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Modeling vulnerability of groundwater to pollution under future scenarios of climate change and biofuels-related land use change: A case study in North Dakota, USA

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HIGHLIGHTS

► Groundwater vulnerability can be affected by both climate and land use change.
► A framework to model potential change in groundwater vulnerability was developed.
► The model was evaluated through a case study of North Dakota, USA.
► Expansion of biofuel crops was shown to increase risks of groundwater pollution.

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ABSTRACT

Modeling groundwater vulnerability to pollution is critical for implementing programs to protect groundwater quality. Most groundwater vulnerability modeling has been based on current hydrogeology and land use conditions. However, groundwater vulnerability is strongly dependent on factors such as depth-to-water, recharge and land use conditions that may change in response to future changes in climate and/or socio-economic conditions. In this research, a modeling framework, which employs three sets of models linked within a geographic information system (GIS) environment, was used to evaluate groundwater pollution risks under future climate and land use changes in North Dakota. The results showed that areas with high vulnerability will expand northward and/or northwestward in Eastern North Dakota under different scenarios. GIS-based models that account for future changes in climate and land use can help decision-makers identify potential future threats to groundwater quality and take early steps to protect this critical resource.

1. Introduction

Globally, at least two billion people depend upon groundwater as the principal source of their drinking water (National Research Council, 2008; Sampat, 2000). Dependence upon groundwater is especially great in areas such as Northern China, Eastern Europe, Northern India and the U.S. Great Plains. Recent forecasts suggest that the combined effects of population growth, global warming and land use change will, in the near future, lead to even greater reliance on groundwater for public water supply (Rosenzweig et al., 2007; Hall et al., 2008).

Resource managers are increasingly concerned about human health and ecological effects of contaminants such as nitrates and pesticides (National Research Council, 2008; Sampat, 2000; Merchant, 1994). The application of fertilizer and pesticides on croplands, for example, has often been shown to result in deterioration of the quality of drinking water and increasing health concerns, such as blue baby syndrome, gastric cancer and non-Hodgkin's lymphoma (Knobeloch et al., 2000; Karkouti et al., 2005). Since detection, monitoring and treatment of groundwater pollution are relatively cost-prohibited; management of groundwater quality has emphasized protection of the resource (i.e., prevention of contamination). Protection strategies, however, need to be targeted so that staff, funds and technology can be focused upon those areas that are most threatened (Merchant, 1994). Today it is recognized that targeting must be based upon reliable forecasts of the risk of groundwater pollution under a variety of possible future climate/socio-economic/land use scenarios (Twarakavi and Kaluarachchi, 2006).

During recent decades, a variety of methods for modeling and mapping groundwater vulnerability have been developed (see, for example, National Research Council, 1993; Gogu and Dassargues, 2005; Focazio et al., 2005). These models typically involve the analysis of the interrelationships between key hydrogeologic characteristics (e.g., depth-to-water, soils, aquifer hydrogeology, and groundwater recharge). Although groundwater vulnerability models generally consider similar factors, the models employ different approaches for data integration

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and analysis. These can be grouped into three categories: index methods (Aller et al., 1985), statistical procedures (Nolan et al., 2002; Masetti et al., 2009), process-based methods (Neukum and Azzam, 2009) and/or a combination of these methods (Yu et al., 2010). One of the groundwater vulnerability models used most often is "DRASTIC". The model is formulated as a weighted sum of hydrologic factors that are related to the movement of pollutants from the ground surface to aquifers (Aller et al., 1985). The model's simple formulation and the ease of integration with geographic information systems (GIS) make it well-suited for regional analyses of groundwater pollution potential. Another significant advantage of DRASTIC is its flexibility as it can be adapted to incorporate other factors (Rahman, 2008; Lima et al., 2011), such as land use and land cover (LULC), a factor important in assessing impacts of contaminants such as farm chemicals on groundwater quality (Eckhardt and Stackelberg, 1995; Scanlon et al., 2007).

The DRASTIC model is usually implemented based on "static" conditions, i.e., the model assesses vulnerability for a single point in time based on current hydrogeologic and LULC conditions (Butscher and Huggenberger, 2009). However, groundwater vulnerability is strongly dependent on factors such as depth-to-water table, recharge and LULC conditions, all of which are influenced by climate conditions and human activities. Groundwater quality is expected to respond to changes in climate and anthropogenic activities due primarily to the influences of recharge and land use on groundwater systems (Green et al., 2011). Climate change can potentially alter the vulnerability of shallow aquifers by affecting depth-to-water table and recharge (Pointer, 2005; Scibek and Allen, 2006; Toews and Allen, 2009). And, human activities such as changes in LULC can also affect groundwater vulnerability. It has been forecasted that agricultural land use, and associated application of farm chemicals, may change quite significantly as a result of global warming and/or changing socio-economic circumstances such as increasing demands for biofuels (Ojima et al., 1999; Foley et al., 2004; National Research Council, 2008). Elevated grain-based bioethanol demands may lead to expansion of corn production and increased use of nitrogen-based fertilizers (Simpson et al., 2008). As a result, in some locations there could be concomitant, though currently unknown, changes in risks of groundwater pollution (Dams et al., 2007; Graham, 2007).

Previous studies have shown that the vulnerability of groundwater may vary over time due to changing climate and/or LULC. For example, Ducci (2005) demonstrated that patterns of regional groundwater pollution vulnerability will vary between drought, average, and wet climatic conditions. Butscher and Huggenberger (2009) analyzed a karst aquifer system in Switzerland based on a lumped parameter model and found that groundwater vulnerability depends on climate-affected recharge conditions. Lima et al. (2011) predicted future groundwater vulnerability based on a modified DRASTIC model and future agricultural expansion scenarios simulated by Dyna-CLUE model. However, no investigation has yet focused on groundwater vulnerability that may be affected by both climate and LULC change especially at the regional level. Decision-makers need tools to identify "hotspots" of high groundwater vulnerability in order to facilitate allocation of resources for groundwater protection.

The U.S. northern Great Plains is characterized by high natural variability of climate, highly fertile soils and widespread agricultural land use. During the 20th century, the average temperature of this region rose by more than 1 °C, with increases up to 3 °C observed in parts of North Dakota and South Dakota (U.S. Global Change Research Program, 2000). Precipitation has also increased over most of the region (U.S. Global Change Research Program, 2000). It is expected that average temperature will continue to rise into the 21st century (up to around 3 °C in the mid-21st century), and increasing precipitation is also expected to occur in many areas (up to about 6 cm in the mid-21st century) (IPCC, 2007). Meanwhile, there has also been significant LULC change in the region. The U.S. Department of Agriculture (USDA) has documented that, during the period 2000–2009, thousands of acres in other crops were converted to corn production in the northern Great Plains (Wallander et al., 2011). It has been projected that agricultural land use will continue to expand as a result of increasing demands for biofuels and global warming (Ojima et al., 1999; Foley et al., 2004; National Research Council, 2008). Biofuel crops (i.e. corn and soybeans) are expected to dominate the future agricultural landscape of the northern Great Plains as a result of (1) increasing demands for bioethanol stemming from the federal Renewable Fuel Standard (RFS) (Brooke et al., 2009); and (2) increasing suitability for biofuel crops that prefer a warmer climate and longer growing season. It has also been noted, however, that shifts in climate and land use patterns may result in a range of potentially negative environmental consequences including elevated groundwater pollution risks (de Oliveira et al., 2005; Kennedy, 2007).

This research presents a modeling approach that integrates groundwater vulnerability, climate change scenarios, and modeled LULC scenarios essential for future water quality management in North Dakota, a northern Great Plains state. The objective is to determine if, how and where the vulnerability of groundwater to pollution in this area may be impacted by projected land use change driven by both climate change and increasing demands for biofuels. In this study, the focus is on the vulnerability of groundwater to pollution from nitrates, a constituent of chemical fertilizers used widely in the U.S. Great Plains and known to have implications for human health (Power and Schepers, 1989).

2. Methods

2.1. Study area

North Dakota was selected as the study area because it is representative of the northern Great Plains, a region that has been experiencing significant changes in both climate and land use. The state has a continental climate typified by cold winters and hot summers. As noted above, however, during the past century average temperatures in North Dakota have increased up to 3 °C (U.S. Global Change Research Program, 2000), among the highest in the northern Great Plains. Apart from climate change, North Dakota is also experiencing land use changes driven by demand for biofuels. At least fifteen incentive programs, laws and regulations are in place to govern the production, transportation and sale of biofuels (U.S. Department of Energy, 2011). And, North Dakota has joined with northern Great Plains states such as South Dakota, Nebraska and Iowa under the Energy Security and Climate Stewardship Platform to create a regional biofuels corridor program (see http://www.midwesterngovernors.org/resolutions/Platform.pdf).

North Dakota spans four principal ecoregions (Fig. 1): the Lake Agassiz plain, the Northern Glaciated Plains, the Northwestern Glaciated Plains, and the Northwestern Great Plains (the figure were produced based on Omernik, 1987). The Lake Agassiz Plain, situated along the eastern edge of the state, features highly fertile soils and includes the most productive farmlands in the state. The regions west of the Lake Agassiz Plain gradually rise in elevation and have lower soil fertility. North Dakota is the leading producer of wheat, barley, sunflowers and dry edible beans in the U.S. By 2009, however, the three most important farm commodities changed to wheat, soybeans and corn at 29.4%, 16.1% and 12.7%, respectively (Economic Research Service, 2011).

Groundwater in North Dakota occurs in two major rock types, unconsolidated beds of gravel, sand, silt and/or clay and the underlying bedrocks. The most productive aquifers were formed by fluvial unconsolidated deposits and distributes along the surface drainage system with well yields between 0.19 and 1.9 m^3/min (Paulson, 1983). Away from the major fluvial aquifers, those unconsolidated minor aquifers, although occurring with smaller well yields, can generally meet the rural domestic needs. Bedrock aquifers are another important water source. These aquifers are mostly confined, but are