# Estimating Phosphorus Losses from Agricultural Lands for MPCA's Detailed Assessment of Phosphorus Sources to Minnesota Watersheds

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## Executive Summary

The objective of this study was to assess phosphorus loadings to Minnesota's ten major drainage basins from agricultural runoff and erosion, as well as to evaluate the uncertainty in these assessments. This study was achieved by using and extending a regional phosphorus index approach published by Birr and Mulla (2001). Phosphorus index values were estimated for Minnesota watersheds and agroecoregions based on phosphorus transport and source factors such as erosion during dry, average and wet years, streamflow during dry, average and wet years, contributing distance from surface waterbodies during dry, average and wet years, soil test phosphorus, and rate and method of land applied phosphorus from fertilizer and manure.

Phosphorus index values were compared with field data on phosphorus loss from four sites over five years to estimate phosphorus export conditions. Phosphorus export coefficients show considerable variation across major drainage basins and across climatic conditions (Table 3 and Fig. 26). Export coefficients (kg/ha) during average climatic conditions vary from 0.54 kg/ha for the Minnesota River basin, 0.4 kg/ha for the Red River basin, 0.39 kg/ha for the Upper Mississippi River basin, and 0.66 kg/ha for the Lower Mississippi River basin.

Phosphorus export coefficients were multiplied by the cropland contributing area within 100 m of surface water bodies to obtain phosphorus loadings from the edge of this contributing area. Phosphorus loads exported to surface waters from agricultural lands under average climatic conditions are greatest for the Minnesota River basin (517,862 kg/yr), followed by the Red River (384,695 kg/yr), the Upper Mississippi (359,681 kg/yr) and the Lower Mississippi (232,581 kg/yr) River basins. All of the other basins have phosphorus export loads that are considerably smaller than the loads exported in these four basins. With agroecoregion based export coefficients, the magnitudes of phosphorus loadings are about

7% smaller for these same basins in an average year than the magnitudes obtained using the watershed based analysis.

Several alternative agricultural management scenarios were investigated and compared to a baseline scenario involving an average climatic year and existing rates of adoption of conservation tillage and existing rates of phosphorus fertilizer applications. The first alternative management was a scenario in which moldboard plowing is used on all row cropland. This is a worst case scenario for erosion, and exemplifies phosphorus losses typical of an era that existed twenty or more years ago. This scenario allows us to evaluate the extent of progress in controlling phosphorus losses over the last twenty years due to improvements in tillage management. In the Minnesota River basin, compared to an era when moldboard plowing was widely practiced, current day phosphorus losses from agricultural cropland have been reduced by about 146,000 kg/yr (from about 664,000 to 518,000 kg/yr), for a 28% reduction. In the Upper Mississippi River basin, current phosphorus losses from agricultural land have been reduced by about 87,000 kg/yr, for a 24% reduction. Similar comparisons show a 7% reduction for the Red River basin.

The last scenario involves decreasing or increasing the area of cropland within 100 m of surface waterbodies. Decreases in area of cropland could correspond to land retirement programs such as those promoted in the Conservation Reserve and Conservation Reserve Enhancement Programs. Increases in cropland area would correspond to putting grass or forest riparian areas into production, alternatively this could be viewed as increasing the distance for cropland areas (now assumed to be 100 m) that contribute phosphorus to surface waters. The results from this scenario indicate that every one percent decrease in the area of cropland within 100 m of surface waters leads to a one percent decrease in phosphorus loadings. Alternatively, every one percent increase in the area of cropland near surface waters leads to a one percent increase in the phosphorus loadings.

There are many possible sources of uncertainty in the estimated phosphorus loadings. These can be divided into errors in input data, errors in converting phosphorus index values to phosphorus export coefficients, errors in estimating the proportion of cropland that contributes to phosphorus loadings, and errors due to a lack of consideration for impacts of surface and subsurface drainage, wind erosion or snowmelt runoff on phosphorus loadings. This study provides a list of suggestions for further research to reduce these uncertainties.

## Introduction

In 2003, the Minnesota State Legislature authorized the Minnesota Pollution Control Agency to contract for a comprehensive study to assess phosphorus loadings to Minnesota's ten major drainage basins from all major sources during low flow, average flow, and high flow conditions. These sources include point sources such as publicly owned wastewater treatment plants, privately owned wastewater treatment plants, and commercial or industrial wastewater treatment systems. Nonpoint sources addressed in the study included agricultural runoff and erosion, feedlot runoff, non-agricultural rural runoff, streambank erosion, urban runoff, individual sewage treatment systems, and atmospheric deposition. The subject of the study described below is limited simply to assessing the phosphorus loadings to Minnesota's ten major drainage basins from agricultural runoff and erosion, as well as evaluating the uncertainty in these assessments. This study was achieved by using and extending a regional phosphorus index approach published by Birr and Mulla (2001).

## Methods

The following sections provide an overview of the modified phosphorus index, developed at the regional scale by Birr and Mulla (2001), and an approach for revising and utilizing the modified phosphorus index to estimate phosphorus loadings from agricultural sources to each of the ten major drainage basins in Minnesota during low, high and average flow conditions.

## Overview of Modified Phosphorus Index at the Regional Scale

Birr and Mulla (2001) developed a modified version of the P Index, originally developed jointly by the USDA (ARS, CSREES, and NRCS), to prioritize phosphorus (P) loss vulnerability at the regional scale from 60 watersheds located within Minnesota. This modified (regional) version of the P Index uses readily available data associated with the transport and sources of P. Validation of the P Index rating was conducted using long-term water quality monitoring data consisting of total P concentrations collected from 37 watersheds and 1800 lakes within the study area.

A combination of transport and source factors directly influence P movement from agricultural systems to surface waters (Sharpley et al., 1993). The USDA developed a P Index that integrates both transport and source factors to identify areas vulnerable to P export (Lemunyon and Gilbert, 1993). Transport factors include the mechanisms by which P is delivered to surface waters, such as erosion and runoff. Source factors represent the amount of P available for transport, including soil test P and P applied (rate and method) in fertilizer and organic forms. Table 1 (taken from Birr and Mulla, 2001) summarizes the transport and source factors used to develop the regional P Index ratings, as well as the weighting factors for each loss class and transport or source factor. The following discussion describes how each of the transport and source factors were initially computed by Birr and Mulla (2001). The section after this discussion describes how the initial computations were modified and refined for the final analyis.

## Birr and Mulla (2001) Regional Phosphorus Index Methods

- Soil erosion potential was calculated using the Universal Soil Loss Equation (USLE) as outlined by Wischmeier and Smith (1978). The Minnesota state soil geographic database (STATSGO) was used to supply many of the variables needed to calculate erosion potentials for each of the watersheds (USDA, 1991). Erosion potential was calculated for each soil type within a STATSGO map unit. Rainfall runoff factors (R) for each county were based on values provided by Wischmeier and Smith (1978). The STATSGO database provided a soil erodibility factor (K) for each soil type within a STATSGO map unit. The slope-steepness factor (S) represents an average of the high and low slope values given for each soil type within a STATSGO map unit. The slope-length factor (L) was assumed to be 46 m. A 1:250 000 scale landuse/landcover coverage developed by the USGS in the late 1970s and early 1980s was used to determine erosion potentials spatially coincident with cropland and pastureland (USEPA, 1994).

  An erosion potential value for all cropland and pastureland within a watershed was determined using the percent of each STATSGO map unit covering a watershed. The landuse coverage did not differentiate spatially between cropland and pastureland; however, Census of Agriculture data indicate that pastureland represents about 11% of this classification category in Minnesota (National Agricultural Statistics Service, 1999). Differences in potential erosion for the two land uses were accounted for in the determination of the C factor based on the proportion of hay reported for a particular county. Cropping management factors (C) were adapted from values provided by the

USDA (1975) and Wischmeier and Smith (1978) for corn, wheat, soybean, hay, sugar beet, potato, oat, and barley. The C factors were calculated for each county based on the area of each harvested crop covering the county. Watershed values for the C factors were weighted based on the proportion of the watershed that was covered by the county. The C factor calculations include crop rotation effects but not the variation in tillage effects. There is no reliable method for estimating the variation in crop residue cover across the watersheds studied. The conservation practice factor (P) was assumed to be 1, because it could not be accurately quantified at the regional scale. The overall erosion potential value for each watershed represents the product of the area-weighted C factor and the variables R, K, and LS for each watershed (A = RKLSCP).

- Average annual runoff values for each watershed were derived from the average annual discharge monitored from 1951 to 1985 for 327 stations distributed throughout Minnesota (Lorenz et al., 1997). The average annual runoff value is calculated as the average annual discharge divided by the drainage basin area defined for the station.
- The area of cropland and pastureland within 91.4 m of drainage ditches and perennial streams (the primary contributing corridor) was determined using hydrography coverages developed by the Minnesota Department of Transportation (1999) and the USGS (1999). The USGS landuse/landcover coverage (USEPA, 1994) was used to determine the percentage of cropland and pastureland within the 91.4 m proximity to watercourses for each watershed.
- Mean soil test P levels for each county represented a 5-yr database consisting of 22,421 Bray-1 extractable P (Brown, 1998) samples analyzed by the University of Minnesota's soil testing laboratory. Soil test P levels for each watershed were based on the area of the watershed covered by each county.
- Data for P-fertilizer sales by county were obtained from the Minnesota Department of Agriculture (1997). Fertilizer P values for watersheds were based on a summation of area-weighted county-based values intersecting the watersheds. The total area of fertilized land within each watershed was determined using the same procedure based on reported county values (National Agricultural Statistics Service, 1999). The aggregated fertilizer P value was divided by the aggregated reported fertilized land for each watershed to determine fertilizer P application rates.
- The P content of livestock manure was calculated based on the total number of cattle, swine, broilers, and turkeys reported within each county (Midwest Planning Service, 1985; Schmitt, 1999; National Agricultural Statistics Service, 1999). The total amount of manure P was derived for each watershed based on the summation of area-weighted county values intersecting the watersheds. The reported total cropland area

> was also determined using the same procedure (National Agricultural Statistics Service, 1999). The aggregated total P content of manure was normalized by the aggregated total cropland area for each watershed to determine organic P application rates. This approach underestimates the actual rates of land applied P from manure, but at the regional scale it accurately represents the mass of P from land applied manure.

For the modified P Index (Table 1), each site characteristic is assigned a weighting factor based upon the premise that site characteristics have a varying impact on P loss to runoff. Each site characteristic has an associated P loss rating value (very low, low, medium, high, and very high) using a base of 2 to reflect the higher potential for P loss associated with higher rating values. The P Index rating is the summation of the product of the rating value and corresponding weighting value for each site characteristic. Because P application method could not be accurately depicted at the regional scale, the highest organic and fertilizer P application method rating values were used to represent a worst-case scenario. Categories corresponding to the rating values were derived by segregating the distribution of statewide values for each site characteristic into five classes using the quantile classification method available in ArcView software (ESRI, 2000).

P Index rating values resulting from the application of the modified P Index were validated using two different sets of data. The first set of data consists of a 27-yr record (1968-1994) of total P concentrations collected at the mouth and at interior points in 54 of the 60 watersheds in the study. P Index ratings were correlated with the percentage of samples in which total P concentrations exceeded 0.25 mg/L for 37 of the 60 watersheds in the study area. Seventeen of the 54 watersheds with monitoring data derived from main stems of the six major rivers were excluded from the statistical comparison to ensure that both cumulative (upstream effects from other major watersheds) and point source (urban) effects did not influence the total P observations. The second set of validation data consists of lake water quality parameters maintained by the United States Environmental Protection Agency's (USEPA) STORET national water quality database. P Index ratings were statistically compared with median total P concentration of lakes for 20 of the 60 watersheds having greater than 14 lakes assessed. A majority of the lakes (66%) were monitored during summer months (June-Sept.) between 1989 and 1998. The remaining data were collected between 1970 and 1988, including non-summer samples (Heiskary and Wilson, 2000). The regional phosphorus index of Birr and Mulla (2001) showed an excellent statistical correlation with both water quality validation data sets, with coefficients of determination between 65 and 70%.

## Refined and Updated Approach for Estimating Regional Phosphorus Index

This section provides an approach for revising and utilizing the modified (regional) phosphorus index (from Birr and Mulla, 2001) to estimate phosphorus loadings from agricultural sources to each of the ten major drainage basins (Fig. 1) in Minnesota during low, high and average flow conditions. In addition, this approach will attempt to evaluate the variability and uncertainty associated with estimating phosphorus loadings from the various types of farm systems using the modified phosphorus index.

Agroecoregions were developed by the University of Minnesota's Department of Soil, Water, and Climate on behalf of the Minnesota Department of Agriculture (Hatch et al., 2001). Thirty-nine agroecoregions were delineated in Minnesota using data related to soils, surficial geology, climatic patterns, topography, and land use (Fig. 2). Birr and Mulla (2002) found that the Minnesota agroecoregion framework was effective at characterizing regional lake water quality trends. The same transport and source factor (soil erosion, average runoff, percentage of cropland and pastureland within 300 feet of a watercourse, soil test P, fertilizer P and organic P application rates) inputs, used to determine the modified phosphorus index values for each of the 37 watersheds in Birr and Mulla (2001), have already been developed for each agroecoregion unit throughout Minnesota (Mulla, 2003).

The following adjustments to the modified phosphorus index computations and supplementary tasks will be used to improve and update the analysis of phosphorus loading:

- The MPCA has developed and updated a feedlot inventory and manure management database (with an associated GIS coverage), based on registered feedlot data obtained from each of the counties. The total amount of manure P was derived for each agroecoregion and watershed based on the summation of area-weighted township values intersecting the agroecoregions or watersheds. The aggregated total P content of manure can then be normalized by the aggregated total cropland area for each agroecoregion or watershed to determine and revise the organic P application rates. Again, this underestimates the actual rates of land applied P from animal manure, but not the regional amounts applied, nor the regional patterns in amounts applied, which are critical for this analysis.

- Data for phosphorus fertilizer sales by county were obtained from the Minnesota Department of Agriculture (1997) and used in Birr and Mulla (2001) to estimate the modified phosphorus index values based on a summation of area-weighted county-based values intersecting the watersheds. Phosphorus fertilizer sales data by county for the most current crop year (2002) were obtained and used to update this part of the modified phosphorus index computations based on a summation of area-weighted county-based values intersecting the agroecoregions or watersheds.

- GIS coverages for runoff volumes in each agroecoregion or watershed under average, high and low flow conditions were developed to evaluate how phosphorus export from agricultural lands would be expected to change with varying climate conditions. Runoff volumes were estimated by Barr Engineering based on average annual discharge from long-term monitoring stations representative of the major watersheds of the state, consistent with Birr and Mulla (2001). Along with runoff volumes estimated by Barr Engineering for low, average and high flow condition s, we estimated rainfall runoff erosivity (R values) for the USLE for dry, average and wet years corresponding to the low, average and high flow conditions. These estimates were based on an algorithm developed for monthly precipitation data by Renard and Freimund (1994). The modified phosphorus index values and total phosphorus export were then computed for each of the agroecoregions or watersheds under high and low flow conditions, using the corresponding values for runoff volume and rainfall runoff erosivity.

- The highest rating for both P fertilizer and organic P application method was used by Birr and Mulla (2001). Application methods with less potential for P losses will lower the estimated P Index values; however, the relative rankings of the P Index ratings across watersheds would only change if the practices varied significantly from one basin to the next. Based on farm survey data collected by the Minnesota Department of Agriculture, phosphorus application methods are generally much better than those assumed by Birr and Mulla (2001). A majority of farmers apply their phosphorus fertilizer with the planter or using incorporation before crop planting. In view of this, we have chosen to use a statewide medium loss potential for method of fertilizer P application method, corresponding to fertilizer applied before the crop and incorporated immediately.

An initial scenario involving a medium loss potential for the method of manure application was developed for the entire state. Subsequently, a second scenario was developed assuming variability in the loss potential associated with method of manure application. Manure P application methods vary primarily in response to the type of animal species. Manure from beef, dairy, and poultry is high in solids, while manure from hogs is high in liquid. Beef operations tend to be small in scope, have a tendency towards inadequate manure storage facilities, and manure from these operations tends to be hauled on a daily basis. Beef operations also tend to involve cattle wading in streams. Dairy operations tend to have adequate manure storage facilities, and manure is applied followed by a tillage operation to incorporate manure. Poultry operations tend to have adequate manure storage facilities, and the manure is incorporated using tillage following land application. Hog operations tend to have adequate storage facilities, and the manure is land applied using injection. In terms of the phosphorus index, this means that beef operations tend to have a very high phosphorus loss potential, dairy and poultry operations tend to have a medium loss potential, while hog operations tend to have a low loss potential. The geographic variability in phosphorus loss potential associated with these variations in method of manure application was evaluated using the number of animal units of different species from the MPCA feedlot inventory database. The effect of this variability and/or uncertainty in method of manure application was estimated using the modified phosphorus index.

- Birr and Mulla (2001) states that spatial trends in soil erosion potential observed throughout Minnesota are potentially influenced by both the underlying assumptions used in the methodology and the exclusion of factors that control soil erosion. A lack of detailed information pertaining to the spatial variation in C and P factors may have caused the spatial distribution of erosion potential values to vary more gradually across the region than is realistic. The spatial variation in the C factor of the USLE was estimated by accounting for the effects of crop rotations, the effects of conservation tillage on crop residue levels, and the effects of existing acreage of land in Conservation Reserve Program (CRP). Typically the C factor for land in CRP is 0.001 or so, while row cropland has a C factor varying from 0.05 to 0.4 depending on the rotation and the amount of crop residue present.

  Three scenarios were evaluated to account for the influence of tillage methods on crop residue levels remaining after planting. These were a scenario involving conventional tillage with no residue left (worst C scenario), and a scenario involving conservation tillage leaving more than 50% of the soil covered by crop residue (best C scenario). This is not typical of existing crop rotations or tillage management systems in Minnesota, nor is it a goal of existing watershed restoration or conservation programs to achieve this high level of crop residue cover. Also estimated was a scenario for average crop residue cover (average C scenario) based on county tillage transect data for the percent of fields with conservation tillage (30% residue cover). In the average C scenario, we developed a weighted C factor based on the relative area of cropland in conservation tillage versus moldboard plowing. Data for the C factors of various crop rotations with varying levels of crop residue were estimated using tables provided by the USDA-NRCS. Thus, using information on crop rotations, crop residue levels, and acreage of land in CRP, we developed scenarios for both soil erosion by water and the modified phosphorus index involving the C factor of the USLE.

  Variability in the P factor of the USLE was estimated using the Local Government Annual Reporting System (LARS) database of conservation practices provided by the

Board on Soil and Water Resources (BWSR). This database was edited to estimate the area of supporting conservation practices affecting the P factor implemented from 1997-present in Minnesota counties. These practices include terracing, contour strip cropping, filter strips, sediment basins, and restored wetlands. Each practice was assigned a typical P factor. Since supporting conservation practices have typically been implemented for the last 50 years, we assumed that the area where these practices were implemented was 10 times greater than the area determined using the LARS database. A county average P factor was then determined using the area weighted P factors for land with supporting practices and the land without supporting practices (P=1). The variability and/or uncertainty associated with conservation practices, such as conservation tillage, contour stripcropping, terracing, and other supporting practices was then estimated for agroecoregions and watersheds using the modified phosphorus index.

## Regional Modified Phosphorus Index Results

### Water Erosion Estimates for Agricultural Land

#### *Average Rainfall Runoff Erosivity, Varying Cover Management Conditions*

The first scenario for erosion involves using the worst possible values for the cover management factor (C) in the USLE, and keeping all other factors from the first scenario constant. This represents erosion rates that could be expected when moldboard plowing is used on cropland, thereby burying all crop residue. As shown in Fig. 3a, most of the watersheds in southern Minnesota have erosion rates greater than 21 Mg/ha/yr (11.2 Mg/ha corresponds to 1 ton/ac) due to poor crop residue cover. The maximum rate of erosion estimated was about 190 Mg/ha (about 17 ton/ac). Erosion rates typically decrease towards northern Minnesota. Similarly, erosion rates greater than 21 Mg/ha/yr occur in a large number of agroecoregions located in southern Minnesota (Fig. 3b).

The second scenario illustrates the erosion rates that correspond to average cover management conditions based on tillage transect surveys of the percent of cropland with 30% residue cover at planting. About one-third of all watersheds have erosion rates that exceed

21 Mg/ha/yr (Fig. 4a), these are located primarily in southern Minnesota. About one-fourth of all watersheds have erosion rates less than 5 Mg/ha/yr, these are located primarily in northern Minnesota. Agroecoregions with erosion rates greater than 21 Mg/ha/yr include the Blufflands, Rolling Moraine, Rochester Plateau, Steep Wetter Moraine, Coteau, Undulating Plains, Inner Coteau, Wetter Blue Earth Till, Level Plains, and Steep Dryer Moraine (Fig. 4b). These are located primarily in the Minnesota River basin and the Lower Mississippi River basin in southeastern Minnesota.

The third scenario involves using the best possible values for the cover management factor (C) in the USLE, representing erosion rates that could be expected when all cropland uses conservation tillage that leaves at least 50% of the soil surface covered with crop residue at planting (Fig. 5ab). As expected, rates of erosion are generally smaller in this scenario in comparison with the previous two scenarios. With widespread adoption of conservation tillage, watersheds in the northern half of Minnesota have erosion rates that are less than 5 Mg/ha/yr, and much of central, south central and southwestern Minnesota have erosion rates ranging between 6 and 14 Mg/ha/yr (Fig. 5a). The number of watersheds in southeastern Minnesota having erosion rates greater than 21 Mg/ha is relatively unchanged in comparison to the results from the first scenario which uses the lowest possible C factors based on moldboard plowing (Fig. 3a). This is because southeastern Minnesota has steep landscapes and heavy precipitation which are conducive to high rates of erosion.

### *Low and High Rainfall Runoff Erosivity, Best Cover Management Conditions*

The next erosion scenarios involve using best cover management factor (C) values based on widespread adoption of conservation tillage, existing crop rotations and acreage of CRP, but with varying values of rainfall runoff erosivity (R). The first of these scenarios is with low rainfall runoff erosivity values that represent dry climatic conditions typical of low flow hydrologic conditions. As shown in Figs. 6a and 6b, erosion rates in this scenario are typically less than 5 Mg/ha/yr for watersheds and agroecoregions across the entire state. The second scenario is with high rainfall runoff erosivity values that represent wet climatic conditions typical of high flow hydrologic conditions. As shown in Figs. 7a and 7b, erosion rates with this scenario are typically greater than 21 Mg/ha/yr in most of central and southern

Minnesota. Only the northeastern portion of Minnesota has erosion rates smaller than 5 Mg/ha/yr in this scenario. Based on these model predictions, it is clear that erosion rates are much more sensitive to variations in climate than variations in tillage management.

## Runoff Estimates for Hydrologic Flow

Runoff estimates for average, dry and wet flow regimes are shown in Figs. 8-10. Runoff under average conditions typically increases from west to east across the state (Fig. 8). The greatest runoff occurs in watersheds along Lake Superior in northeastern Minnesota (up to 15 cm), followed by watersheds in southeastern Minnesota (Fig. 8). The smallest runoff occurs in watersheds in northwestern and west central Minnesota (less than 4 cm). For dry years (Fig. 9), runoff increases from west to east, but the magnitudes of runoff are much smaller (maximum runoff of about 11 cm). For wet years the greatest runoff occurs in northeastern and southern Minnesota (Fig. 10), and the magnitude of runoff is considerably greater than for average years (up to about 21 cm).

## Agricultural Land in Close Proximity to Rivers and Ditches

The transport of phosphorus to surface waters depends to a large extent on the percent of land in a watershed that is within 91.4 m (300 ft) of a waterway. As the proximity of agricultural land to a waterway increases, so too does the potential for transport of phosphorus to the waterway (Gburek et al., 2000, Soranno and Hubler, 1996). The latter two citations indicate that the risk for P transport is greatest for lands from 50 – 300 m from surface waterways. Gburek et al. (2000) studied agricultural phosphorus losses in a small watershed located in Pennsylvania. This watershed receives on average 1100 mm/yr of precipitation, has landscapes with slopes ranging from 1-19% in steepness, and is dominated by silt loam soils. Gburek et al. (2000) found that the distance of cropland contributing phosphorus loads to surface waters varied with the amount of rainfall, with contributing distances varying from 5 to 100 m in dry to wet years.

In most of Minnesota, we believe that the risks of phosphorus transport to surface waters are greatest in the contributing corridor within about 100 m from surface waterbodies. This is consistent with research results from across the country, and with recommendations of the primary group of soil scientists conducting research on phosphorus transport to surface waters (the SERA-17 group). Due to topographic variations along surface waterbodies, in some areas phosphorus contributions from overland runoff and erosion may occur from as far away as several hundreds of meters. In contrast, where berms are present along waterbodies it may be unlikely for any surface runoff or erosion to enter surface water. Thus, the 100 m contributing corridor should be viewed as a regional average for contributions of P to surface waters from runoff and erosion on adjacent cropland.

In the Minnesota River basin, where significant acreage of cropland has surface tile intakes and subsurface drains, the transport of phosphorus to surface waters can arise from cropland much farther than 100 m from surface waterbodies. The critical contributing corridor in the case of surface tile intakes is the area of cropland immediately surrounding the surface tile intake that contributes surface runoff and erosion to the intake. The risks of phosphorus transport from surface tile intakes and subsurface drains have not been studied extensively, however, and so P losses from these sources will be addressed in the section at the end of this report dealing with uncertainties.

To estimate the losses of P from surface runoff and erosion, we used an approach that identifies the contributing corridor around surface waterbodies for dry, average and wet climatic conditions. Three methods were used to estimate the percent of land in close proximity to waterways for these conditions The first method was based on hydrologic coverages for perennial streams and ditches (these reflect the potential for transport in average climatic years), the second was based on coverages for perennial streams and ditches plus intermittent streams. Intermittent streams flow primarily during wet years and are generally dry during dry years. The third method was based on hydrologic coverages for perennial streams only, this is based on the observation that ditches flow only sporadically during dry years.

Figs. 11ab show the percent of cropland and pastureland within 91.4 m of perennial streams and ditches for Minnesota watersheds and agroecoregions, normalized for watershed or agroecoregion area. Up to 12% of the cropland lies within 91 m of perennial streams and ditches. Watersheds with the highest percentage of cropland near streams and ditches include the Lac Qui Parle, Grand Marais, South Fork of the Crow, Hawk Creek-Yellow Medicine, and Lower Minnesota watersheds (Fig. 11a). The corresponding agroecoregions include Swelling Clay Lake Sediments, Very Poorly Drained Lake Sediments, Dryer Clays and Silts, and Wetter Clays and Silts (Fig. 11b). Figs. 12ab show the percent of cropland and pastureland within 91.4 m of perennial streams and ditches and intermittent streams for watersheds and agroecoregions. When intermittent streams are included in the analysis, the percent of cropland within 91.4 m of waterways is greatly increased in comparison with the cropland near perennial streams and ditches. The percent of cropland within the 91 m of perennial and intermittent streams and ditches is as great as 50% when intermittent streams are included. Large increases in the percent of cropland in close proximity to surface waters occur in watersheds and agroecoregions of northwestern Minnesota, the Coteau of southwestern Minnesota, and southeastern Minnesota. Figs. 13ab show the percent of cropland and pastureland within 91.4 m of perennial streams only. The maximum percent of crop and pastureland within 91 m of perennial streams is about 5% for watersheds and about 12% for agroecoregions. In general, these percentages are much lower than the percentages for perennial streams and ditches as would be expected. The greatest concentration of cropland near perennial streams is in three areas, southeastern, southwestern, and central Minnesota (Fig. 13b).

### Soil Test Phosphorus Levels on Agricultural Land

Soil test phosphorus (STP) is typically measured in Minnesota using the Bray or Olson extractants. For consistency, we show spatial patterns in Bray-P soil test levels. As Bray-P soil test levels increase, there can be an increase in the risk of phosphorus loss from agricultural land. Bray-P levels are affected by several factors, including natural sources of phosphorus in soil, as well as additions of phosphorus from fertilizer and manure.

Bray-P soil test levels are typically largest in watersheds or agroecoregions of central Minnesota (Figs. 14ab) due to naturally high soil P levels and applications of animal manure to cropland. As a general guideline, the University of Minnesota does not recommend application of phosphorus fertilizer for crop production if Bray-P soil test levels exceed 21 ppm. Only 21 out of 81 major watersheds in Minnesota have average Bray-P levels less than

21 ppm. Caution should be used in interpreting these data, because there can be considerable spatial variability in Bray-P levels within and across farms. Just because the average is above 21 ppm does not mean that no phosphorus fertilizer should be applied. As much as one-third of the area within a farm may have Bray-P levels less than 21 ppm, even if the average is above 21 ppm.

### Fertilizer Phosphorus Application Rates for Agricultural Land

Addition of phosphorus fertilizer to cropland increases the risk of phosphorus transport to surface waters under certain conditions. Figs. 15ab show that rates of phosphorus fertilizer application vary considerably throughout Minnesota watersheds and agroecoregions. This is due to variations in crop rotation, variations in soil test phosphorus levels, and variations in the rates of manure application. Application rates are generally the highest in watersheds and agroecoregions of the Minnesota River Basin. Application rates are generally smallest in northeastern and north central Minnesota.

### Manure Phosphorus Application Rates for Agricultural Land

Manure is applied to cropland as a by product of animal production practices. Manure is typically enriched in phosphorus relative to nitrogen. If applied at high rates using improper application methods, manure can increase the potential for losses of phosphorus to surface waters. Figs.16ab show the variation in phosphorus application rates from animal manure across Minnesota watersheds. Application rates are greatest in central and southeastern Minnesota, where there are large concentrations of dairy and/or poultry operations. Watersheds with high rates of manure P application include the Sauk, Platte-Spunk, and North Fork of the Crow in central Minnesota, the La Crosse-Pine, Buffalo-Whitewater, Cannon, Zumbro, and Root watersheds in southeastern Minnesota, and the Blue Earth, Middle Minnesota, and Lower Minnesota watersheds in south central Minnesota (Fig. 16a). Application rates are lowest in the Red River of the North Basin and in northeastern Minnesota.

## Phosphorus Risk Index Estimates for Agricultural Land

### *Average Hydrologic Runoff Volume, Average Rainfall Runoff Erosivity, Poor Crop Residue Cover Management Conditions*

This scenario was based on long-term average stream flows, average rainfall erosivity, and no crop residue cover due to moldboard plow tillage methods. It is a worst case scenario for tillage methods, and is similar to the scenario developed in Birr and Mulla (2001), except that the effects of supporting conservation practices such as contour strip cropping, terracing, and filter strips are here considered. From a practical standpoint, most areas of Minnesota use tillage systems that leave more crop residue than assumed in this scenario, so the phosphorus risks are overestimated in this scenario. As a rough guideline to identify impaired surface waters, Birr and Mulla (2001) suggested that values of the phosphorus index should not exceed 32 in Minnesota watersheds, except in the Red River of the North Basin, where a critical level of 25 should not be exceeded. There are seventeen watersheds in south central Minnesota with a phosphorus index value greater than 32 (Fig. 17a), these include the Lower Minnesota, Winnebago, Upper Cedar, Hawk Creek-Yellow Medicine, Blue Earth, Lac Qui Parle, Cannon, Rush-Vermillion, Middle Minnesota, South Fork of the Crow, Cottonwood, and Watonwan watersheds. Note that watersheds in southeastern Minnesota that had a high rate of soil erosion (Zumbro and Root) have only intermediate values for the phosphorus index (27-30). This is because of other factors that are not conducive to high risk, such as a moderate density of cropland near waterways and moderate to low application rates of phosphorus fertilizer. Watersheds such as the Le Sueur, Redwood, Chippewa, Watonwan and South Fork of the Crow also have high phosphorus index scores (ranging from 30-31). It is well known that the Minnesota River basin generates the largest phosphorus losses of any major river basin in Minnesota. Thus, it is not surprising that nine of the twelve major watersheds in the Minnesota River basin have a phosphorus index value that exceeds 30. Watersheds in the northern half of Minnesota generally have phosphorus index values less than 21. Agroecoregions with phosphorus index values greater than 32 in this scenario are primarily located in the Minnesota River Basin, and include the Wetter Clays and Silts, Dryer Clays and Silts, Steeper Till, Wetter Blue Earth Till, and Dryer Blue Earth Till (Fig. 17b).

### *Average Hydrologic Runoff Volume, Average Rainfall Runoff Erosivity, Average Crop Residue Cover Management Conditions*

This scenario is similar to the previous one, except that erosion and phosphorus index values are based on the average crop residue levels as reported in tillage transect surveys. Fig. 18a shows that thirteen watersheds have phosphorus index values that exceed 32, including the Lower Minnesota, Blue Earth, Shell-Rock, Cannon, Rush-Vermillion, Middle Minnesota, South Fork of the Crow, and Watonwan watersheds. These are primarily in the Minnesota River basin and Lower Mississippi River basin. Not as many watersheds have phosphorus index values exceeding 32 in this scenario as in the previous scenario, due to greater crop residue cover in this scenario. Agroecoregions with phosphorus index scores greater than 32 in this average crop residue scenario are located primarily in the Minnesota and portions of the Lower Mississippi River basins, including Steeper Till, Wetter Blue Earth Till, Wetter Clays and Silts, Dryer Clays and Silts, and the Steep Wetter Moraine (Fig. 18b).

### *Average Hydrologic Runoff Volume, Average Rainfall Runoff Erosivity, Best Crop Residue Cover Management Conditions*

This scenario was the same as the previous scenario, except that we assumed that conservation tillage leaving 50% of the soil covered by crop residue was practiced on row cropland. From a practical standpoint, most areas of Minnesota use tillage systems that leave less crop residue than assumed in this scenario, so the phosphorus risks are underestimated in this scenario. In general, the increase in crop residue cover produces lower phosphorus index scores in this scenario in comparison with the previous scenario involving average residue cover. Phosphorus index values exceed a score of 32 with this scenario for the Lower Minnesota, Winnebago, Cannon, Rush-Vermillion, and La Crosse-Pine watersheds (Fig. 19a). Then next highest scores occur primarily in the Minnesota River basin and in southeastern Minnesota, including the Coon-Yellow, Buffalo-Whitewater, Shell-Rock, Root, Hawk Creek-Yellow Medicine, Zumbro, Blue Earth, and Lac Qui Parle watersheds. Most of the northern half of Minnesota shows low risks for phosphorus transport in this scenario. For agroecoregions (Fig. 19b), the phosphorus index scores exceed 32 primarily in the Steep Wetter Moraine agroecoregion. The Wetter Clays and Silts and Rolling Moraine agroecoregions also have relatively high phosphorus index scores that are in the range of 30 and 31.

### *Dry Hydrologic Runoff Volume, Dry Rainfall Runoff Erosivity, Best Crop Residue Cover Management Conditions, Cropland Contributing Corridor Based on Perennial Streams and Ditches*

In this scenario, the hydrologic runoff and rainfall runoff erosivity values were typical of dry years. Crop residue cover was based on widespread adoption of conservation tillage. One caveat is that the percent of cropland within 91.4 m of perennial streams and ditches may be unrealistic for this scenario. In dry years the cropland that contributes eroded sediment and runoff to surface waters may be considerably less in area than the cropland that contributes in average years. Thus, the phosphorus index values in this scenario may be overestimated. Phosphorus index values for this scenario are always smaller than those for the scenario based on an average climatic year. The maximum phosphorus index value for watersheds in the dry year scenario is about 29, whereas the maximum value for an average year is about 41. Figs. 20ab show the spatial patterns in phosphorus index values for Minnesota watersheds and agroecoregions. No watersheds exceed the critical phosphorus index value of 32 in this scenario, and none are in the next highest category ranging from 31 to 34 either. Only one watershed, the Lower Minnesota watershed has a phosphorus index score between 27 and 30. Only a handful of watersheds have phosphorus index scores ranging from 22-26, while a majority have scores below 21 (Fig. 20a). Agroecoregions with phosphorus index scores between 22 and 26 fall mainly in the Minnesota River Basin (Fig. 20b), but the vast majority of agroecoregions have scores less than 21.

### *Dry Hydrologic Runoff Volume, Dry Rainfall Runoff Erosivity, Best Crop Residue Cover Management Conditions, Cropland Contributing Corridor Based on Perennial Streams Only*

This scenario is the same as the previous, except that the cropland contributing corridor is reduced in area by assuming that only croplands near perennial streams contribute to phosphorus losses in dry years. This is reasonable, since most ditches flow only sporadically during dry years. Figs. 21ab show the phosphorus index values for this scenario in Minnesota watersheds and agroecoregions. No watersheds or agroecoregions have phosphorus index values that exceed 25 or 27, respectively, in this scenario. Only two small watersheds have phosphorus index scores greater than 21, the La Crosse-Pine and Rush-Vermillion watersheds of southeastern Minnesota. Only two small agroecoregions have phosphorus index scores greater than 21, the Steeper Stream Banks and Steeper Alluvium agroecoregions. This scenario is probably a more accurate representation of the risks of phosphorus transport to surface waters in dry years than the scenario that was based on a contributing corridor around both perennial streams and ditches.

### *Wet Hydrologic Runoff Volume, Wet Rainfall Runoff Erosivity, Best Crop Residue Cover Management Conditions, Cropland Contributing Corridor Based on Perennial Streams and Ditches*

This scenario indicates the risk of phosphorus transport to surface waters from agricultural land during wet years. It is based on runoff volumes and rainfall runoff erosivity values for wet years, on widespread adoption of conservation tillage, and on a cropland contributing corridor 91.4 m wide around perennial streams and ditches. Comparing this scenario (Figs. 22ab) with that for an average climatic year (Figs. 19ab), it is evident that the risks of phosphorus loss have increased by a large amount (phosphorus index scores as high as 43) in a significant number of watersheds and agroecoregions. In the wet year scenario there are 24 watersheds with a phosphorus index score exceeding 32, whereas there were only 5 in the average year scenario. The watersheds exceeding the critical score in wet years are spread across south central and central Minnesota, as well as the Red River of the North basin (Fig. 22a). It is interesting to note that many of the watersheds in southeastern Minnesota are still below this critical threshold in wet years. This is primarily because of their relatively smaller percent area of cropland within 91.4 m of perennial streams and ditches. As will be shown in the next scenario, if the effects of intermittent streams are considered, the risk of phosphorus transport is considerably increased in southeastern Minnesota.

### *Wet Hydrologic Runoff Volume, Wet Rainfall Runoff Erosivity, Best Crop Residue Cover Management Conditions, Cropland Contributing Corridor Based on All Streams and Ditches*

This scenario differs from the previous one in that the effects on phosphorus transport of cropland near intermittent streams, which flow during wet years, was considered. Figs. 23ab show that the risks of phosphorus transport to surface waters are considerably increased all across Minnesota in comparison to the scenario for wet years which does not consider intermittent streams (Figs 22ab). Most of the southern two thirds of Minnesota watersheds and agroecoregions exceed the critical phosphorus index score of 32 in this scenario. Only the watersheds and agroecoregions in the far northeastern portion of Minnesota are relatively unaffected by including the effects of intermittent streams on phosphorus transport. This scenario is probably a more accurate representation of the risks of phosphorus transport to surface waters in wet years than the scenario based on a contributing corridor around only perennial streams and ditches.

### *Average Hydrologic Runoff Volume, Average Rainfall Runoff Erosivity, Average Crop Residue Cover Management Conditions, Reduced Phosphorus Fertilizer, Cropland Contributing Corridor Around Perennial Streams and Ditches*

This scenario illustrates the reductions in risk of phosphorus transport to surface waters (based on a contributing corridor around perennial streams and ditches only) due to reductions in rate of application of phosphorus fertilizer. These reductions were only made in watersheds or agroecoregions that had both high soil test phosphorus levels and high rates of phosphorus fertilizer application. More specifically the reductions were made where STP was greater than 32 ppm and fertilizer P application rates exceeded 27 kg/ha or where STP was greater than 39 ppm regardless of fertilizer P application rates. In both these cases, the rate of phosphorus fertilizer application was reduced to 5 kg/ha. These reductions reduce the risk of phosphorus transport in about one third of watersheds and agroecoregions, namely those units where the soil is generally capable of supplying P for crop production with little or no phosphorus fertilizer application. The phosphorus index values for this scenario are shown in Figs. 24ab for Minnesota watersheds and agroecoregions. For watersheds (Fig. 24a), the phosphorus index values in the Middle Minnesota, Cottonwood, Lower Minnesota, Rush-Vermillion and Cannon watersheds are reduced significantly in this scenario in comparison to their phosphorus index values for the scenario shown in Fig. 18a (scores decrease from generally above 32 to generally below 27), thus bringing them below the critical threshold. Large reductions in phosphorus index values also occur in the Le Sueur watershed. Agroecoregions with a significant reduction in phosphorus index scores include the Anoka Sand Plains, Dryer Blue Earth Till, Rochester Plateau, and Wetter Blue Earth Till (Fig. 23b). A moderate reduction also occurred in the Undulating Plains agroecoregion.

### *Average Hydrologic Runoff Volume, Average Rainfall Runoff Erosivity, Average Crop Residue Cover Management Conditions, Variable Manure Application Method*

This scenario involves consideration of the variations in manure application method arising from differences in animal species and manure storage facilities. The baseline scenario represented by Figs. 18ab assumes that manure is applied and incorporated immediately just before planting a crop. This is most likely an overly optimistic scenario for most manure applications in the state. More realistic are the phosphorus index values illustrated in Figs. 25ab for Minnesota watersheds and agroecoregions based on consideration of differences across regions in manure application methods. Phosphorus index scores increase in this scenario relative to the baseline scenario that assumes relatively good methods of manure application. The increases are particularly noteworthy in northern Minnesota, where beef cattle operations are relatively abundant relative to other types of animal production. Beef cattle operations tend to be small, and many lack adequate manure storage facilities. This results in frequent hauling and land application of manure, generally without incorporation, including application of manure during the winter to frozen or snow covered cropland. Agroecoregions where the risk of phosphorus loss to surface waters increases due to poor manure application methods include the Red Lake Loams, Forested Lake Sediments, Peatlands, Northern Till, and Northshore Moraine (Fig. 25b). Increases in phosphorus index values in these northern regions are still not large enough to produce scores that are greater than the criticial threshold of 32, in fact the scores are still far below the critical threshold value. Small increases in phosphorus index scores occur in the Blufflands and Rochester Plateau agroecoregions of southeastern Minnesota, where dairy operations predominate. These increases do bring the phosphorus risks close to the critical threshold value of 32. Small increases in phosphorus index scores also occur in portions of the Red River of the North basin, in areas with relatively abundant beef cattle. These small increases bring the phosphorus index scores close to the critical threshold value of 25 in that region. Phosphorus index scores are relatively unaffected in southern Minnesota in regions where hog production dominates, because hog producers tend to have adequate manure storage and inject their manure rather than spreading it on the soil surface where it is very susceptible to losses by erosion and runoff.

## Estimating Phosphorus Losses from Edge of Cropped Fields to Surface Waters

Two different approaches were tested for converting phosphorus index values to edge of field phosphorus losses to surface waters. The first method attempted to estimate phosphorus losses from the edge of field based on monitoring data for phosphorus loads in 53 Minnesota streams and rivers. This method was unsuccessful, but is described below. The second method estimated phosphorus losses from the edge of cropland fields based on export coefficients which were derived from the phosphorus index values. This is the method used for final estimates of basin wide phosphorus loadings to surface waters from the edge of cropland fields. The detailed methodology is described below.

### *Unsuccessful Method for Estimating Phosphorus Losses Based on Monitoring Data*

Barr Engineering summarized existing data for phosphorus loads measured by water quality monitoring in 53 ditches, streams and rivers throughout Minnesota. They separated the data according to flow conditions into phosphorus loads for dry, average and wet years. They also supplied estimates for phosphorus losses discharged to surface waters in the same watersheds from non-agricultural rural, streambank erosion, and point sources of phosphorus. No data were supplied for the phosphorus losses from individual septic treatment systems (ISTS), atmospheric deposition, or urban runoff in these watersheds.

The phosphorus loads supplied by Barr Engineering were adjusted by subtracting the losses from non-agricultural rural and point sources of phosphorus, and by subtracting half of the phosphorus losses from streambank erosion. Only half of the streambank erosion losses were subtracted because much of the sediment from streambank erosion is transported as bedload, which is not measured in most water quality monitoring studies. The remaining phosphorus loadings were then divided by the area of cropland within 91 m of streams and ditches to provide an estimate of the potential phosphorus losses from the edge of cropland fields.

The resulting adjusted phosphorus yields were not very consistent with expected results, and were not deemed meaningful. Many of the adjusted phosphorus yields were negative in dry years because the point source loadings were larger than the monitored phosphorus loadings in the watershed. This could be due to phosphorus uptake by algae or plants. In wet years the adjusted phosphorus yields exhibited a huge range, from nearly zero to several hundreds of kg P/ha. This was most likely the result of several factors. The first factor is that the phosphorus monitoring load data were collected using a variety of methods, ranging from grab samples to automated water quality sampling. The second is that the monitored loads were collected over different lengths of time, ranging from a single season to multiple years. The third factor is that the adjusted phosphorus losses were not corrected to account for contributions of phosphorus from ISTS, atmospheric deposition, or urban runoff. This led to unrealistically high adjusted phosphorus loads during average and wet years. The fourth factor is that the phosphorus delivery ratio from each non-agricultural source should be varied by source and by flow regime when adjusting the monitored loads. For example, the delivery ratio for point sources would probably be a number between 0.8 and 1, but this would vary for dry and wet years. Similarly, the delivery ratio for streambank erosion (assumed to be 0.5) would vary with flow regime. One can conclude from this exercise that a considerable amount of additional research and monitoring effort is needed before this approach can provide accurate estimates of edge of cropland field phosphorus losses. As a result, this approach for estimating edge of field phosphorus losses from agricultural sources was abandoned.

*Successful Method for Estimating Phosphorus Losses Based on Export Coefficient Approach*

Birr et al. (2002) found that there is a strong linear correlation ($r^2$ =0.82) between a version of the modified phosphorus index values (from Birr and Mulla, 2001) and the pathway (or field scale) phosphorus index values. The modified phosphorus index values are typically thirteen times higher than the pathway phosphorus index values. Similarly, there is a strong linear correlation between the estimated pathway phosphorus index values and the observed phosphorus export (expressed in kg/ha/yr) at the field scale. The pathway phosphorus index values are typically five times higher than the total phosphorus export, at the field scale (Mulla, 2003). This suggests that we can estimate phosphorus losses from the edge of cropland fields by dividing the phosphorus index results by a factor of approximately 65. This gives an estimate of the losses of total phosphorus to surface waters from cropland and pastureland in units of kg/ha/yr, which represents the phosphorus export coefficient for agricultural land. Basin scale phosphorus losses from the edge of cropland fields to surface waters can then be estimated by multiplying the phosphorus loss per ha (export coefficient) by the area of cropland within 91 m of surface water bodies for the entire basin.

Since the version of the modified phosphorus index used in this study is slightly different from the one used by Birr et al. (2002), we decided to develop a relationship between the phosphorus index and the phosphorus export coefficient using phosphorus loss data compiled from University of Minnesota research at four sites in or near Minnesota. The sites are located near Morris, Minnesota (Ginting et al., 1998), Lancaster, Wisconsin (Munyankusi, 1999), and two sites in Scott County, Minnesota (Hansen et al., 2001). These sites involved measurements of total phosphorus losses from the edge of agricultural fields (typically a corn and soybean rotation) ranging in area from 0.5 to 1.6 ha. Data from these sites were collected between 1996 and 2000. Two of these years experienced average climatic conditions, two were a little wetter than average, and one was a little drier than average. Fields were treated using a range of tillage and manure management methods. The tillage treatments included moldboard plowing, chisel plowing, ridge tillage, and no-tillage. Manure treatments included no manure, heavy rates of manure, and variations in timing of manure application. Total phosphorus losses from the fourteen individual treatments at these four sites ranged from 0.1 to 2.3 kg/ha/yr, with an average of 0.68 kg/ha/yr in total phosphorus loss from the edge of field.

The counties where these four research sites are located have a range of tillage practices, with the percent of farmland having at least 30% crop residue cover ranging from about 47% in Scott and Stevens counties to about 64% of cropland with at least 30% residue cover in Houston county, the nearest county in Minnesota to Lancaster, Wisconsin. The phosphorus index values for an average climatic year and the existing residue cover adoption rates indicated above are 24, 32, and 43 in the Chippewa, Root and Lower Minnesota watersheds, respectively. If we take the P Index values for each watershed and divide them by the average phosphorus losses for the study sites in that watershed, the resulting conversion factor (or divisor) is 78. If on the other hand, we take the average phosphorus index value for these three regions of 33 and divide this by the average phosphorus loss from the edge of field in these experiments at four sites (0.68 kg/ha), we obtain 48.5 as the conversion factor between the phosphorus index and the phosphorus losses from the edge of field. This conversion factor is somewhat lower than both the conversion factor of 65 initially obtained using the relationship between the matrix and pathway versions of the phosphorus index, and the conversion factor of 78 obtained by averaging the divisors obtained for each watershed. A sensitivity analysis of the effects of varying the divisors (and hence the resulting export coefficients) on phosphorus loadings is included in the section of this report dealing with uncertainties.

Taking the divisor of 48.5 as the most realistic estimate for the conversion factor, and rounding this conversion factor up to 50 for significant digits, we then divided all the phosphorus index values for each watershed and agroecoregion in Minnesota by 50 to obtain phosphorus export coefficients. The resulting phosphorus export coefficients for an average year are 0.43 kg/ha/yr for major watersheds and 0.44 kg/ha/yr for agroecoregions. For wet years the export coefficients are 0.65 kg/ha/yr for watersheds and 0.68 kg/ha/yr for agroecoregions. For dry years the export coefficients are 0.21 kg/ha/yr for watersheds and 0.22 kg/ha/yr for agroecoregions. According to Heiskary and Wilson (1994), recommended phosphorus export coefficients for Minnesota agricultural lands are 0.2, 0.4, or 0.6 kg/ha/yr for low, mid, and high export risk conditions. Hence, our statewide average export coefficients for low, mid, and high export risk conditions (0.21, 0.43, and 0.65 kg/ha/yr) compare favorably with those recommended by Heiskary and Wilson (1994).

The procedure for estimating basin wide loads of phosphorus exported from the edge of agricultural fields is to multiply the export coefficients described above by the area of cropland within a distance of 100 m of surface water bodies (perennial and intermittent streams, ditches, wetlands, and lakes). On average, about 32% of all cropland lies within this distance of surface water bodies statewide, with a range of from 21 to 52% in major river basins (Table 2). This procedure accounts for the variability in risk of phosphorus loss from the edge of field due to climatic effects as well as the variability in soil, management and hydrologic factors. Variability in the phosphorus index values across the state are translated into variability in phosphorus losses from the edge of field using the export coefficient. On top of this, we added another 10% to the phosphorus loadings to account for contributions from cropland farther than 100 m from surface waterbodies. This is consistent with results from research conducted by Sharpley et al. (1994), Daniel et al. (1994) and Gburek et al. (2000), who concluded (SERA-17, 2004) that only 10% of the phosphorus loadings to surface waters from overland transport on agricultural lands arise from outside the primary contributing corridor (100 m or farther from surface water bodies). This 10% does not include additional phosphorus contributions that arise from surface tile inlets or subsurface tile drains.

## Phosphorus Loads to Minnesota Surface Waters from Agricultural Lands

### *Major Watershed Based Analysis*

Phosphorus export coefficients show considerable variation across major drainage basins and across climatic conditions (Table 3 and Fig. 26). Export coefficients (kg/ha) during average climatic conditions vary from 0.54 kg/ha for the Minnesota River basin, 0.4 kg/ha for the Red River basin, 0.39 kg/ha for the Upper Mississippi River basin, and 0.66 kg/ha for the Lower Mississippi River basin. During wet years, the export coefficients are increased to 0.81 kg/ha for the Minnesota River, to 0.54 kg/ha for the Red River, to 0.69 kg/ha for the Upper Mississippi River, and to 0.80 kg/ha for the Lower Mississippi River basin. The export coefficients decrease during dry years to 0.28, 0.13, 0.22, and 0.36 kg/ha for the Minnesota, Red, Upper Mississippi, and Lower Mississippi River basins, respectively.

Phosphorus export coefficients for river basins with relatively sparse agricultural cropland are smaller than the coefficients for river basins with intensive agricultural land use. For example, during average climatic years, the phosphorus export coefficients for the Lake Superior, Rainy, and St. Croix River basins are only 0.24, 0.23 and 0.38 kg/ha, respectively.

Phosphorus loads exported to surface waters from agricultural lands under dry, average and wet climatic conditions are shown in Table 4 and Fig. 27 (based on an analysis of phosphorus index values and export coefficients for major watersheds). Under average climatic conditions, the phosphorus loads exported to surface waters from the edge of agricultural fields are greatest for the Minnesota River basin (517,862 kg/yr), followed by the Red River (384,695 kg/yr), the Upper Mississippi (359,681 kg/yr) and the Lower Mississippi (232,581 kg/yr) River basins. All of the other basins have phosphorus export loads that are considerably smaller than the loads exported in these four basins.

As expected, phosphorus loads exported from agricultural lands to surface waters are considerably greater during wet years than average years. Under wet climatic conditions, the phosphorus loads exported in the Minnesota, Red, Upper Mississippi, and Lower Mississippi River basins are 759,749, 545,247, 652,266, and 282,780 kg/yr, respectively. In dry years the phosphorus loads exported are 262,851, 131,311, 200,865, and 116,810 kg/yr, respectively, for these same basins.

Phosphorus loads exported from agricultural lands are much smaller for the Rainy, Lake Superior and St. Croix River basins than the basins with larger proportions of agricultural cropland (the Minnesota, Red, Upper and Lower Mississippi River basins). For example, during years with average climatic conditions, phosphorus loads exported from agricultural land to surface waters are only 13,112, 20,713, 59,931 kg/yr for the Lake Superior, Rainy and St. Croix River basins, respectively. Similar comparisons can be made for wet and dry climatic years.

### *Agroecoregion Based Analysis*

Phosphorus loads exported to surface waters from agricultural lands during dry, average and wet climatic conditions based on phosphorus index values and export coefficients calculated using agroecoregion boundaries are shown in Table 5 and Fig. 28. The relative rankings of major drainage basins are similar for the agroecoregion and watershed based analyses. With agroecoregion based export coefficients, the Minnesota River basin generates more phosphorus loadings to surface waters (516,768 kg/yr) than any other basin, a result that is consistent with the watershed based analysis. Significant phosphorus loadings for other basins include 361,759 kg/yr in the Red River basin, 332,313 kg/yr in the Upper Mississippi River basin, and 203,702 kg/yr in the Lower Mississippi River basin. In general, the magnitudes of phosphorus loadings are about 7% smaller for these basins in an average year than the magnitudes obtained using the watershed based analysis.

Four alternative agricultural management scenarios were investigated and compared to a baseline scenario involving an average climatic year and existing rates of adoption of conservation tillage and existing rates of phosphorus fertilizer applications. The first alternative management was a scenario in which moldboard plowing is used on all row cropland. This is a worst case scenario for erosion, and exemplifies phosphorus losses typical of an era that existed twenty or more years ago. This scenario allows us to evaluate the extent of progress in controlling phosphorus losses over the last twenty years due to improvements in tillage management. The second scenario involves reductions in the rate of phosphorus fertilizer applications in watersheds where soil test phosphorus levels are higher than 27 ppm. In this case, fertilizer P application rates were reduced on row cropland to reflect the fact that soil phosphorus levels are sufficient for crop production. The third scenario involves improvements in manure application methods. Manure application methods were improved in watersheds where manure is primarily applied to the soil surface without incorporation (weighting factor of 8 in P Index matrix). In these watersheds the method of manure application was improved so that manure was incorporated immediately after application (weighting factor of 2 in P Index matrix). The fourth scenario involves variation in the area of cropland within 91 m of surface waterbodies.

The results of the first three alternative scenarios are shown in Fig. 29. In the Minnesota River basin, compared to an era when moldboard plowing was widely practiced, current day phosphorus losses from agricultural cropland have been reduced by about 146,000 kg/yr (from about 664,000 to 518,000 kg/yr), for a 28% reduction. In the Upper Mississippi River basin, current phosphorus losses from agricultural land have been reduced by about 87,000 kg/yr, for a 24% reduction. Similar comparisons show a 7% reduction for the Red River basin. No significant reductions have occurred in the Lower Mississippi River basin.

The potential future impacts of improved phosphorus fertilizer management can be quite significant (Fig. 29). Reductions in phosphorus fertilizer usage could occur if University of Minnesota recommendations were followed more consistently. For instance, phosphorus fertilizer is spread on significant areas of land in the Minnesota River basin even if soil test phosphorus levels exceed the threshold set by the University above which crops do not respond to additional fertilizer. This is because recommendations made by the fertilizer industry are often based on the concept of fertilizing at a rate equivalent to crop removal, if soil test phosphorus levels are above 21 ppm. In the Minnesota River basin, reductions in the rate of phosphorus fertilizer application could potentially reduce phosphorus losses to surface waters by about 81,000 kg/yr as compared to existing conditions, for a 16% reduction. Comparable levels of reduction could occur with improved phosphorus fertilizer management in the Red River, and the Upper and Lower Mississippi River basins.

The potential impact of improved manure application methods is illustrated in Fig. 29. In the Red River basin, phosphorus loads to surface waters could be reduced by about 75,000 kg/yr, for a 20% reduction. Reductions are much smaller in other basins with significant phosphorus loads from agricultural land. Improved manure application methods could potentially reduce phosphorus loads to surface waters by 12%, 7% and 7% in the Upper Mississippi, Lower Mississippi, and Minnesota River basins. In general, the effects on phosphorus loads of improvements in method of manure application are greatest for basins that have large numbers of beef cattle, and least for basins with large numbers of hogs.

The last scenario involves decreasing or increasing the area of cropland within 100 m of surface waterbodies. Decreases in area of cropland could correspond to land retirement programs such as those promoted in the Conservation Reserve and Conservation Reserve Enhancement Programs. Increases in cropland area would correspond to putting grass or forest riparian areas into production, alternatively this could be viewed as increasing the distance for cropland areas (now assumed to be 100 m) that contribute phosphorus to surface waters. The results from this scenario (Fig. 30) indicate that retiring land in close proximity to surface waters would decrease the phosphorus loadings as expected. Every one percent decrease in the area of cropland within 100 m of surface waters leads to a one percent decrease in phosphorus loadings. Alternatively, every one percent increase in the area of cropland near surface waters leads to a one percent increase in the phosphorus loadings.

### *Uncertainties in Estimated Phosphorus Loadings*

There are many possible sources of uncertainty in the estimated phosphorus loadings. These can be divided into errors in input data, errors in converting phosphorus index values to phosphorus export coefficients, errors in estimating the proportion of cropland that contributes to phosphorus loadings, and errors due to a lack of consideration for impacts of surface and subsurface drainage, wind erosion or snowmelt runoff on phosphorus loadings. The primary sources of errors in input data include those due to spatial variations in farm management practices at scales smaller than watersheds or agroecoregions, errors in estimating slope length for erosion calculations, and errors due to out of date landuse information (all cropland estimates in the contributing corridor around surface water bodies are based on 1992 landuse data).

Errors in estimating phosphorus export coefficients also lead to uncertainties in phosphorus loadings. A sensitivity analysis was conducted to determine the impact of uncertainties in export coefficients on phosphorus loadings. We estimated phosphorus loadings under three scenarios for watershed based phosphorus index values, namely; phosphorus index divisor factors of 50 (recommended baseline value from this study), 70 and 30. For phosphorus index divisors greater than 50, the basin phosphorus loadings decreased on average by 1.4% for an increase of one in the divisor (e.g. a 1.4% decrease when the divisor is increased from 50 to 51). For phosphorus index divisors less than 50, the basin phosphorus loadings increased on average by 3.3% for an decrease of one in the divisor (e.g. a 3.3% increase when the divisor is decreased from 50 to 49).

Errors can arise from improperly estimating the area of cropland within 100 m of surface water bodies. This influence was described in the section above (Fig. 30). Also, we do not vary the area of cropland within 100 m of surface water bodies when computing basin scale phosphorus loadings for dry, average, and wet years. For each climatic scenario we are using the maximum possible area of cropland, thus overestimating the agricultural contributions during average and dry years. To illustrate the effects of this uncertainty, we estimated the percent of all cropland within 91 m of waterbodies for dry, average and wet years using different hydrologic coverages. For dry years, using hydrologic coverages for perennial streams, there was only 1.14% of all cropland within 91 m of surface waters. Using perennial streams plus ditches in average years, 3.8% of all cropland was within 91 m of surface waters. In wet years, using perennial streams, ditches, and intermittent streams, 17.2% of all cropland was within 91 m of surface waters. These area percentages were used to account for the effects of climatic variability in estimating phosphorus index values. However, in calculating phosphorus loads from agricultural areas phosphorus export coefficients were multiplied by the area of cropland within 100 m of perennial streams, ditches, intermittent streams, lakes and wetlands (accounting on average for 32% of cropland area). In view of these results, phosphorus loadings from agricultural lands are overestimated for average and dry years.

Our method of estimation does not consider the influence that surface tile intakes farther than 100 m may have on phosphorus loadings. To include the effects of surface tile intakes we would need to know the number of tile intakes per unit area, the area of cropland contributing to tile intake flow, and the phosphorus export coefficients for surface tile intakes. These data are not available for Minnesota in enough detail to be confident about their representativeness. Since depressional areas around tile inlets generally trap 60-80% of the sediment and phosphorus flowing to the inlets, the phosphorus export coefficient for surface tile intakes is smaller than that for direct overland flow to surface waters (Ginting et al., 2000). Ginting et al. (2000) studied phosphorus loads carried by surface tile intakes in two small catchments located in the Watonwan watershed of the Minnesota River basin. They found that, over a three year period with slightly below precipitation amounts, phosphorus loads carried by surface tile intakes averaged 0.099 kg/ha annually, with measured concentrations of phosphorus in surface tile intakes as high as 4 mg/L. This loading (0.099 kg/ha) is significantly smaller than the amounts of phosphorus transported by surface runoff and erosion in the same region (0.68 kg/ha).

There were three surface tile intakes studied by Ginting et al. (2000), and the average phosphorus load transported by each tile intake annually was 2.82 kg/yr. Surveys of surface tile intake density in 32 small watersheds within the Minnesota River basin (MPCA, 1994) show that there is one surface tile intake for every 23 to 1210 acres in the watershed. The average is one surface tile intake for every 100 or so watershed acres (the acreage that actually contributes to surface tile intake P loads is smaller than this, but few data exist to know what the contributing acreage actually is). If we assume that there is one surface tile intake for every 100 acres within the poorly drained soils of the Minnesota River basin, we estimate that there are roughly 33,333 surface tile intakes in the basin. At a phosphorus loading of 2.8 kg/yr for each tile intake, the total phosphorus loading from surface tile intakes to surface water bodies in the Minnesota River basin would be about 94,000 kg/yr. This is approximately 18% of the phosphorus loading from cropland within 91 m of surface waters in the Minnesota River basin during an average year (517,862 kg/yr).

Similarly, our method does not consider the influence of subsurface tile drainage on phosphorus export to surface waters. Randall et al. (2000) studied losses of phosphorus in subsurface drainage in a four year manure and fertilizer study on a Webster clay loam typical of the poorly drained soils in the Minnesota River basin. According to Randall et al. (2000), on average over half of the drainage flows carry non-detectable amounts of phosphorus. The remainder of drainage flows have a concentration of total phosphorus averaging about 0.03 mg/L (with maximum observed concentrations of about 0.12 mg/L), for an average annual loss of 0.027 kg P/ha. If this rate is applied to the area of cropland in the Minnesota River basin having tile drainage, it gives a phosphorus loading of about 30,000 kg/yr, which is quite small (6% of total) compared to the phosphorus loading from cropland within 91 m of surface waters during an average year (517,862 kg/yr). Subsurface drainage phosphorus loads from other basins would be much smaller, because tile drainage is of limited extent in basins other than the Minnesota River basin.

The phosphorus loadings from subsurface tile drains collected by Randall et al. (2000) are the only data published in peer reviewed journals from Minnesota studies. Other studies of phosphorus losses in Minnesota subsurface tile drainage include those conducted by Alexander and Magdalene (1998) from 1995 to 1997 at the Rollings East Tile (RET) site, and by the Minnesota Department of Agriculture from 1998 to 2001 at the Red Top farm, both of which are located in the Minnesota River basin. The study by Alexander and Magdalene (1998) does not estimate phosphorus loadings from subsurface tile drainage, instead, it reports only the concentrations of phosphorus measured. The concentrations of phosphorus measured in subsurface tile drainage by Alexander and Magdalene (1998) are very comparable in seven out of ten storms they monitored to the concentrations measured by Randall et al. (2000) over a four year period. In two other storms monitored by Alexander and Magdalene (1998), the phosphorus concentrations ranged between 0.42 and 1.5 mg/L, much higher than those measured by Randall et al. (2000). At the Red Top farm study, based on 9 field years of water quality monitoring data for average climatic years, the annual average phosphorus loading from subsurface tile drains was 0.11 kg/ha. These larger field drainage systems were constructed of concrete tiles which differ from the smaller plot based plastic drain tiles studied by Randall et al. (2000). Based on this comparison, we conclude that more research is needed to accurately define the mean and range in phosphorus loading from subsurface drainage tiles in the Minnesota River basin.

Not enough research data are available to reliably estimate the phosphorus loadings from surface tile intakes or subsurface tile drains to surface waters in the Minnesota River basin during dry or wet climatic years. As a first approximation, we can scale the phosphorus loadings from tile drains so that they have the same relative ratio as the phosphorus index based loadings for the Minnesota River basin in dry, average and wet years (262,851; 517,862; and 759,749 kg/yr, respectively). This gives phosphorus loadings from subsurface tile drains of 15,227 kg/yr during dry years and 44,013 kg/yr during wet years. Using the same approach, phosphorus loadings from surface tile inlets during dry and wet years would be 47,711 and 137,906 kg/yr, respectively. As mentioned previously, this approach substantially overestimates the phosphorus loadings in dry years.

Finally, we do not explicitly account for the effects of wind erosion or snowmelt runoff on phosphorus loadings to surface waters. Wind erosion may be particularly important in the Red River basin. Snowmelt erosion is indirectly accounted for in the regional phosphorus index through the runoff factor, as well as in the method of manure application factor, so this error may not be large.

## Recommendations

This study provides a broad overview of the impacts of agricultural lands on phosphorus loadings to surface waters. There are many detailed questions remaining that could be studied in further detail. Some of these are listed below:

- Comparison of watershed based phosphorus loadings with agroecoregion based phosphorus loadings at the scale of major watersheds
- Development of phosphorus delivery ratios for agricultural as well as non-agricultural sources of phosphorus as a function of area of contribution watershed, area of lake and wetland storage in the watershed, and landscape characteristics
- Investigation of the impacts that farm scale variability has on estimated phosphorus loadings within watersheds
- Further study of the distance from surface waters within which the majority of phosphorus losses from cropland to surface waters originate
- Further investigation of the variable source area concept as applied to phosphorus transport during dry, average and wet climatic years
- Further investigation of the contribution of surface tile intakes and subsurface drainage to phosphorus loads
- Study of the impact that wind erosion has on phosphorus loading to surface waters

## Summary

The risk of phosphorus transport to surface waters depends on many factors. These include factors affecting soil erosion by water (conservation tillage, landscape steepness, climate), soil test phosphorus levels, rate of application of phosphorus from fertilizer or manure, and method of application of manure. Extensive databases for Minnesota watersheds and agroecoregions were developed to explore the variation in risks of phosphorus transport to surface waters in response to these factors. The results show that phosphorus losses are more sensitive to climatic variability than any other factor. The fraction of cropland near streams and ditches also has a large impact on phosphorus losses, during both wet and dry years.

Watersheds and agroecoregions in Minnesota exhibit a considerable amount of variation in the risks of phosphorus loss. In general, the watersheds and agroecoregions with the greatest potential for phosphorus loss are located in the Lower Mississippi and Minnesota River basins. This is because of a combination of high rates of erosion, high rates of phosphorus application from fertilizer or manure, and a high percentage of cropland near streams and ditches. From a basin wide perspective, however, the greatest phosphorus loads are exported from agricultural lands to surface waters in the Minnesota River basin, followed by the Red River, Upper Mississippi, and Lower Mississippi River basins. Basins with relatively small areas of agricultural land use, such as the Lake Superior, Rainy and St. Croix River basins have significantly smaller phosphorus loads exported from agricultural lands to surface waters than basins with significant amounts of agricultural land use.

Analysis shows that farmers have made considerable progress in controlling phosphorus losses from agricultural cropland over the last twenty years or more due to accelerated adoption of conservation tillage. Additional progress can be made through continued adoption of best management practices, including reductions in the amount of phosphorus fertilizer applied to cropland when soil phosphorus levels are sufficient for crop production. Improved methods of manure application are also important in northern drainage basins for reductions in phosphorus loads to surface waters. Land retirement programs can be effective at reducing phosphorus loads to surface waters if cropland near surface waters is targeted for retirement.

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## Table 1

### (from Birr and Mulla, 2001)

### The modified version of the P Index representing conditions controlling P movement in Minnesota (adapted from Lemunyon and Gilbert, 1993)

| | Phosphorus loss potential (value) | | | | |
|---|---|---|---|---|---|
| **Site characteristic (weight)** | **Very low (0)** | **Low (1)** | **Medium (2)** | **High (4)** | **Very high (8)** |
| **Transport factors** | | | | | |
| Soil erosion (1.5)† | 0 | 1-5 | 6-14 | 15-21 | > 21 |
| Runoff (0.5)‡ | 0-8 | 9-13 | 14-16 | 17-21 | > 21 |
| Percentage of cropland and pastureland within 91.4 m of a watercourse (1.5) | 0-1.2 | 1.3-3 | 3.1-4.2 | 4.3-6.2 | > 6.2 |
| **Source factors** | | | | | |
| Soil test P (0.75)§ | 0-19 | 20-26 | 27-31 | 32-39 | > 39 |
| Fertilizer P application rate (1.0)¶ | 0-7 | 8-13 | 14-19 | 20-24 | > 24 |
| Fertilizer P application method (0.5) | None applied | Placed with planter deeper than 5 cm | Incorporated immediately before crop | Incorporated >3 mo before crop or surface applied <3 mo before crop | Surface applied >3 mo before crop |
| Organic P source application rate (0.5)¶ | 0-2 | 3-6 | 7-8 | 9-11 | > 11 |
| Organic P source application method (1.0) | None applied | Placed with planter deeper than 5 cm | Incorporated immediately before crop | Incorporated >3 mo before crop or surface applied <3 mo before crop | Surface applied >3 mo before crop |

† Units for soil erosion are Mg/ha.

‡ Units for runoff are cm.

§ Soil test P is Bray-1 extractable P and units are mg P/kg.

¶ Units for P application are kg P/ha

Table 2: Percent of Cropland Area in River Basins in the Primary Contributing Corridor for Phosphorus Loading to Surface Waters.

| Basin | Cropland Area in the Primary Contributing Corridor* (%) |
|---|---|
| St. Croix River | 42.8 |
| Upper Mississippi | 36.9 |
| Lower Mississippi | 23.9 |
| Red River | 29.5 |
| Rainy River | 40.8 |
| Lake Superior | 52.2 |
| Minnesota River | 23.5 |
| Missouri River | 25.9 |
| Cedar River | 20.9 |
| Des Moines River | 20.7 |

*The primary contributing corridor includes cropland within 100 m of surface water bodies. Significant phosphorus loadings to surface waters can arise from surface tile inlets and subsurface tile drainage that are outside the primary contributing corridor.

Table 3: Phosphorus Export Coefficients (kg/ha) from Agricultural Cropland by Major Drainage Basin Based on a Watershed Analysis of Phosphorus Index Values.

| | Phosphorus Export Coefficients* from Agricultural Land (kg/ha) | | |
|---|---|---|---|
| Basin | Dry Year | Average Year | Wet Year |
| St. Croix River | 0.18 | 0.38 | 0.69 |
| Upper Mississippi | 0.22 | 0.39 | 0.70 |
| Lower Mississippi | 0.36 | 0.66 | 0.80 |
| Red River | 0.36 | 0.66 | 0.54 |
| Rainy River | 0.09 | 0.23 | 0.41 |
| Lake Superior | 0.15 | 0.24 | 0.43 |
| Minnesota River | 0.28 | 0.54 | 0.81 |
| Missouri River | 0.25 | 0.44 | 0.79 |
| Cedar River | 0.26 | 0.63 | 0.79 |
| Des Moines River | 0.27 | 0.44 | 0.78 |

*These export coefficients are an average of the export coefficients for each of the major watersheds within each river basin. These do not include contributions from surface tile inlets or subsurface tile drains.

Table 4: Phosphorus Loadings (kg/yr) to Minnesota Surface Waters from Agricultural Cropland by Major Drainage Basin Based on an Analysis of Phosphorus Index Values in Major Watersheds.

| | Phosphorus Loads* Exported from Agricultural Land (kg/yr) | | |
|---|---|---|---|
| Basin | Dry Year | Average Year | Wet Year |
| St. Croix River | 27857 | 59931 | 110046 |
| Upper Mississippi | 200865 | 359681 | 652266 |
| Lower Mississippi | 116810 | 232581 | 282780 |
| Red River | 131311 | 384695 | 545247 |
| Rainy River | 8988 | 20713 | 36072 |
| Lake Superior | 7617 | 13112 | 22528 |
| Minnesota River | 262851 | 517862 | 759749 |
| Missouri River | 36055 | 58758 | 109222 |
| Cedar River | 13722 | 33270 | 42444 |
| Des Moines River | 24670 | 37743 | 73149 |

*These loads are computed by multiplying the phosphorus export coefficients for each major watershed by the area of cropland within the contributing corridor for the same major watershed, and then summing over all major watersheds with the river basin. An additional 11.1% load is then added to account for phosphorus contributions by overland flow from outside the contributing corridor, excluding the contributions from surface tile inlets and subsurface tile drains.

Table 5: Phosphorus Loadings (kg/yr) to Minnesota Surface Waters from Agricultural Cropland by Major Drainage Basin Based on an Analysis of Phosphorus Index Values in Agroecoregions.

| | Phosphorus Loads* Exported from Agricultural Land (kg/yr) | | |
|---|---|---|---|
| Basin | Dry Year | Average Year | Wet Year |
| St. Croix River | 49193 | 84486 | 148546 |
| Upper Mississippi | 183184 | 332313 | 595252 |
| Lower Mississippi | 98474 | 203702 | 270490 |
| Red River | 130163 | 361759 | 561684 |
| Rainy River | 16524 | 30050 | 56620 |
| Lake Superior | 14145 | 24416 | 45569 |
| Minnesota River | 259198 | 516768 | 750293 |
| Missouri River | 30110 | 52024 | 102969 |
| Cedar River | 14138 | 31890 | 45137 |
| Des Moines River | 26575 | 51182 | 80991 |

*These loads are computed by multiplying the phosphorus export coefficients for each agroecoregion by the area of cropland within the contributing corridor for the same agroecoregion, and then summing over all agroecoregions with the river basin. An additional 11.1% load is then added to account for phosphorus contributions by overland flow from outside the contributing corridor, excluding the contributions from surface tile inlets and subsurface tile drains.

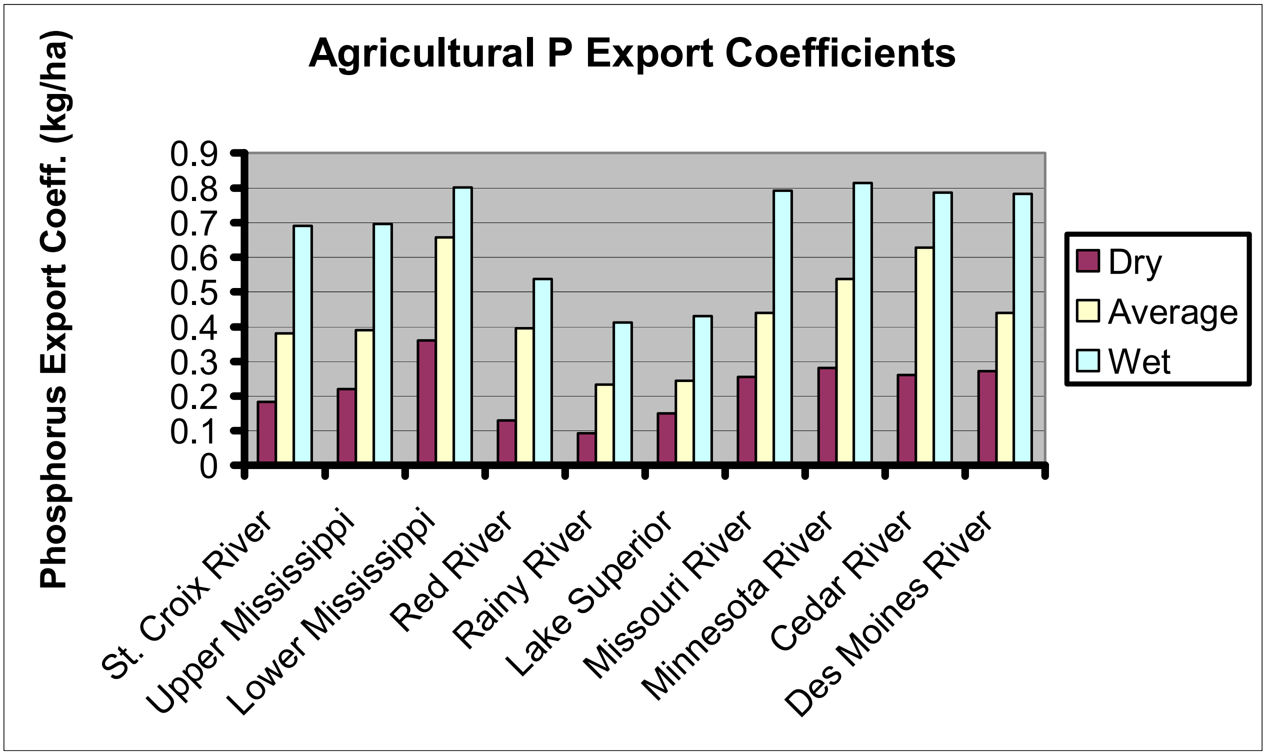

Fig. 26: Agricultural P export coefficients (kg/ha) for major drainage basins in dry, average, and wet climatic years. Export coefficients are derived from major watershed based phosphorus index values. These do not include contributions from surface tile inlets or subsurface tile drains.

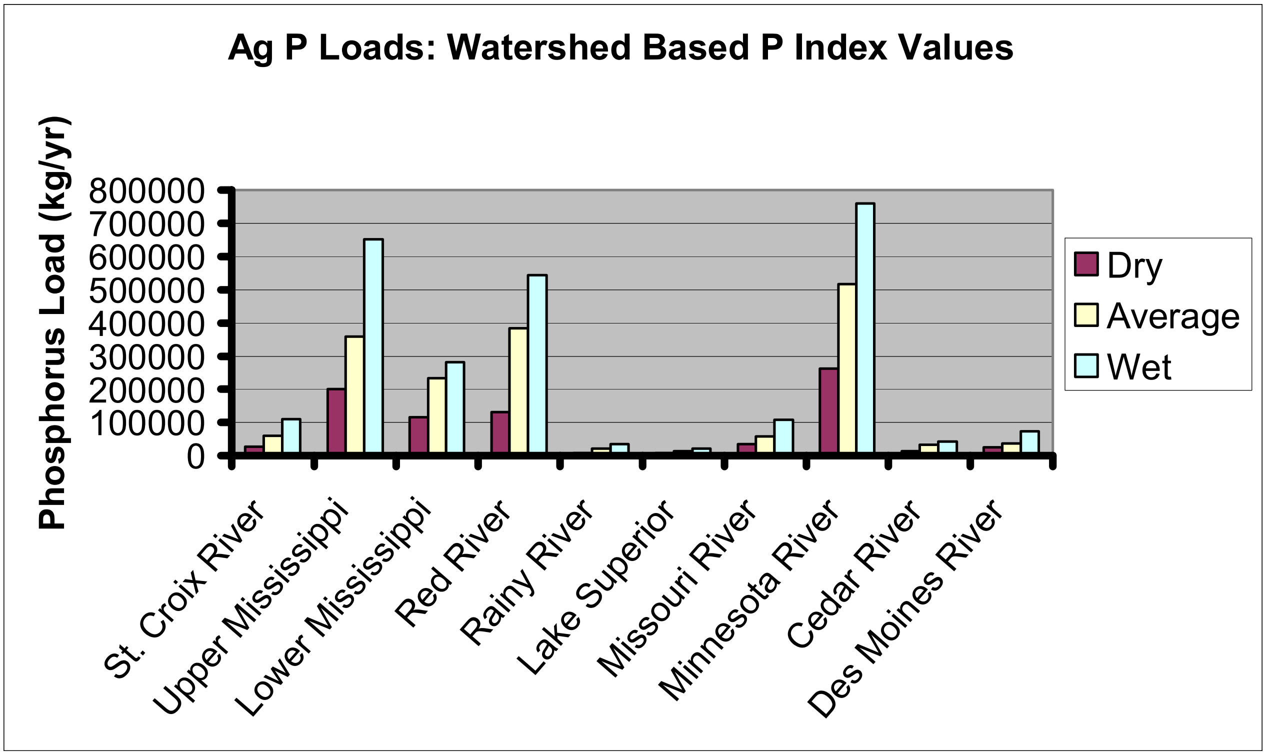

Figure 27: Agricultural phosphorus loads (kg/yr) exported to surface waters in major drainage basins of Minnesota under dry, average and wet climatic conditions. These results are based on phosphorus export coefficients derived from major watershed based phosphorus index values. These do not include contributions from surface tile inlets or subsurface tile drains.

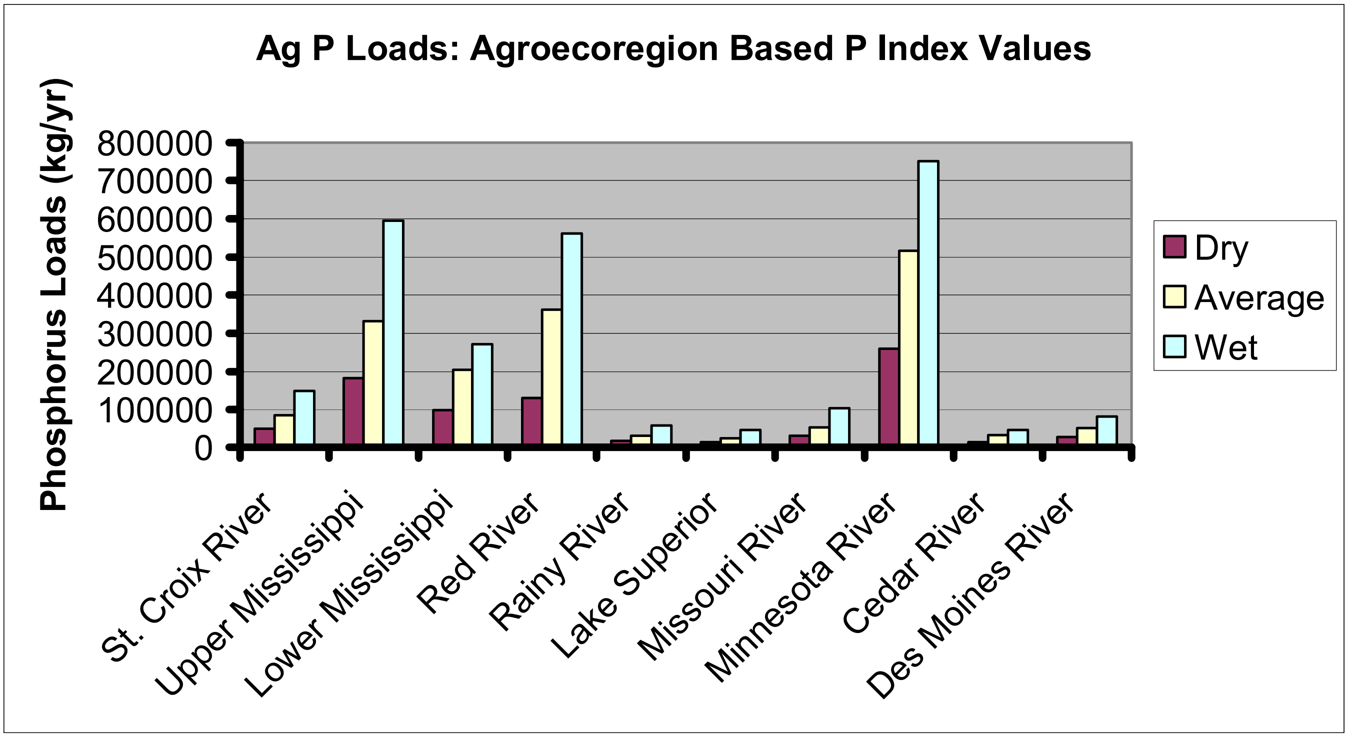

Figure 28 Agricultural phosphorus loads (kg/yr) exported to surface waters in major drainage basins of Minnesota under dry, average and wet climatic conditions. These results are based on phosphorus export coefficients derived from agroecoregion based phosphorus index values. These do not include contributions from surface tile inlets or subsurface tile drains.

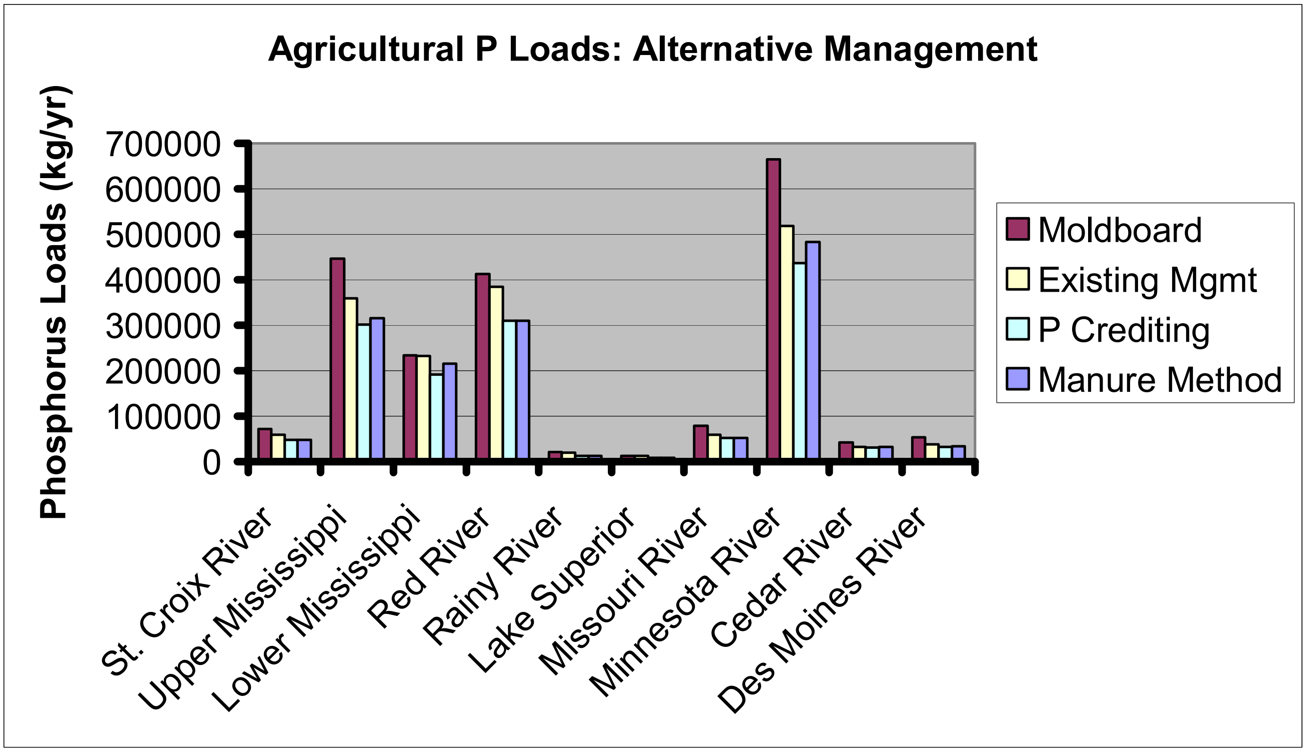

Figure 29: Agricultural phosphorus loads (kg/yr) exported to surface waters in major drainage basins of Minnesota under average climatic conditions for a worst case scenario involving moldboard plowing on all row cropland, a scenario involving improved phosphorus fertilizer management, a scenario for improved methods of manure application, and a baseline scenario for existing rates of phosphorus fertilizer and existing rates of adoption of conservation tillage. These results are based on phosphorus export coefficients derived from major watershed based phosphorus index values. These do not include contributions from surface tile inlets or subsurface tile drains.

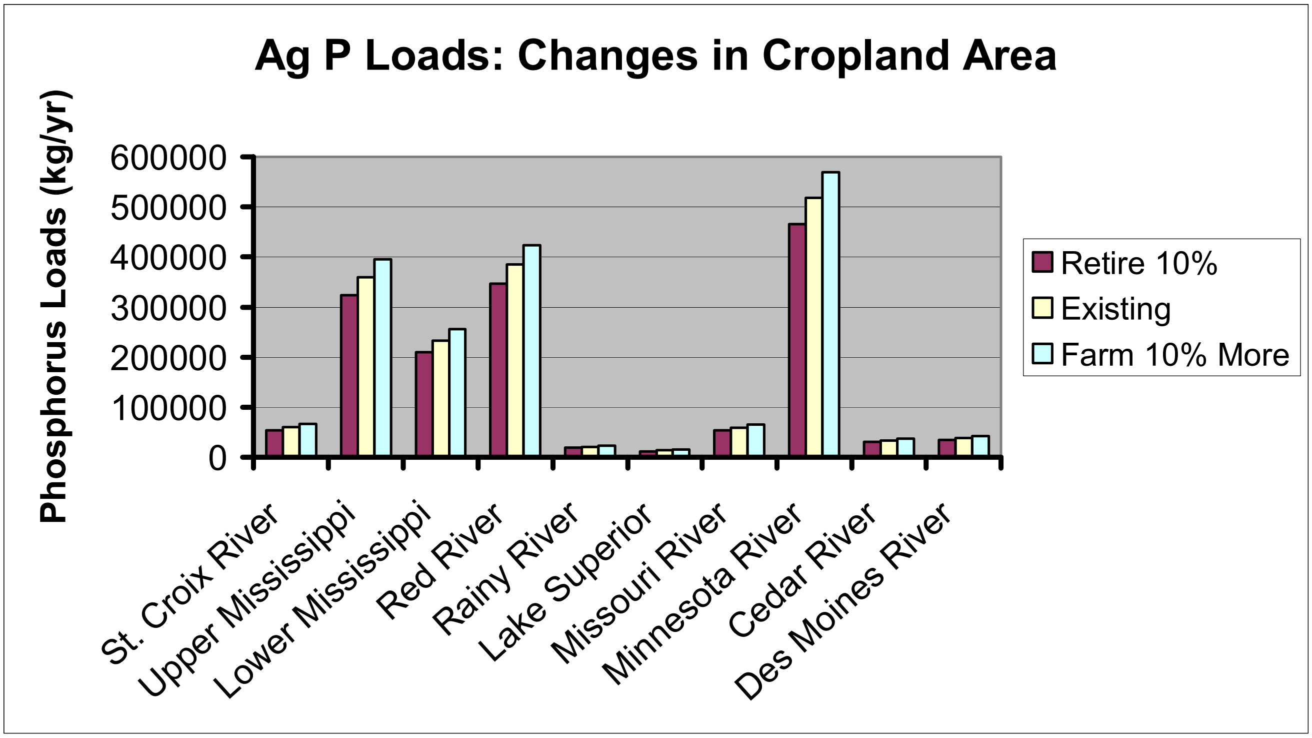

Figure 30: Agricultural phosphorus loads (kg/yr) exported to surface waters in major drainage basins of Minnesota under average climatic conditions for a scenario involving retirement of 10% of the row cropland within 100 m of waterbodies, a scenario involving a 10% increase in the area of row cropland within 100 m of waterbodies, and a baseline scenario for the area of cropland within 100 m of waterbodies under existing conditions. These results are based on phosphorus export coefficients derived from major watershed based phosphorus index values. These do not include contributions from surface tile inlets or subsurface tile drains.

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Figure 28 Agricultural phosphorus loads (kg/yr) exported to surface waters in major drainage basins of Minnesota under dry, average and wet climatic conditions. These results are based on phosphorus export coefficients derived from agroecoregion based phosphorus index values. These do not include contributions from surface tile inlets or subsurface tile drains.

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