

Sensitive Aquifers in Ohio – Relationship to Highly Susceptible Public Water Systems

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INTRODUCTION

One of Ohio Environmental Protection Agency's goals is to identify aquifers in Ohio that are sensitive to ground water contamination as a result of land use activities. The primary benefit of identifying sensitive aquifers within the state is to help prioritize limited resources in order to maximize ground water protection efforts. This article outlines the approach Ohio has used to identify sensitive aquifers (Ohio EPA, 2006) by integrating geologic and chemical water quality data with digital mapping to develop a derivative map product. Data utilized in this effort includes geologic information presented in Ohio Department of Natural Resources Aquifer Maps (ODNR, 2000), water quality information from Ohio's Ambient Ground Water Monitoring Program, and Ohio's public water system (PWS) water quality compliance monitoring data. PWSs with chemical water quality impacts (criteria outlined in Ohio's Source Water Protection and Assessment Program) are also used to evaluate Ohio's sensitive aquifers. The complex nature of ground water contamination will always require site-specific investigations to identify sources and pathways for impacts to ground water. These site-specific studies help refine our hydrogeologic knowledge and may result in refinement of sensitive aquifers. The goal here, however, is to use state-wide data to identify aquifer settings that are most likely to be impacted by land use activities.

OHIO SENSITIVE AQUIFERS

The major aquifers in Ohio include widespread, unconsolidated sand and gravel units, sandstone bedrock in the eastern half of Ohio, and carbonate bedrock in the western half, as illustrated in Figure 1. The sand and gravel aquifers fill pre-glacial and glacial valleys cut into

bedrock and are referred to as buried valley aquifers. The sandstone and carbonate bedrock aquifers generally provide sufficient production for water wells except where dominated by shale, as in southwest and southeast Ohio. Glacial drift overlies most of Ohio except for the unglaciated southeastern quarter of the state.

An understanding of ground water recharge pathways and water quality data were used to identify those aquifers most likely to be impacted by land use activities; that is, sensitive aquifers. The concept that short or rapid recharge pathways increase aquifer sensitivity is widely accepted and used to identify and evaluate sensitive aquifers. Applying this concept within the state of Ohio suggests that sand and gravel aquifers are the most sensitive. Shallow bedrock aquifers, particularly fractured or karst bedrock aquifers that underlie thin glacial drift (tills or lacustrine deposits), comprise a second group of sensitive aquifers. Elevated nitrate concentrations from PWS compliance monitoring data confirmed that these aquifers were sensitive based on ground water quality impacts (Ohio EPA, 2003a). An underlying assumption is that the distribution of potential contaminant sources is widespread and evenly distributed, and the results of this analysis reflect the influence of recharge pathways, not potential source distribution. The widespread distribution of nitrate sources (agricultural, residential) in Ohio makes this a reasonable assumption; however, high concentrations of potential sources close to a PWS well increases the likelihood that the well will exhibit water quality impacts.

The geologic information used in this analysis was derived from the Glacial Aquifer Map (ODNR, 2000), and consequently, the analysis does not provide information about the sensitivity of aquifers not included within, or occurring below, glacial deposits. Geologic settings with rapid recharge are identified as sensitive aquifers and include the following as described in the ODNR Glacial Aquifer Map:

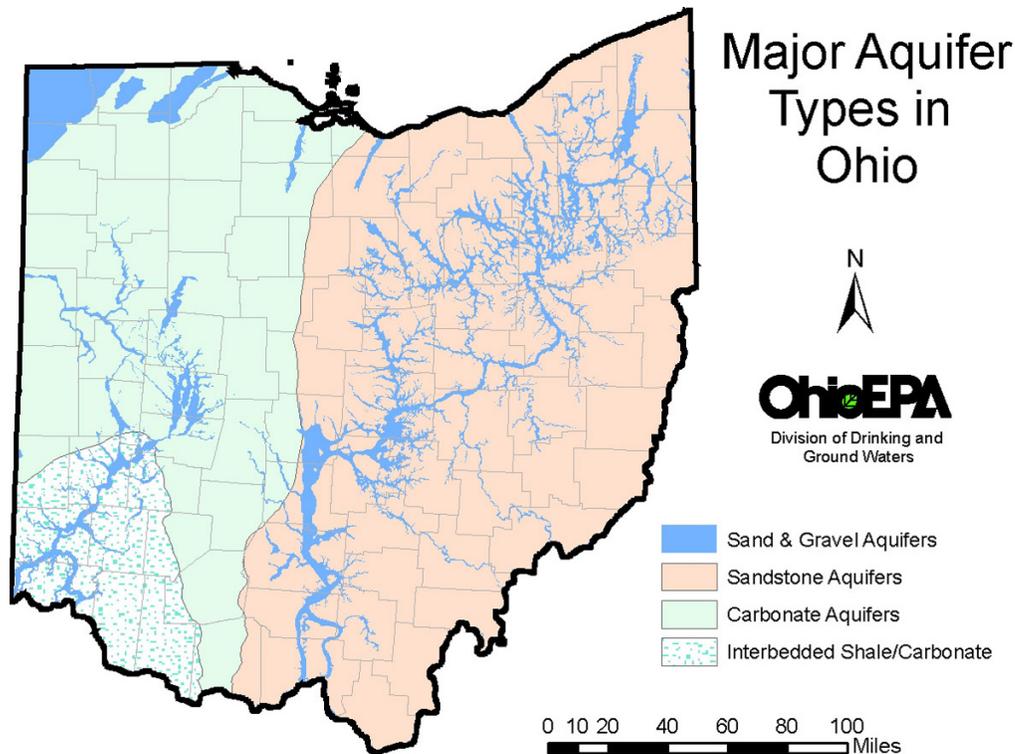


Figure 1. Distribution of major aquifers in Ohio, modified from ODNr Aquifer Maps (Ohio EPA, 2000).

Sand and Gravel Aquifers:

- Buried Valley
- Alluvial
- Valley Fill
- Outwash/Kame
- Beach Ridge

Bedrock Aquifers Below Thin Uplands and Lacustrine Deposits (<25 feet):

- Thin Uplands (thin till)
- Lacustrine

In contrast, areas of thick till (e.g., glacial moraines) generally retard recharge, thereby reducing the sensitivity of aquifers within or below the tills. The following geologic settings in the ODNr Glacial Aquifer Map are not sensitive where the till is relatively thick (>25 feet):

Moraine Deposits:

- Ground Moraine
- End Moraine
- Complex

These geologic settings are associated with different glacial material thicknesses across the state. It is generally assumed that the greater the glacial thickness, the greater the protection provided to the aquifer. The longer recharge

pathways and increased recharge travel time to the aquifer reduces the overall sensitivity of the aquifer. The ODNr Aquifer Maps groups glacial drift into three thickness categories: thin (<25 feet), moderate (25-100 feet), and thick (>100 feet). This thickness describes either the thickness of the glacial drift that includes the aquifer or the thickness of glacial material that overlies a bedrock aquifer. Each of the hydrogeologic settings was separated into these thickness groups to evaluate whether water quality impacts were influenced by the glacial overburden thickness. Even though these groupings are coarse, differences between geologic setting and thickness groups are clear, as discussed in later sections.

This analysis was also performed using lithologic attributes included in the Glacial Aquifer Maps. The lithologic attributes describe the primary materials within mapped polygons in the ODNr Aquifer Maps and provide further division of some geologic settings. The lithologic parameters were divided into three groups for this analysis:

- Sand and Gravel Lithologies: Includes coarse to fine sand and gravel units with minor fine-grained material, including thin lenses of alluvium, lacustrine deposits, or till.
- Fine Grained Lithologies: Predominantly fine grained geologic materials with minor sand and

gravel lenses. Alluvium, slack water, till, and colluvium deposits are included in this group.

- **Till Lithologies:** Predominantly tills with little evidence of sand and gravel lenses. In thin tills, wells generally penetrate through the till into bedrock aquifers. In thicker tills, limited production may be associated with sand and gravel lenses, but larger production wells will generally be drilled through the till into bedrock aquifers.

Overall, the coarser lithologies would be expected to allow more rapid recharge and, consequently, be associated with more sensitive aquifers. Figure 2 illustrates the distribution of the sand and gravel aquifers that are sensitive, and the areas of thin glacial drift that overlie sensitive bedrock aquifers.

PWSs WITH GROUND WATER QUALITY IMPACTS

The 1996 Amendments to the Safe Drinking Water Act established a program for states to assess drinking water sources for all public water systems (PWSs). The purpose was to provide PWSs information for developing

drinking water protection plans. These assessments included a susceptibility analysis. As outlined in the Source Water Assessment and Protection (SWAP) Program, Susceptibility Analysis Process Manual (Ohio EPA, 2003b), a PWS in Ohio is considered to have “high susceptibility” if it has been impacted by anthropogenic contaminants, regardless of its geologic setting or lithology. Water quality impacts are defined as two or more nitrate concentrations greater than 2.0 mg/L, or two or more confirmed detections of organic constituents (VOC or SVOC) using PWS compliance monitoring data since 1991. The SWAP staff reviewed more than 60,000 samples, including over 1,100,000 results, to identify the subset of high susceptibility PWSs based on water quality impacts. This effort identified a subset of 561 PWSs out of a total of 5,151 ground water sourced PWSs. This subset of PWSs can be used as an independent data set to evaluate the identification of sensitive aquifers in Ohio. Figure 3 shows the locations of the 561 PWSs with documented water quality impacts (highly susceptible in SWAP terminology) in relationship to sensitive aquifers. The visual association of the PWSs that exhibit water quality impacts to sensitive aquifers is most obvious along buried valleys, but is not particularly obvious on a state scale map.

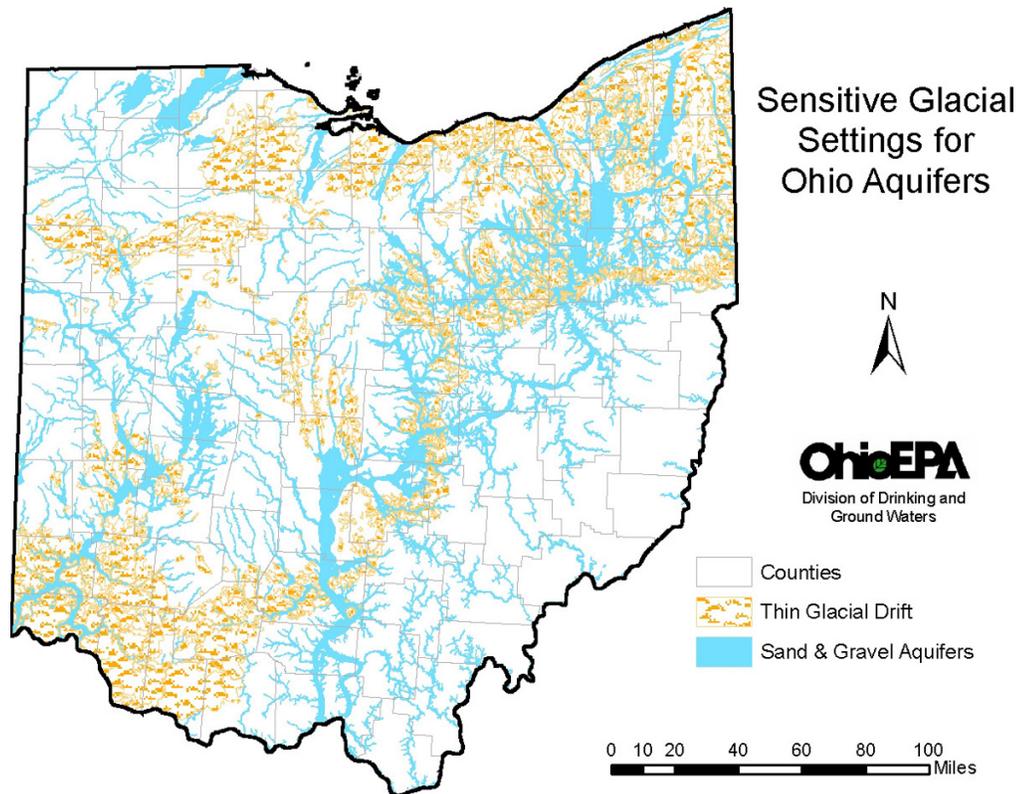


Figure 2. Distribution of sensitive sand and gravel aquifers and thin glacial drift over sensitive bedrock aquifers.

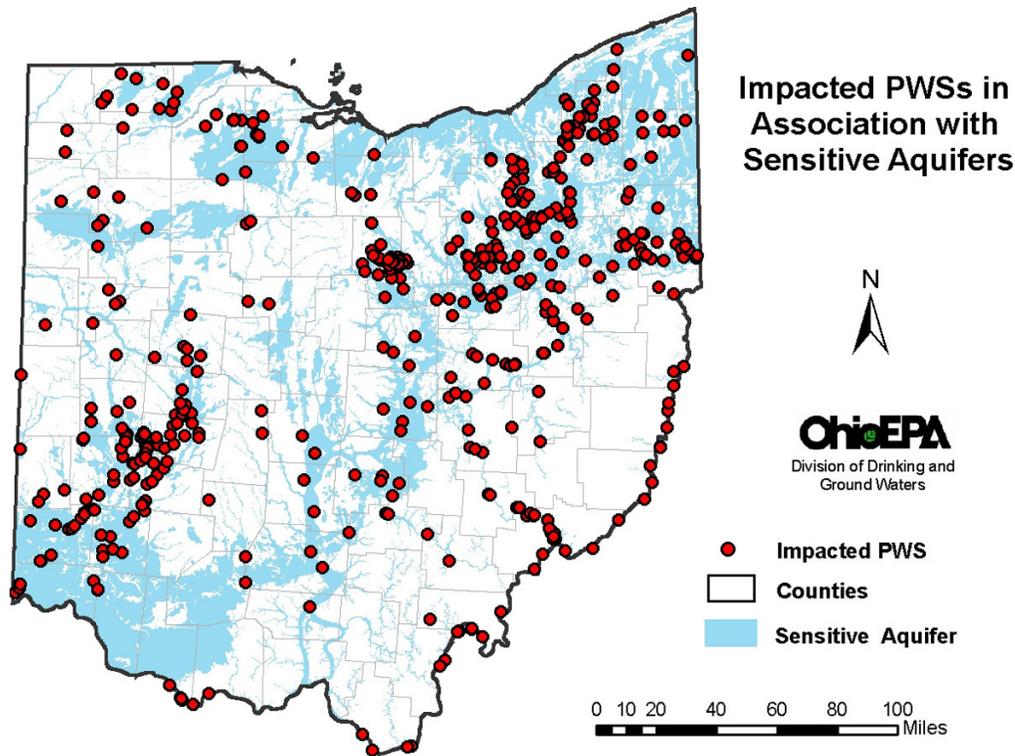


Figure 3. PWSs with documented water quality impacts in relation to sensitive aquifers.

ASSOCIATION OF HIGH SUSCEPTIBILITY PWSs WITH SENSITIVE AQUIFERS

The following analysis utilized the ODNR Glacial Aquifer maps to determine whether the highly susceptible PWSs are located where sensitive aquifers occur, with the implication that the well is probably completed in that aquifer. To accomplish this, the 561 highly susceptible PWSs were associated by location to the attributes of the ODNR Glacial Aquifer Maps. These attributes, including geologic setting, thickness, and lithology, were used to count the number of impacted PWSs that occur in different glacial settings or the number associated with different glacial lithologies. These counts were compared to the number of all ground water based PWSs associated with the same groupings of glacial settings or lithologies to normalize the results for accurate comparisons. The following section presents the results as percentages of ground water-based PWSs.

Extracting the Glacial Aquifer Map's attribute data based on PWS locations has several limitations that need to be considered with regard to the results presented in Tables 1 and 2. The thickness of the glacial drift at a given PWS location is not the well depth or average well depth of the PWS wells, but rather an estimate of the glacial drift thickness that controls the recharge pathways. The PWS well may be producing water from the glacial drift, or the well

may be cased through the glacial drift and producing water from a bedrock aquifer. If the glacial thickness is thin (< 25 feet thick), it is reasonable to deduce that the well is a bedrock well. In thicker glacial drift, it is not possible to know whether the well is producing water from the glacial aquifers or bedrock aquifers without additional information such as well depth or casing length. If the PWS wells are located in thick glacial drift in geologic settings that are considered sensitive (buried valley, beach ridge, outwash/kame), it is likely that the well is producing from sand and gravel aquifers that lie within the drift. For example, a well may be 45 feet deep in an area of drift greater than 100 feet thick. These data limitations need to be taken into account when reviewing the data presented in Tables 1 and 2. Overall, there appears to be a strong association between impacted PWSs and glacial attributes associated with sensitive aquifers, in spite of these data limitations.

GEOLOGIC SETTING ASSOCIATIONS

The percentages of impacted PWSs associated with categories of geologic settings by increasing thickness of glacial drift are listed in Table 1. Overall the highest percentages of PWSs with impacted source water are associated with the sand and gravel aquifers. The major aquifer groups associated with geologic settings are discussed below.

Table 1. Documented water quality impacts at PWSs, and associations between impacts and hydrogeologic setting* of glacial units.

Thickness of Glacial Unit (Feet)	Number of ground water-based PWSs with Impacts	Total Number of ground water-based PWSs	Percentage of Impacted PWSs
Sand and Gravel Aquifer Settings			
(Aquifer Map settings - Buried Valley, Alluvial, Valley Fill, Outwash/Kame, Beach Ridge)			
0-25	10	39	26%
25-100	92	487	19%
>100	153	1066	14%
Bedrock Aquifers Below Thin Uplands and Lacustrine Deposits			
(Aquifer Map settings - Thin Uplands and Lacustrine)			
0-25	133	904	15%
25-100	103	1032	10%
>100	8	28	29%
Moraine Deposits			
(Aquifer Map Settings - Ground Moraine, End Moraine, Complex)			
0-25	0	0	0%
25-100	27	704	4%
>100	13	559	2%
Unglaciaded Areas			
(No glacial units on ODNr Aquifer Map)			
0	22	332	7%

*Hydrogeologic settings are from ODNr Glacial Aquifer Map (ODNR, 2000).

Table 2. Documented water quality impacts at PWSs, and associations between impacts and lithology* of glacial units.

Thickness of Glacial Unit (Feet)	Number of ground water-based PWSs with Impacts	Total Number of ground water-based PWSs	Percentage of Impacted PWSs
Sand and Gravel Lithologies			
(including: sand and gravel, minor fines, confined, thin till included within or over unit)			
0-25	6	9	67%
25-100	50	133	38%
>100	113	495	23%
Fine Grained Lithologies			
(including: fine grained sediments undifferentiated, fines with minor sand and gravel lenses)			
0-25	4	36	11%
25-100	44	405	11%
>100	37	464	8%
Till Lithologies			
(including: till, till with sand and gravel lenses)			
0-25	133	898	15%
25-100	128	1682	8%
>100	24	697	3%
Unglaciaded Areas			
(no glacial units on ODNr Aquifer Map)			
0	22	332	7%

*Lithology divisions are from ODNr Glacial Aquifer Map (ODNR, 2000).

Sand and Gravel Settings

The percentage of PWSs with documented water quality impacts is higher for the geologic settings dominated by sand and gravel deposits (buried valley, alluvial, valley fill, outwash/kame, and beach ridge) as illustrated in Table 1, column 4. The percentage of impacted systems decreases with increasing glacial drift thickness: 26 percent for thin sand and gravel deposits (statistic based on small number of PWSs), 19 percent for intermediate sand and gravel deposits, and 14 percent for sand and gravel deposits of more than 100 feet thick. This trend supports the concept of increased protection as the recharge pathways lengthen. Based on the statutory requirement of 25 feet of casing for PWS wells, wells associated with the 0-25 foot group of sand and gravels probably represent wells drilled through the glacial sand and gravel into bedrock.

Bedrock Aquifers Below Thin Uplands and Lacustrine Deposits

PWS wells producing from bedrock aquifers below thin and intermediate-thickness upland till or lacustrine deposits (< 25 and 25-100 feet thick) exhibit ground water quality impacts in 15 and 10 percent of the PWSs, respectively. These percentages suggest that thin till and lacustrine material provides a bit more protection from land use activity than sand and gravel. The low yield from till and lacustrine deposits requires most of these wells to be bedrock production wells. The 29 percent of PWSs that showed ground water impacts with glacial drift greater than 100 feet thick is based on relatively few wells and appears anomalous. Two of the eight impacted wells include sensitive buried valley or beach ridge geologic settings within their Drinking Water Source Protection Area inner management zone (one year time-of-travel). These settings provide rapid recharge pathways. The other six wells are deep wells (>120 feet) and, based on available well logs, are presumed to produce water from confined aquifers. This is an unlikely set of wells to exhibit elevated nitrate, since most nitrate detections > 2.0 mg/L occur in Ohio wells with depths less than 75 feet. Three of these four wells were drilled in the 1950's. One explanation is that well construction deficiencies or corrosion of the casing may allow leakage of shallow, nitrogen rich ground water into these wells. Several of these wells are within a few miles of each other and exhibit similar nitrogen time series patterns, which suggests a regional rather than a local control. This example illustrates some of the problems with applying broad interpretations, as shown in Table 1, to site-specific cases.

Moraine Deposits

Protection of ground water resources by thick till cover is demonstrated in the moraine deposits category of Table 1, where the percentage of impacted PWSs does not exceed 4 percent. In Table 1, the thin tills are grouped with the thin upland and lacustrine deposits; 15 percent of PWSs located in thin till settings exhibit water quality impacts. Thicker tills, however, are associated with relatively few impacted PWSs; 4 percent for the intermediate (25-100 feet) group, and 2 percent for the thick (>100 feet) group of the moraine deposits category. These low percentages suggest that thick till provides significantly more protection than sand and gravel or thin tills. The role that fractures and macropores play in controlling recharge to aquifers through tills is a current topic of discussion in Ohio (Weatherington-Rice and Christy, 2000; Weatherington-Rice and others, 2006). Fractures and macropores certainly affect the movement of recharge through thin tills; this is supported by the high percentage (15 percent) of impacted PWSs associated with thin upland and lacustrine settings. Fractures and macropores appear to be significantly less important in recharge and contaminant transport in thick tills as documented by the much lower percentages (4 percent and 2 percent) of impacted PWSs associated with thicker moraine deposits. This is believed to be caused by the limited vertical extent of fractures in till, typically 20-25 feet (Scott Brockman, personal communication, 2006).

Unglaciaded Areas

The last category in Table 1 includes PWSs located in the unglaciaded areas of Ohio, primarily the southeastern uplands. These areas include weathered bedrock (colluvium) that overlies late Paleozoic sandstones and shales, and in places is overlain by loess deposits. In most cases, wells produce water from bedrock aquifers; however, yields are generally low and relatively few PWSs use these aquifers. Consequently, we have limited data for the unglaciaded areas. The available data, however, indicates that the colluvium is better than sand and gravel and thin till in glaciaded areas, but not as good as thicker tills at protecting wells from land use impacts. From Table 1, PWSs in unglaciaded areas are impacted in 7 percent of the sites, a value that is intermediate between sand and gravel and thicker tills. The lower population density and reduced number of potential pollution sources in unglaciaded, southeastern Ohio uplands also tends to depress the percentage of impacted PWSs in this region.

LITHOLOGIC ASSOCIATIONS

The lithologic attributes can be divided for further analysis into sand and gravel, fine grained, and till lithologies. The percentages of impacted PWSs associated with these lithologic groups, ordered by increasing thickness of glacial drift, are presented in Table 2. The percentage of PWSs with documented water quality impacts is highest for the sand and gravel lithologies and lowest for the till materials. This is similar to the results presented in Table 1 for geologic settings, but the percentages associated with the lithologic divisions indicate that recharge processes are more dependent on the lithologic material than on the geologic setting. The major lithologic groups are discussed individually below.

Sand and Gravel Lithologies

For sand and gravel lithologies, the low number of wells in the < 25 feet thickness category results from the statutory requirement that PWS wells have a minimum of 25 feet of casing installed. Thus, the few wells in this thickness grouping are either old wells with short casing lengths or bedrock wells cased through thin glacial sand and gravel. With 67 percent of these wells having water quality impacts, it appears that they are highly susceptible, but because the percentage is based on a very low number of wells, it cannot be given much significance. The percentage of impacted PWSs decreases to 38 percent and 23 percent for the 25-100 feet and >100 feet groupings, respectively. These wells probably do not penetrate the entire glacial thickness, but it appears that the thicker section of sand and gravel provides more filtration and increased travel time, as one would expect.

Almost all of the areas of sand and gravel lithologies in Table 2 are included within the geologic settings that are considered most sensitive in Table 1. The sensitive geologic settings that include sand and gravel aquifers also include fine grained lithologies. The higher correlation between coarser sand and gravel lithologies and PWSs with water quality impacts (Table 2) emphasizes the importance of identifying coarser sand and gravel lithologies as more sensitive than finer grained sand and gravel lithologies. This is consistent with the understanding that aquifer sensitivity is controlled by recharge and transport rate of surface or near surface contaminants to aquifers.

Fine Grained Lithologies

The fine grained portions of the glacial lithologies in the ODNR Aquifer Maps are predominantly undif-

ferentiated fine grained sediments with minor sand and gravel lenses. Approximately 8 percent to 11 percent of the PWSs associated with these fine grained lithologies exhibit water quality impacts, which is significantly less than coarse sand and gravel deposits (23 percent to 38 percent for the sand and gravel lithologies). The percentage of impacted PWSs decreases with increasing glacial drift thickness, but not appreciably, which may result from the variability of well depths independent of the glacial deposit thickness. The low number of samples in the 0-25 feet thickness group (36) suggests that the result (11 percent) should not be given much significance, except that the 25-100 feet group exhibits the same percentage of impacted PWSs.

Till Lithologies

Table 2 documents a sizable difference between impacted PWSs in thin tills and the thicker tills. Only limited protection is provided by thin glacial drift overlying bedrock aquifers, as evidenced by the 15 percent of impacted PWSs associated with thin tills (< 25 feet). Wells producing from fractured bedrock just below thin glacial cover will be the most vulnerable and probably account for the bulk of the PWSs with water quality impacts in this category. The percentage of PWSs with water quality impacts drops dramatically for thicker tills: 8 percent for tills in the 25-100 feet group, and 3 percent for tills greater than 100 feet thick.

Unglaciaded Areas

The unglaciaded areas include the same subset of wells in Table 2 as presented in Table 1. As stated earlier, the limited data restrict broad conclusions, but the low percentage of impacted PWSs suggests that colluvium provides some protection for these wells from land use activities. The lower population density and reduced number of potential pollution sources in southeast Ohio may also help to keep this percentage low.

DISCUSSION

This analysis documents the importance of distinguishing the coarser grained lithologies in buried valleys, alluvial, valley fill, outwash/kame, and beach ridge deposits as being more sensitive to contaminant impact than the finer grained deposits in these same settings. Figure 4 illustrates the association of the PWSs with water quality impacts along a section of the Great Miami buried valley aquifer in southwest Ohio. This figure illustrates

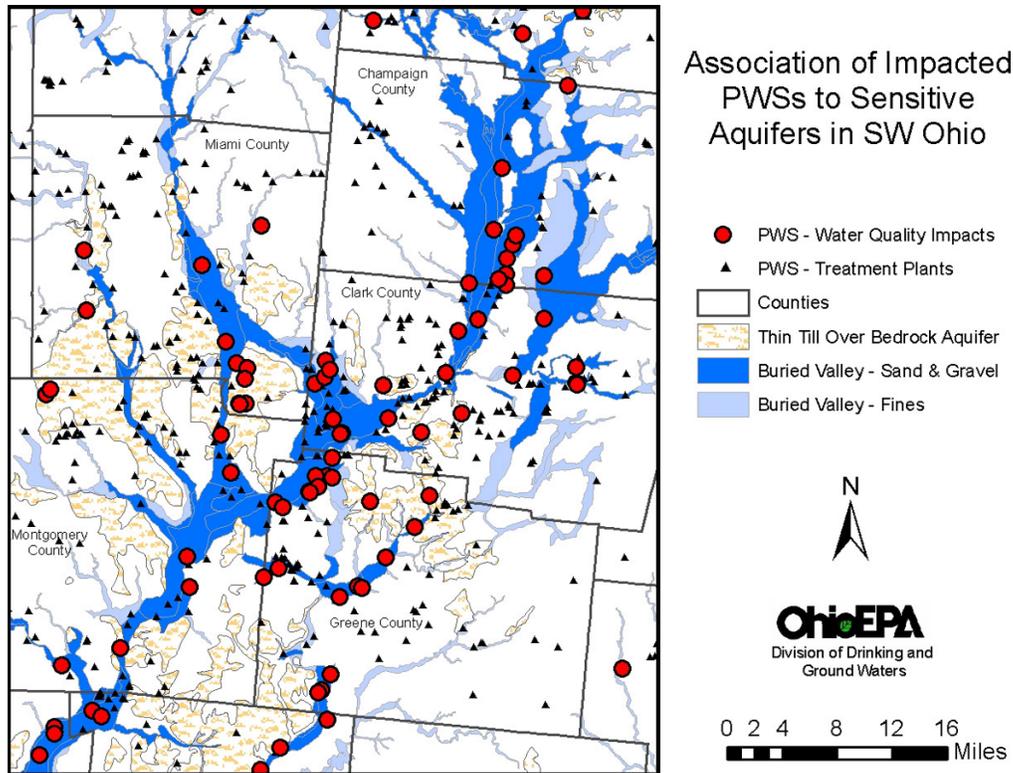


Figure 4. Impacted PWSs and sensitive aquifers and in southwest Ohio.

the relationship between the high concentrations of water quality impacts and sections of the buried valley identified as sand and gravel. Water quality impacts are also associated with finer grained buried valley deposits and thin tills in the uplands (where wells penetrate the till to produce from bedrock aquifers), but with lower frequency as documented in Table 2. The locations of PWS treatment plants are provided to illustrate the wide distribution of PWSs used in the analysis.

Highlighting Sand and Gravel Aquifers

The divisions on the glacial aquifer map are general groupings that were selected to represent glacial material on a state scale based on geologic and well log data. Analyses using PWS empirical water quality data (elevated nitrate, VOC detections) exhibit significant correlations with the identified sensitive geologic settings and lithologies. The stronger association of impacted PWSs with coarser and more permeable sand and gravel lithologies underscores the role recharge plays in making aquifers sensitive, and suggests that coarse sand and gravel units should be emphasized in the identification of Ohio's sensitive aquifers.

Figure 5 illustrates the distribution of sensitive glacial geologic settings across Ohio, utilizing attributes identified in ODNr's Glacial Aquifer Maps (ODNR,

2000). This figure represents the combined analysis of sensitive aquifers and water quality impacts based on nitrate and VOC concentrations. In the glacial settings where sand and gravel deposits are common, the lithology is divided into fine and coarse grained units. The analysis presented in this paper documents that the coarser grained units are more sensitive. The classification processes used in developing the glacial aquifer maps required a great deal of simplification, and consequently, these generalizations need to be considered in any application of Figure 5. Nevertheless, the correlation of the empirical PWS water quality data to the lithologic and geologic setting descriptors supports the simplifications made in developing the ODNr Glacial Aquifer map and the validity of using recharge controls in determining sensitive aquifers.

The goal of identifying sensitive aquifers is to help set priorities for protecting the state's ground water resources. Statewide, aquifers that have more than 25 feet of till or fine grained glacial deposits overlying the well production zone are less likely to exhibit anthropogenic water quality impacts than unconfined sand and gravel aquifers. If till that overlies a bedrock production aquifer is less than 25 feet thick, the bedrock aquifer's sensitivity is elevated, but the sand and gravel aquifers are even more sensitive. The data summaries in Tables 1 and 2, and Figure 5, illustrate the high geologic sensitivity (based on

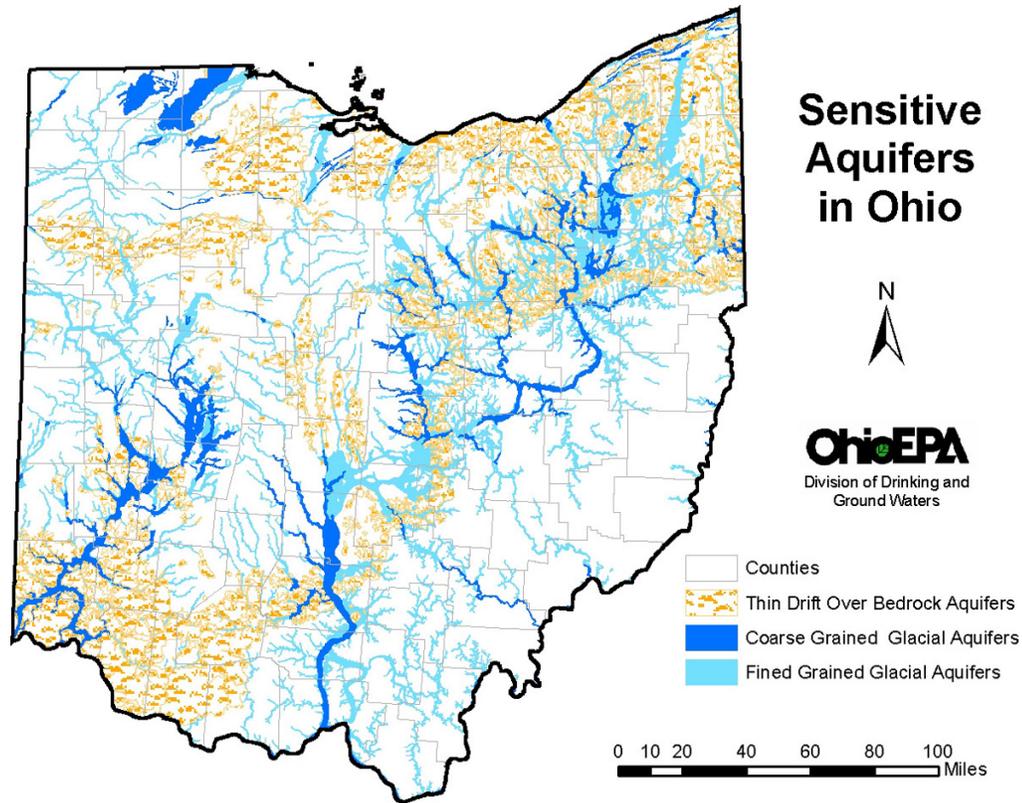


Figure 5. Distribution of sensitive aquifers in Ohio.

chemical water quality data) of Ohio's productive sand and gravel aquifers, in particular the areas of coarser sand and gravels. These conclusions are not unexpected, and they support the generally accepted views of hydrogeologists familiar with the fate and transport of contaminants within sensitive aquifers in Ohio. These empirical data provide significant support for judgments based on professional experience and, consequently, increase our confidence in applying the identified sensitive aquifer settings to protecting Ohio's ground water resources.

Thin Till Over Bedrock Aquifers

Several situations in areas of thin glacial till (< 25 feet) over bedrock have been identified and emphasize the sensitivity of this geological setting, especially where the till that overlies the bedrock is less than 10 feet. Waste-water management (septic, manure) and agricultural or residential facilities placed in close proximity to private or public wells can result in health issues if contaminants move rapidly through the thin till along macropores, fractures, or other pathways to fractured bedrock aquifers. It appears that microbiological contamination is more likely in these thin till settings than in sensitive, unconsolidated sands due to the limited filtration capacity of macropores and fractures in till and bedrock. Invariably, ground water

microbiological contamination increases proportionally to increasing population concentration in areas of closely spaced septic systems and wells. Figure 6 is a schematic geologic cross section that illustrates the sensitive geologic setting of fractured bedrock below thin glacial drift. Water quality impacts associated with similar geologic setting are recognized across the state. The 2004 infectious disease outbreak at South Bass Island in Lake Erie, which was determined to be associated with ground water contamination (Ohio Department of Health, 2005), is an example of the potential water quality impact to sensitive bedrock aquifers in areas of thin to no glacial overburden.

Horizontal Flow Pathways

The previous analysis has assumed that recharge pathways are dominantly vertical. Although this is generally true, there are geologic settings where recharge contributions can have significant horizontal components that increase the sensitivity of aquifers. The schematic cross section in Figure 7 illustrates this situation. Wells located in flood plains close to rivers are examples of locations where horizontal flow paths can become significant contributors to recharge. Many of these wells are located close to the river to increase production by inducing recharge from the river. At flood stage, the elevated river

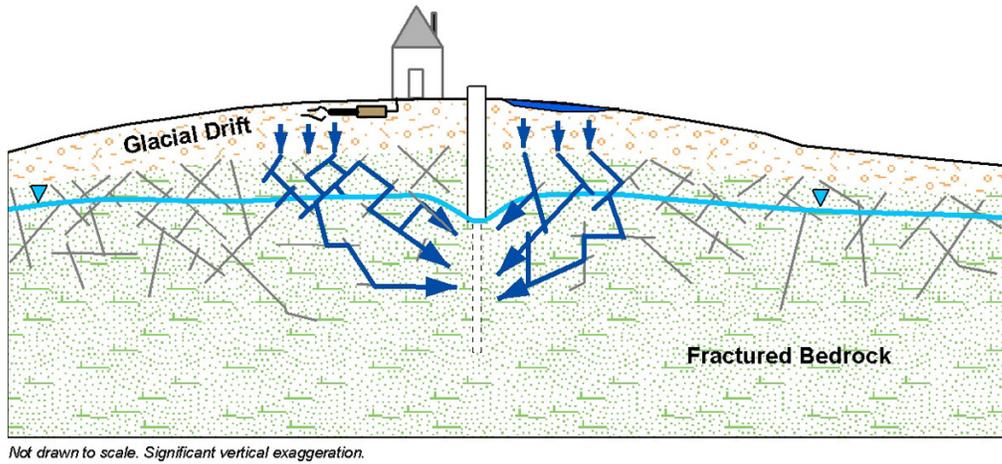


Figure 6. Schematic cross section illustrating rapid pathways in areas of thin glacial drift. The ground water table is indicated by the thick line with triangles above it.

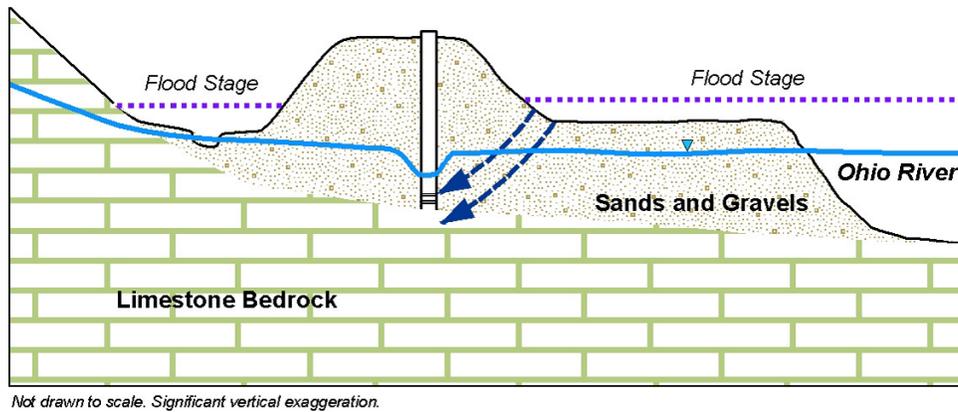


Figure 7. Schematic cross section illustrating shortened flow paths for wells in flood plains.

level can shorten the horizontal flow path and increase the pressure gradient to a pumping well, with the result of shortening recharge pathways and reducing transport time. There are also areas where fractured bedrock exposed in streams and stream banks can provide rapid recharge to bedrock aquifers, especially during flooding events. The areas of the state where horizontal components of recharge are potentially significant also need to be identified as areas of sensitive aquifers.

CONCLUSIONS AND FUTURE ACTIVITIES

This approach to identifying sensitive aquifers demonstrates a practical integration of digital geologic mapping and water quality data analysis to generate a derivative map of sensitive aquifers. The intention of this map is to help prioritize ground water protection activities. The map is certainly not a final product but rather a work in

progress. The current draft illustrates the core logic of using recharge pathways to determine sensitivity and documents the validity of the approach based on water quality impacts. Refinements of this map will include:

- Assignment of glacial drift thickness to PWS wells for more precise analysis of water quality impact and drift thickness;
- Incorporation of well depth and casing length into the analysis;
- Evaluation of differences in aquifer sensitivity between dissolved components and particulate components such as pathogens;
- Completion of analysis of variability of aquifer sensitivity as related to increased concentration or more persistent occurrences of anthropogenic contaminants; and
- Identification of areas where horizontal flow paths are significant.

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