Estimating Potential for Nutrient Delivery to Surface Water Resources in North Dakota

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Introduction

The relationship between nutrients and water resources may be described in terms of availability, mobility, and accessibility. There are many factors that influence nutrient behavior in the environment and their interrelationships may be complex. Nitrogen (N) and phosphorus (P) are the main plant nutrients that warrant concern with respect to surface water systems. Elevated concentrations of these nutrients contribute to eutrophication of streams and lakes. In many ways nitrogen and phosphorus work in tandem with respect to plant growth. The nutrient of least availability will limit plant growth. In aquatic systems it is generally recognized that an N to P weight ratio of approximately 10 is an indication of nutrient balance (Forsberg, 1980; Thomann and Mueller, 1987). N to P ratios less than 10 indicate N limitation, while greater than 10 indicate P limitation. The limiting nutrient will control biotic growth. In the northern prairies both N and P limited aquatic systems have been observed (Shubert, 1980; German et al., 1991). The impacts of nutrients on the trophic status of surface water in the northern prairies may be dependant on the status of either N or P and may vary with the season (German et al., 1991). The potential for either N or P to contribute to surface water degradation may be estimated by accounting for those factors that are most influential in determining nutrient behavior in the northern prairies.

Review of studies related to N and P in surface water systems reveals complicated relationships, but also some predictable patterns with respect to certain factors. Research shows that some factors consistently exert significant control over the processes that affect mobility, availability, and accessibility. Combinations of these factors may be used to estimate potential for delivery of nutrients to surface water. Modeling of nutrient transport to surface water resources on a watershed scale has been used to predict impacts to water quality for many years

(Beyerlein and Donigian, 1979; Donigian et al., 1983; Knisel et al., 1983; Beasley, 1985; Bicknell et al., 1985; McTernan et al., 1987; Donigian et al., 1993; Mostaghimi et al., 1997). With time these models have become more dependable; however, the need for significant input of data continues to hamper their use over large areas (Mostaghimi et al., 1997). In addition, calibration and validation requirements add significantly to the time and cost of using these types of models (Young and Alward, 1983; Mostaghimi et al., 1997).

The analysis of factors related to surface water contamination with N and P in Wells County North Dakota was intended to provide information related to potential problems. Qualitatively, it categorized possible surface water problems with respect to nutrients, and was based primarily on the Soil Survey Geographic (SSURGO) database maintained by the Natural Resources Conservation Service (NRCS). Ready accessibility of data required to determine potential nutrient delivery minimized the cost and time required to complete the analysis on a relatively large area. A disadvantage of the methodology was the inability to N and P loading to surface water resources.

Methods

The data required to estimate potential nutrient delivery to surface water resources is available for any area of North Dakota. However, manipulation of the data, particularly on extensive areas, is tremendously cumbersome and time-consuming if done without the aid of a computer. In the following example the GIS computer program ARC VIEW 3.2 (ESRI, 1999) was used to process the Wells County (Fig. 1) data for assessment. A Pentium 4 (1.7 GHz) microprocessor, 260 MB RAM, and 37 GB hard drive was used to do the analysis.

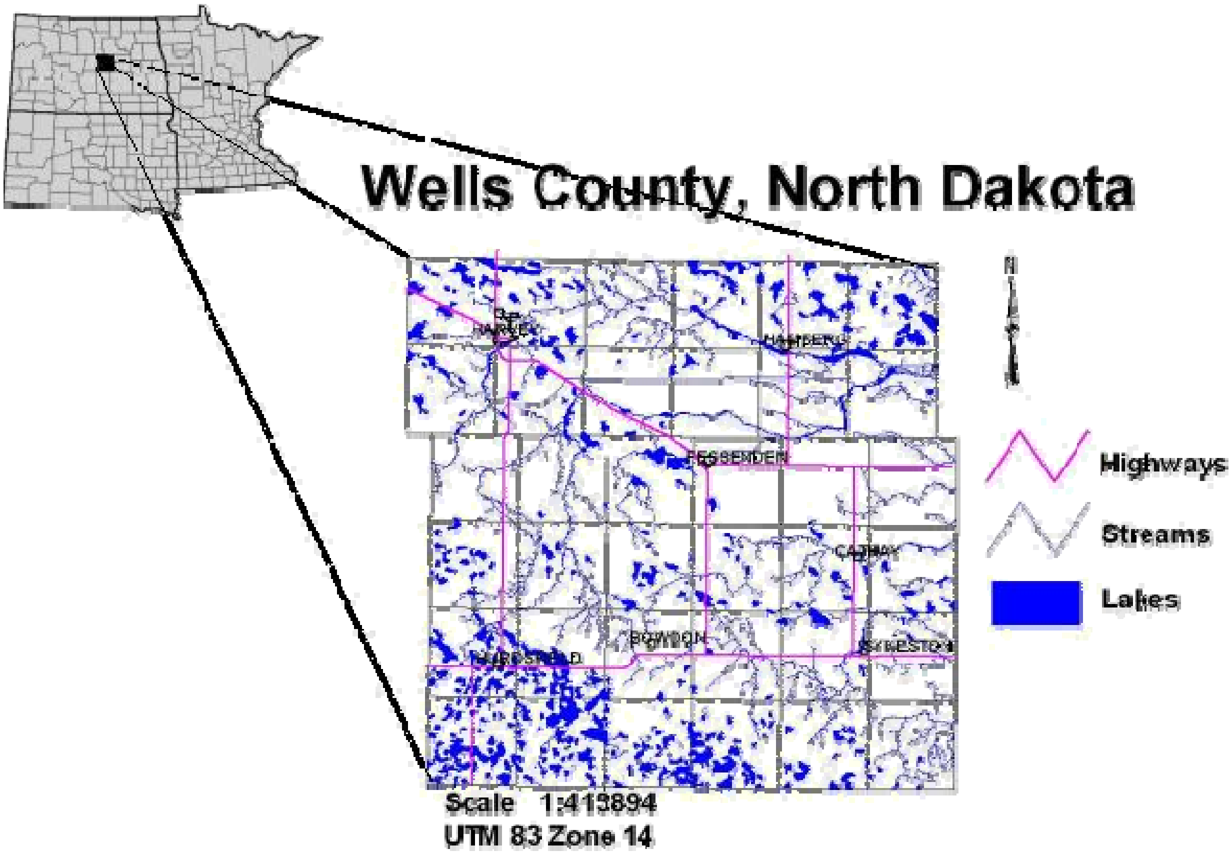

Figure 1. Wells County, North Dakota study area.

The combination of factors listed in Tables 1 and 2 can be accomplished in many ways. In other words, factors may be weighted to account for their importance or dominance with respect to the natural processes that affect water and solute flow. Assignment of factor weights should be done with extreme care and should be supported by a significant amount of evidence, preferably experimental results. The methodology used for the Wells County analysis did not assign weights to the factors, because evidence to justify weighting was not available. Instead, potential delivery of nutrients to surface water was related to the intensity that each factor was manifested.

Each factor was expressed as a separate data layer in raster format using the GIS program. The Spatial Analyst extension to ArcView 3.2 was used to accomplish this task. Raster data layers were presented in UTM 83 Zone 14 projected coordinates with feet as the mapping unit. The data was organized in grids composed of 100 X 100 ft pixels. Each pixel was assigned a value according the intensity of expression of the potential for that factor to contribute to nutrient delivery to surface water. The value assigned to intensity levels depended on the number of potential categories. For example, most factors were divided into three intensity categories; therefore, the highest intensity category was assigned a 3 and the lowest a 1. All grid layers except for human activity were filtered to eliminate areas less than 5 acres in extent.

With the ArcView map calculation tool the seven factor layers were summed to provide a composite potential for delivery of nutrients to surface water. The analysis was done for both nitrogen and phosphorus. The composite range in scores for both nitrogen and phosphorus was 0 to 20. The categories for potential nutrient delivery were: 1) High (17-20); 2) Intermediate (12-16); and 3) Low (0-11).

Natural Factors

Different forms of N and P may be delivered to surface water resources. Modes of delivery will vary depending on the chemical form of the nutrient. Both N and P may be delivered as solutes dissolved in runoff or attached to sediment entrained in runoff. The portion of both N and P exist in soils as relatively immobile organic or inorganic compounds. Physical detachment and transport of sediment with associated immobile forms of N and P accounts for the greatest loss of these nutrients. However, the transport of the soluble forms of these nutrients, nitrate (NO_3) and orthophosphate (PO_4) is important due to their high bio-reactivity. Nutrient delivery that impacts the trophic status of water resources must account for both insoluble and soluble chemical forms. Factors that affect processes of removal, transport, and delivery of nutrients in both phases must be assessed. Just as important is the need to assess factors that affect the processes of nutrient conversion from one form to another. The factors (Table 1) were selected based on results of studies that observed their effects on the fate of nutrients in the environment.

Table 1. Natural factors that contribute to nutrient delivery.

Natural Factors	Criteria for high potential
Soil aeration (nitrogen)	Excessive, somewhat excessive, and well drained soils as defined by NRCS
Soil aeration (phosphorus)	Poorly and very poorly drained soils as defined by NRCS
Soil erodibility	NRCS k factor 0.4 – 0.69
Runoff	High and very high NRCS runoff class
Flooding frequency	Frequent to common flooding as defined by the NRCS
Surface water proximity	Areas 0 – 500 feet from a stream or lake as identified by the ND DOT

Soil aeration

Nitrification is the predominant process that contributes NO_3 to soils and is performed by microorganisms that require oxygen (Schmidt, 1982). Therefore, soil environments that allow relatively unimpeded exchange of gases are likely to be well oxygenated and favor the presence of NO_3. Soil environments depleted of oxygen due to impeded gas exchange with the atmosphere have little or no available NO_3, because it is reduced to nitrous oxide by anaerobic microorganisms (Broadbent and Clark, 1965; Firestone, 1982).

The relatively higher amount of available NO_3 in well-aerated soils increases the potential for NO_3 translocation to surface water resources. Soil aeration was estimated by assessing soil internal drainage as defined by the Natural Resources Conservation Service (NRCS) (Soil Survey Staff, 1997). The distribution of soils in Wells county was determined using the NRCS Soil Survey Geographic database (SSURGO) as downloaded from the National

SSURGO Database website at: http://www.ftw.nrcs.usda.gov/ssur_data.html. Soil Data Viewer 3.0 was used with Arc View 3.2 to extract the data. The original source for the SSURGO data for Wells County is the Wells County Soil Survey Report (Seago, J. B. et al., 1970). **Excessive, somewhat excessive, and well drained soils were considered to have high potential to serve as the source of NO_3 contamination of surface water. Moderately well and somewhat poorly drained soils were considered as intermediate, and poorly and very poorly drained soils were considered as low.**

Mineralization in a well-aerated environment also contributes to the release of PO_4, but availability of phosphorus is reduced substantially by adsorption and mineral precipitation. Increased availability of phosphorus through the release of adsorbed PO_4 has been demonstrated to readily occur in waterlogged soils (Ponnamperuma, 1972; Gotoh and Patrick, 1974; and Khalid et al., 1977).

The relatively higher amount of available PO_4 in poorly aerated soils increases the potential for PO_4 translocation to surface water resources. **Poorly and very poorly drained soils were considered to have high potential to serve as the source of PO_4 contamination of surface water. Moderately well and somewhat poorly drained soils were considered as intermediate and excessive, somewhat excessive, and well drained soils were considered as low.**

Soil erodibility

The soil erodibility was used as indicator of the soil influence on nutrient translocation in the sediment phase. Similar methods of estimating potential translocation of pesticides in the sediment phase have been proposed (Goss and Wauchope; 1990; Goss, 1992; Seelig; 1998). Soil erodibility was estimated by determining the soil k factor defined by the NRCS (Soil Survey

Staff, 1997). The soil k factor indicates the susceptibility to sheet and rill erosion. Soil k factors range from 0.02 to 0.69 with the higher values indicating greater potential for erosion losses by water. **Soils with a k factor from 0.4 to 0.69 would have a high potential to allow nutrients to be translocated with eroded sediment. Soils with a k factor from 0.2 to 0.4 have intermediate potential and soils with a k factor from 0.02 to 0.2 would have low potential.**

Runoff

Runoff is an important to nutrient translocation in both the solution and sediment phases of transport. Some surface water assessment methods have estimated this factor by determining the NRCS soil hydrologic group (Goss and Wauchope; 1990; Goss, 1992; Seelig; 1998). A more direct method of characterizing runoff is the runoff class as defined by the NRCS (Soil Survey Staff, 1997). The NRCS runoff class is based on the minimum soil permeability in the upper meter and slope. The soil permeability class is related to the saturated hydraulic conductivity (K_{sat}). The permeability classes are defined by the following ranges of K_{sat}: 1) 141 – 705 μ/sec (very rapid); 2) 42-141 μ/sec (rapid); 3) 14 – 42 μ/sec (moderately rapid); 4) 4 – 14 μ/sec (moderate); 5) 1.4 – 4 μ/sec (moderately slow); 6) 0.42 – 1.4 μ/sec (slow); 7) 0.01 – 0.42 μ/sec (very slow); 8) 0.00 – 0.01 μ/sec (impermeable).

The permeability is then combined with the slope to determine the runoff class. A positive correlation exists between the slope of the land surface (vertical ÷ horizontal distance) and the amount of runoff and eroded sediment (Stewart et al., 1975; Wischmeier, 1976; Wischmeier and Smith, 1978). If the lowest K_{sat} occurs between 0.5 and 1.0 m then the runoff is reduced by one class. NRCS runoff class ranges from negligible where permeability is > 42 μ/sec and slope is $< 1\%$ to very high where permeability < 0.42 μ/sec and slope is $\geq 20\%$. **Very high and high NRCS runoff classes were considered to have a high potential to contribute**

to nutrient translocation. Medium runoff class was considered to have intermediate potential. Low, very low, and impermeable runoff classes were considered to have low potential.

Flooding Frequency

The process of flooding moves large quantities of materials along and down stream floodplains. An estimate of the occurrence of flooding along a given stream segment may be used as an indicator of the potential for nutrient detachment and transport from floodplain soils. Analogous methods of estimating potential translocation of pesticides due to flooding have been proposed (SCS Staff, 1991; Hornsby, 1992; Seelig, 1998). Flooding frequency was defined by the NRCS (Soil Survey Staff, 1997). **Frequent and common flooding as defined by the NRCS was considered to have a high potential to contribute to nutrient transport. Occasional flooding was considered to have intermediate potential. Rare to never flooding were considered to have low potential.**

Surface water proximity

Stewart et al. (1975) recognized proximity of cropped fields to surface water resources as a critical factor in determining acceptable levels of soil loss from fields. In the case of nutrient impacts to water quality, Tufford et al. (1998) found that management effects were minimal beyond 150 m from the stream. The concept of proximity is further strengthened by the fact that only a small portion of eroded sediment actually leaves the watershed (Boyce, 1975; Renfro, 1975; Campbell, 1985). In fact, some studies show that most eroded sediment is merely translocated to the bottom of the hill slope (Stall, 1985). These sediments with attached nutrients are subject to a continual cycle of detachment, translocation, and deposition that moves them closer to streams and lakes each time runoff occurs.

Runoff is not the same from all areas of a watershed, and large areas usually yield no runoff or sediment (Campbell, 1985). Increasing evidence indicates that most stream-transported sediment is derived from a relatively small area of the basin (Stewart et al., 1975; Campbell, 1985). Runoff and sediment losses from watersheds are most closely associated with ephemeral streams or gullies (Renard and Lane, 1975; Vandaele and Posen, 1995). Rill erosion losses were found to be closely related to the system of surface drainage collectors (Ludwig et al., 1995).

During runoff-producing events, areas contributing water to the drainage network expand outward with increasing duration of the event (Satterlund, 1972). This hydrologic phenomenon accentuates the importance of runoff and contaminant transport from areas immediately adjacent to the drainage network, particularly in drier climates. As the density of the network of surface drains increases, so does the amount of sediment delivered to streams (Campbell, 1985).

The spatial relationship between fields, drainage ways, and lakes determine potential for delivery of nutrients to water resources. Stream and lake boundaries were defined by the North Dakota Department of Transportation (ND DOT) GIS database (version 1.1a). **Areas within 500 ft of a stream or lake were considered to have high potential for nutrient delivery. Areas between 500 and 1000 ft were considered to have intermediate potential. Areas > 1000 ft were considered to have low potential.**

Anthropogenic factors

Human activities also affect the potential for nutrient delivery to surface water resources. Anthropogenic factors are considered important because of they impact nutrient availability and accessibility. The use of fertilizers in both urban and agricultural areas increases the availability of nutrients for transport. Domesticated animal and human waste is a source of both nitrogen and phosphorus. Locations where organic waste is concentrated have increased potential for nutrient translocation. Locations where fertilizer is stored and handled have increased potential for losses due to accidental spillage. When confined in small areas (towns etc.), the activities of man lead to conditions that increase the accessibility and availability of N to surface water runoff.

Human manipulation of surface cover has significant impacts on mineralization of organic matter, water infiltration, runoff, and erosion. Mueller et al. (1995) found that surface water from watersheds where agriculture was the main land use had higher nutrient concentrations compared to streams from undeveloped watersheds. These results are supported by many other studies. Cultivated soils contribute to greater availability of NO_3 through increased mineralization (Stevenson, 1965; Bartholomew, 1965). It has also been demonstrated that cultivated crops generally are not as efficient users of nutrients compared to native vegetation (Harmsen and Kolenbrander, 1965). Cultivation or tillage exposes the soil surface to the erosive power surface runoff, which causes soil detachment and removal (Wischmeier and Smith, 1978). Wischmeier and Smith (1978) showed that erosion from cultivated soils is dependent on many factors. The type of crop and management of its residue has a significant effect on soil erosion. Crop rotations that maintain residue on the surface during the erosive periods will reduce soil erosion, which has water quality benefits (Wischmeier, 1976).

Table 2. Anthropogenic factors that contribute to increased nutrient delivery.

Anthropogenic factors	Criteria for high potential
Concentrated human activity	< 200 ft of facilities or residences and areas within incorporated city limits
Land use	Summer fallow fields and areas within incorporated city limits

Concentrated human activity

Mueller et al. (1995) reported that high NH_3 levels in streams were significantly correlated with proximity to urban areas. Nelson et al. (1979) found that septic system discharge to a nearby stream contributed significantly to nutrient loads particularly in drier years. After review of research and monitoring studies, Fedkiw (1991, 1992) concluded that strong evidence supported the contention that waste from animal production facilities have played a role in observed increases in N concentrations in surface water near those facilities. The ND DOT GIS database (version 1.1a) was used to locate incorporated city boundaries, and rural residences or facilities including amusement parks, barracks, cemeteries, churches, parks, drive-in theaters, non-farm dwellings, factories, fair grounds, farms, garbage dumps, golf courses, grain elevators, green houses, highway garages, picnic grounds, play grounds, post offices, railroad stations, rifle clubs, school houses, stock yards, stores, town halls, and vacant facilities. **All areas within incorporated cities and within a radius of 200 ft of rural buildings listed previously were assumed to have relatively high quantities of available nutrients and were considered to have high potential for nutrient delivery to surface water resources. Radial areas between 200 – 500 ft from rural buildings and 500 ft from the incorporated city boundaries were considered to have intermediate potential. All other areas were considered to have low potential.**

Land use

Evidence shows that undisturbed natural systems or permanently vegetated systems utilize N with greater efficiency than cultivated crops (Harmsen and Kolenbrander, 1965; Evans et al., 1994), which results in less NO_3 available to surface runoff. Wischmeier (1975) used the universal soil loss equation to determine runoff and erosion from permanently vegetated sites, which was substantially less compared to disturbed soils. Sharpley and Smith (1994) found that conversion of grassland to conventional tillage caused a 2.5-fold increase in total-N in stream water.

Under conditions beneficial to water quality, vegetation utilizes N efficiently, allowing only minimal quantities of residual NO_3 to exist in the soil. Little impact from sediment derived N occurs to surface water under these conditions because runoff is minimized due to soil structure that promotes high infiltration and soils are well protected by vegetation and residue. Water often reaches streams in these areas as groundwater flow. Minimal amounts of N were found in streams from watersheds dominated by undisturbed forestland (Mulholland and Hill, 1997) and grassland (Dodds et al., 1996) and was almost entirely of soluble form.

It is recognized that grazing causes soil disturbance within permanently vegetated areas, and the disturbance increases with intensity of grazing. Consequently, overgrazing of pastureland and rangeland contributes to soil degradation and erosion (Stoddert et al., 1975).

Although the benefits of certain types of cropping systems are recognized, the evidence continues to show that much greater losses of N occur from cropland compared to less intensive land use. Maintaining a protective cover on the soil surface is recognized as generally being a benefit to water quality with respect to N.

Soil maintained bare of vegetation by tillage is the most vulnerable to erosive energy and generates the greatest soil losses. N associated with the eroded sediment substantially exceeds the N that may be lost in the solution (Dean, 1983). The combination of stored NO_3 in summer fallow (Hedlin and Cho, 1974; Swenson et al., 1979) plus large losses of N with eroded sediment increases the availability of N to water resources.

Remote sensing-based digital imagery (USDA/NASS/Research Division, 2001) was used to identify land use in Wells County. Data was extracted from the land use image that discriminated between areas of woods, range and pasture, cultivated row crops, other cultivated crops, summer fallow, and urban areas. The cropland data layer is one of the first sets of publicly releasable crop specific digital data layers, suitable for use in geographic information systems (GIS) applications. Imagery was generated from the Thematic Mapper (TM) instrument on the Landsat 5 and the Enhanced Thematic Mapper (ETM+) on the Landsat 7 satellite. Extensive and annual ground truth data are captured and utilized to provide the most current and accurate delineation of land use change and crop-type specificity.

Wooded areas with minimal quantities of available nutrients and negligible rates of soil erosion were considered to have low potential for nutrient delivery to surface water resources. Range and pasture have greater rates of erosion due to grazing and the potential to deliver nutrients was considered as somewhat low. Cultivated fields of wheat, barley, durum and other crops that form a dense canopy quickly were considered to have intermediate potential. Cultivated fields of row crops including corn, sunflower, soybeans, dry beans, and potatoes were considered to have a somewhat high potential. Due to relatively high levels of available nutrients and runoff summer fallow fields and urban areas were considered to have high potential.

Results and Discussion

In general, the results of the spatial analyses of composite potential for nutrient delivery to water resources in Wells County indicates that no extensive areas exist that have a high potential for nutrient delivery (Figs. 2 and 3). However, large areas of intermediate potential occur with relatively complex patterns. Inspection of the distribution of potential nutrient delivery for specific factors reveals extensive areas that have high potential for nitrogen delivery as related to soil aeration and for nitrogen and phosphorus delivery as related to runoff. Other extensive areas of high and somewhat high potential related to land use also exist in the county. These are areas where summer fallow and row crops are used in the crop rotation. The distribution of these conditions would have an impact on regional management strategies to control nutrient delivery within the county.

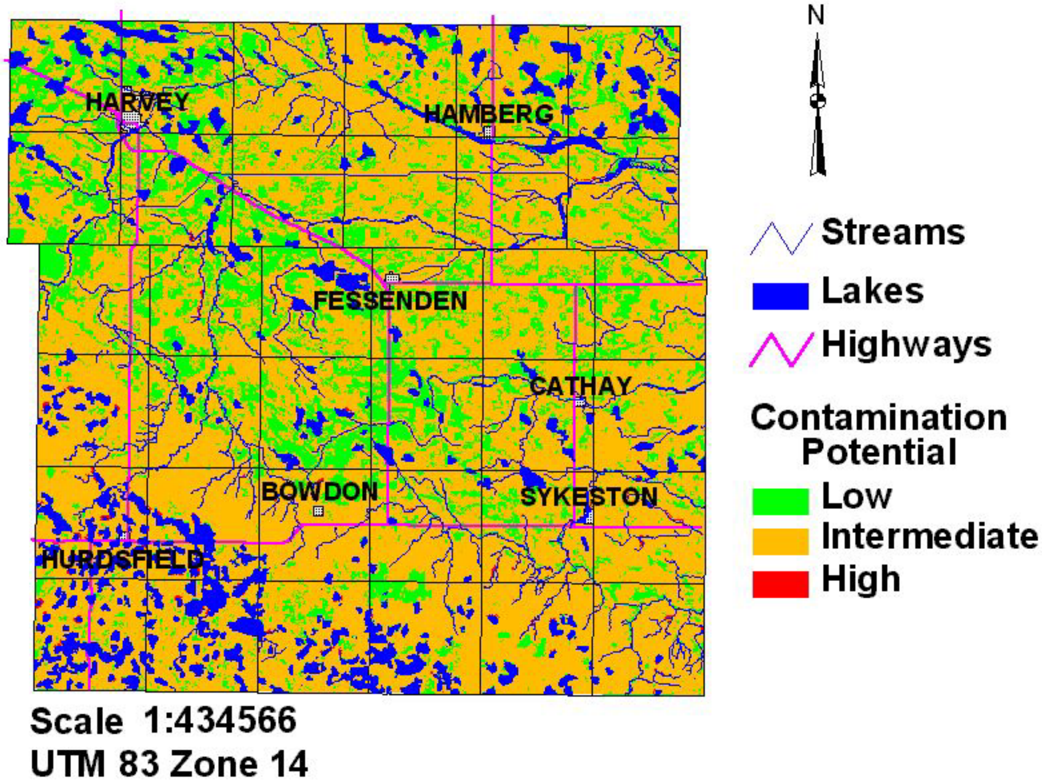

Figure 2. Nitrogen potential for surface water contamination.

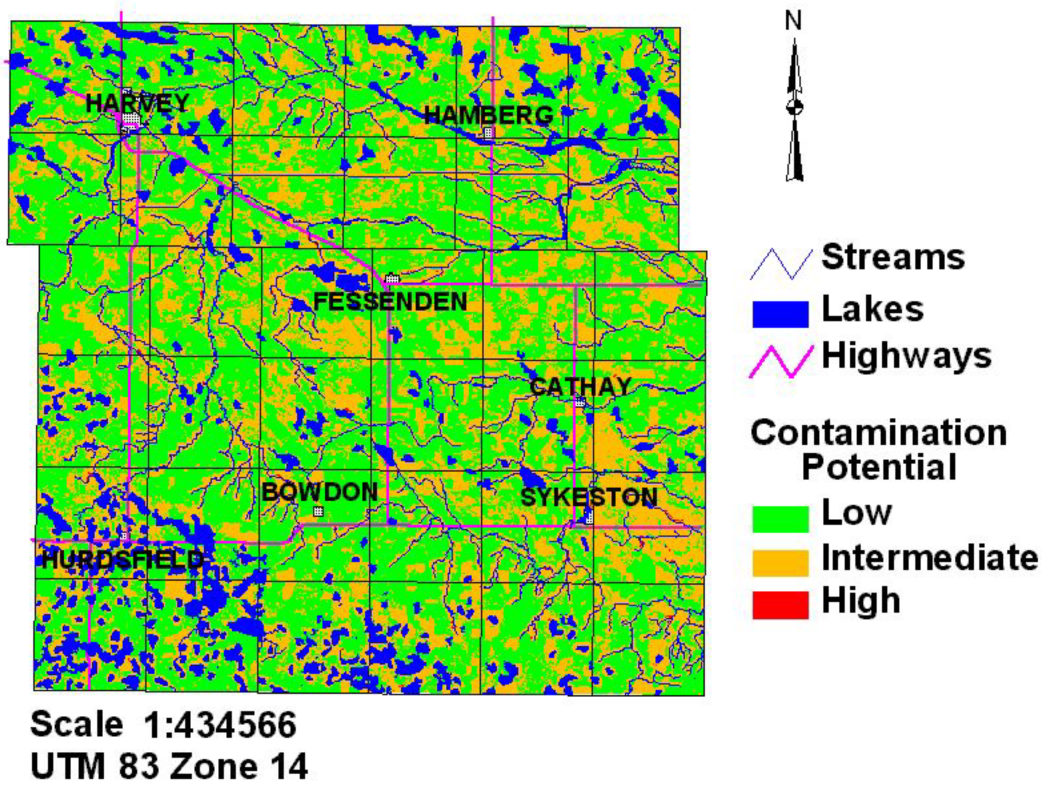

Figure 3. Phosphorus potential for surface water contamination.

Field level inspection of the results showed that complex patterns of potential nutrient delivery existed. These patterns influenced the effectiveness of methods implemented on individual operations. Although extensive areas of high composite nutrient delivery do not exist at the county level, high potential will dominate some fields. Theoretically, implementation of management techniques specifically designed for these critical areas should contribute to observable water quality improvement over a shorter period of time as compared to areas of less potential.

The analyses performed on Wells County appear to be a reasonable initial step for watershed projects with water quality as the primary objective. The inventory of areas likely to contribute to excessive nutrient delivery will provide a framework for monitoring and evaluation. The second step should be to use the results of the county analyses to focus monitoring and evaluation on locations that will represent watershed management activities. The end result should be improved estimation of management practice impacts, which will contribute to greater overall effectiveness for water quality protection projects.

Conclusions

Estimation of nutrient delivery to surface water resources over large areas appeared to be a useful exercise to determine critical areas in Wells County. Access to ND DOT GIS, NRCS SSURGO, and NDASS Landuse digital databases made the computer analyses possible. An individual with expertise in GIS can do an analysis of this type in a period of about three weeks. The return for the time invested is improved planning and implementation of effective management. Assessment results at any scale can be disseminated easily to a large audience over an extensive area via an interactive GIS program such as ARC IMS. County residents with internet access can easily obtain assessment results for specific parcels of land

The results from this analysis do not replace the need for more accurate estimates of nutrient loading to surface water. Hopefully, the information from this level of analysis would be used to select critical locations where more sophisticated techniques could be or should be applied.

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