Applications of hydrogeologic settings in groundwater vulnerability mapping in LaGrange County, Indiana

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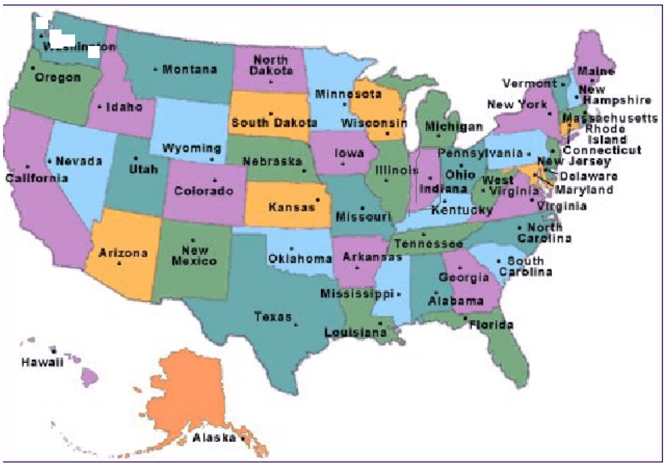
INTRODUCTION

An increased awareness of the role of groundwater in the hydrological cycle would result in better understanding of the resource, its susceptibility to pollution, and the need for increased efforts to protect its quality. Economic pressures have shifted the paradigm in the management of groundwater resources from the command and control approach to a focus on using risk-based remediation standards and efforts in public education and prevention (Canter, 1997).

About half of the US population depends on groundwater as its primary water resource. In the State of Indiana, about 60% of the population is supplied by groundwater, rising to 90% in the rural areas. The population of LaGrange County (Figure 1) is one of the fastest growing in the state of Indiana, having increased by 18.4% between 1990 and 2000 (Fed



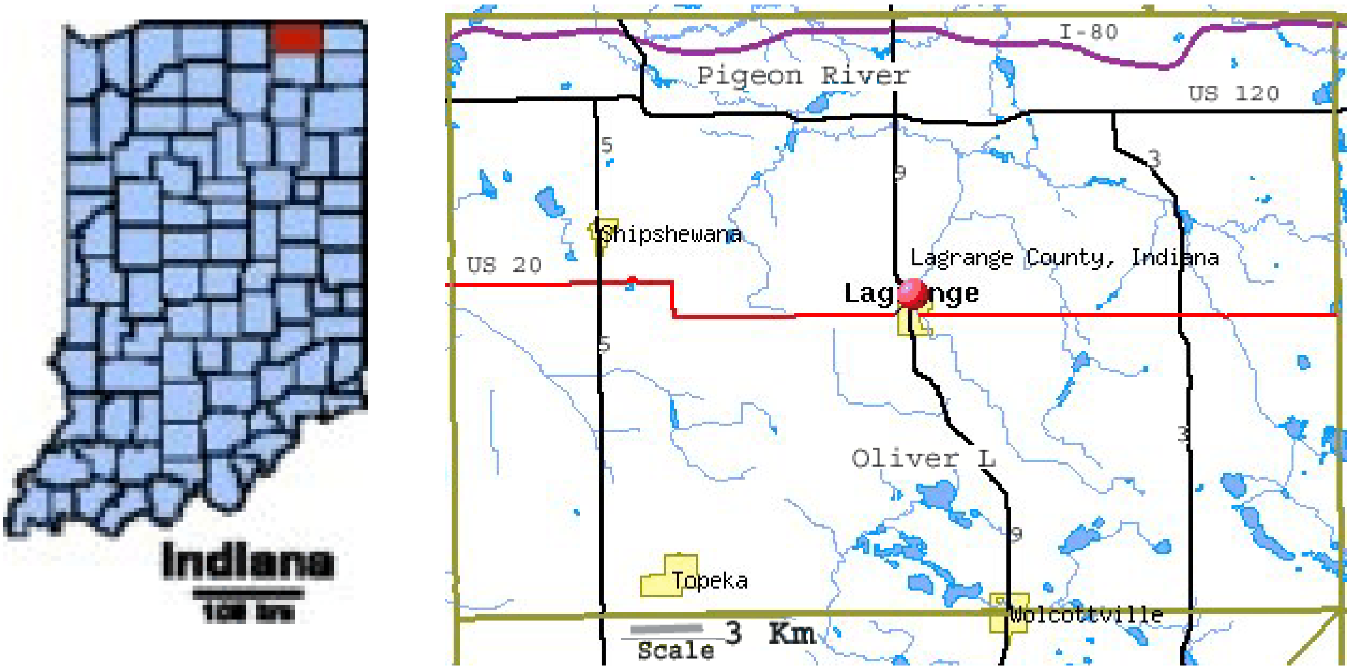


Fig. 1 Map showing location of LaGrange County, Indiana, USA.

Statistics, 2003). Residents of LaGrange County in northern Indiana are entirely dependent on groundwater for their water supply.

Water supply is abundant within LaGrange County, but there are indications of growing threats to the quality of this important resource. Kennedy *et al*. (1991) show that approximately 39% of the lakes (33) in the county have bacteria levels that can be a health hazard. Studies of groundwater in the county also show well water with elevated bacteria and/or high nitrate levels that may be hazardous to human health (Grant *et al*., 1996; Isiorho, 1994).

In evaluating groundwater risk from pollution, several methods have been used that produce groundwater vulnerability maps of varying reliability (Lobo-Ferrira and Oliviera, 2003; Piscopo, 2001; Rupert, 2001; Radig, 1997). How would vulnerability maps produced by different methods compare for a given area? Nitrate well-water data in LaGrange County will be used to answer this question.

This paper synthesises data to determine: locations of aquifers, classification of aquifers, probable areas of recharge to aquifers and locations susceptible to nitrate pollution. It also describes nitrate level distribution in the county, compares this with a vulnerability map produced from DRASTIC, explaining the difference between the nitrate level distribution map and that of the DRASTIC map. The underlying goal is to produce materials that will be educational to citizens and policy makers of the county, in the belief that the approach could be applicable in other areas of the world.

STUDY AREA

Eighty percent of the area of LaGrange County is rural (75.4% farmland, 4.6% pasture). It is relatively flat with several lakes dotted around the county. Growth in population and agricultural activities tends to result in groundwater pollution in rural areas (Isiorho, 1997).

Nitrate occurs naturally in drinking water, and in LaGrange County, it is usually at concentrations less than 2 parts per million (ppm). Elevated nitrate levels in groundwater may result from human activities such as overuse of fertilisers and improper disposal of human and animal wastes. Nitrates are very soluble in water and move easily through soil into drinking water supplies. High levels can build up over time as nitrate accumulates in drinking water, and at elevated levels, nitrate can be a health hazard for very young infants and susceptible adults, and may have contributed to spontaneous abortion in the county (Grant *et al.*, 1996; Kross *et al.*, 1992).

The most common sources of nitrate are municipal and industrial waste waters, refuse dumps, animal feed lots and septic systems. Other sources are runoff or leachates from manured or fertilised agricultural lands and urban drainage. In addition, nitrogen compounds are emitted into the air by power plants and automobiles and are carried from the atmosphere to the earth with rain. All of theses sources occur in the county (Isiorho, 1997; Fleming *et al*., 1995). Evaluation and protection of the ground water resources of the study area will require systematic geological framework mapping, based on a three-dimensional, facies-defined approach.

Geological framework

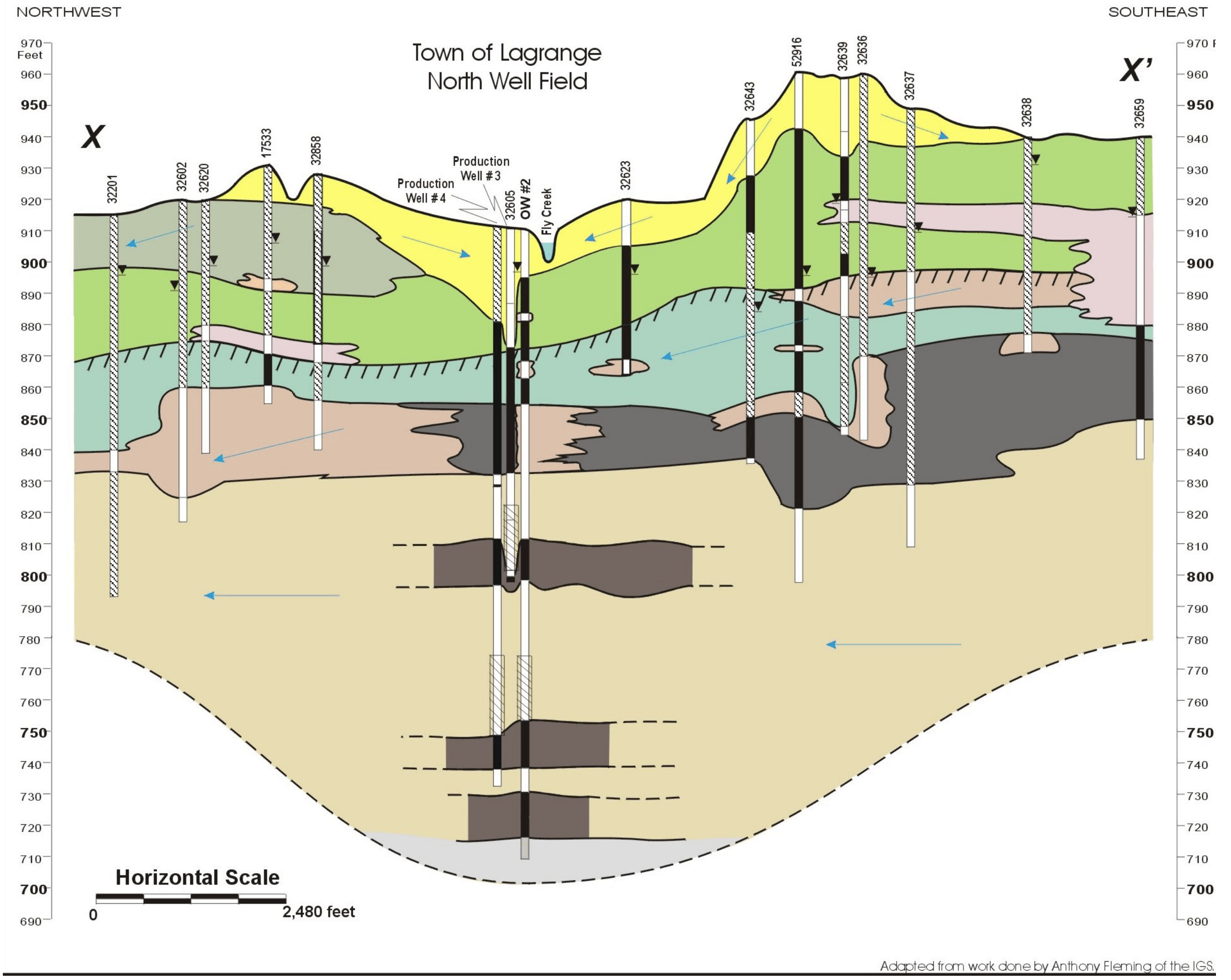
Figure 2 is a cross-section through the town of LaGrange in LaGrange County showing the hydrogeological settings: likely direction of groundwater flow in shallow aquifers, probable recharge areas, thickness range of unconfined sand and gravel, and near-surface confining units. The groundwater flow directions are similar to the regional water table map produced by Clendenon and Beaty (1987).

Hydrogeology

In northern Indiana, where the climate is humid, groundwater is generally present at relatively shallow depths (less than 15 m) in most types of geological materials. In the area around the town of LaGrange, sand and gravel deposit (Pre-Wisconsin age) overlying shale bedrock provides the main aquifer. This aquifer is, in turn, overlain by younger deposits, and is also water-bearing. (Clendenon and Beaty, 1987; Dryer, 1984; Fleming *et al.*, 1995).

It is possible for a particular aquifer to be confined in some places, but under water table conditions (unconfined) in others, according to the continuity of the confining units above. In fact, different aquifers often exhibit different types of hydraulic interconnection with one another because the confining units that separate them are locally thin, absent, or pierced by permeable lenses of sand and gravel. These interconnections give rise to aquifer systems, which are defined as heterogeneous bodies of permeable and poorly permeable materials that function regionally as water-yielding units; they consist of two or more aquifers separated at least locally by confining units that impede water movement, but do not affect the overall hydraulic continuity of the system. The concept of aquifer systems is extremely significant as it implies that, under certain conditions, water and contaminants can and do migrate from one aquifer into other aquifers situated in both deeper and shallower parts of the subsurface that are part of the geological framework (Fleming *et al*., 1995).

A geological framework refers to the architecture of rocks and sediments at and beneath the surface of the earth and their relationship to landscape. A relatively detailed knowledge of this framework is essential to the interpretation and management of groundwater systems in any given area because this framework ultimately determines the distributions and



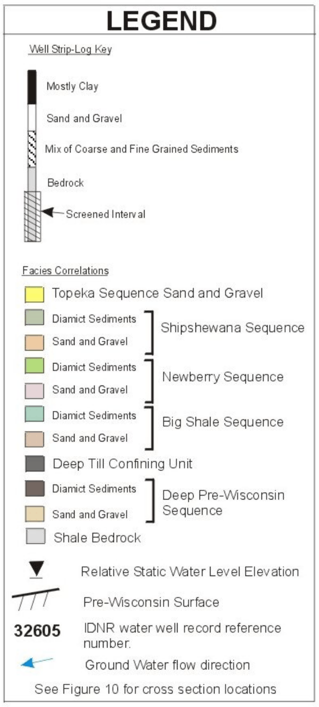


Fig. 2 Map showing geologic cross section through the town of LaGrange in LaGrange County, Indiana (From Summit Services Risk, Inc., 2003)

properties of aquifers and confining units. Variations in the arrangement of these units result in distinct differences in the abundance, distribution and sensitivity to contamination of groundwater from place to place.

Sensitivity of Ground Water to Contamination

It is well known that the behaviour of many contaminants in groundwater is determined as much by their particular chemical and physical characteristics as by the hydrogeology of the affected aquifer. Consequently, it is problematic to make an assessment of groundwater contamination potential without *a priori* knowledge of which contaminants are present and pose a potential threat to groundwater. For example, pesticides, metals, and most inorganic constituents (such as road salt and nitrates), are among the better-known examples of contaminants that are relatively soluble and tend to migrate more or less parallel to the prevailing direction of groundwater flow and at a similar rate. This means that such contaminants are much more prone to penetrate deeply into a groundwater system if they are released in recharge areas (downward flow) but may not penetrate at all if they are released in areas of groundwater upwelling.

VULNERABILITY MAPS

The terminology employed to describe the subject of actual or potential contamination of groundwater can be confusing or misleading. A few common terms include groundwater vulnerability, aquifer sensitivity, susceptibility to contamination, and potential for groundwater contamination. These terms are frequently used interchangeably when, in fact, they have quite different connotations.

The concept of 'aquifer sensitivity' relates to the intrinsic hydrogeological susceptibility of an aquifer to contamination from the universe of surface or near-surface sources. In contrast, the idea of 'vulnerability' adds to sensitivity the potential of or contamination from actual land use practices or specific contaminants and sources. However, groundwater vulnerability maps are based on the assumption that potential sources of contaminants actually exist at the land surface above, and the disposal of those contaminants could threaten groundwater quality. All of the above concepts represent the forecasting of the probability of contamination events occurring at some time in the future, and are thus time-dependent (Isiorho, 1997).

Derivation of DRASTIC map

Several different methods may be used to assess groundwater vulnerability. DRASTIC is a numerical rating scheme that was developed for evaluating potential groundwater pollution in a given area based on seven hydrogeologic criteria: **D**epth to groundwater, **R**echarge rate, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone and **C**onductivity of the aquifer (DRASTIC). The DRASTIC method presupposes that data or information is available on each of the seven factors. The most common sources for the seven factors are as presented in Table 1 (Aller *et al*., 1987).

The developers of DRASTIC note that (1) the method is not designed to replace site specific investigations, (2) the method provides the user with only a measure of relative groundwater vulnerability to pollution (and thus only one of the many criteria used in decision making) and (3) erroneous or inaccurate data could be entered which may affect the reliability of the results. These same observations have been noted by other workers (Radig, 1997; Piscopo, 2001; Lobo Ferreira and Oliviera, 2003).

Table 1

Criteria	*Data Source*
Well logs	Depth to groundwater
Water resource Reports	Net recharge
Geologic/Hydrogeologic reports	Aquifer media
Soil Survey	Soil media
Published Topographic maps	Topography
Published geologic reports	Impact of vadose zone media
Published hydrogeologic reports	Hydraulic conductivity of an aquifer

The vulnerability map derived using the above method is shown in Figure 3, which is part of the DRASTIC map for the state of Indiana (Cooper, 1996). From the DRASTIC method, the study area was divided into five categories: low, moderate, average, high, and very high. The high and very high groundwater vulnerability areas are generally north of US 20 and along the rivers, and correspond to Sebewa-Gilford-Homer, Boyer-Oshtemo, Plainfield-Gilfford, and Shipse-Parr soil types. Moderate and average vulnerability areas correspond to the Wawasee-Hillsdale-Conover soil type that covers about 40% of the county to the south, and Shipse-Parr. The low rating from DRASTIC corresponds to the Blount-Pewamo soil type found in the south-west part of the county. The above method does not consider the hydrological settings of the county. Most of the well data used in the DRASTIC method were supplied by professional well drillers. Goings and Isiorho (1994) found several well data from north-eastern Indiana to be inaccurate. DRASTIC has similarly been shown

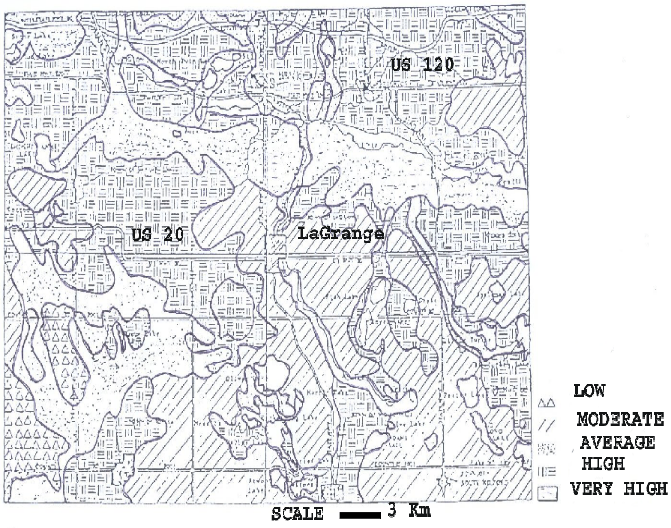


Fig. 3 Vulnerability map of LaGrange County using DRASTIC method

to give results that are inaccurate in glacial drift in the neighbouring state of Michigan (Chowdury *et al*., 2003; Rupert, 2001).

Confining units vulnerability map

Another kind of groundwater vulnerability map is produced using the thickness of confining units. Thompson *et al.* (1996) used this method to determine vulnerability rankings for municipal well fields in Iowa. They identified four vulnerability classes (high=1 to low = 4): (1) less than 8 m thick, (2) 8–15 m, (3) 15–30 m thick, and (4) greater than 30 m. This method divides Lagrange County into three vulnerability classes (Figure 4). The high risk areas are found along rivers and near some lakes, and the low risk area is found to the south-west of the study area. The rest of the study area is considered to be of intermediate risk. This method is used as a screening tool, like the DRASTIC method, but does not consider hydrogeological settings or anthropogenic effect.

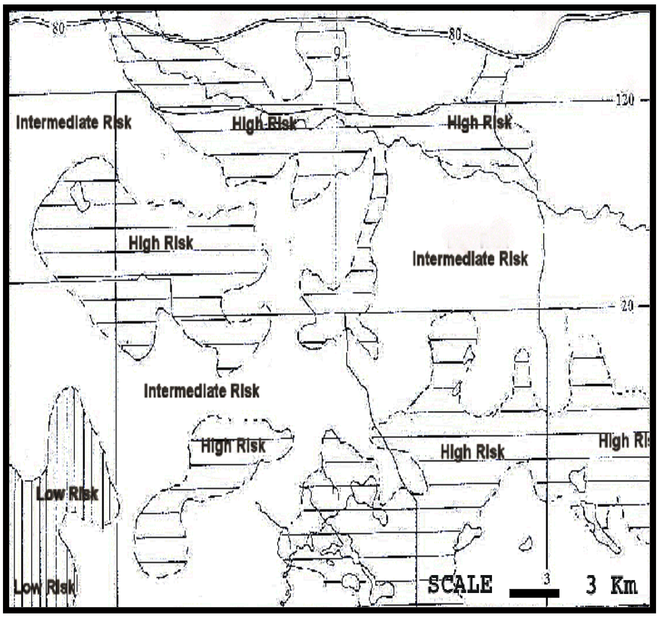


Fig. 4 Vulnerability map using confining units

Soil type vulnerability map

Figure 5 is a soil map for LaGrange County (Hillis *et al*., 1980). Using soil type as a criterion for groundwater vulnerability mapping, only areas with sandy or loamy soils that are permeable and would allow water and contaminants to infiltrate through them relatively rapidly, are considered susceptible. As stated above, the vulnerability map from the DRASTIC method is identical to that derived from the soil types in the county. This method would imply that most of the northern half of the county, that is, north of US 20, would be susceptible to nitrate contamination.

Fig. 5 Soil map of LaGrange County (from Hollis et al., 1980)

Groundwater modelling

This model was used in delineating areas susceptible to groundwater pollution. It was a part of the well head protection plan created for the town of LaGrange (Summit Risk Services Inc., 2003). A three-dimensional hydrostratigraphic modelling assisted in delineating aquifer source water vulnerability. The method was also used to track the potential movement of contaminants within the multi-aquifer systems with numerous pumping wells screened in different aquifer levels (Nelson and Isiorho, 2003). The computer method used hydrogeological settings, well installation logs, gamma response log, and pumping data to constrain WHPAs. Capture zones for the municipal wells were delineated. The work is being extended to the catchment scale. Although the modelled area is only a small portion of the county, the relationship with other vulnerability maps produced using other methods is clear.

The vulnerability maps produced for the LaGrange area are not the same, and they do not account for the distribution of nitrates in the study area. The high nitrate levels in some areas of the county may be explained by anthropogenic activities in those areas. In other words, in addition to the hydrogeological settings, land use and activities around the wells are important contributors to the presence of nitrates in those wells.

OBSERVED NITRATES IN GROUNDWATER

Four hundred survey questionnaires were given to residents of the county to obtain data concerning their wells, farming practices, demography and general health. Approximately eight hundred sample bottles were given to county residents to collect water for analysis. Instructions were given to volunteers on how to collect the water samples for both nitrate and bacteria analysis.

Five water samples were collected for heavy metal analysis using a commercial lab. The heavy metals tested for were lead, cadmium, chromium, selenium and mercury. The commercial lab was also used to test for bacteria in the water samples. Also, water samples from four wells in an area identified as a 'hot' zone in the south-west portion of the study area (Milford Township) were tested for sodium, calcium, potassium, and magnesium using a Perkin-Elmer 2280 Atomic Absorption Spectrophotometer. Manganese was tested for using a DR2000 direct reading spectrophotometer. All the other water samples were tested for nitrate in the field by County health officials.

A total of 507 nitrate data points were collected and additional points obtained from other studies, resulting in a total of 1010 data points; these were plotted on the county topographic map. The nitrate level distribution map was then compared with several county vulnerability maps, including the map derived using the DRASTIC method.

Well water nitrate levels vulnerability map

All currently available water well nitrate levels were plotted on a map of LaGrange County, including wells with no nitrate (Figure 6). The wells were divided into four groups: (i) no nitrates detected, (ii) <2 ppm (i.e. background level), (iii) 2–9.9 ppm, and (iv) 10 ppm and above. Twenty percent (n=202) of the wells had no nitrate, and 48% (485) had nitrate levels less than 2 ppm. Approximately 16% (161) of the wells had nitrate levels between 2 and 10 ppm, and 15% (150) had nitrate levels above the maximum contaminant level (MCL). This means that 31% of the wells in the county have nitrate elevated above background levels. About 90% of the wells with high nitrate levels were shallow (< 15m), and there was a negative correlation between nitrate level and water level. When nitrate was used as a dependent variable, a regression analysis performed suggest that the combined depth/animal waste present was significant with respect to nitrate level (F= 5.26, p<0.008) (Isiorho, 1994).

It is not surprising that some areas with elevated well water nitrate levels are found around towns and lakes in the county. These areas are characterised by larger population densities and human activities that include septic systems. In addition to the towns and lakes, high nitrate levels are also found in and around farm lands in the county. Based on well water nitrate level distribution, LaGrange County is divided into low, intermediate and high risk (see Figure 6).

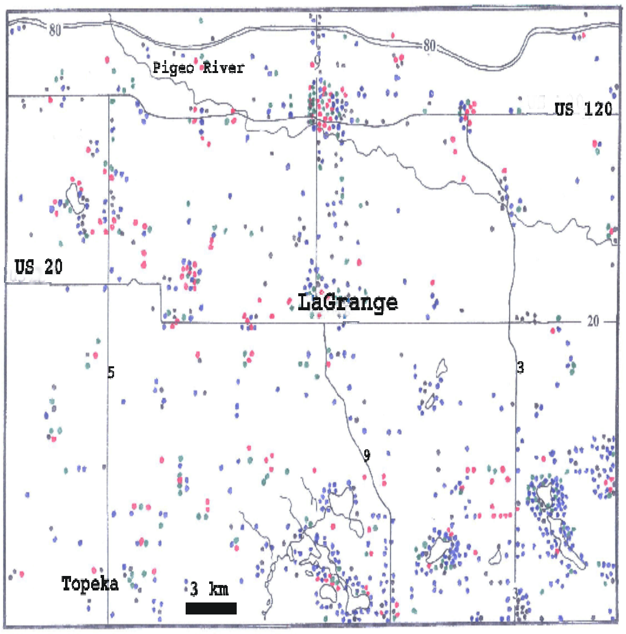


Fig. 6 Nitrate distribution map of LaGrange County (Red>10ppm; Green 2-9ppm; Blue 0.1-1.9 ppm and Black 0 ppm)

COMPARISON AND DISCUSSION OF REAL DATA AND VULNERABILITY MAPS

There is some disparity between the distribution of actual nitrate detections and the distribution expected by the DRASTIC, soil and confining units vulnerability maps for the county. As noted before, the DRASTIC map is nearly identical to the soil map of the region. Shipshe-Parr and Boyer-Oshtemo soil types were included in the high category in the DRASTIC map. Examination of the current well water nitrate levels distribution map shows discrepancies between the various vulnerability maps. The nitrate data show that the majority of the wells with high nitrate levels are north of US state route 20. It is interesting to note that there are wells with high nitrate levels in all types of soil in the study area, meaning that soil type alone is not sufficient to delineate areas susceptible to contamination. The south-west quadrant of the study area has more wells (24%) above the MCL, followed by the NW quadrant (22%), NE 19% and the SE (12%). This is where the hydrogeological setting comes into play. The south-east portion of the study area has high nitrate levels in places forecasted to have low vulnerability.

From a geological perspective, the nature of variability is very important in the determination of nitrate distribution in any geological terrain. Some areas characterised by vulnerability mapping as moderate because they appear to be clay-capped are, in reality, characterised by numerous discontinuities in the capping unit that result from the particular depositional environments that operated as depicted in the geologic cross section in Figure 2. Other reasons for the observed discrepancies include recharge/discharge potentials.

Recharge/Discharge potentials

Places where surface water can infiltrate and percolate into the ground water system tend to be very sensitive to contamination. In LaGrange County, such areas are usually uplands underlain by thick sand and gravel (see Figure 2).

Generally, the greatest recharge occurs where aquifers are unconfined and overlain by thin, sandy soils (Aller *et al*., 1987; Fetter, 1988; Freeze and Cherry, 1979) and under such conditions, recharge can occur very rapidly following a precipitation event: potential recharge may be as much as 254 mm per year or more in a humid climate. Thus large, unconfined aquifers tend to receive consistently large amounts of recharge, which is one reason why they are highly productive, but also contributes to a relatively great sensitivity to surface-derived contamination. The presence of even a small thickness of permeable materials at the land surface can greatly increase the amount of precipitation water that infiltrates to the subsurface.

Discharge areas are found in low positions in the landscape, where the potentiometric surface or water table in an aquifer system is at, near, or above the land surface. Topographic position and soil patterns can be indicators of probable discharge areas, but discharge conditions are determined most reliably on the basis of potentiometric surface maps, relative water levels and groundwater flow patterns. River and stream valleys, lakes and many kinds of wetlands tend to be significant groundwater discharge areas. At least two general kinds of groundwater discharge can be identified in LaGrange County. The first includes small springs and diffuse seepage emanating from saturated materials exposed along valley walls, steep slopes, or in low spots (the latter may form wetlands). Such discharge is commonly ephemeral and of local origin, being restricted primarily to wet periods. Regional discharge, in contrast, is characterised by upward flow of ground water from subjacent aquifers and occurs in the vicinity of major river valleys and lake basins. At some places, the subjacent aquifer is in full hydraulic connection with the surface water body, but elsewhere the subjacent aquifer(s) may be separated from the surface water by a confining unit. In the first instance, a large volume of water actually discharges to the surface, whereas in the second case, discharge occurs only as slow upward seepage across the slowly permeable confining unit. Other variables such as future anthropogenic activities such as septic systems, farming practices, abandoned and improperly constructed wells, not given serious consideration in most states, should be considered. The placement and decommissioning of wells are serious issues with groundwater vulnerability.

Wells

Proper construction of wells is important as they can become potential channels for surface contaminants to get into all types of groundwater systems. Wells may be abandoned or become unused either because the well is no longer in service/in a state of disrepair or because the owner connects to a public supply, or drills a bigger well. Wells also become abandoned when their yield diminishes or the water quality has degraded. Many wells are abandoned every year, but the actual number of abandoned wells in the county is not known. Abandoned wells may lie hidden beneath weeds, brush, or in urban areas.

Abandoned wells can very easily transmit contaminants such as fuel, fertilizers, solvents, sewage, animal waste, pesticides, herbicides and other contaminants directly into aquifers. Abandoned wells are considered a serious threat to groundwater quality in other parts of Indiana (Fleming, 1994), and several reasons exist for properly sealing abandoned wells: (1) it eliminates physical hazards (children or animals falling in); (2) reduces the possibility of groundwater contamination (providing routes for contaminants to ground water); and (3) prevents further loss of confining pressure in confined aquifers (Isiorho, 1997).

The US federal government safe drinking water act (SDWA) requires that public water supplies define well head protection areas (WHPAs). The location and operation of some anthropogenic activities, including septic tank systems, hog farm operations, should be examined closely. Also, the presence of drain tiles that are no longer in use could pose several challenges in vulnerability mapping of the region.

Land use

Groundwater flow direction can be changed locally as a result of human activities. Future land use may affect the hydrogeological settings. For example, the presence of a mining operation can change the groundwater flow direction. It is possible to have groundwater flow reversal when such mining pits act as giant wells. On the other hand, a high density septic system could create a groundwater mound that can result in localised changes in groundwater flow direction. The siting and operation of such system should be considered with regard to the effect it may have on the groundwater quality and quantity.

Aquifer characteristics such as porosity can be altered as a result of human activities that include well drilling (for water, oil/gas, or any other type of wells) and construction blasting. Some of the activities could increase the space openings that allow more liquid to flow through the aquifer per unit time. The effects of these activities are usually local but could have some impact if a contaminant source is nearby.

A new PC-based computer model AQUIPRO (U.S. EPA 1993) is in the offing. Chowdury *et al*. (2003) are using it to determine aquifer vulnerability of glacial aquifers in Michigan, testing its accuracy and validity by comparing nitrate concentration distribution. With the increase widespread uses of geographical information systems, and the computerisation of water well records, the new AQUIPRO method may prove useful in groundwater vulnerability mapping.

Vulnerability maps produced for any area should be regarded as a working document. Future land use, including well construction and abandonment, would have great impact on such vulnerability maps. The possibility of groundwater pollution from septic systems, farming practices and old dumps is well documented. However, the role of abandoned and improperly constructed wells has not been completely documented or given serious consideration in groundwater protection plans in all states.

CONCLUSIONS

Available nitrate data were reviewed along with hydrogeological settings. About a third of the wells in LaGrange County have elevated nitrate levels. Wells with high nitrate levels were found in places depicted as low to average in the DRASTIC model. Susceptibility maps produced from DRASTIC and other methods did not exactly match the elevated nitrate distribution map, however, these maps are still useful as planning tools. In other words, susceptibility maps produced from any of these methods should be considered as working documents which can change with availability of new data. All townships in the county have wells with nitrate levels above the 10 ppm MCL drinking water standard. No one single method can be used to explain the observed nitrate level distribution in the county. The lack of consideration of the presence of abandoned wells, other anthropogenic effects, and/or the hydrogeological settings could be used to explain the observed apparent disparity. Computer modeling may be useful when all available data are plugged into computer programs like MODFLOW.

The high sensitivity areas must be protected as these are either recharge areas or places where human activities may contribute contaminants to the area. Some of these areas also have concentrations of septic systems, which are sources of contaminants. Areas susceptible to groundwater contamination should be protected from contamination through public education, land use compliance and the identification and decommissioning of abandoned wells.

Education of the public would be a step in the right direction to protecting the ground water resources of the county. Data and public awareness would make for informed management decisions. Citizen participation is very important to the success of any groundwater protection plan for the county.

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