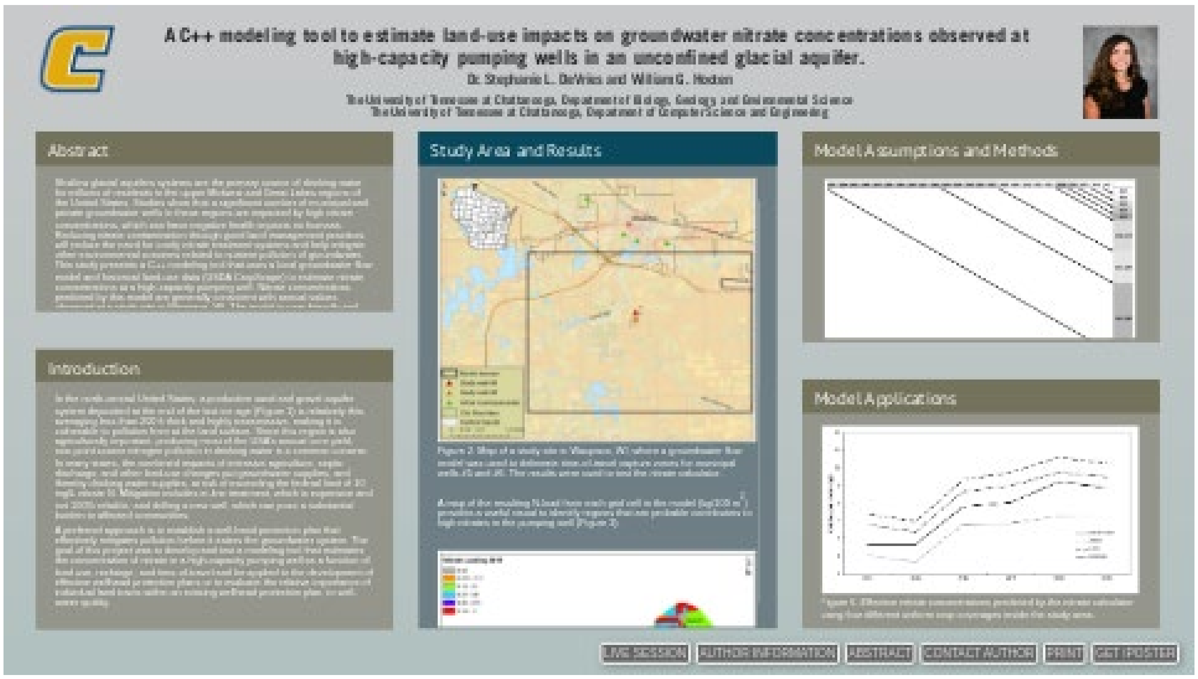
A C++ modeling tool to estimate land-use impacts on groundwater nitrate concentrations observed at high-capacity pumping wells in an unconfined glacial aquifer.



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ABSTRACT

Shallow glacial aquifers systems are the primary source of drinking water for millions of residents in the upper Midwest and Great Lakes regions of the United States. Studies show that a significant number of municipal and private groundwater wells in these regions are impacted by high nitrate concentrations, which can have negative health impacts on humans. Reducing nitrate contamination through good land management practices will reduce the need for costly nitrate treatment systems and help mitigate other environmental concerns related to nutrient pollution of groundwater. This study presents a C++ modeling tool that uses a local groundwater flow model and historical land-use data (USDA CropScape) to estimate nitrate concentrations at a high-capacity pumping well. Nitrate concentrations predicted by this model are generally consistent with annual values observed at a study site in Waupaca, WI. The model is user-friendly and can easily be adapted to other locations, where it has the potential to help local and state agencies, landowners, and growers make cost-effective decisions about land-use and agricultural practices.

INTRODUCTION

In the north-central United States, a productive sand and gravel aquifer system deposited at the end of the last ice age (Figure 1) is relatively thin, averaging less than 200 ft thick and highly transmissive, making it is vulnerable to pollution from at the land surface. Since this region is also agriculturally important, producing most of the USA's annual corn yield, non-point source nitrogen pollution in drinking water is a common concern. In many states, the combined impacts of intensive agriculture, septic discharge, and other land-use changes put groundwater supplies, and thereby drinking water supplies, at risk of exceeding the federal limit of 10 mg/L nitrate N. Mitigation includes in-line treatment, which is expensive and not 100% reliable, and drilling a new well, which can pose a substantial burden to affected communities.

A preferred approach is to establish a well-head protection plan that effectively mitigates pollution before it enters the groundwater system. The goal of this project was to develop and test a modeling tool that estimates the concentration of nitrate in a high-capacity pumping well as a function of land use, recharge, and time-of-travel and be applied to the development of effective wellhead protection plans or to evaluate the relative importance of individual land tracts within an existing wellhead protection plan, to well-water quality.

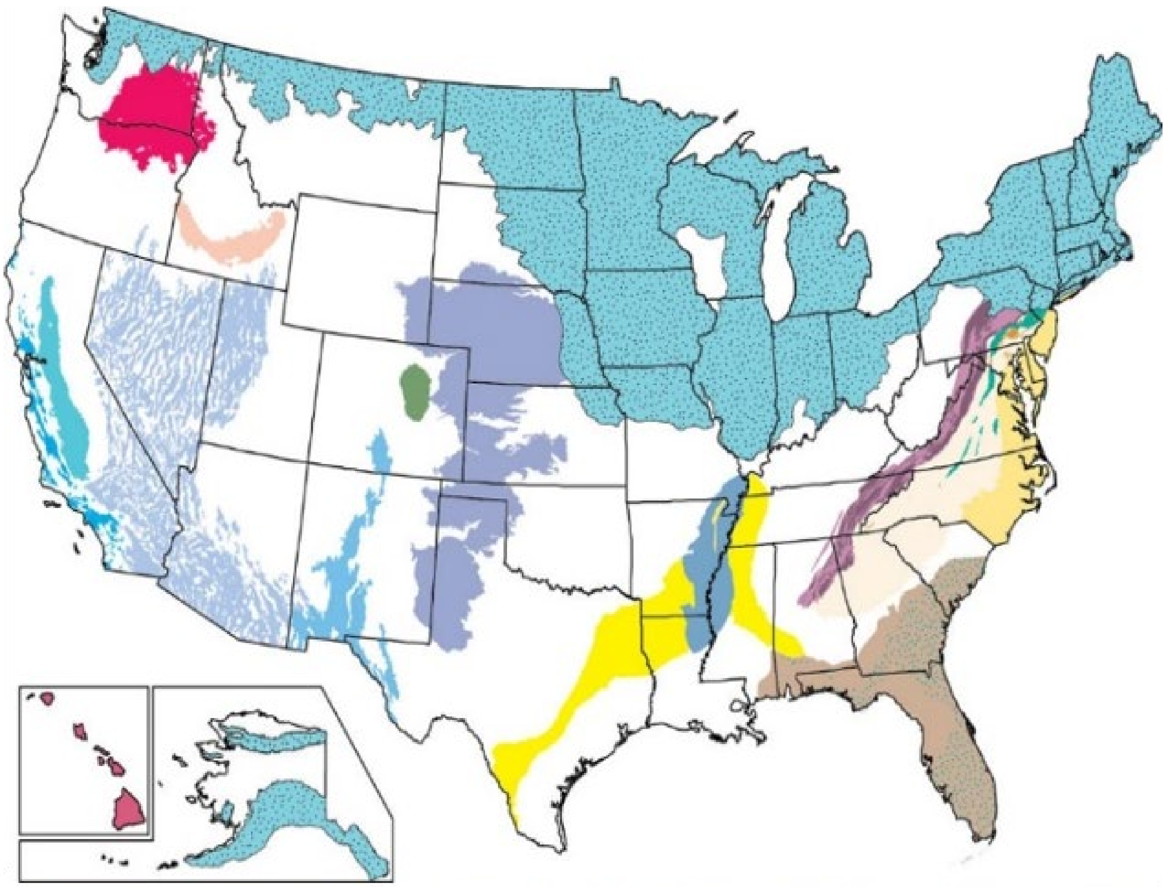

Figure 1. Aquifer systems of the United States. Light blue stippled area represents surficial glacial aquifers composed of sand and gravel. https://www.usgs.gov/media/images/outlines-principal-aquifers-us

STUDY AREA AND RESULTS

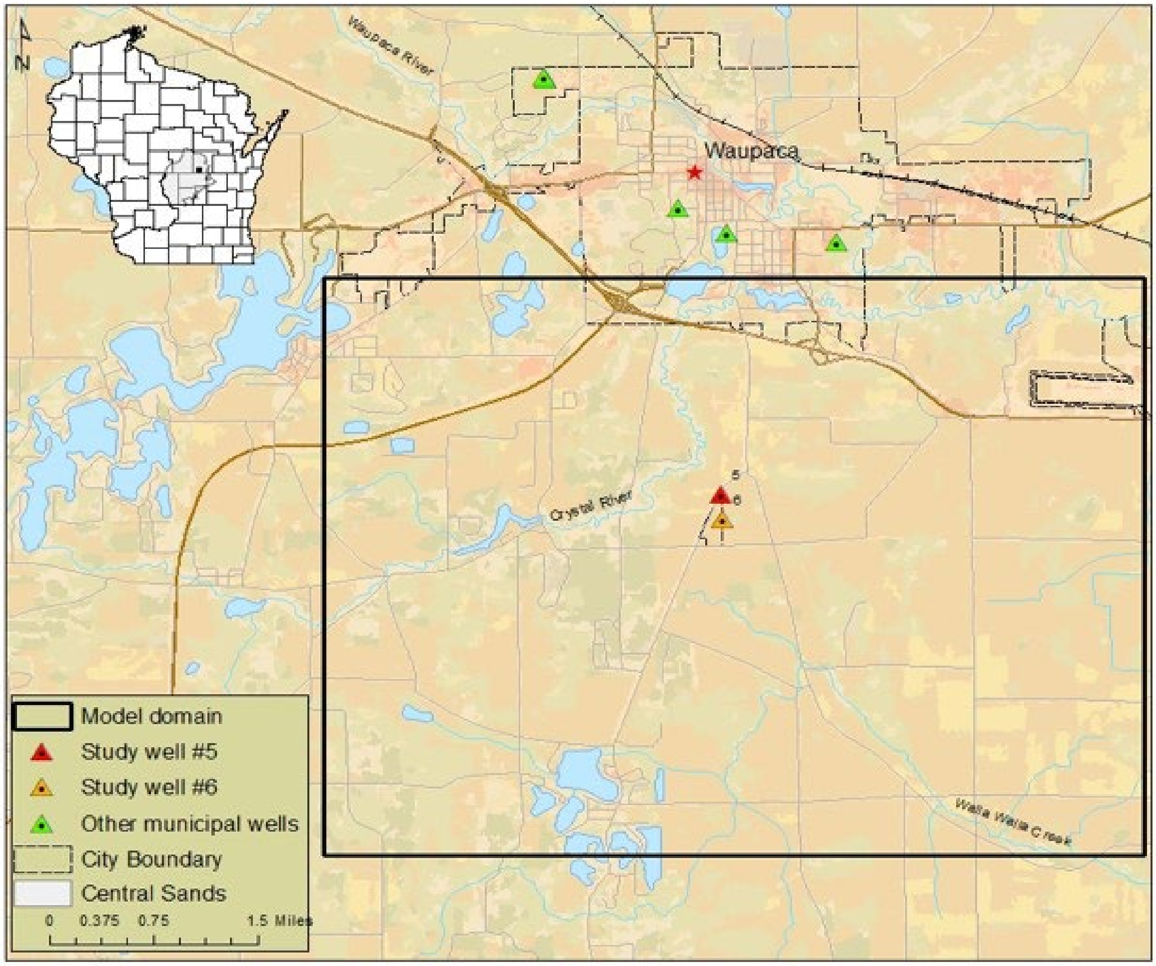

Figure 2. Map of a study site in Waupaca, WI, where a groundwater flow model was used to delineate time-of-travel capture zones for municipal wells #5 and #6. The results were used to test the nitrate calculator.

A map of the resulting N-load from each grid cell in the model (kg/100 m^2) provides a useful visual to identify regions that are probable contributors to high nitrates in the pumping well (Figure 3).

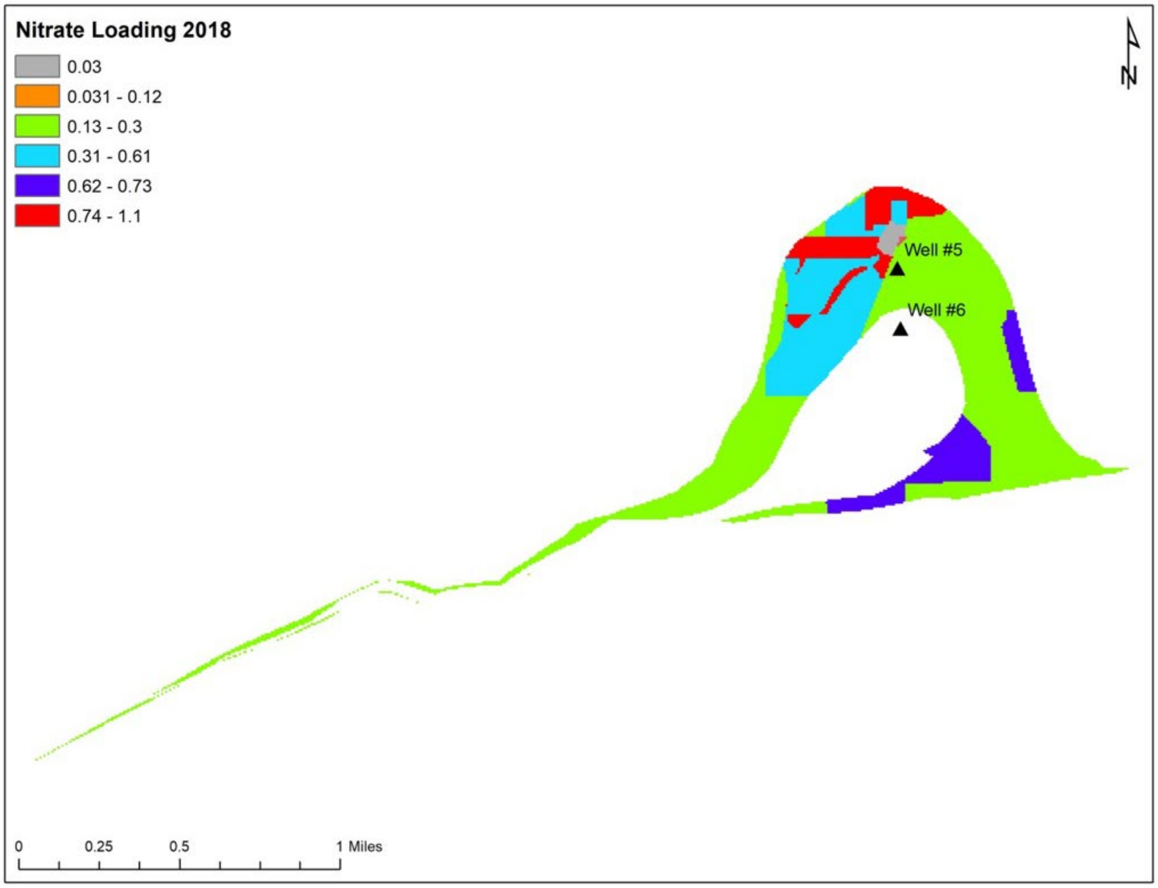

Figure 3. Map of aerial nitrate load (kg/100m^2) to well water extracted from municipal well #5 in 2018, as estimated by the nitrate calculator.

Mean nitrate concentration estimated for both wells (2014-2019) show agreement with the annual range of observed nitrate concentrations (Figure 4).

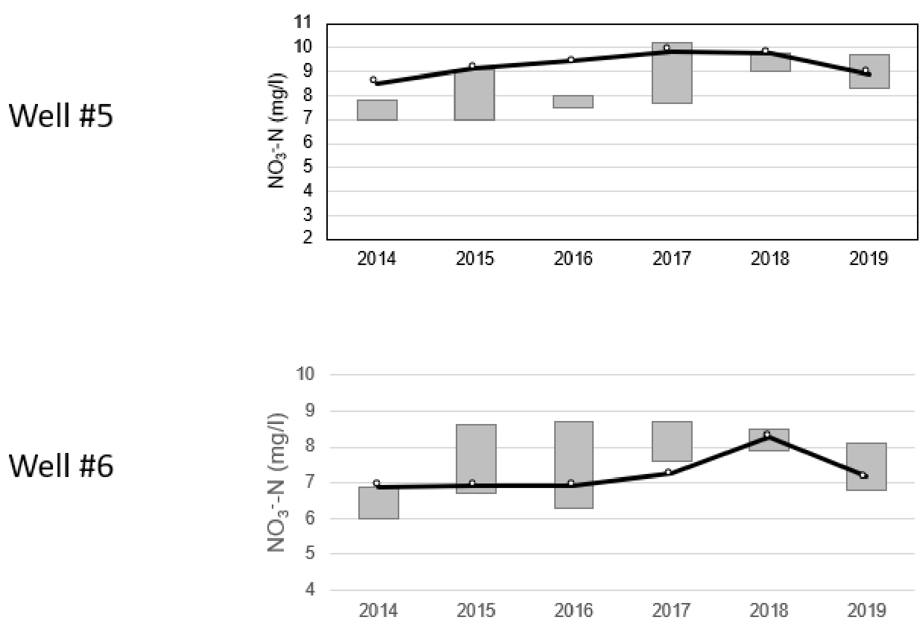

Figure 4. Estimated mean nitrate concentration in study wells #5 and #5 from 2014-2019 and the range of observed nitrate concentrations for the same time period.

MODEL ASSUMPTIONS AND METHODS

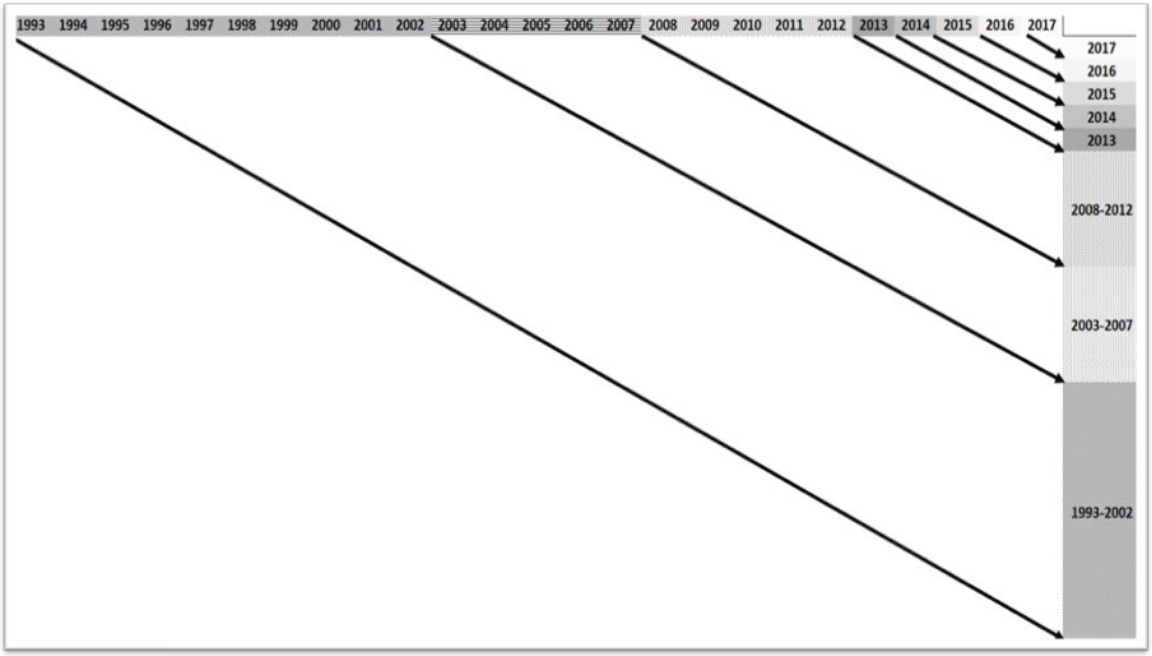

Figure 4. Schematic representation of groundwater flow to a pumping well, according to the assumptions of the present model.

The model is based on the following assumptions:

•recharge is uniform

•nitrate behaves conservatively in groundwater, i.e., does not undergo biological or chemical degradation

•Nitrate is transported by advective flow at a rate equal to the rate of groundwater flow and uninhibited by sorption

•the concentration of nitrate in recharge directly relates to land use and is uniform for all recharge that originates under a given land use designation

•recharge enters the aquifer along discreet flow paths that mix only slightly within the aquifer, therefore the nitrate concentration at each point along a flow path is representative of the concentration at its point of origin at the water table

•recharge is displaced downward as it travels through the aquifer, and a vertical column of groundwater adjacent to the municipal well can be represented as a “stack” of water in which the oldest (~25 years) is at the bottom and the youngest (0-1 year) is at the top (Figure 4).

•when groundwater is withdrawn at the municipal wells, complete mixing occurs in and around the well screen and the resulting nitrate concentration is the volume-weighted average from each contributing water year.

•We note that the assumption of limited mixing along flow paths would be unlikely to hold in significantly stratified or heterogeneous aquifers but argue that it is reasonable in a shallow sandy aquifer.

On the basis of these assumptions, the effective concentration of nitrate in water pumped at the municipal well can be estimated as a simple arithmetic function using time of travel data provided by capture zone analysis, historical land-use data, and nitrate loading estimates tied to different land uses (see Figure 5). The C++ model incorporates these files using by prompting the user to enter a model year and subsequently directing the user to drag land use, time of travel, and N-loading tables into the model spaces as .csv files. Recharge depth and grid cell dimensions are directly entered by the user.

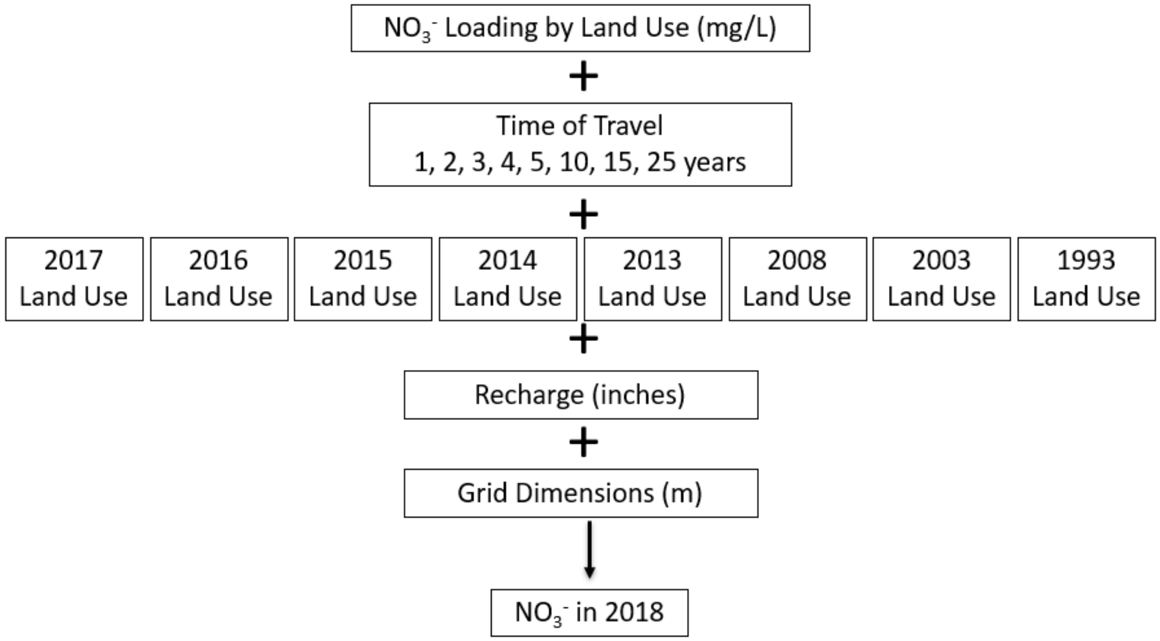

Figure 5. Flow chart illustrating the logical input to the effective nitrate calculator tool.

A nitrogen loading rate (mg/L) is assigned to each land use category in the watershed and then for each grid cell inside the capture zone, the following additional information is provided: time of travel value and a land-use code. Recharge is entered in inches and the total N load for each grid cell is calculated as

$\text{mg N} = \text{N load (mg/L) X Recharge depth X Grid Area}$

MODEL APPLICATIONS

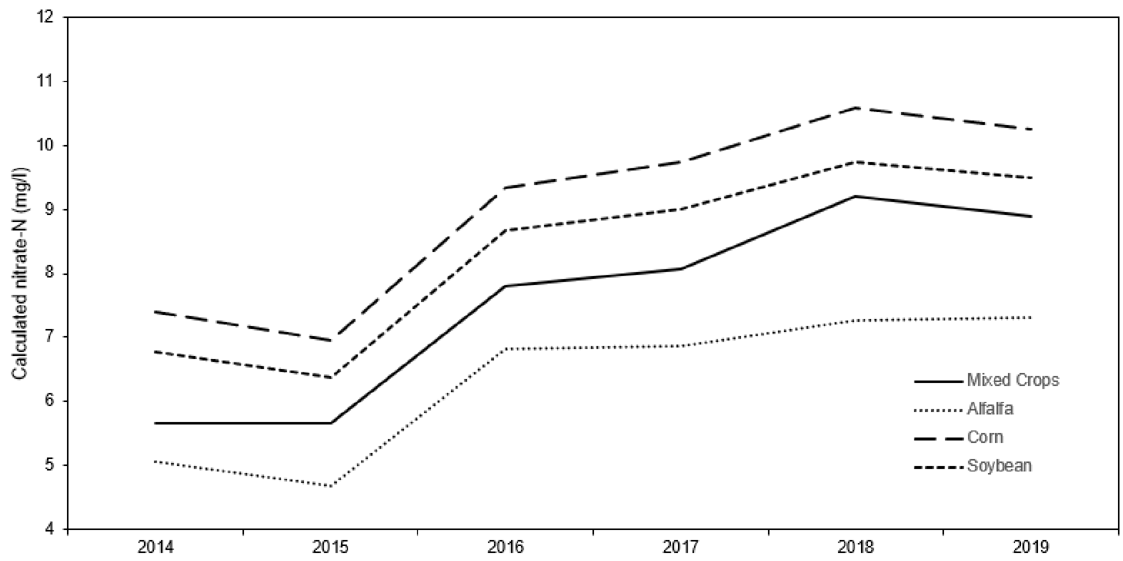

Figure 6. Effective nitrate concentrations predicted by the nitrate calculator using four different uniform crop coverages inside the study area.

The effective nitrate calculator has the potential for use as a planning tool to determine how different land or even pumping rates could affect nitrate concentrations observed at a municipal well. For example, this comparison (Figure 6) evaluated how the concentration of nitrate at well #5 might have varied if cultivated land within the capture zone had been 100% of any of these 4 crop types. This was tested by creating input land use files that were modified to the specified coverage.

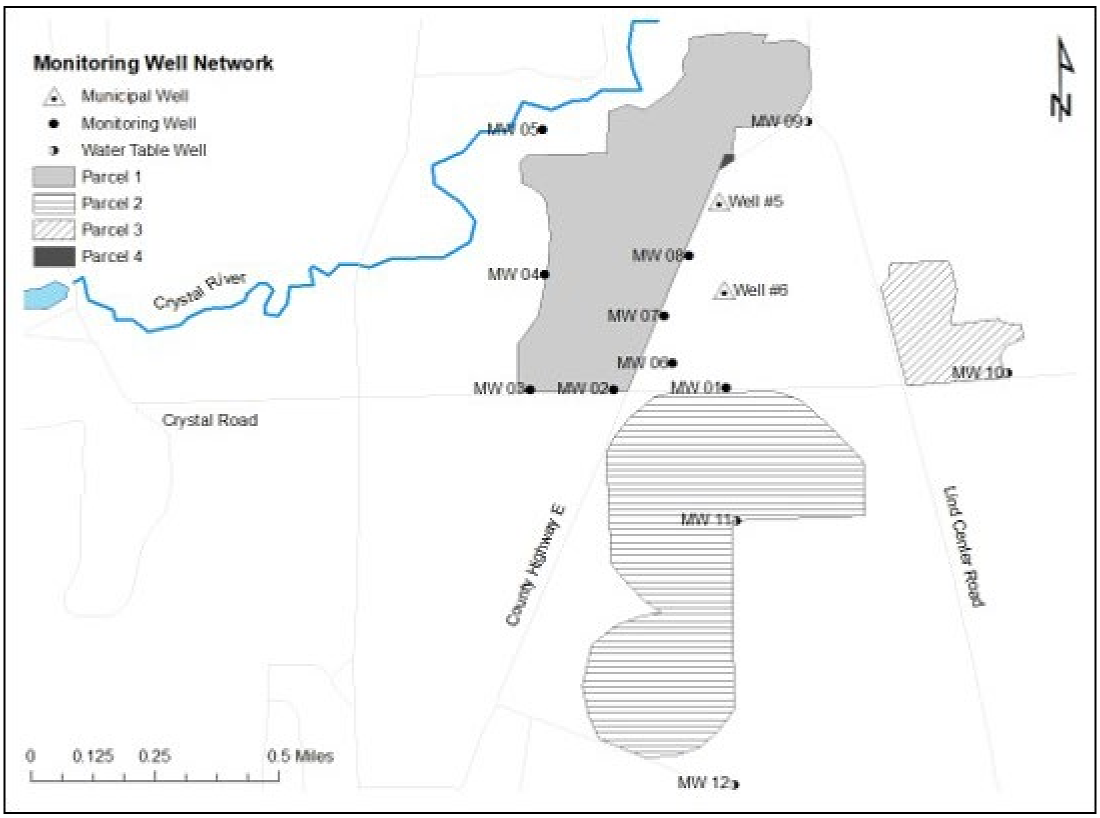

Figure 7. Map of land use and parcel designation in the study area. Parcel 4 is an unlined manure lagoon serving >100 head of cattle.

The nitrate calculator also has potential values as a forensic tool to evaluate individual contaminant sources. In this example, a manure lagoon was considered a probable source of elevated nitrate at well #5, but when the manure lagoon was omitted from the land-use input file, model-predicted nitrate concentration is reduced a mere 0.17 mg/L, which indicates that the manure lagoon is less important than overall agricultural activity in determining the effective nitrate concentration in municipal well water at this location (Figure 7).

ABSTRACT

Shallow glacial aquifers systems are the primary source of drinking water for millions of residents in the upper Midwest and Great Lakes regions of the United States. Studies show that a significant number of municipal and private groundwater wells in these regions are impacted by high nitrate concentrations, which can have negative health impacts on humans. Reducing nitrate contamination through good land management practices will reduce the need for costly nitrate treatment systems and help mitigate other environmental concerns related to nutrient pollution of groundwater. This study presents a C++ modeling tool that uses a local groundwater flow model and historical land-use data (USDA CropScape) to estimate nitrate concentrations at a high-capacity pumping well. Nitrate concentrations predicted by this model show strong agreement with median annual values observed at a study site in Waupaca, WI. The model is user-friendly and can easily be adapted to other locations, where it has the potential to help local and state agencies, landowners, and growers make cost-effective decisions about land-use and agricultural practices.