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Research Addendum for Peer Review

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Abstract

Minnesota has widespread water-quality impairments due to nonpoint-source (NPS) pollution generated by agricultural, urban, and other human-altered lands. Mitigation of these impairments requires implementing best-management practices (BMPs) that are designed to limit soil erosion and nutrient transport from lands to receiving waters. Long-term data sets of water quality and land-use history are needed to tease apart the many factors that impact water quality. In particular, data sets that span periods before and after BMP implementation are needed to determine BMP effectiveness. However, such data sets are lacking, because water-quality monitoring of our lakes and rivers did not begin until well after humans altered the landscape. In this project, we will fill this data gap by constructing long-term water-quality records as preserved in lake sediments. We will select five to ten lake basins in Minnesota for a detailed assessment of whole watershed loads of sediment and nutrients. The chronology of these loads will be compared against the history of land use and BMP implementation in each basin to search for correlations. Finally, watershed models will be fit to these basins as constrained by the long-term data extracted from the sediment-core records, thereby both testing and improving the models. The benefits include development of critical long-term data sets, a test of BMP effectiveness at the watershed scale, and improvement of modeling tools to make results more realistic and predictive. These results will be transmitted to state and local resource managers in a series of workshops in the Twin Cities and in each study watershed. The long-term data sets will greatly enhance the value of existing watershed monitoring in the state by providing temporal context, without which the current records are unanchored relative to natural, pre-industrial conditions.

Background

Nonpoint-source (NPS) pollution is a persistent and vexing water-quality problem in Minnesota and across the nation. Despite the relative success of the 1972 Clean Water Act (CWA) in addressing point-source pollution, significant water-quality impairments remain because of NPS pollution. However, NPS pollution is difficult to control because of the many diffuse sources scattered across the land and the various transport pathways that deliver pollutants to receiving waters. Mitigation of NPS pollution commonly requires establishment of best-management practices (BMPs) that are designed to limit soil erosion and nutrient transport from agricultural, urban, and other human-impacted lands. The development of agricultural BMPs began during the 1930s Dust Bowl era with the establishment of the Soil Conservation Service (now the Natural Resources Conservation Service). Recent federal farm bills have continued to promote good conservation practices through programs such as the Conservation Reserve Program (CRP), which in Minnesota has converted about 1.5 million acres of erodible cropland to perennial vegetation. About the same time, changes in technology allowed reduced tillage practices, which now account for about 30% of row crops in Minnesota (Figure 1). While these BMPs may create wildlife habitat and reduce soil erosion, their effectiveness in improving water quality is much less certain.

Whether a best management practice (BMP) is effective depends on both spatial and temporal scales, and the scale of BMP implementation is disjunct from its effect on water quality. By “effective” we mean a measurable reduction in the concentration (mass per volume) or load (mass per time) of a NPS pollutant generated by a landscape unit. Load per unit landscape area is termed “yield” (mass per time per area). The NPS pollutants of concern here are largely sediment and nutrients. Agricultural tillage and cropping BMPs are without doubt effective in reducing sediment and nutrient losses from test plots (a fraction of an acre) during a runoff event or growing season. Urban BMPs such as storm-water detention ponds certainly trap some sediment from their contributing basins. Thus, at small spatial scales and short temporal scales soon after BMP implementation, such BMPs must be effective to some degree.

However, water-quality impairments are defined for our lakes and rivers, not test plots. Here, “water quality” refers to the chemical and physical content of water resulting from processes occurring over entire watersheds and integrating multiple years. The question then becomes, how does the local and short-term effectiveness of BMPs scale up to full-sized watersheds over many years? Can we see water-quality improvement resulting from BMP implementation, or not? To know, we would need to have water-quality records spanning the period before and after BMP implementation. River or lake monitoring records over such long periods are rare to non-existent. The longest water-quality monitoring record in Minnesota is for suspended sediment in the Minnesota River at Mankato, which only extends back to 1968. The results are not encouraging: despite many years of BMP implementation in the contributing watershed, the suspended-sediment content at Mankato is worsening, not improving (Figure 2). Likewise, a shorter record from the Minnesota River at Jordan shows no improvement in sediment, phosphorus, or nitrate (Figures 3-4). The sediment accumulation record from Lake Pepin, which provides a long-term measure of erosion from the entire upper Mississippi River basin including the Minnesota River, echoes the same lack of improvement over the past 50 years and also shows that current accumulation rates are about ten times the natural background rate prior to Euroamerican settlement (Figure 5). Together, the sediment-core record and monitoring data lead to the following conclusions: the current erosion rates and riverine sediment loads are far above natural, and they’re not getting better.

Because of the lack of data documenting impairments of water bodies and (ideally) their recovery following mitigation efforts, water-resource managers have taken a dual approach. First, monitoring efforts are ramping up, at least since 2010 in Minnesota, to provide a statewide assessment of the current condition of our major rivers. This is exactly the right thing to do, yet it can only provide data on water quality going forward in time. It cannot go back in time to characterize our rivers and lakes prior to and during the vast changes in our landscape from urbanization, agriculture, and forestry. Nor can it predict the future effectiveness of BMP implementation.

The second approach of water-resource managers is to use computer models of NPS pollutant transport to estimate load reductions due to BMPs. By running watershed models of past conditions both with and without BMPs, researchers have estimated load reductions afforded by the past few decades of BMP implementation (e.g., USDA 2012). Because model algorithms and parameters are generally based on data from test plots, at which scale BMPs have noted effectiveness, model results can indicate substantial load reductions, which may be overly optimistic especially when scaled up to whole watersheds. Both state and national agricultural policy decisions are being informed in part by these model results, which have been used to justify the many millions of dollars spent on BMPs. Clearly, watershed models attempting to simulate BMP effectiveness in improving water quality are in dire need of being tested against real data. Yet, as noted above, real data are lacking.

Consequently, in this project we will fill the data gap by constructing long-term water-quality records as preserved in lake sediments. Each year, a lake lays down a layer of sediment, the composition of which can be used to infer watershed-scale loads of sediment and nutrients. As noted earlier, this approach has been used with success for very large basins: Lake Pepin sediments document the NPS pollution history of the upper Mississippi River basin, as do Lake St. Croix sediments for its basin. We here will select another five to ten lake basins within Minnesota for a similarly detailed assessment of whole watershed loads of sediment and nutrients. The chronology of these loads will be compared against the history of BMP implementation in each basin to search for correlations. Finally, watershed models will be fit to these basins as constrained by the long-term data extracted from the sediment-core records, thereby both testing and improving the models. The benefits include development of critical long-term data sets, a test of BMP effectiveness at the scale at which our waters are deemed impaired, and improvement of modeling tools to make results more realistic and predictive. The long-term data sets will greatly enhance the value of existing watershed monitoring in the state by providing temporal context, without which the current records are unanchored relative to natural, pre-industrial conditions. Limitations of the approach, which stem from complicated transport pathways from multiple sources at the watershed scale and from uncertainty in the sediment chronology, are discussed as needed below. State and local resource managers will be informed of the project results in a series of workshops, and summary fact sheets for each study watershed will be distilled from the final report for use by local managers.

Hypotheses

Minnesota has a nonpoint-source pollution problem, and our goal here is to identify and quantify the relative influences of the causal practices at the watershed scale. Which practices make the problem worse, which practices (namely, BMPs) make it better, and by how much? Strict falsification testing of current hypotheses regarding BMP effectiveness would require holding all other variables constant except the BMP in question. In practice, this approach is almost never strictly followed (Kuhn 1970, Cleland 2001) and is effectively unachievable even for experiments in controlled laboratory settings (Hempel 1966). The problem becomes more acute in the geological and environmental fields where long time frames and complex systems make controlling for all variables impossible. Especially for these natural sciences, inquiry consists of seeking clues, or evidence, of past events that explain current observations (Cleland 2001). Such evidence either corroborates (supports) or contradicts a stated hypothesis. Multiple lines of corroborating evidence add considerable weight to a hypothesis (Hempel 1966), yet all conclusions are equivocated by the degree to which other variables are uncontrolled. Care must be taken to not reject a true hypothesis based on limited contradicting evidence. In our case, we must not conclude BMP ineffectiveness based on poor water quality alone because it could well be that a BMP is effective but simply overwhelmed by other uncontrolled-for concurrent practices that impair water quality. We need ways to distinguish among the multiple factors (practices) affecting water quality. That is, we need to multiple lines of evidence in the face of multiple working hypotheses (Chamberlin 1897).

This project will use multiple lines of evidence recorded in lake-sediments as proxies for watershed-scale water quality. Many studies support the general observation that proxies in the lake sediment, such as sediment chemistry, algal remains, and radioisotopic signatures, are in fact related to watershed-scale processes and water quality. We will focus on the suspended sediment and phosphorus loadings in the watershed as reflected in the lake sediment, and plan on attaining a record at least a century long and ideally extending to before the arrival of Euroamerican settlers. The various time series developed from the sediment record will be assessed against the following set of hypotheses, as a first step:

H_o: Water quality has not changed (null hypothesis)
H_a: Water quality has changed
  H_{a1}: Water quality has improved
  H_{a2}: Water quality has worsened

Whether water quality has changed over time depends in part on the time period chosen for analysis. A common assumption (working hypothesis) seems to be that the bad farming practices in the early part of the 20th century have been replaced with more conservation-minded practices in the last few decades, implying that NPS pollution and water-quality degradation peaked sometime during the 1940-90 time period. Is this pattern borne out in the lake-sediment record? Differences between periods will be assessed either by breaking the data set into discrete time periods and testing whether they were sampled from the same population, or by parametric or non-parametric trends tests. The results will be interesting because we have few other long-term water-quality data records, but we must connect these data to causal factors.

There are many possible causal factors affecting watershed-scale water quality and loads of sediment and nutrients. Most of these factors are not mutually exclusive and are expected to be concurrent. Each study watershed will have its own unique combination of factors that worsen or improve water quality, with the net result determining whether H_o, H_{a1}, or H_{a2} is supported for the watershed as a whole.

Factors (i.e., BMPs) favoring H_{a1} that could improve water quality include the following:

- Gain of perennial cover as grassland (CRP) or alfalfa from row crops or other erodible lands
- Reduced tillage with greater residue
- Contour tillage, strip cropping, cover crops
- Buffer strips, filter strips, grassed waterways, and terraces
- Controlled drainage, bioreactors, and saturated buffers
- Wetland restoration to trap sediment and nutrients
- Low-impact development BMPs in urbanizing areas

Factors favoring H_{a2} that could worsen water quality include the following:

- Increased area of row crops
- Loss of perennial vegetation (both grasslands and forest)
- Increased tillage with less residue
- Increased precipitation driving overland runoff and channel scour
- Increased artificial drainage by ditches and tiles, and channelization of existing streams
- Loss of depressional storage on the landscape (wetlands)
- Increased application of inorganic fertilizer or manure
- Increased urbanization (affecting physical runoff and infiltration functions along with increasing sediment and nutrient loads)

Factors favoring H_o that could mask water-quality changes include the following:

- Compensating factors from the above lists
- Lags in the systems that delay water-quality change with respect to a causal factor (e.g., see Meals et al. 2010)

Regardless of whether H_o, H_{a1}, or H_{a2} is supported by the lake-sediment proxy evidence, the next set of analyses will be the same. We will seek correlations between the pattern of water-quality change and the pattern of historical change among the above factors in the watershed that can affect water quality. Significant correlations would help refine further hypotheses regarding mechanism. And because correlation is not causation, we will model watershed processes in order to assess whether purported correlations are mechanistically realistic. The modeling exercise will test not only purported correlations, but also the ability of the model itself to simulate transport processes and generate realistic loads of NPS pollutants.

Methodology

The proposal for this project lists four activities: site selection and characterization, lake-sediment collection and lab analysis, data statistical analysis and modeling, and knowledge transfer. The first three activities will be discussed here in the Methodology section, and the fourth in the Dissemination and Use section.

Activity 1: Select new sites, characterize watersheds, & document BMP histories

This activity has two principal outcomes: (i) site selection based on existing data and state-agency needs, and (ii) characterization of selected watersheds, particularly for land-use and BMP histories for the selected watersheds. Selection of the first few sites must be done rapidly, within the first few months of Year 1 (which begins 1 July 2014), to allow fieldwork before winter of that year.

(i) Site selection and analysis of existing database of lake-sediment records

A careful selection of study sites will be critical to the success of this research effort. We expect that our lake-sediment records will differ from one another depending on land-use history as well as local geographic conditions such as watershed size, topography, and soils. Moreover, the quality of sediment records (dating reliability, spatial coherence, temporal resolution) depends on lake morphometric factors such as lake depth, surface area, and bathymetric complexity, and hydrological factors affecting residence time, water-level fluctuations, and overall rates of sediment accumulation. Our selection strategy will thus focus on sites representing a range of land-use change and BMP implementation, and those sites likely to possess high-quality sediment records. We expect the principal study lakes will have significant riverine input with a mix of field and non-field (i.e., channel erosion) sources on a watershed scale. These lakes will be chosen to have enough volume and hydraulic residence time such that sediment trapping efficiencies will not have changed appreciably over the past several centuries, our main period of concern. Subsidiary lakes nested within the same watershed with simpler hydrology may be chosen as well to help tease apart field versus non-field sources. We will also consider availability of stream flow records within the study watersheds, given their value in calculating mass fluxes and calibrating watershed models. The U.S. Geological Survey will be contacted to assess the availability of water-quality data (principally suspended sediment data) that might not be evident from web-accessible sources. The total number of lakes to be sampled will depend on the complexity of the principal-lake watersheds selected. For example, if six principal-lake watersheds are chosen and each has one or two subsidiary lakes, then about 12 to 18 lakes would be included in the study.

Fortunately, the St. Croix Watershed Research Station (SCWRS), though previous research initiatives, holds a large database of ^{210}Pb-dated lake-sediment cores collected from throughout Minnesota (as well as world-wide). Statewide records currently exceed 130 lakes. These records will serve two functions in the proposed research: (1) as a basis for selecting new study sites with high-quality sediment records, and (2) for scaling up to a larger population of lakes and assessing regional differences owing to underlying gradients in geology, climate, and dominant land-use. We will first search our state-wide archive of lake-sediment cores to identify trends in sediment accumulation rates, and thus erosion rates, over the last century. Then, depending on watershed size and complexity, five to ten additional lake watersheds with representative BMP implementations in agricultural and urban settings will be chosen for detailed study. Site selection will mesh with state agency needs and consider existing initiatives (Sentinel Lake & Watersheds). Watersheds will be characterized for their physical features, land use, and BMP histories in consultation with watershed-specific local agencies.

The SCWRS core database will be screened for core records with reliable ^{210}Pb dating extending back to the early to mid-1800s. Records will be sorted by ecoregion (Omernik 1987) and temporally integrated on a common time-step (decadal back to 1930 and multi-decadal for earlier periods) to allow quantitative comparisons among sites. Lake-wide accumulation rates for total sediment and the inorganic fraction (representing mineral soil erosion) will be determined from core-specific accumulation rates corrected for sediment focusing – the preferential deposition of fine-grained sediments in the deeper areas of lake basin. Focusing correction will be based on ^{210}Pb inventories in the cores and previously measured rates of atmospheric ^{210}Pb deposition (Engstrom and Rose 2013, Hobbs et al. 2013). Mean rates of sediment accumulation and trends over time will be determined for each ecoregion and for specific sub-groups representing common land-use history – e.g., urban lakes in the Twin Cities area or agricultural lakes throughout southern Minnesota (approximately 30 each in our current database).

In addition to assessing regional patterns of erosion over time (and their likely historical drivers), we will also compare present-day sediment accumulation rates with watershed characteristics including watershed/lake area ratios and local land use, including extent of conservation practices. This effort will allow us to calculate sediment yields and evaluate modeled erosion estimates including those from the USLE (universal soil loss equation). Watersheds for roughly half the lakes in our data archive have been analyzed for land cover and other topographic variables by GIS (Engstrom et al. 2007). This detailed watershed assessment will allow us to evaluate the effects of local land-use on present-day erosion rates. Moreover, cores from these same lakes have been measured for sediment phosphorus, which we will use to estimate changes in P loading to the lakes over time. The sediment and phosphorus flux from Greenleaf Lake (LeSueur County) exemplify the results to be extracted from these lakes (Figure 6).

(ii) Watershed characterization of existing geography and land-use history

Watershed geography will be characterized with readily available spatial data sets principally for the purposes of modeling. Watershed boundaries and hydrologically conditioned flow networks will be obtained from the Minnesota Department of Natural Resources. LiDAR digital elevation models (DEMs) will be used to calculate stream power index (SPI) to identify sites of high erosion potential. Soils data will be obtained from the SSURGO database. Current land use will be based on recent USDA Crop Date Layer (CDL) satellite-derived grids, which provides good detail on areas of different crops. Hydrologically conditioned DEMs (based on 10-m grids or LiDAR if available) will be used to generate flow-length grids (distance between the grid cell and receiving water), thereby providing a measure of hydrologic proximity useful for weighting BMP impact.

The more difficult data to compile will be land-use and BMP histories. Some land-use change may be inferred by using earlier satellite imagery, e.g. the 1992 National Land Cover Dataset (NLCD), but pixel-interpretation algorithms were different from current methods and care must be taken to avoid spurious apparent changes. Statewide data on agricultural land cover are available back to 1982 from the National Resources Inventory (NRCS 2009). Countywide data on crop areas are available as digital tables from the National Agricultural Statistics Service (NASS) back to the 1970s, and as printed tables from the USDA Census of Agriculture back to the 1920s. Land-use practices on these agricultural lands will be assessed from a variety of sources, including local information from county soil and water conservation district (SWCD) offices, statewide databases tracking BMP implementation (e.g., BWSR e-link conservation database), and federal data on conservation practices and land retirement. Tillage transects summarize percentages of row-cropped land with conservation tillage for each county over the past two decades (MSU 2012). Data generated for the Conservation Effects Assessment Project (CEAP, see USDA 2012) will be queried to the degree available. We already possess snapshots of land polygons in the Conservation Reserve Program (CRP) in Minnesota for the 1990s and 2000s. Ultimately, data from agency-derived databases and spatial layers will need to be vetted by local agency personnel, likely from the SWCD offices, who provide the most direct knowledge to “ground-truth” the data. Land-cover, land-use, and BMP histories will be aggregated into time slices corresponding to those available in the sediment core records, probably no finer than decadal resolution.

Activity 2: Collect and analyze lake-sediment cores

Activity 2 comprises the field and laboratory work needed to develop the sediment-core records that will be interpreted to infer long-term, watershed-scale records of water quality in our study watersheds. New laboratory capability will be added to allow for analysis of historical and contemporary harmful algal types.

(i) Core collection

To calculate whole-basin mass fluxes (Engstrom and Rose 2013), about five sediment cores of 100-150 cm in length will be collected from each principal study lake with a piston corer equipped with a 6.5-cm diameter polycarbonate core barrel and operated from the lake surface with Mg-alloy drive-rods. To assure reaching sediment older than about 1800 C.E., deeper sediment sections will be collected as needed with a square-rod Livingstone piston sampler (Wright 1991). Core sites will be located using sonar and bathymetric maps in deep flat areas of the basin, distant from any steep slopes that might be subject to slumping. Cores will be either extruded vertically on site in 1-2 cm increments into polypropylene collection jars, or the overlying water and surface sediments will be stabilized using a gelling agent (e.g., Zorbitrol) with further subsampling of the cores done in the laboratory.

(ii) Geochemical analysis (LOI, nutrients, and C/N isotopes)

Samples will first be analyzed for dry-density (dry mass per volume of fresh sediment) and water, organic, and carbonate content by standard loss-on-ignition (LOI) techniques (Heiri et al. 2001). Subsamples from each core increment will be frozen for subsequent analysis of algal pigments, and the remaining sediments will be freeze dried for all other analyses and for core archiving.

Total sediment phosphorus and phosphorus fractions will be analyzed colorimetrically on a Lachat QuikChem 8000 Autoanalyzer following sequential peroxide/HCl digestion (Engstrom and Wright 1984) to quantify total P, organic P, iron- and aluminum-bound P, and carbonate-bound P at decadal resolution for the past 200 years (approximately 20 samples from each core). Phosphorus accumulation in sediments provides a measure of watershed P inputs to the lake, though interpretations must take into account the potential for in-lake remobiliation as well as post-depositional diagenesis (Engstrom and Wright 1984). Our experience in well-conformed lake sediments with large deposition rates of fairly inorganic sediment is that a TP record can be well-preserved. However, vertical TP mobility in lake sediments is a real concern and may obliterate the record in some lakes. This project will help determine why sediment TP records are reliable in some lakes, and unreliable in others.

Total nitrogen and organic carbon will be measured on selected core intervals (20/core) by combusting the freeze-dried sediments in a Carlo-Erba NA 1500 CNS elemental analyzer. The samples will be pretreated with concentrated HCl to remove inorganic carbon prior to analysis. Ratios of C:N can help distinguish between organic matter of terrestrial origin (high C:N) from in-lake algal sources (low C:N) and hence changes in lake productivity (Meyers and Teranes 2001).

Stable C and N isotopes will be quantified from freeze-dried subsamples using a Thermoquest (Finnigan-MAT) Delta Plus^{XL} mass spectrometer interfaced with a Carlo Erba NC-2500 elemental analyzer following the procedures of Savage et al. (2004). Stable nitrogen isotopes will be used to track changes in source N over time. Possible fractionation effects associated with aquatic production (e.g. changes in trophic enrichment; N assimilation) and post-depositional diagenesis will be considered (Peterson and Fry 1987, Gälman et al. 2009). Analysis of C isotopes will be undertaken on the same sediment sample to gain confirmation of the organic matter source and aquatic productivity (Brenner et al. 1999). Carbon and nitrogen isotope analyses will be performed by Dr. Peter Leavitt at the University of Alberta. Dr. Leavitt will also assist in the interpretation of these proxy records.

(iii) Dating and sediment accumulation rates

Cores will be dated by ^{210}Pb using alpha spectrometry methods (Eakins and Morrison 1978), with dates and sediment accumulation rates calculated according to the CRS model (Appleby 2001). The ^{210}Pb chronology will be augmented as needed by locating the 1963 peak in ^{137}Cs, identified by gamma spectroscropy. Based on typical sediment accumulation rates in Minnesota lakes, it should be possible to obtain reliable dates back to the mid to early 1800s in all lakes. Dating resolution will be roughly decadal. Older material in selected lakes will be dated by ^{14}C to assess natural background sediment accumulation rates.

(iv) Sediment fingerprinting

Erosion of non-field sediment sources such as streambanks and bluffs has been identified as a major source of suspended sediments in several agricultural river basins (Schottler et al. 2010, Belmont et al. 2011). Recent studies have shown that sediment eroded from streambanks and bluffs now accounts for more than half of the current annual sediment load in the Minnesota River and Lake Pepin. These non-field sediment sources are natural features along the river – owing to its deep incision by glacial River Warren at the end of the last ice age – and have always been eroding. However, radioisotope fingerprinting on cores collected from Lake Pepin show that the rate of non-field erosion has increased about 5X since European settlement (Schottler et al. 2010). These increases in non-field sediment loads could be overwhelming decreases in field erosion thus masking the effectiveness of BMPs that would otherwise be apparent in the Mankato TSS monitoring record (Figure 2).

Most source apportionment studies have been conducted at the outlets of watersheds, and therefore include contributions from both the incised and less incised reaches. Given that the incised reaches often have large near-channel erosion features such as bluffs, inputs from these regions can obscure the signature of sediments coming from the upper portion of the watershed. This is important for two reasons: (1) management practices may have reduced inputs from fields in the upper portions of a watershed, but these benefits are masked by non-field increases from the lower incised portion of the watershed, and (2) we need to know how large the contribution from non-field sources is in the upper portions of the watershed, i.e. are streambanks a significant source of sediment in the non-incised portions of a watershed? Because the riverine lakes targeted for this study will integrate smaller watersheds that are not overwhelmed by large inputs from incised regions, they offer a good opportunity to see how field and non-field erosion sources have responded to adoption of soil conservation practices. Current and past loading rates of sediment eroded from field and non-field will be compared to installation records of best management practices to provide a long-term evaluation of BMP effectiveness.

Numerous studies (Walbrink and Murray 1993, Collins et al. 1997, Brigham et al. 2001, Walling et al. 2002, Schottler et al. 2010, Belmont et al. 2011, Stout et al. 2013) have used the meteorically deposited radioisotopes (^{210}Pb, ^{137}Cs, and ^{10}Be) as tracers to discriminate between sediment sources in small watersheds. The underlying premise is that soils with extended exposure to rainfall will be enriched in these radioisotopes as compared to streambanks, ravines and near channel bluffs that have minimal exposure to atmospheric inputs. Thus, sediment eroded from fields should have much higher activities (i.e., concentration) of ^{210}Pb, ^{10}Be and ^{137}Cs than suspended sediment eroded from non-field sources. Comparing the resulting isotopic signature of lake sediments to reference fingerprints of soils from different erosion sources permits the contribution of each erosion source to be calculated.

The relatively short half-life (22.3 years) and direct deposition of ^{210}Pb to a lake surface (and subsequent sorption to the suspended sediments) limits the useful of ^{210}Pb as sediment tracers in lake cores. For this reason, this study will rely on ^{137}Cs and ^{10}Be as radiometric tracers. Stout et al. (2013) and Belmont et al. (2011) have demonstrated that because ^{10}Be has a very long half-life ($1.39\text{x}10^{6}$ years) the amount of ^{10}Be accumulated on soil particles from decades of deposition is orders of magnitude larger than the amount that can be supplied directly by rain during transport of the particles to the core site. The nearly conservative nature of ^{10}Be makes it especially useful for separating field and non-field inputs over the entire post-settlement period. ^{137}Cs, which was released to the atmosphere through above ground nuclear bomb testing, declined to negligible concentrations in rainfall within about 20 years after the international ban on testing took effect in 1963. Sediments entering the lake after ~1980 receive no additional inputs of ^{137}Cs through direct deposition to the lake surface and reflect only the concentration of their source environment.

The ^{137}Cs activity will be determined using gamma spectrometry at the SCWRS. A 4.3 cm^3 (1-3 grams) sample of freeze-dried sediment will analyzed in an ORTEC high-purity germanium crystal well detector, coupled to *Gamma Vision* spectral integration software. Meteoric ^{10}Be will be extracted from five to ten grams of freeze dried and processed for subsequent analysis by atomic mass spectrometry (AMS) at the Purdue Rare Isotope Measurement Laboratory (PRIME). Grain size distribution (necessary for correcting to reference samples) will be measured on a sub-sample from each interval using a Sequoia Scientific laser diffractometer.

Sediment from 10-15 depths in one core from each lake will be analyzed for ^{10}Be. Analytical time and cost constraints limit the amount of samples that can be analyzed for ^{10}Be. ^{137}Cs will be analyzed in at least three cores from each lake at five depth intervals that are determined to be post 1980. Recent studies in Minnesota rivers have established the reference concentrations of ^{137}Cs and ^{10}Be for field and non-field sources (Schottler et al. 2010, Belmont et al. 2011, Stout et al. 2013). Measured concentrations of ^{10}Be and ^{137}Cs will be ratioed to the known reference values to determine the percentage of field-eroded sediment in each interval. Both ^{10}Be and ^{137}Cs will provide estimates on the relative importance and changes in field versus non-field erosion over the past ~20 years. Changes in the activity of ^{10}Be will be used to estimate trends in field and non-field contributions over the entire core record.

(v) Biological analyses

The effects of nutrient and sediment loading to lakes are recognized through changes in water quality and a lake's biological communities (what species are present and their abundances). To fully assess the historical impacts (or not) of nutrient and sediment loading we analyze multiple biological proxies preserved in sediment cores (Birks and Birks 2006) that are here centered on the historical response of algal communities. Diatoms are a group of common algae characterized by having a cell wall of biologically produced glass (opaline silica) and that are very responsive to changing lake conditions. Species and community changes identify periods of environmental change associated, for example, with nutrient loading or shifts in lake state (macrophyte- to algae-dominated) (Edlund et al. 2009, Hobbs et al. 2012). Diatoms further serve as a invaluable tool for estimating historical water column total phosphorus levels using models designed specifically for Minnesota lakes (see below; Ramstack et al. 2003). The historical abundance of diatom algae, especially in response to nutrient loading, is estimated with biogenic silica analysis. Historical levels of other algal groups are quantified using fossil pigments in cores. Different algal groups (e.g., cyanobacteria, green algae) have specific pigment complements; preserved pigments show the presence, abundance, and shifts in algal groups as lakes respond to environmental change. Finally, several algal groups produce decay-resistant microfossils that are quantified using special microscopical techniques. Important among the microfossil group are the cyanobacteria, whose overabundance can result in severe water quality degradation and production of toxins.

(v.1) Diatom analysis and inferred water-column total phosphorus

Fifteen to twenty increments per core will be analyzed for diatom microfossils; at least ten of the samples will be concentrated in the upper part of the core representing about the last 100 years (ca. 10-year resolution). The remaining samples will be taken at core intervals representing 10-20 year resolution from pre- settlement times (pre-1900). Samples will be pre-treated with dilute HCl and 30% H_2O_2, with the cleaned residue dried onto microscope coverslips, and the coverslips mounted on microslides using Naphrax.

Diatoms and chrysophyte cysts will be identified to species level using light microscopes with full immersion optics capable of 1200X magnification and N.A. of 1.4. A minimum of 400 valves will be counted in each sample. Abundances will be reported as percentage abundance relative to total diatom counts. Identification of diatoms will use regional floras (e.g. Patrick and Reimer 1966, 1975, Edlund 1994, Camburn and Charles 2000) and primary literature.

Stratigraphies of predominant diatoms (species greater than or equal to 5% relative abundance) will be plotted against core date. Relationships among diatom communities within a sediment core will be explored using Detrended Correspondence Analysis (DCA); analyses will be performed using the software package R (Ihaka and Gentleman 1996). Core depths/dates will be plotted in ordinate space and their relationships and variability used to identify periods of change, sample groups, and ecological variability among core samples. Diatom community data will be further used to determine the timing and extent of major ecological changes in each lake including shifts between benthic and planktonic dominance and shifts between diatoms and chrysophytes.

A diatom calibration set from a suite of 155 Minnesota lakes will be available for this study (Ramstack et al. 2003, Edlund and Ramstack 2006, Edlund and Ramstack unpublished data). The calibration set has been used to develop models called transfer functions that are based on independent and significant relationships between modern diatom communities and environmental variables such as total phosphorus (Ramstack et al. 2003). The transfer functions will be applied to fossil diatom assemblages in sediment cores to provide estimates of historical water column total phosphorus in our study lakes (Ramstack et al. 2003). The relationship between diatom community assemblage and measured environmental variables in the calibration set can also be used to determine the primary drivers of diatom community change in the cores. For lakes where phosphorus appears to be a major driver of change, a chronology of water-column total phosphorus will be inferred from the diatom spectra.

(v.2) Biogenic silica

Changes in overall lake productivity can be assessed through the selective extraction and analysis of biologic silica (bSi) derived from siliceous algae, principally diatoms and chrysophytes. Sediment bSi concentrations will be measured using a time-step digestion (DeMaster 1981, Conley and Schelske 2001). In this procedure, freeze-dried subsamples are digested in 1% Na_2CO_3 for five hours in an 85°C water-bath shaker. The solutions are sub-sampled at 3-, 4- and 5-hour time steps to chart the progressive silica dissolution over time and thereby correct for Si contributed by mineral silicates. Twenty sediment intervals will be analyzed from each core.

(v.3) Pigments

Sedimentary pigments will be extracted, filtered and dried under N_2 gas following the procedures of Leavitt et al. (1989). Carotenoids, chlorophylls (Chl), and pigment-derivative concentrations will be quantified using a Hewlett-Packard 1050 HPLC system following the reversed-phase procedure of Mantoura and Llewellyn (1983), as modified by Leavitt et al. (1989). Spectral characteristics, chromatographic mobility, and functional group assays will be used to identify pigments from all sources (Leavitt and Carpenter 1989). Pigment analysis will focus on carotenoids characteristic of cryptophytes (alloxanthin), diatoms, chrysophytes, and some dinoflagellates (fucoxanthin), mainly diatoms (diatoxanthin), chlorophytes and cyanobacteria (lutein-zeaxanthin), all cyanobacteria (echinenone), filamentous or colonial cyanobacteria (myxoxanthophyll, canthaxanthin), and potentially N_2-fixing cyanobacteria (aphanizophyll), as well as the major parent and derivative compounds of Chl *a*, *b*, and *c*. Pigment concentrations will be expressed as nmoles pigment g^{-1} organic matter, an index that is linearly related to algal biomass in the water column (Leavitt and Findlay 1994). Pigment analyses will also be carried out by Dr. Peter Leavitt, an internationally-recognized expert in fossil pigments analysis and interpretation.

(v.4) Blue-green algae and microfossils

In spite of the many problems linked to excess algae in our lakes and rivers, we have few laboratories in Minnesota that are currently outfitted for complete analysis of algal samples in water, periphyton, and sediment. As such, many projects rely on outside laboratories and consultants to perform these needed analyses. For example, plankton samples from our lakes and rivers are often sent to labs in California, Michigan, or Canada for routine algal analysis that could easily be done in a suitably outfitted Minnesota lab. The SCWRS is currently well positioned for analysis of diatom microfossils and qualitative algae analysis but lacks the capacity for specialized quantitative analysis of algal samples from sediment or water. The acquisition of a research grade inverted microscope will be the centerpiece of the new Center for Harmful Algae Research in Minnesota (CHARM lab) at the SCWRS. Research capacity will include not only the quantitative analysis of algae via settled samples but also the analysis of soft algal microfossils in sediment samples, specifically relevant to our analysis of BMP effectiveness in this project. Soft algae microfossils are an underutilized component of sediment that provide a historical record of algae problems, including harmful algal blooms, in a lake. Many types of algae produce spores or resistant cellular components, which are preserved in lake sediments as microfossils that can be quantified only through the use of inverted microscopy. This research investment within our state will support an "in-house" capacity for the specialized analysis of algae in water and sediment samples in an already established lab facility with analytical expertise in sediment and water chemistry. We envision the lab to also have extended capacity for the detection of algal toxins.

Algal microfossils including cyanobacterial akinetes (resting spores), filament sheaths, and green algal colonies and cell walls are preserved in lake sediments. These structures provide direct and quantitative evidence of past algal communities, and consequently they will be stratigraphically quantified in the central core of each principal lake with use of the equipment and techniques developed as part of the CHARM lab. Algal microfossils will be directly quantified using modified Ütermohl settling chamber technique coupled with inverted microscopy (Kling 1998). A 250-mL sample of wet sediment will be initially diluted to 20 ml. This suspension will be diluted as needed (typically 8- to 32-fold) to provide countable subsamples using a 2.0 mL Ütermohl settling chamber. At least half of the settling chamber will be counted in an inverted microscope at high-dry magnification (250-400x) for larger microfossils and the other half enumerated in 200 µm-wide fields (400 cell counts) under oil immersion to quantify smaller and more numerous cells.

Activity 3: Quantify BMP effectiveness by linking land to water

Activity 3 will link land-cover and land-use practices (namely BMPs) to water quality as recorded in the sediment cores by two semi-independent methods: statistical correlation and watershed modeling.

(i) Statistical analysis of sediment-core inferred water-quality trends and correlation to BMP histories

As noted in the Hypothesis section, the first step in data analysis will be to search for trends in the water-quality records as inferred from lake-sediment analysis. In particular, we seek to test the working hypothesis that the peak in water-quality degradation occurred in the mid- to late-20th century as a consequence of poor farming practices, and that water quality has improved as farming practices have become more conservation-minded. What pattern is evident in the lake-sediment core records of water quality? Differences among time periods will be assessed by common non-parametric tests (Mann-Whitney or Kruskal-Wallace tests). Or, where appropriate, trends tests will be applied to assess change over time and rate of change.

The second data analysis step will seek correlations between changes in water quality and changes in land use and BMP implementation. Do changes in water quality occur at the same time as those on the land, or are there lags in the response (Meals et al. 2010)? Are there compensating factors that mutually mask the effect of the other? Distinguishing among the multiple possible factors will require careful analysis of (a) chemical or radioisotopic signatures that bear fingerprints of their sources, and (b) timing and magnitude of changes. With a number of land-use changes and BMPs in operation, multivariate methods such as multiple regression and MANCOVA will be explored to help tease apart possible relations.

(ii) Watershed modeling to assess mechanistic links between land and water

Finally, because correlation is not causation, we will model watershed processes in order to assess whether purported correlations are mechanistically realistic. Similar to direct monitoring efforts, watershed models are critically important tools, yet they have serious limitations. In particular, up-scaling model results to entire watersheds remains an uncertain art, variable across spatial and temporal scales and from one geographic region to another. When constrained by real data, models can have tremendous predictive value. But unconstrained model results should be treated as hypotheses, which in the worst cases are misleading artifacts of improper scaling algorithms. In this project, we plan to constrain the model to not only present-day data, but to past data as well.

We will use the Soil and Water Assessment Tool (SWAT), a watershed modeling program developed by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) (Arnold et al. 1998). SWAT's purpose is "to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time" (Neitsch et al. 2011, p. 1). Routines to handle urban landscapes have been added and continually improved, but SWAT's real strengths remain in agricultural landscapes, where it is the evolutionary result of decades of prior USDA models of crop growth, soil erosion, and nutrient transport. A major strength of SWAT is its ability to explicitly handle the details of modern agricultural crop rotations, tillage practices, fertilizer applications, and subsurface tiling. Because agriculture is the single largest source of NPS pollution to streams and rivers in the USA (USEPA 2009), SWAT was the best choice for a modeling platform. Further, SWAT can interface with the Agricultural Policy Environmental eXtender (APEX; Williams and Izaurralde 2006), which is a farm-scale modeling tool that is appropriate at the spatial scale at which BMPs are implemented. Model construction requires inputs of hydrography, topography, soils, land cover, and agricultural management practices, all of which will be compiled during Activity 1 above. SWAT offers many options for algorithms that simulate hydrologic processes, such as evapotranspiration, infiltration (curve numbers versus Green-Ampt), channel routing, and sediment transport. Data input is facilitated by the program ArcSWAT (Winchell et al. 2010), an interface with ArcGIS geographic information systems (GIS) software (ESRI 2012).

For each study watershed, a SWAT model will be constructed and calibrated to the recent land-use and climate conditions, probably a 2000-2010 average condition. Depending on availability of monitoring data, model hydrology will be calibrated to daily flows and sediment to monthly loads. If monthly sediment loads have not been monitored, then modeled sediment loads will be calibrated to the recent record indicated by the whole-lake sediment accumulation record (of necessarily coarser resolution than monitoring data). Goodness of fit will be assessed according to methods and criteria given in Legates and McCabe (1999) and Moriasi et al. (2007). In particular, the model will be constrained to match the sediment and phosphorus loads inferred from the sediment core data for this recent time period. Then, the model will be tested by its ability to simulate loads of sediment and phosphorus for selected periods in the past. Although these periods remain to be chosen, we expect they will relate both to observed changes in the sediment-inferred water quality and to critical dating horizons likely to be found in the cores. The period 1986-2000 would be useful in representing the landscape after establishment of CRP and widespread adoption of conservation tillage, which may contrast with the period 1963-86, before these BMPs were common, going back to the ^{137}Cs peak commonly found in sediment cores as a reliable marker horizon. The period 1940-63 would represent the post-Dust Bowl period when agriculture became more mechanized and with access to inorganic phosphorus fertilizers, and the 1900-30 period would represent the period of major cropland expansion on the prairies and beginning of ditching and wetland drainage. For each time period selected in the past, SWAT's weather generator will be used to create model input data representative of that time and place. Then, the model will be run by incrementally changing configuration parameters, starting with those most likely to be best known. That is, land cover (total and relative areas of different crops, pasture, and set-aside lands) will be relatively well known and altered first. Next, land practices will be altered, i.e., fertilizer application rate, tiling extent, and tillage practices. These sequential alterations will help assess the relative sensitivity of the model to each parameter change, and further constrain the model to a smaller set of acceptable parameter values. Finally, each watershed will be run with native vegetation only, to simulate natural rates of sediment and nutrient loads, as constrained by the sediment cores for the period prior to Euroamerican settlement. Bracketing model parameters to match both a natural, pre-settlement condition and a modern, highly altered condition -- end-members along a land-disturbance continuum -- should lend considerable mechanistic believability to model simulations for conditions within that continuum. Such highly constrained models may serve as a springboard for further work (a) estimating benefit from further BMP implementation, (b) estimating impact from climate change, or (c) comparing to larger-scale watershed models (e.g., the HUC8 HSPF models employed by the MPCA).

We recognize *a priori* that this exercise has inherent circularity. Can we use the model to help distinguish among the data sets to identify causality? Or will we simply use the data to constrain the model, given uncertainties in its parameters and simplifications in its algorithms? In other words, to what degree is the model mechanistically predictive, and to what degree is it empirically dependent on being fit to real data? We expect interplay between the data and model, with the hope that constraining the model to selected long-term data from the lake-sediment cores will improve the realism of model mechanism for other variables. In any case, assessing the model for realism against observed, long-term sediment and nutrient trends will lead to a better understanding of where models succeed, and where they fail, in simulating watershed processes.

Results and Deliverables

This project will generate results with significant implications for resource management and will package those results into deliverables and presentations designed to inform those who need to know.

(i) Results

- General trends in sediment and phosphorus accumulation in single cores from over 100 lakes in the SCWRS sediment archives, as proxies for watershed-scale erosion and nutrient loads, extending back to before Euroamerican settlement in many cases.
- Detailed trends in lake sediment and phosphorus accumulation in 5-10 new watersheds, where multiple cores per lake will allow quantitative whole-basin mass budgeting as measures of watershed-scale erosion and nutrient loads.
- Biological response to these loads will be measured by the algal remains in the sediment cores, including diatoms, pigments, and blue-green algal cellular remnants.
- Development of new capability in Minnesota to analyze algal samples and remains, the Center for Harmful Algal Research in Minnesota, i.e., the CHARM lab.
- Statistical relation of long-term sediment and nutrient loads to watershed land-use and BMP histories, to better understand potential causal relations.
- SWAT watershed models calibrated for each study watershed, with parameters constrained by both current and past conditions, to allow better mechanistic understanding of erosion and nutrient transport at watershed scales.

These results in aggregate will allow us to assess the overall effectiveness of BMPs in improving water quality at the watershed scale across a range of Minnesota landscapes.

(ii) Deliverables

- Final project report documenting results from Activities 1-3.
- Fact sheets (1-4 pages each) summarizing results for each watershed, suitable for use by local resource managers.
- Peer-reviewed publications and presentations at state or national conferences.

Dissemination and Use

Activity 4 of this project focuses on knowledge transfer to watershed resource managers through a series of half-day workshops. These will include the following:

- One half-day workshop in the Twin Cities to present results to state and federal resource managers and interested university scholars
- One half-day workshop for each study watershed to present results to local resource managers at out-state venues.

In addition, as listed above in the project deliverables, we will produce a series of fact sheets (2-4 p. each), for each of the detailed-study watersheds for use by local resource managers. These fact sheets will be targeted for the educated lay reader, to assist local managers in making and justifying BMP implementation decisions. A final project report will document all findings for reference by state personnel, and publications in peer-reviewed journals will inform the wider academic research community.

Timetable

Timeline for Sedimental Journey project

FY2016

Activity	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
(1) Site selection & watershed characterization																																				
(a) Analyze existing archives; select new sites	●	●	●	●	●	●	●	●	●	●	●	●																								
(b) Characterize watershed geography, BMP history							●	●	●	●	●	●	●	●	●	●	●	●																		
(2) Collect and analyze lake-sediment cores																																				
(a) Fieldwork: collect cores		●	●	●	●					●	●	●	●	●	●	●	●																			
(b) Lab work: analyze cores				●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●						
(3) Link land to water, to quantify BMP effectiveness																																				
(a) Statistical analysis of core data and BMP histories																●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
(b) Model watershed processes to test mechanism							●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
(4) Transfer knowledge to resource managers																																				
(a) Workshops for state and local managers																															●	●	●	●	●	●
(b) Final report & fact sheets																															●	●	●	●	●	●

Budget

Item	Activity 1	Activity 2	Activity 3	Activity 4	Total
FT Salary+Benefits	$ 133,000	$ 148,000	$ 294,000	$ 46,000	$ 621,000
Analytical – External	$ -	$ 48,000	$ -	$ -	$ 48,000
Analytical – Internal	$ -	$ 147,000	$ -	$ -	$ 147,000
Supplies	$ 3,000	$ 27,000	$ 3,000	$ 2,000	$ 35,000
Travel	$ 4,000	$ 11,000	$ -	$ 4,000	$ 19,000
Equipment	$ -	$ 30,000	$ -	$ -	$ 30,000
Grand total	$ 140,000	$ 411,000	$ 297,000	$ 52,000	$ 900,000

Credentials

(see following four pages)

CREDENTIALS: DANIEL R. ENGSTROM

Director	St. Croix Watershed Research Station	Tel:	651-433-5953
	Science Museum of Minnesota	Fax:	651-433-5924
	16910 152nd St. N	Email:	dre@smm.org
	Marine on St. Croix, MN 55047	Web:	www.smm.org/SCWRS

Research Expertise

Environmental chemistry, geochemistry, and radiometric dating; human impacts on water quality, atmospheric chemistry, and biogeochemical processes; understanding long-term environmental change from lake sediment records mechanistically linked to modern-day processes

Current Research:

- Atmospheric mercury deposition and cycling in temperate, tropical, and arctic regions
- Agricultural impacts on nutrient and sediment loading to the upper Mississippi River
- The effects of climate change on boreal lake ecosystems

Professional Preparation

B.A.	1971	University of Minn., Duluth (Zoology / Chemistry; Magna Cum Laude)
	1971-73	University of Wisconsin, Madison (Zoology / Limnology)
M.S.	1975	University of Minnesota, Duluth (Zoology / Botany)
Ph.D.	1983	University of Minnesota, Minneapolis (Ecology)

Appointments

1999-	Director, St. Croix Watershed Research Station, Science Museum of Minnesota
1995-99	Sr. Scientist, St. Croix Watershed Research Station, Science Museum of Minnesota
1990-	Adjunct Professor, University of Minnesota (Earth Sciences, Water Resources Science)
1983-95	Research Associate, Limnological Research Center, Univ. of Minnesota

Selected Publications (130 Total)

Engstrom, D.R. and N.L. Rose. 2013. A whole-basin, mass-balance approach to paleolimnology. *Journal of Paleolimnology* 49: 333-347.

Hobbs, W.O., **D.R. Engstrom**, S.P. Schottler, K.D. Zimmer, and J.B. Cotner. 2013. Estimating modern carbon burial rates in lakes using a single sediment sample. *Limnology and Oceanography Methods* 11: 316-326.

Anderson, N.J., R.D. Dietz, and **D.R. Engstrom**. 2013. Land-use change, not climate, controls organic carbon burial in lakes. *Proceedings of the Royal Society B* 280: 20131278.

Blumentritt, D.J., **D.R. Engstrom**, and S.J. Balogh. 2013 A novel repeat-coring approach to reconstruct recent sediment, phosphorus, and mercury loading from the upper Mississippi River to Lake Pepin, USA. *Journal of Paleolimnology* DOI 10.1007/s10933-013-9724-8.

McLauchlan, K.K., J.J. Williams, and **D.R. Engstrom**. 2013. Nutrient cycling in the palaeorecord: fluxes from terrestrial to aquatic ecosystems. *The Holocene* 23: 1635-1643.

Lamborg, C.H., **D.R. Engstrom**, W.F. Fitzgerald, and P.H. Balcom. 2013. Apportioning global and non-global components of mercury deposition through ^{210}Pb indexing. *Science of the Total Environment* 448: 132-140.

Schottler, S.P., J. Ulrich, P. Belmont, R. Moore, J.W. Lauer, **D.R. Engstrom**, and J.E. Almendinger. 2013. Twentieth century agricultural drainage creates more erosive rivers. *Hydrological Processes* DOI: 10.1002/hyp.9738.

Synergistic Activities

- Elected Member: *Academy of Science and Engineering,* Swenson College of Science and Engineering, University of Minnesota – Duluth, 2011-
- Executive Board and Advisory Committee: *International Paleolimnology Association*, 2006-present
- Recipient (on behalf of the SCWRS): *Gulf Guardian Award*, 2010, US Environmental Protection Agency, Gulf of Mexico Program.

CREDENTIALS: JAMES E. ALMENDINGER

Senior Scientist	St. Croix Watershed Research Station	Tel:	651-433-5953
	Science Museum of Minnesota	Fax:	651-433-5924
	16910 152nd St. N	Email:	dinger@smm.org
	Marine on St. Croix, MN 55047	Web:	www.smm.org/SCWRS

Research Expertise

Watershed hydrology models; land-use and small stream hydrology; Quaternary paleoecology; groundwater/surface-water interactions; wetland hydrology

Current Research:

- Modeling land-use impacts on streams, lower St. Croix basin, MN & WI
- Water quality and aquatic biodiversity in western Mongolia
- Watershed-scale erosion in agricultural western Minnesota

Professional Preparation

B.A.	1978.	Ohio Wesleyan University (Botany; Valedictorian; Summa Cum Laude)
Ph.D.	1988.	University of Minnesota (Ecology)

Appointments

1995-	Senior Scientist, St. Croix Watershed Research Station, Science Museum of Minnesota
2000-	Adjunct Associate Professor, University of Minnesota (Water Resources Science Program; Dept. of Fisheries, Wildlife and Conservation Biology; and Dept. of Earth Sciences)
1990-95.	Hydrologist, U.S. Geological Survey, Mounds View, MN.
1989-90.	Fellow, American-Scandinavian Foundation, Univ. of Lund, Sweden.

Selected Publications

Almendinger, J.E., M.S. Murphy, and J.S. Ulrich. 2012. Use of SWAT to scale sediment delivery from field to watershed in an agricultural landscape with topographic depressions. Journal of Environmental Quality: DOI: 10.2134/jeq2011.0340.

Hobbs, W.O., S.C. Fritz, J.R. Stone, J.J. Donovan, E.C. Grimm, and **J.E. Almendinger**. 2011. Environmental history of a closed-basin lake in the US Great Plains: Diatom response to variations in groundwater flow regimes over the last 8500 cal. yr BP. The Holocene 21(8): 1203-1216.

Engstrom, D.R., **J.E. Almendinger**, and J.A. Wolin. 2009. Historical changes in sediment and phosphorus loading to the upper Mississippi River: mass-balance reconstructions from the sediments of Lake Pepin. Journal of Paleolimnology 41: 563-588.

Tesoriero, A.J., J.H. Duff, D.M. Wolock, N.E. Spahr, and **J.E. Almendinger**. 2009. Identifying pathways and processes affecting nitrate and orthophosphate inputs to streams in agricultural watersheds. Journal of Environmental Quality 38: 1892-1900.

Clark, J.S., E.C. Grimm, J.J. Donovan, S.C. Fritz, D.R. Engstrom, and **J.E. Almendinger**. 2002. Drought cycles and landscape responses to past aridity on prairies of the northern Great Plains, USA. Ecology 83(3): 595-601.

Engstrom, D.R., S.C. Fritz, **J.E. Almendinger**, and S. Juggins. 2000. Chemical and biological trends during lake evolution in recently deglaciated terrain. Nature 408:161-166.

Almendinger, J.E. 1999. A method to prioritize and monitor wetland restoration for water-quality improvement. Wetlands Ecology and Management 6:241-251.

Synergistic Activities

SWAT watershed model training and development: Named “Online Model Supporter of the Year” at 2013 International SWAT Conference in Toulouse, France. Joint founder of the SWAT Midwest America Users Group (SMAUG). Revised model code to facilitate surface-water / groundwater connections. Created web site (http://www.smm.org/scwrs/tapwaters) to provide modeling advice and to make code revisions, data processing scripts, and model reports publicly available.

CREDENTIALS: MARK B. EDLUND

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Research Expertise

Aquatic biology and the use of algae in basic and applied research. Special expertise includes large and ancient lake ecology, algology, biodiversity survey, and using paleoecological techniques to address environmental change on multiple spatial and temporal scales.

Current Research:

- Historical and recent ecological change in Lake of the Woods
- Resurrection ecology to determine organismal response to environmental change
- Use of algae for biomonitoring in the Great Lakes region national parks

Professional Preparation

B.A.	1987	University of Minnesota (Biochemistry)
M.S.	1992	University of Michigan, (Natural Resources)
Ph.D.	1998	University of Michigan, (Natural Resources & Environment)

Appointments

2007-	Senior Scientist, St. Croix Watershed Research Station, Science Museum of Minnesota
2002-07	Assoc. Scientist, St. Croix Watershed Research Station, Science Museum of Minnesota
2000-02	Ass't. Scientist, St. Croix Watershed Research Station, Science Museum of Minnesota
2004-	Graduate Faculty, Affiliate Sr. Member, University of Minnesota (Water Resources Science)
1998-2001	Postdoctoral Research Fellow, University of Michigan

Selected Publications (76 Total)

Hobbs, W.O., Ramstack Hobbs, J.M., LaFrancois, T., Zimmer, K.D., Theissen, K.M., **Edlund, M.B.**, Michelutti, N., Butler, M.G., Hanson, M.A., and Carlson, T.J. 2012. A 200-year perspective on alternative stable state theory and lake management from a biomanipulated shallow lake. Ecological Applications 22:1483–1496.

Shinneman, A.L.C., Umbanhowar, C.E., Jr., Almendinger, J.E., **Edlund, M.B.** and Soninkhishig, N. 2009. Paleolimnologic evidence for recent eutrophication in the Valley of the Great Lakes (Mongolia). Ecosystems 12: 944-960.

Triplett, L.D., Engstrom, D. R. and **Edlund, M.B.** 2009. A whole-basin stratigraphic record of sediment and phosphorus loading to the St. Croix River, USA. Journal of Paleolimnology 41: 659-677

Edlund, M. B., Triplett, L. D., Tomasek, M. and Bartilson, K. 2009. From paleo to policy: partitioning of historical point and nonpoint phosphorus loads to the St. Croix River, Minnesota-Wisconsin, USA. Journal of Paleolimnology 41: 679-689

Serieyssol, C. A., **Edlund, M. B.** and Kallemeyn, L.W. 2009. Impact of logging, damming, and hydromanagement on two boreal lakes: a paleolimnological before—after, control—impact study. Journal of Paleolimnology 42: 497-513

Edlund, M. B., Engstrom, D.R., Triplett, L., Lafrancois, B.M. and Leavitt, P.R. 2009. Twentieth-century eutrophication of the St. Croix River (Minnesota-Wisconsin, USA) reconstructed from the sediments of its natural impoundment. Journal of Paleolimnology 41: 641-657

Synergistic Activities

- Visiting Professor, 2003-present, University of Iowa, Iowa Lakeside Laboratory, co-teach Ecology and Systematics of Diatoms
- Associate Editor, *Diatom Research*, International Society for Diatom Research, 2013-present
- Editorial Review Board, Diatoms of the United States website, http://westerndiatoms.colorado.edu/, (2010-present)

CREDENTIALS: SHAWN P. SCHOTTLER

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Research Expertise

Quantifying the relationship between changing land use and water quality conditions in agricultural watersheds; use of lake sediment records and geo-chemical tracers to understand changes in sources and transport of contaminants from large watersheds.

Current Research:

- Radioisotopic fingerprinting of sediment sources
- Historic nutrient and contaminant loading to the Minnesota River
- Evaluating the role of crop conversion, artificial drainage and climate in changing river hydrology.

Professional Preparation

B.S.	1989.	University of Minnesota (Geotechnical Engineering)
Ph.D.	1996.	University of Minnesota (Environmental Engineering)

Appointments

1997- Senior Scientist, St. Croix Watershed Research Station, Science Museum of Minnesota

Selected Publications

Stout J. C., Belmont P., **Schottler S.P.**, Willenbring, J.K. 2013. Identifying sediment sources and sinks in the Root River, Southeastern Minnesota. Annals of the Association of American Geographers, Online Nov. 2013, DOI: ***10.1080/00045608.2013.843434,*** ***http://www.tandfonline.com/doi/abs/10.10***

Hobbs W.O., Engstrom D. R., **Schottler S. P.**, Zimmer K.D., Cotner J.B. 2103. Estimating modern carbon burial rates in lakes using a single sediment sample. Limnology and Oceanography: Methods, v. 11, 316-326.

Schottler S. P., Ulrich J., Belmont, P., Moore, R., Lauer, J.W., Engstrom, D.E., Almendinger, J.E. 2103. Twentieth century agricultural drainage creates more erosive rivers. Hydrological Processes, Online, March 2013, DOI: 10.1002/hyp.9738

P. Belmont, K. B. Gran, **S. P. Schottler**, P. R. Wilcox, S. S. Day, C. Jennings, J. W. Lauer, E. Viparelli, J. K. 2011. Large shift in source of fine sediment in the upper Mississippi River. *Environ Sci Technol.*, Published on web: http://dx.doi.org/10.1021/es2019109

Schottler S. P. and Engstrom, D. R. 2006. A chronological assessment of Lake Okeechobee (Florida) sediments using multiple dating markers. Journal of Paleolimnology, v. 36, 19-36.

Schottler, S. P., Engstrom, D. R., Blumentritt, D. (2010) Fingerprinting sources of sediment in large agricultural river systems, Final Report to Minnesota Pollutions Control Agency CFMS # A94798.

Schottler S. P. and Engstrom, D. R. 2006. A chronological assessment of Lake Okeechobee (Florida) sediments using multiple dating markers. Journal of Paleolimnology, v. 36, 19-36.

Engstrom, D. R., **Schottler, S. P**., Leavitt, P. R., and Havens K. E. 2006. A Re-evaluation of the cultural eutrophication of Lake Okeechobee using multiproxy sediment records, Ecological Applications, v.16(3), 1194-1206.

Schottler, S.P., Identification of Sediment Sources in an Agricultural Watershed, Final Report to the Legislative Commission on Minnesota's Resources, December 30, 2002

Synergistic Activities

- Minnesota Water Conference, Planning Committee, 2010- present. Co-chair committee to select abstracts and organize scientific content of annual statewide conference.
- Frequent presenter and participant in TMDL advisory meetings for Minnesota watersheds. Provide scientific results on causes and trends of water quality impairments to audiences that include water quality professionals, farmers and stakeholders.

References

Appleby, P.G. 2001. Chronostratigraphic techniques in recent sediments. Pages 171-203 *in* W.M. Last and J.P. Smol, editors. Tracking Environmental Change Using Lake Sediments. Volume 1: Basin Analysis, Coring, and Chronological Techniques. Kluwer Academic Publishers, Dordrecht.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modeling and assessment part I: Model development. Journal of the American Water Resources Association (JAWRA) 34(1): 73-89.

Belmont, P., K.B. Gran, S.P. Schottler, P.R. Wilcock, S.S. Day, C.J. Jennings, J.W. Lauer, E. Viparelli, J.K. Willenbring, D.R. Engstrom, G. Parker. 2011. Large shift in source of fine sediment in the upper Mississippi River. Environmental Science and Technology 45(20): 8804-8810.

Birks, H.H., and H.J.B. Birks. 2006. Multi-proxy studies in palaeolimnology. Vegetation History and Archaeobotany 15: 235-251.

Blumentritt, D.J., D.R. Engstrom, and S.J. Balogh. 2013. A novel repeat-coring approach to reconstruct recent sediment, phosphorus, and mercury loading from the upper Mississippi River to Lake Pepin, USA. Journal of Paleolimnology DOI 10.1007/s10933-013-9724-8.

Brenner, M., T.J. Whitmore, J.H. Curtis, D.A. Hodell, and C.L. Schelske. 1999. Stable isotope (δ^{13}C and δ^{15}N) signatures of sedimented organic matter as indicators of historic lake trophic state. Journal of Paleolimnology 22:205-221.

Brigham, M.E., C.J. McCullough, and P. Wilkinson. 2001. Analysis of suspended sediment concentrations and radioisotope levels in the Wild River basin, Northwest Minnesota. U.S. Geological Survey Water Resources Investigations Report 01-4192, 21 p.

Camburn, K.E., and D.F. Charles. 2000. Diatoms of low-Alkalinity Lakes in the Northeastern United States. Special Publication 18. Academy of Natural Sciences of Philadelphia.

Chamberlin, T.C. 1897. The method of multiple working hypotheses. Journal of Geology 5: 837-848.

Cleland, C.E. 2001. Historical science, experimental science, and the scientific method. Geology 29 (11): 987-990.

Collins, A.L., D.E. Walling, G.J.Leeks. 1997. Source type ascription for fluvial suspended sediment based on a quantitative composite fingerprinting technique. Catena 29:1- 27.

Conley, D.J., and C.L. Schelske. 2001. Biogenic silica. Pages 281-293 *in* J. P. Smol, H. J. B. Birks, and W. M. Last, editors. Tracking Environmental Change Using lake Sediments: Biological Methods and Indicators. Kluwer, Dordrecht.

DeMaster, D.J. 1981. The supply and accumulation of silica in the marine environment. Geochimica et Cosmochimica Acta 45:1715-1732.

Eakins, J.D., and R.T. Morrison. 1978. A new procedure for the determination of lead-210 in lake and marine sediments. International Journal of Applied Radiation and Isotopes 29:531-536.

Edlund, M.B. 1994. Additions and confirmations to the algal flora of Itasca State Park. II. Diatoms of Chambers Creek. Journal of the Minnesota Academy of Science 59: 10-21.

Edlund, M.B., D.R. Engstrom, L.D. Triplett, B.M. Lafrancois, and P.R. Leavitt. 2009. Twentieth-century eutrophication of the St. Croix River (Minnesota-Wisconsin, USA) reconstructed from the sediments of its natural impoundment. Journal of Paleolimnology 41: 641-657.

Edlund, M.B., and J.M. Ramstack. 2006. Diatom-Inferred TP in MCWD Lakes. Final Report 116-04. Minnehaha Creek Watershed District.

Engstrom, D.R., J.E. Almendinger, and J.A. Wolin. 2009. Historical changes in sediment and phosphorus loading to the upper Mississippi River: mass-balance reconstructions from the sediments of Lake Pepin. Journal of Paleolimnology 41: 563-588.

Engstrom, D.R. and N.L. Rose. 2013. A whole-basin, mass-balance approach to paleolimnology. Journal of Paleolimnology 49: 333-347.

Engstrom, D.R., E.B. Swain, and S.J. Balogh. 2007. History of mercury inputs to Minnesota lakes: influences of watershed disturbance and localized atmospheric deposition. Limnology and Oceanography 52: 2467-2483.

Engstrom, D.R., and H.E. Wright, Jr. 1984. Chemical stratigraphy of lake sediments as a record of environmental change. Pages 11-67 *in* E. Y. Haworth and J. W. G. Lund, editors. Lake Sediments and Environmental History. Univ. Minnesota Press, Minneapolis.

ESRI (Environmental Systems Research Institute). 2012. ArcGIS Desktop software. Release 10.1. Redlands, CA.

Gälman, V., J. Rydberg, and C. Bigler. 2009. Decadal diagenetic effects on δ13C and δ15N studied in varved lake sediment. Limnology and Oceanography 54:917-924.

Heiri, O., A.F. Lotter, and G. Lemcke. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology 25:101-110.

Hempel, C.G. 1966. Philosophy of Natural Science. Prentice-Hall, Inc., Englewood Cliffs, NJ. 116 p.

Hobbs, W.O., D.R. Engstrom, S.P. Schottler, K.D. Zimmer, and J.B. Cotner. 2013. Estimating modern carbon burial rates in lakes using a single sediment sample. Limnology and Oceanography Methods 11: 316-326.

Hobbs, W.O., J.M. Ramstack Hobbs, T. LaFrancois, K.D. Zimmer, K.M. Theissen, M.B. Edlund, N. Michelutti, M.G. Butler, M.A. Hanson, and T.J. Carlson. 2012. A 200-year perspective on alternative stable state theory and lake management from a biomanipulated shallow lake. Ecological Applications 22:1483–1496.

Ihaka, R., and R. Gentleman. 1996. R: a language for data analysis and graphics. Journal of Computational and Graphical Statistics 5:299-314.

Kling, H.J. 1998. A summary of past and recent plankton in Lake Winnipeg, Canada using algal fossil remains. Journal of Paleolimnology 19:97-307

Kuhn, T. 1970. The Structure of Scientific Revolutions. University of Chicago Press, Chicago, IL. 210 p.

Leavitt, P.R., and D.L. Findlay. 1994. Comparison of fossil pigments with 20 years of phytoplankton data from eutrophic lake 227, Experimental Lake Area, Ontario. Canadian Journal of Fisheries and Aquatic Sciences **51**:2286-2299.

Leavitt, P.R., and S.R. Carpenter. 1989. Effects of sediment mixing and benthic algal production on fossil pigment stratigraphies. Journal of Paleolimnology 2:147-158.

Leavitt, P.R., S.R. Carpenter, and J.F. Kitchell. 1989. Whole-lake experiments: the annual record of fossil pigments and zooplankton. Limnology and Oceanography 34:700-717.

Legates, D.R. and McCabe, G.J., Jr., 1999. Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. Water Resources Research, 35(1): 233-241.

Mantoura, R.F.C., and C.A. Llewellyn. 1983. The rapid determination of algal chlorophyll and carotenoid pigments and their breakdown products in natural waters by reverse-phase high performance liquid chromatography. Analytica Chimica Acta 151:297-314.

Meals, D.W., Dressing, S.A. and Davenport, T.E., 2010. Lag time in water quality response to best management practices: A review. Journal of Environmental Quality, 39(1): 85-96.

Meyers, P.A., and J.L. Teranes. 2001. Sediment organic matter. Pages 239-270 *in* W. M. Last and J. P. Smol, editors. Tracking Environmental Change Using Lake Sediments. Volume 2: Physical and Geochemical Methods. Kluwer, Dordrecth.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE (American Society of Agricultural and Biologial Engineers), 50(3): 885-900.

MSU (Minnesota State University Mankato). 2012. Minnesota Tillage Transect Survey Data Center: http://mavdisk.mnsu.edu/moorer2/transect/minnesotamn.htm (accessed November 2013)

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2011. Soil and Water Assessment Tool Theoretical Documentation, Version 2009. U.S. Department of Agriculture Agricultural Research Service (USDA/ARS) and Texas AgriLife Research. Texas Water Resources Institute Technical Report No. 406, Texas A&M Univ., College Station, TX, 618 p.

Omernik, J.M. 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers. 77: 118-125.

Patrick, R., and C.W. Reimer. 1966. The diatoms of the United States, exclusive of Alaska and Hawaii, Volume 1 – Fragilariaceae, Eunotiaceae, Achnanthaceae, Naviculaceae. Monograph No. 13. Academy of Natural Sciences of Philadelphia.

Patrick, R., and C.W. Reimer. 1975. The diatoms of the United States, exclusive of Alaska and Hawaii, Volume 2, Part 1 – Entomoneidaceae, Cymbellaceae, Gomphonemaceae, Epithemaceae. Monograph No. 13. Academy of Natural Sciences of Philadelphia.

Peterson, B.J., and B. Fry. 1987. Stable isotopes in ecosystem studies. Annual Review of Ecology and Systematics 18:293-302.

Ramstack, J.M., S.C. Fritz, D.R. Engstrom, and S.A. Heiskary. 2003. The application of a diatom-based transfer function to evaluate water-quality trends in Minnesota since 1970. Journal of Paleolimnology 29:79-94.

Savage, C., P.R. Leavitt, and R. Elmgren. 2004. Distribution and retention of effluent nitrogen in surface sediments of a coastal bay. Limnology and Oceanography 49(5): 1503-1511.

Schottler S.P., D.R. Engstrom, and D. Blumentritt. 2010. Fingerprinting sources of sediment in large agricultural river systems. Final Report to Minnesota Pollution Control Agency CFMS # A94798. *http://www.smm.org/static/science/pdf/scwrs-2010fingerprinting.pdf*

Stout J.C., P. Belmont, S.P. Schottler, and J.K. Willenbring. 2013. Identifying sediment sources and sinks in the Root River, Southeastern Minnesota. Annals of the Association of American Geographers, Online Nov. 2013, DOI: 10.1080/00045608.2013.843434, http://www.tandfonline.com/doi/abs/10.10

Triplett, L.D., D.R. Engstrom, and M.B. Edlund. 2009. A whole-basin stratigraphic record of sediment and phosphorus loading to the St. Croix River, USA. Journal of Paleolimnology 41: 659-677.

USEPA (U.S. Environmental Protection Agency). 2009. National Water Quality Inventory: Report to Congress, 2004 Reporting Cycle. EPA 841-R-08-001, U.S. Environmental Protection Agency, Washington, DC.

UMN (University of Minnesota). 2012. 100 Years of MAES Research. http://www.maes.umn.edu/Research/Highlightsofmorethanacenturyofachievements/1900_1920/index.htm (accessed November, 2013)

USDA (U.S. Department of Agriculture). 2012. Assessment of the effects of conservation practices on cultivated cropland in the Upper Mississippi River Basin. Conservation Effects Assessment Project (CEAP). USDA Natural Resources Conservation Service. 187 p.

USDA (U.S. Department of Agriculture). 2012. Conservation Programs. USDA Farm Service Agency. /www.fsa.usda.gov/FSA/webapp?area=home&subject=copr&topic=rns-css (accessed November, 2013)

Wallbrink, P.J., and Murray, A.S. 1993. Use of fallout radionuclides as indicators of erosion processes. Hydrological Processes, 7:297-304

Walling, D.E., M.A.Russell, R.A. Hodgkinson, and Y. Zhang. 2002. Establishing sediment budgets for two small catchments in the UK. Catena 47: 232-353.

Williams, J.R., and R.C. Izaurralde. 2006. The APEX model. In Watershed Models, 437- 482. V. P. Singh and D. K. Frevert, eds. Boca Raton, Fla.: CRC Press.

Winchell, M., R. Srinivasan, M. Di Luzio, and J. Arnold. 2010. ArcSWAT Interface for SWAT2009 User's Guide. Blackland Research and Extension Center, Texas AgriLife Research, Temple, TX; and Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, Temple, TX.

Wright, H. E., Jr. 1991. Coring tips. Journal of Paleolimnology **6**:37-49.

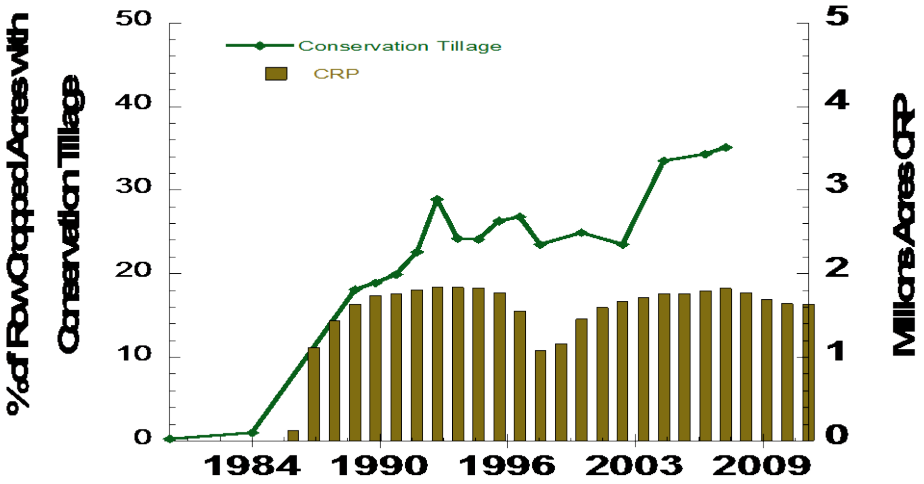

Figure 1. Trends in acres enrolled CRP (USDA, 2012) and percentage of row-cropped acres with conservation tillage (UMN, 2012 and MSU, 2013) in Minnesota. Data for individual counties are also available. Conservation tillage is defined as greater than 30% residue remaining on field after tillage.

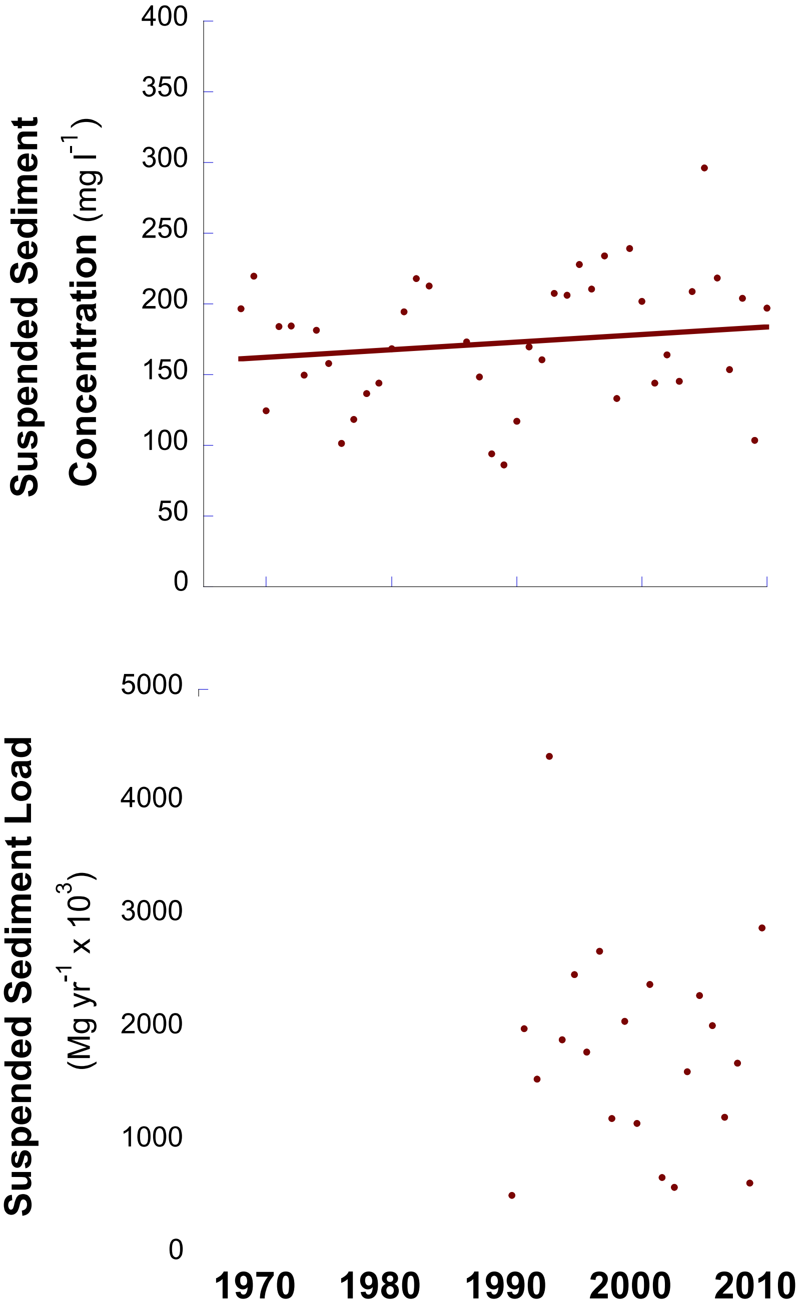

Figure 2. Trends in suspended sediment at Mankato, MN. This dataset represents the longest monitoring record for any river in Minnesota river watershed. Trend in sediment load reflects a significant increase ($p = 0.045$) since 1968.

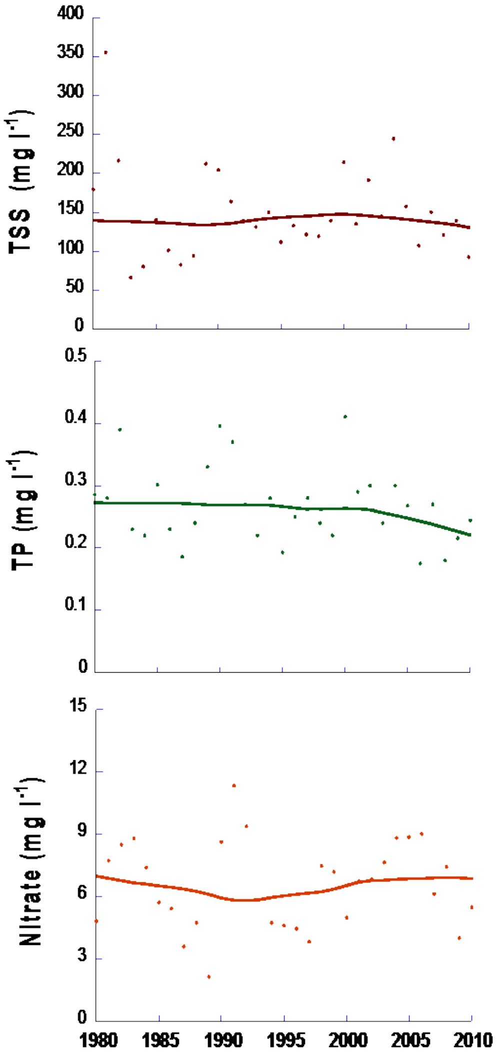

Figure 3. Monitored trends in annual flow-weighted concentrations of sediment (TSS), total phosphorus (TP) and nitrate in the Minnesota River at Jordan, MN. Lines shown are LOWESS fits.

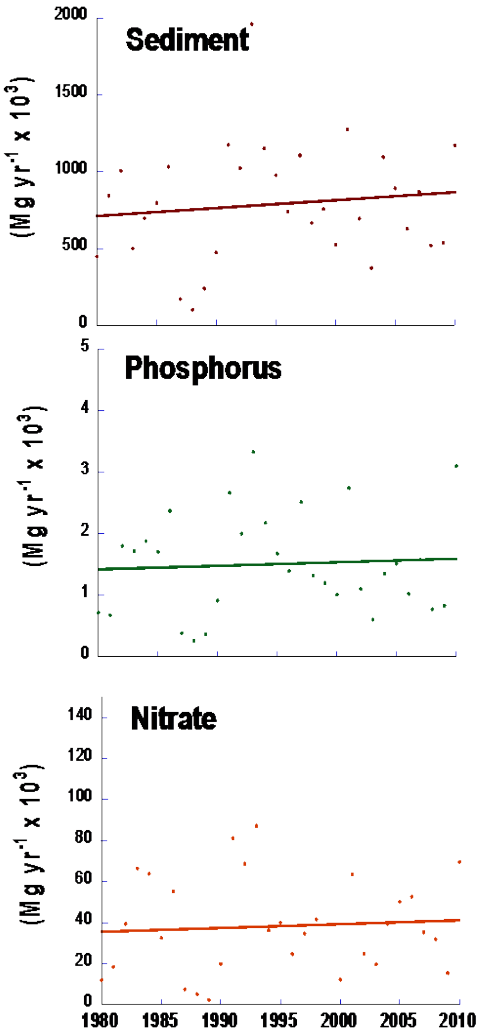

Figure 4. Monitored trends in annual loads of sediment, total phosphorus (TP) and nitrate in the Minnesota River at Jordan, MN. The slope of all trend lines are non-significant, e.g., based on linear fit, there is no increase or decrease over the period 1980 to 2010.

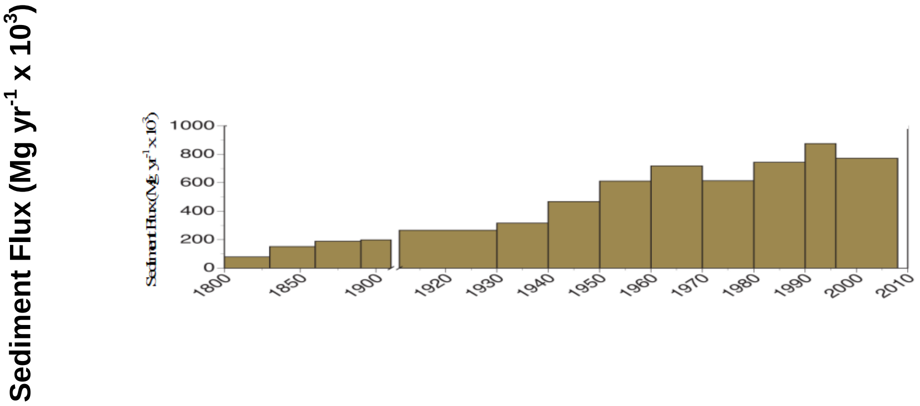

Figure 5. Sediment accumulation rate for Lake Pepin (from Engstrom et al. 2009; Blumentritt et al. 2013). Accumulation rates over the past 30 years have not declined and are about 10X greater than pre-Euroamerican settlement rates.

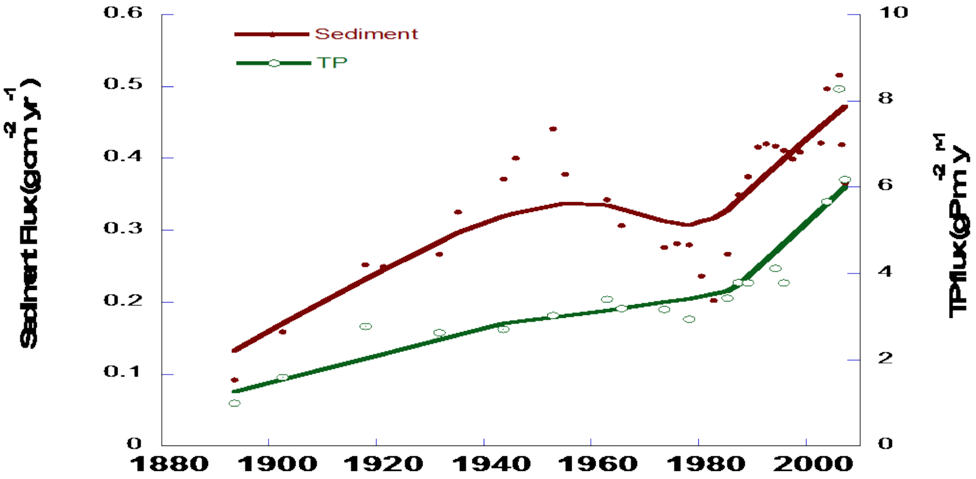

Figure 6. Sediment and phosphorus trends as recorded in a single core from Greenleaf Lake, LeSueur County, Minnesota. To remove variability due to in-lake production of carbonate and organic matter, sediment flux is presented for siliciclastic fraction only.