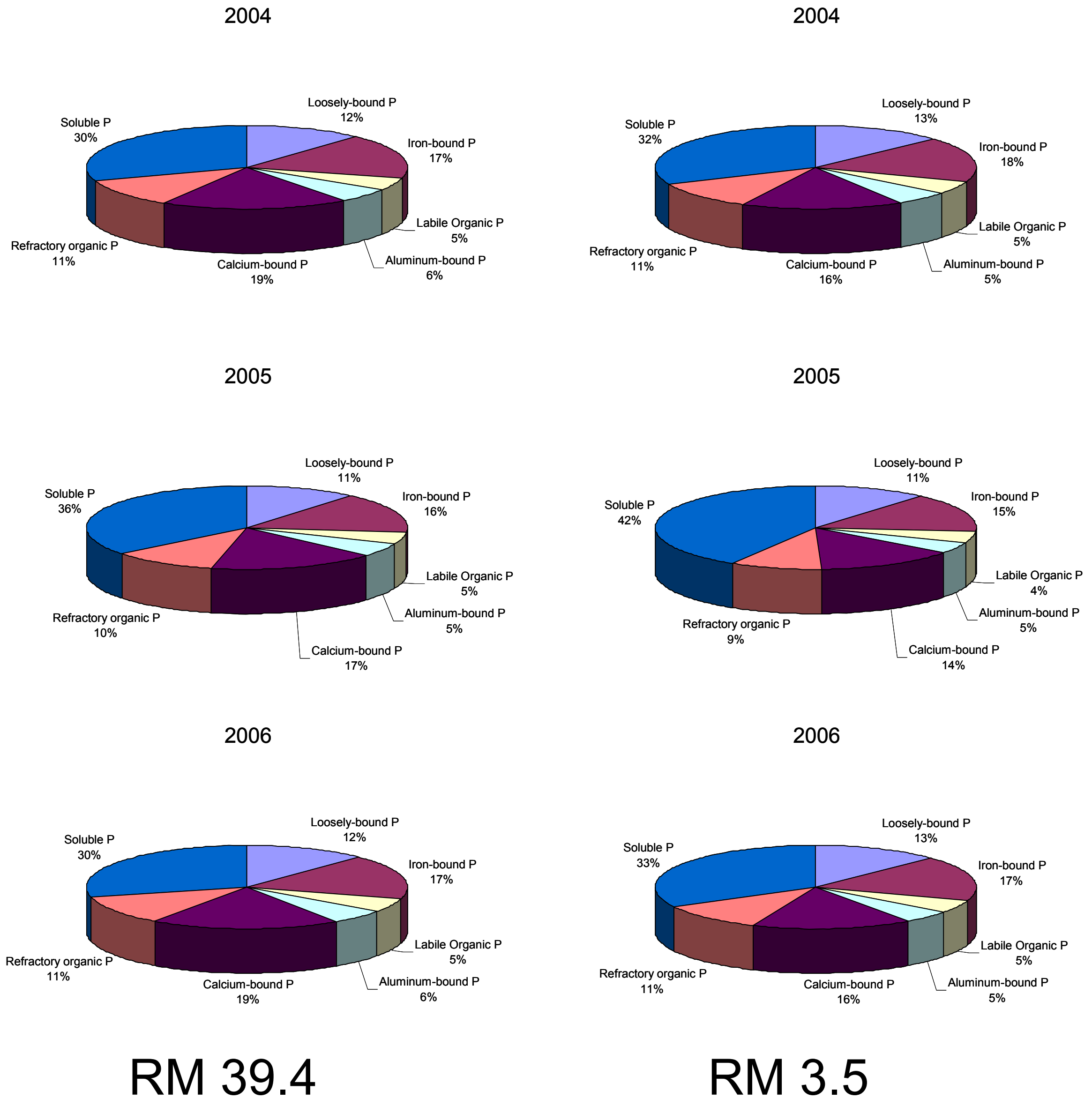


Figure 23. Percent contribution of soluble phosphorus (P) and biologically labile and refractory particulate P fractions to total P loading at river mile 39.4 and 3.5 of the lower Minnesota River. Partitioning of biologically labile and refractory particulate P fractions are based on extractions conducted on TSS collected from the Minnesota River during periods when flows exceeded 200 $m^3 s^{-1}$ in 2005-06.

APPENDICES

A1. Annual hydrological inputs and outputs for the water years 2004-06.

Annual 2004 Loads		Station	Flow (cfs)	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	4075	92.0
		Bluff Creek	4	0.1
		Carver Creek	35	0.8
		Chaska Creek	5	0.1
		Credit Creek	12	0.3
		Eagle Creek	8	0.2
		Nine-Mile Creek	17	0.4
		Purgatory Creek	13	0.3
		Riley Creek	4	0.1
		Sand Creek	86	2.0
		Willow Creek	4	0.1
		Total	4265	
	Point sources	Blue Lake WWTP	42	1.0
		Seneca WWTP	36	0.8
		Black Dog GP	86	1.9
		Other	3	0.1
		Total	168	
Output		Minnesota River at river mile 3.5	4462	
Net			-29	100.7

Annual 2005 Loads		Station	Flow (cfs)	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	5830	94.1
		Bluff Creek	5	0.1
		Carver Creek	27	0.4
		Chaska Creek	4	0.1
		Credit Creek	14	0.2
		Eagle Creek	8	0.1
		Nine-Mile Creek	19	0.3
		Purgatory Creek	18	0.3
		Riley Creek	2	0.0
		Sand Creek	99	1.6
		Willow Creek	4	0.1
		Total	6030	
	Point sources	Blue Lake WWTP	43	0.7
		Seneca WWTP	36	0.6
		Black Dog GP	86	1.4
		Other	4	0.1
		Total	169	
Output		Minnesota River at river mile 3.5	6303	
Net			-104	101.7

Annual 2006 Loads		Station	Flow (cfs)	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	7864	95.0
		Bluff Creek	5	0.1
		Carver Creek	58	0.7
		Chaska Creek	6	0.1
		Credit Creek	26	0.3
		Eagle Creek	8	0.1
		Nine-Mile Creek	21	0.3
		Purgatory Creek	18	0.2
		Riley Creek	ND	ND
		Sand Creek	148	1.8
		Willow Creek	5	0.1
		Total	8160	
	Point sources	Blue Lake WWTP	45	0.6
		Seneca WWTP	37	0.4
		Black Dog GP	34	0.4
		Other	5	0.1
		Total	121	
Output		Minnesota River at river mile 3.5	8370	
Net			-90	101.1

A2. Annual total phosphorus (P) inputs and outputs for the water years 2004-06. Blackdog GP is not included as a point source in the budget (insufficient analytical data).

Annual 2004 Loads		Station	Total P (kg/y)	Total P (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	1362796	0.374	0.09	92.3
		[illegible]				
		Bluff Creek	1731	0.524	0.20	0.1
		Carver Creek	7327	0.233	0.05	0.5
		Chaska Creek	1855	0.407	0.34	0.1
		Credit Creek	2920	0.272	0.07	0.2
		Eagle Creek	442	0.058	0.19	0.0
		Nine-Mile Creek	3220	0.206	0.15	0.2
		Purgatory Creek	4197	0.160	0.08	0.3
		Riley Creek	1575	0.445	0.12	0.1
		Sand Creek	50027	0.647	0.14	3.4
		Willow Creek	765	0.233	0.21	0.1
		Total	1436854			
	Point sources	Blue Lake WWTP	14678	0.387	0.04	1.0
		Seneca WWTP	25785	0.795	0.06	1.8
		Other				
		Total	40464			
Output		Minnesota River at river mile 3.5	1405095	0.352	0.09	
Net			72222			4.9
Annual 2005 Loads		Station	Total P (kg/y)	Total P (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	1402904	0.269	0.06	91.3
		Bevins Creek (upstream of 39.4)	14523	0.470	0.15	
		Bluff Creek	1738	0.394	0.16	0.1
		Carver Creek	7273	0.297	0.20	0.5
		Chaska Creek	632	0.173	0.23	0.0
		Credit Creek	4397	0.344	0.08	0.3
		Eagle Creek	416	0.057	0.13	0.0
		Nine-Mile Creek	4652	0.279	0.11	0.3
		Purgatory Creek	2700	0.166	0.13	0.2
		Riley Creek	125.00	0.083	0.29	0.0
		Sand Creek	44361	0.504	0.10	2.9
		Willow Creek	575	0.169	0.20	0.0
		Total	1469773			
	Point sources	Blue Lake WWTP	14067	0.376	0.04	0.9
		Seneca WWTP	52709	1.643	0.06	3.4
		Other				
		Total	66776			
Output		Minnesota River at river mile 3.5	1381346	0.245	0.06	
Net			155203			10.1
Annual 2006 Loads		Station	Total P (kg/y)	Total P (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	1505394	0.214	0.08	88.4
		Bevins Creek (upstream of 39.4)	35245	0.490	0.17	
		Bluff Creek	2652	0.615	0.32	0.2
		Carver Creek	[illegible]	[illegible]	[illegible]	[illegible]
		Chaska Creek	1272	0.228	0.57	0.1
		Credit Creek	6510	0.279	0.20	0.4
		Eagle Creek	442	0.059	0.17	0.0
		Nine-Mile Creek	2095	0.109	0.16	0.1
		Purgatory Creek	1772	0.110	0.21	0.1
		Riley Creek	ND	ND	ND	ND
		Sand Creek	96604	0.654	0.10	5.7
		Willow Creek	1110	0.249	0.27	0.1
		Total	1631055			
	Point sources	Blue Lake WWTP	35362	0.876	0.08	2.1
		Seneca WWTP	36289	1.109	0.05	2.1
		Other	239	0.168	0.55	0.0
		Total	71890			
Output		Minnesota River at river mile 3.5	1517663	0.203	0.10	
Net			185282			10.9

A3. Annual soluble reactive phosphorus (P) inputs and outputs for the water years 2004-06. Blackdog GP is not included as a point source in the budget (insufficient analytical data).

Annual 2004 Loads		Station	SRP (kg/y)	SRP (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	389698	0.107	0.06	89.9
		Bevins Creek (upstream of 39.4)	16168	0.300	0.07	
		Bluff Creek	371	0.112	0.07	0.1
		Carver Creek	1195	0.038	0.29	0.3
		Chaska Creek	616	0.135	0.11	0.1
		Credit Creek	996	0.093	0.11	0.2
		Eagle Creek	73	0.010	0.06	0.0
		Nine-Mile Creek	366	0.023	0.15	0.1
		Purgatory Creek	121	0.010	0.25	0.0
		Riley Creek	119	0.034	0.13	0.0
		Sand Creek	14439	0.187	0.10	3.3
		Willow Creek	121	0.067	0.20	0.0
		Total	408115			
	Point sources	Blue Lake WWTP	7211	0.190	0.20	1.7
		SenecaWWTP	18211	0.561	0.31	4.2
		Other				
		Total	25422			
Output		Minnesota River at river mile 3.5	412217	0.103	0.09	
Net			21320			4.9

Annual 2005 Loads		Station	SRP (kg/y)	SRP (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	461762	0.089	0.06	88.7
		Bevins Creek (upstream of 39.4)	6331	0.205	0.24	
		Bluff Creek	537	0.122	0.22	0.1
		Carver Creek	1369	0.056	0.35	0.3
		Chaska Creek	371	0.101	0.18	0.1
		Credit Creek	1688	0.132	0.22	0.3
		Eagle Creek	59	0.008	0.05	0.0
		Nine-Mile Creek	368	0.022	0.18	0.1
		Purgatory Creek	115	0.007	0.18	0.0
		Riley Creek	39.00	0.026	0.01	0.0
		Sand Creek	15193	0.172	0.20	2.9
		Willow Creek	96	0.028	0.13	0.0
		Total	481597			
	Point sources	Blue Lake WWTP	6892	0.182	0.10	1.3
		Seneca WWTP	32313	1.007	0.23	6.2
		Other				
		Total	39205			
Output		Minnesota River at river mile 3.5	513897	0.091	0.06	
Net			6905			1.3

Annual 2006 Loads		Station	SRP (kg/y)	SRP (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	427398	0.061	0.13	82.9
		Bevins Creek (upstream of 39.4)	15869	0.221	0.55	
		Bluff Creek	587	0.136	0.17	0.1
		Carver Creek	3196	0.062	0.25	0.6
		Chaska Creek	592	0.110	0.54	0.1
		Credit Creek	2050	0.088	0.07	0.4
		Eagle Creek	93	0.012	0.10	0.0
		Nine-Mile Creek	408	0.021	0.18	0.1
		Purgatory Creek	138	0.008	0.24	0.0
		Riley Creek	ND	ND	ND	ND
		Sand Creek	15648	0.118	0.17	3.0
		Willow Creek	101	0.023	0.38	0.0
		Total	450211			
	Point sources	Blue Lake WWTP	34874	0.864	0.23	6.8
		Seneca WWTP	30603	0.935	0.18	5.9
		Other	106	0.074	0.79	0.0
		Total	65583			
Output		Minnesota River at river mile 3.5	450477	0.060	0.14	
Net			65317			12.7

A4. Annual total Kjeldahl nitrogen (TKN) inputs and outputs for the water years 2004-06. Blackdog GP is not included as a point source in the budget (insufficient analytical data).

Annual 2004 Loads		Station	TKN (kg/y)	TKN (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	6001984	1.646	0.06	90.8
		Bluff Creek	6171	1.868	0.15	0.1
		Carver Creek	82077	2.606	0.12	1.2
		Chaska Creek	6583	1.444	0.13	0.1
		Credit Creek	13546	1.262	0.08	0.2
		Eagle Creek	2350	0.310	0.15	0.0
		Nine-Mile Creek	20186	1.290	0.13	0.3
		Purgatory Creek	22667	1.897	0.05	0.3
		Riley Creek	6639	1.877	0.12	0.1
		Sand Creek	281311	3.637	0.09	4.3
		Willow Creek	4818	1.464	0.17	0.1
		Total	6448332			
	Point sources	Blue Lake WWTP	79713	2.102	0.02	1.2
		Seneca WWTP	84282	2.598	0.02	1.3
		Other				
		Total	163995			
Output		Minnesota River at river mile 3.5	6918528	1.733	0.06	
Net			-306201			104.6

Annual 2005 Loads		Station	TKN (kg/y)	TKN (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	7225342	1.388	0.03	92.5
		Bluff Creek	6342	1.438	0.12	0.1
		Carver Creek	56746	2.316	0.09	0.7
		Chaska Creek	5917	1.616	0.24	0.1
		Credit Creek	18137	1.418	0.07	0.2
		Eagle Creek	2236	0.305	0.10	0.0
		Nine-Mile Creek	28281	1.697	0.90	0.4
		Purgatory Creek	30771	1.892	0.08	0.4
		Riley Creek	708	0.474	0.22	0.0
		Sand Creek	224037	2.543	0.05	2.9
		Willow Creek	3716	1.094	0.11	0.1
		Total	7602233			
	Point sources	Blue Lake WWTP	69133	1.821	0.02	0.9
		Seneca WWTP	144154	4.493	0.05	1.8
		Other				
		Total	213287			
Output		Minnesota River at river mile 3.5	7579811	1.347	0.03	
Net			235709			3.0

Annual 2006 Loads		Station	TKN (kg/y)	TKN (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	9365269	1.334	0.03	92.9
		Bluff Creek	7721	1.791	0.24	0.1
		Carver Creek	98357	1.901	0.08	1.0
		Chaska Creek	6602	1.183	0.16	0.1
		Credit Creek	30994	1.327	0.11	0.3
		Eagle Creek	2452	0.324	0.10	0.0
		Nine-Mile Creek	21444	1.337	0.07	0.2
		Purgatory Creek	1772	0.110	0.21	0.0
		Riley Creek	ND	ND	ND	ND
		Sand Creek	383099	2.895	0.08	3.8
		Willow Creek	4427	0.993	0.08	0.0
		Total	9922137			
	Point sources	Blue Lake WWTP	81121	2.010	0.02	0.8
		Seneca WWTP	78766	2.406	0.02	0.8
		Other	866	0.609	0.08	0.0
		Total	160753			
Output		Minnesota River at river mile 3.5	9715084	1.300	0.04	
Net			367806			3.6

A5. Annual nitrate plus nitrite nitrogen inputs and outputs for the water years 2004-06. Blackdog GP is not included as a point source in the budget (insufficient analytical data).

Annual 2004 Loads		Station	Nitrate (kg/y)	Nitrate (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	30040550	8.237	0.08	95.4
		Bluff Creek	2699	0.817	0.13	0.0
		Carver Creek	90378	2.869	0.23	0.3
		Chaska Creek	13218	2.900	0.20	0.0
		Credit Creek	12091	1.127	0.15	0.0
		Eagle Creek	2240	0.295	0.15	0.0
		Nine-Mile Creek	7327	0.468	0.11	0.0
		Purgatory Creek	5035	0.421	0.15	0.0
		Riley Creek	2410	0.682	0.06	0.0
		Sand Creek	478865	6.192	0.13	1.5
		Willow Creek	1386	0.421	0.15	0.0
		Total	30656199			
	Point sources	Blue Lake WWTP	382875	10.097	0.01	1.2
		Seneca WWTP	440707	13.584	0.01	1.4
		Other				
		Total	823582			
Output		Minnesota River at river mile 3.5	32682110	8.156	0.10	
Net			-1202329			103.8

Annual 2005 Loads		Station	Nitrate (kg/y)	Nitrate (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	45373490	8.715	0.04	97.4
		Bluff Creek	3111	0.705	0.10	0.0
		Carver Creek	43965	1.794	0.07	0.1
		Chaska Creek	6215	1.697	0.35	0.0
		Credit Creek	9707	759	0.08	0.0
		Eagle Creek	1617	0.221	0.06	0.0
		Nine-Mile Creek	7483	0.449	0.09	0.0
		Purgatory Creek	4521	0.278	0.10	0.0
		Riley Creek	2510.00	1.683	0.10	0.0
		Sand Creek	347443	3.944	0.10	0.8
		Willow Creek	1128	0.332	0.10	0.0
		Total	45801190			
	Point sources	Blue Lake WWTP	397950	10.480	0.01	0.9
		Seneca WWTP	378433	11.796	0.02	0.8
		Other				
		Total	776383			
Output		Minnesota River at river mile 3.5	48654140	8.644	0.08	
Net			-2076567			104.5

Annual 2006 Loads		Station	Nitrate (kg/y)	Nitrate (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	60955770	8.681	0.05	97.3
		Bluff Creek	2413	0.560	0.10	0.0
		Carver Creek	139259	2.691	0.10	0.2
		Chaska Creek	12459	2.231	0.05	0.0
		Credit Creek	30579	1.310	0.15	0.1
		Eagle Creek	1561	0.207	0.06	0.0
		Nine-Mile Creek	5814	0.304	0.10	0.0
		Purgatory Creek	4133	0.258	0.15	0.0
		Riley Creek	ND	ND	ND	ND
		Sand Creek	563449	4.247	0.10	0.9
		Willow Creek	1478	0.331	0.12	0.0
		Total	61716915			
	Point sources	Blue Lake WWTP	448343	11.142	0.01	0.7
		Seneca WWTP	460300	14.063	0.01	0.7
		Other	252	0.177	0.21	0.0
		Total	908895			
Output		Minnesota River at river mile 3.5	60166680	8.049	0.05	
Net			2459130			3.9

A6. Annual ammonium nitrogen inputs and outputs for the water years 2004-06. Blackdog GP is not included as a point source in the budget (insufficient analytical data).

Annual 2004 Loads		Station	Ammonium (kg/y)	Ammonium (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	183248	0.051	0.12	84.1
		Bluff Creek	107	0.032	0.19	0.1
		Carver Creek	1387	0.044	0.30	0.6
		Chaska Creek	268	0.059	0.32	0.1
		Credit Creek	955	0.089	0.26	0.4
		Eagle Creek	265	0.035	0.14	0.1
		Nine-Mile Creek	1730	0.111	0.31	0.8
		Purgatory Creek	4067	0.340	0.24	1.9
		Riley Creek	265	0.075	0.15	0.1
		Sand Creek	5735	0.074	0.24	2.6
		Willow Creek	727	0.221	0.30	0.3
		Total	198754			
	Point sources	Blue Lake WWTP	9563	0.252	0.08	4.4
		Seneca WWTP	9544	0.294	0.12	4.4
		Other				0.0
		Total	19107			
Output		Minnesota River at river mile 3.5	327041	0.082	0.15	
Net			-109180			150.1

Annual 2005 Loads		Station	Ammonium (kg/y)	Ammonium (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	208142	0.040	0.16	71.1
		Bluff Creek	303	0.069	0.43	0.1
		Carver Creek	1733	0.071	0.33	0.6
		Chaska Creek	161	0.044	0.20	0.1
		Credit Creek	304	0.024	0.07	0.1
		Eagle Creek	243	0.033	0.14	0.1
		Nine-Mile Creek	1945	0.117	0.23	0.7
		Purgatory Creek	2533	0.156	0.33	0.9
		Riley Creek	102	0.068	0.30	0.0
		Sand Creek	6010	0.068	0.24	2.1
		Willow Creek	468	0.138	0.28	0.2
		Total	221944			
	Point sources	Blue Lake WWTP	6437	0.170	0.08	2.2
		Seneca WWTP	63692	1.985	0.10	21.8
		Other	615	0.098	0.20	0.2
		Total	70744			
Output		Minnesota River at river mile 3.5	373428	0.066	0.22	
Net			-80740			127.6

Annual 2006 Loads		Station	Ammonium (kg/y)	Ammonium (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	205120	0.029	0.09	89.1
		Bluff Creek	143	0.033	0.22	0.1
		Carver Creek	3451	0.067	0.29	1.5
		Chaska Creek	132	0.023	0.08	0.1
		Credit Creek	597	0.026	0.10	0.3
		Eagle Creek	238	0.031	0.12	0.1
		Nine-Mile Creek	824	0.043	0.16	0.4
		Purgatory Creek	1679	0.105	0.18	0.7
		Riley Creek	ND	ND	ND	ND
		Sand Creek	7949	0.060	0.15	3.5
		Willow Creek	320	0.072	0.26	0.1
		Total	220453			
	Point sources	Blue Lake WWTP	5082	0.126	0.04	2.2
		Seneca WWTP	4482	0.137	0.11	2.0
		Other	102	0.072	0.17	0.0
		Total	9666			
Output		Minnesota River at river mile 3.5	329577	0.044	0.16	
Net			-99458			143.2

A7. Annual total suspended solids inputs and outputs for the water years 2004-06. Blackdog GP is not included as a point source in the budget (insufficient analytical data).

Annual 2004 Loads		Station	TSS (kg/y)	TSS (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	1119044000	309.1	0.19	95.9
		Bluff Creek	647028	195.8	0.23	0.1
		Carver Creek	4249126	134.9	0.10	0.4
		Chaska Creek	583996	128.1	0.57	0.1
		Credit Creek	582680	54.3	0.21	0.1
		Eagle Creek	161474	212.9	0.31	0.0
		Nine-Mile Creek	1233856	78.8	0.32	0.1
		Purgatory Creek	581807	48.7	0.18	0.1
		Riley Creek	1451283	410.4	0.14	0.1
		Sand Creek	37945510	489.3	0.22	3.3
		Willow Creek	254538	77.3	0.47	0.0
		Total	1166735298			
	Point sources	Blue Lake WWTP	207968	5.5	0.05	0.0
		Seneca WWTP	146808	4.5	0.03	0.0
		Other	22156	14.0	0.20	0.0
		Total	376932			
Output		Minnesota River at river mile 3.5	708883300	179	0.17	
Net			458228930			39.3
Annual 2005 Loads		Station	TSS (kg/y)	TSS (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	859606300	165	0.09	96.7
		Bluff Creek	1263668	286	0.29	0.1
		Carver Creek	2765704	113	0.25	0.3
		Chaska Creek	460317	126	0.72	0.1
		Credit Creek	1173696	92	0.26	0.1
		Eagle Creek	89403	12	0.20	0.0
		Nine-Mile Creek	2826872	170	0.25	0.3
		Purgatory Creek	732281	45	0.12	0.1
		Riley Creek	28735.00	19	0.14	0.0
		Sand Creek	19751520	224	0.13	2.2
		Willow Creek	172598	51	0.30	0.0
		Total	888871094			
	Point sources	Blue Lake WWTP	162288	4	0.06	0.0
		Seneca WWTP	189702	6	0.03	0.0
		Other	41779	15	0.20	0.0
		Total	393769			
Output		Minnesota River at river mile 3.5	694589300	123	0.12	
Net			194675563			21.9
Annual 2006 Loads		Station	TSS (kg/y)	TSS (mg/L)	CV	Input (%)
Inputs	Nonpoint sources	Minnesota River at river mile 39.4	980185000	140	0.17	91.5
		Bluff Creek	1875966	435	0.42	0.2
		Carver Creek	4627685	89	0.12	0.4
		Chaska Creek	648180	116	0.75	0.1
		Credit Creek	3275708	140	0.39	0.3
		Eagle Creek	83737	11	0.20	0.0
		Nine-Mile Creek	654436	34	0.40	0.1
		Purgatory Creek	548142	34	0.28	0.1
		Riley Creek	ND	ND	ND	ND
		Sand Creek	79482780	600	0.18	7.4
		Willow Creek	147039	33	0.24	0.0
		Total	1071528673			
	Point sources	Blue Lake WWTP	129842	3	0.06	0.0
		Seneca WWTP	103955	3	0.03	0.0
		Other	28973	7	0.08	0.0
		Total	262770			
Output		Minnesota River at river mile 3.5	834103500	112	0.15	
Net			237687943			22.2