

DRASTIC Hydrogeologic Settings Modified for Fractured Till: Part 1. Theory¹

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ABSTRACT. The ground water vulnerability assessment model, DRASTIC, has been modified to better evaluate the effect of fractured till. In the mid-1980s, the Ohio Department of Natural Resources (ODNR) Division of Water began statewide, county-by-county mapping of the potential for ground water pollution. Eventually it was recognized that the original DRASTIC methodology needed to be modified to incorporate the concept of double-block porosity and preferential flow through Ohio's fractured glacial tills. Glacial till was eventually recognized as a unique vadose zone media, and different ratings were assigned to the various till lithologies. It was determined that thin, weathered, highly-fractured tills should be more highly rated by increasing the rating of "R" Net Recharge and "I" Impact of the vadose zone media, where appropriate. In rare instances, the ratings of very thin soils ("S" Soil media) were modified to reflect the nature of underlying parent materials. In contrast, extremely thick sequences of unweathered till were given lower ratings for "R" Net Recharge and "I" Impact of the vadose zone media. DRASTIC maps have been completed for 76% of the 88 counties in Ohio. With the advent of Geographic Information Systems (GIS) applications, compiling a county DRASTIC map has become faster, and publication costs have been significantly reduced. GIS provides the tools to review and quickly modify historical mapping efforts that predate the fracture modification. This paper reviews the history of DRASTIC mapping in Ohio, presents the theory of modifications for fractures, and includes some discussion of Ohio regulatory applications.

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INTRODUCTION

A Short History of DRASTIC

In the mid-1980s, the Ohio Department of Natural Resources (ODNR) Division of Water began statewide, county-by-county mapping of the potential for ground water pollution. This effort was to complement the pre-existing county-scale (1:62,500) Ground Water Resources mapping program also generated by ODNR's Division of Water. During this time period several systems to assess ground water pollution potential were being developed. The focus of most of the systems was specific pollution sources. For example, the LeGrand System (LeGrand 1983) was used to evaluate ground water pollution potential from a given waste disposal site. A modification of the LeGrand System by the United States Environmental Protection Agency (US EPA 1983) was used to evaluate ground-water vulnerability from liquid waste ponds as part of the US EPA Surface Impoundment Assessment. Gibb and others (1983) developed a rating scheme, used primarily in Illinois, for establishing priorities for the threat to human health via ground water from existing waste disposal sites. The Michigan Department of Natural Resources (1983) developed a system to rank risk of environmental contamination. New Jersey utilized a rating system by Hutchinson and Hoffman (1983) to prioritize ground-water pollution sites.

During this same time period, the US EPA funded a project that was produced by the National Ground Water Association (NGWA), which would become known

as DRASTIC. DRASTIC used the concepts of LeGrand and had the input of five separate offices of the US EPA and numerous experts in the field of hydrogeology. It was a system designed to utilize existing available information to generate a ranking as well as a mapping system. First published in 1985 as a preliminary system and finalized in 1987 (Aller and others 1987), this system used seven parameters to assess ground-water vulnerability. The seven parameters form the acronym DRASTIC.

With the publication of DRASTIC, the first widely used system using the concept of hydrogeologic settings and an associated rating and ranking system was now available for use. Training programs and seminars were offered across the United States as individuals were trained to evaluate the seven parameters and perform mapping functions. DRASTIC began to be utilized by many state agencies including Virginia, Florida, Nebraska, Texas, and Ohio. DRASTIC was used as part of a nationwide project to evaluate vulnerability to pesticides. DRASTIC also would be used in other countries, including Sweden, South Africa, India, and Australia. The history of the DRASTIC program in Ohio is the subject of this paper, the first of a series of two papers addressing the topic of "DRASTIC Hydrogeologic Settings Modified for Fractured Till". The second paper, written by Weatherington-Rice and others (2006b), follows in this Special Issue of *The Ohio Journal of Science*.

History of DRASTIC Mapping in Ohio

The Ohio Department of Natural Resources (ODNR) Division of Water chose to produce maps of the vulnerability of ground water on a county-by-county basis as had been designed and tested in the original DRASTIC

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methodology. The ODNR program became known as the "Ground Water Pollution Potential Mapping Program" (GWPP). The first map produced in Ohio was for Madison County and was authored by Mike Hallfrisch and John Voytek in 1987.

As of November 2005, 67 of the 88 counties in Ohio (76%) have been mapped using the DRASTIC methodology (Fig. 1). These Ground Water Pollution Potential maps have been developed by seven different initiating authors, including ODNR, several Ohio universities, and two private consulting firms (Weatherington-Rice 2003). Different initiating authors were used in an effort to make the information available to the public as expediently and cost-effectively as possible. Even though there were many initiating authors, ODNR's Division of Water performed the final edits prior to publication.

Due primarily to funding limitations, the maps were not necessarily published in chronological order of their completion. In some cases, as many as ten years or more passed between completion of a DRASTIC county mapping project and its publication date. In other cases, completion and publication took place the same year.

While the mapping projects were being undertaken at a variety of locations, ODNR's publication funds only allowed a limited number of counties to be published each year. Some counties were published immediately upon completion because local funding sources were available. County planning commissions and local Solid Waste Districts were the most common sources of this local funding. Later funding became available from US EPA as a pass-through allocation of Clean Water Act Section 319 (non-point source) money through Ohio

EPA, but with the change in funding sources, a list of counties with top priorities for completion and publication was developed. Not all "older" projects were published before the new prioritization process began.

From 1997 to 2000, ODNR took a hiatus from GWPP mapping to undertake and complete the State Aquifer Mapping Project, producing the Glacial State Aquifer Map and Bedrock State Aquifer Map. These became important data sources for future GWPP mapping, and these products also introduced Geographic Information System (GIS) technology to ODNR. In 2000, ODNR began producing GWPP maps as ArcInfo shape files. The ArcInfo shape file is available for those interested in the raw data and can be obtained via the ODNR-FTP site or from ODNR's Division of Water. A printout of the county map resembling the traditional printed map is produced at the scale of 1:62,500 as an Arc GIS template. The templates are converted to a PDF format and made available at the Division of Water website. A copy of the report resembling the traditional report is also attached to the map as a PDF file that can be downloaded. Approximately 25 county GWPP maps have been completed using the GIS technology. Hard copies of the report and map based on these PDF files can be ordered from ODNR for those interested. A number of older, classically produced DRASTIC maps have been digitized and are available as ArcInfo shape files for those interested in viewing the data itself. Printed copies of these reports and maps can still be ordered through ODNR's website. Madison County, the first county completed, has been recompiled and republished as No. 1R, the new version encompassing all of the new mapping concepts developed by ODNR Division of Water, since the original DRASTIC mapping effort began (Angle and Barrett 2005).

Funding sources remain a combination of Section 319 non-point source grants and Source Water Protection monies. This concept of publication on demand has reduced the overhead costs involved in carrying an inventory of publications and has stepped up the release of both historic and new mapping efforts. The current and ever-changing status of DRASTIC mapping in Ohio can be viewed on one of the ODNR Division of Water's web pages, <http://www.dnr.state.oh.us/water/gwppmaps/>. Specific county sites with modifications are discussed in detail in Weatherington-Rice and others (2006b).

MATERIALS AND METHODS

Making DRASTIC Maps in Ohio

Creation of a DRASTIC Ground Water Pollution Potential Map requires that information be gathered and compiled for seven hydrogeologic, geologic, and soils parameters. DRASTIC is an acronym for seven parameters used to assess vulnerability of ground water to a water-soluble pollutant introduced at the surface of the ground including: "D" Depth to water, "R" Net Recharge, "A" Aquifer media, "S" Soil media, "T" Topography, "I" Impact of the vadose zone media, and "C" hydraulic Conductivity. DRASTIC uses the hydrogeologic setting concept as a basis for mapping, and a weighting and

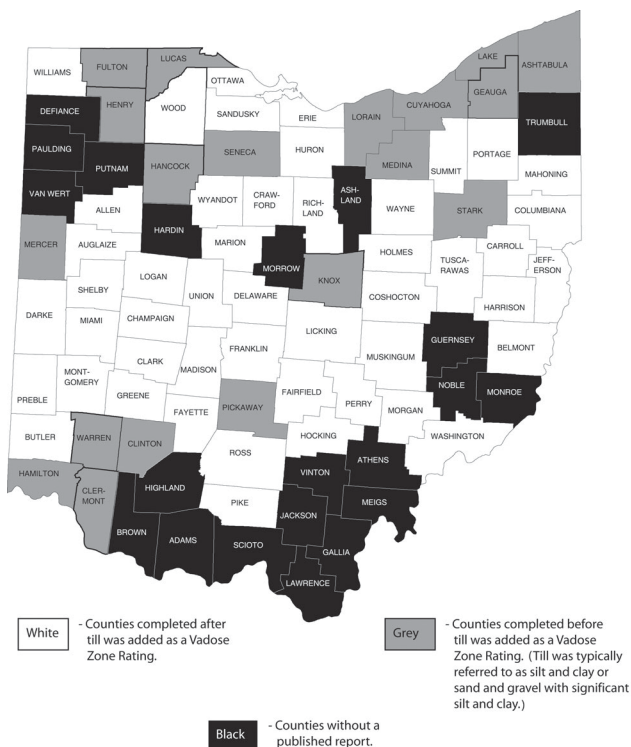


FIGURE 1. Status of Ground Water Pollution Potential mapping in Ohio as of November 2005.

ranking system to generate a relative vulnerability number. The vulnerability number is then frequently color-coded for ease of visualization.

One of the early precepts of DRASTIC was that it would utilize existing data sources (Aller and others 1987). In Ohio, depth to water is obtained primarily from water well log records, USGS data, and miscellaneous potentiometric surface maps. Recharge is based on statewide studies such as Pettyjohn and Henning (1979), Dumouchelle and Schiefer (2002), and localized data where available. Aquifer media is based on ODNR's Division of Water and the ODNR Division of Geological Survey (DGS) data; especially the Bedrock State Aquifer Map and Glacial State Aquifer Map, USGS reports, water well log records, and miscellaneous studies. Soil media is derived from county soil surveys. Topography (% slope) is derived from USGS topographic maps and the soil surveys. Impact of the vadose zone media is inferred from ODNR's DGS and Division of Water reports, especially Bedrock Topography and Glacial State Aquifer Maps, and well log records. Hydraulic conductivity data are from site-specific reports and are inferred from aquifer characteristics.

The advent of GIS technology has had a profound influence on GWPP mapping. The availability of digital data including ODNR Division of Water's Glacial State Aquifer Map and Bedrock State Aquifer Map and DGS's Bedrock Reconnaissance, Bedrock Topography, and Glacial surficial geology ("stack maps") have greatly increased the accuracy and speed of producing of GWPP maps.

DRASTIC Modification in Ohio

During the creation of the original DRASTIC methodology, the variability of the properties of soil and rock that affect pollution potential was discussed extensively by the thirty-seven member advisory committee. The final methodology addressed transport through fractured fine-grained soils by allowing the user to choose a category of "Shrinking and/or Aggregated Clay" in order to assign a higher number to account for the fractures. However, this category was only selected for soils listed as having high shrink-swell potential in the county soil survey. (In DRASTIC, higher numbers indicate greater pollution potential.) The original methodology did not account for fractures other than by assigning this one category. At that time, the concept of fractured till was in the infancy of understanding, but was illustrated by the "unexpected" movement of contaminants from a solid waste landfill in Wilsonville, IL, where the tills were previously thought to be "protective" (Follmer 1984).

Even though the concept of fractured glacial till was not widely understood, the influence of fractures on the movement of contaminants in the vadose zone could be valued by varying the rating of a silt/clay medium from a rating of 2 to a rating of 6 (on a scale of 1 to 10). Again, this adjustment began to acknowledge that fracturing was an important mechanism for movement of contaminants, even when contaminants did not move readily through the till matrix.

As the GWPP mapping process in Ohio progressed, the understanding of movement through fractures in glacial till began to be researched and defined. ODNR personnel kept abreast of the research on fractured tills and participated actively in some aspects of the research. By 1995, ODNR personnel had significant experience with the DRASTIC methodology and had modified the conceptual model for bedrock aquifers in parts of Ohio in order to incorporate the concept that fractures caused leakage in media previously thought to be "aquicludes." Aquicludes, by definition, retard water movement to lower, more permeable aquifers. Similarly, ODNR determined that true confining conditions are rare in Ohio geology, and that units tend to be semi-confined or "leaky."

It was only a natural progression to begin to apply the same scientific principles to movement through fractures in glacial materials. The concept of "double porosity" recognizes both primary porosity (flow through the glacial till matrix of silt and/or clay) and secondary porosity (flow through fractures, worm holes, root holes, and along preferential pathways such as varves or other depositional features). "Double porosity" is synonymous to "double-block porosity"; a term more commonly found in the European literature discussing fractured bedrock and fractured tills. The term is used to describe the two, or more, levels of porosity found in a rock (lithified) or fine-grained unlithified formation such as a glacial till or lacustrine deposit. The concept of double-block porosity recognizes that the contribution of flow along preferential flow pathways, such as fractures, may be significantly greater in rate and volume than flow thorough the primary matrix. Double-block porosity is the term of choice because it is more descriptive of the physical conditions being considered.

ODNR's Division of Water recognized the need to modify the original DRASTIC methodology in order to incorporate the concept of double-block porosity and preferential flow through the fractured glacial tills. The modification was first applied to counties mapped during 1995. As mentioned in the previous section, maps were not always printed upon completion. Therefore, maps and reports published after the modification to the DRASTIC process in 1995 may have actually been compiled before that date and so may not be representative of the most current thinking at ODNR. The various changes in GWPP map production over time are illustrated on Figure 1.

RESULTS AND DISCUSSION

Modifying the Application of DRASTIC

The application of the concept of "double-block porosity" to fractured bedrock aquitards was first incorporated in the Stark County GWPP map (Williams 1991). The highly fractured Pennsylvanian sandstone units were assigned higher vadose zone media ratings, where appropriate, to account for this concept. The recognition of double-block porosity in the glacial settings of Ohio came later.

The ODNR's Division of Water was an early member

of the Ohio Fracture Flow Working Group. The Ohio Fracture Flow Working Group, an ad-hoc group functioning under the umbrella of the Ohio Academy of Science, first formed in 1993. It consists of geologists, hydrogeologists, soil scientists, engineers, planners, legal experts, and other interested researchers representing the Federal and statewide Ohio agencies that address ground-water issues in Ohio. University departments, private sector consulting firms, conservation and professional organizations, both within and outside of Ohio, are also represented in the group. ODNR staff members were present at the first gathering in March 1993 (Weatherington-Rice and others 2000). By 1995, the county scale Ground Water Pollution Potential map settings were being modified to acknowledge the hydrogeologic impact of fractures in Ohio's finer-grained glacial materials.

The decision to make modifications in the ranking component of DRASTIC, to better account for fracturing and weathering in glacial settings, was made based on years of professional experience by the scientists who staffed the mapping effort. These modifications were not arbitrary decisions, but rather were reflections of the field experiences of those scientists involved in the actual field mapping and reconnaissance in the counties where projects were underway. While the issue of fracturing in fine-grained glacial materials had been considered in the original DRASTIC design process because of the experience of Keros Cartwright at the Wilsonville, IL, Superfund site (Aller and others 1987), the developing research data in Ohio and internationally showed that a modification of the application of DRASTIC ratings was needed.

The effort to include the fractured components of glacial till and lacustrine materials was developed by ODNR scientists over time. Till was recognized as a vadose zone media in early reports such as Pickaway County (Sugar 1990) but was referred to as sand and gravel with significant silt and clay. An important step occurred when till was recognized as a unique vadose zone media during initial field work for the mapping of Franklin County (Angle 1995a) and Licking County (Angle 1995b) during 1990. Different ratings for till were assigned to the various till lithologies in Portage County (Angle 1991). These till lithologies varied primarily due to the primary porosity of the different till units such as the sandy Kent Till and the clayey Hiram Till. Till was also evaluated as a vadose zone media for Butler County (ODNR and University of Cincinnati 1991) and Sandusky County (Angle 1990) based upon the variable settings found in these counties.

The impact of weathering in till was noted for Columbiana County (Angle 1994), Franklin County (Angle 1995a), and Licking County (Angle 1995b). It was determined that thin, weathered, *highly fractured* tills should be more highly rated. This modification to the system was achieved by increasing the rating of "R" Net Recharge and "I" the Impact of the vadose zone media, where appropriate. In rare instances, the ratings of very thin soils ("S" Soil media) were modified to reflect the nature of underlying parent materials. In con-

trast, extremely thick sequences of unweathered till were given lower ratings for "R" Net Recharge and "I" impact of the vadose zone media. It is important to note that although these areas had low ratings due to the semi-confined nature of the underlying aquifers; the ratings were still significantly higher than if the aquifers had been evaluated as being truly confined. A summary of these evaluations for each county can be found in Weatherington-Rice (2003).

In addition, Tornes and others (2000) provided a list of 95 soils that were identified as being fractured. Table 1 from that publication allows both the ODNR scientist compiling a DRASTIC map and the independent researcher to note soils that are likely to be fractured. As more soils are identified as fractured, this table should be expanded. Furthermore, it is important to check this expanding list of soils in the counties where no fractures had been identified by the soil surveys. As discussed in Tornes and others (2000), the absence of notations of fractures in the "C" horizons in the county level soil surveys does not mean that fractures were not present. After eleven years of research, it is the position of the Ohio Fracture Flow Working Group to assume fractures exist in identified fractured soils unless site-specific conditions prevent them from forming.

The issue of fragipan formation in soils of the low-lime tills of northeast Ohio required additional observation relating to water movement. A number of the 95 soils identified in Tornes and others (2000) have fragipans in the "B" horizon. Preliminary observations indicate that vertical water movement through these cemented soils is through the fractures in the pan. An Ohio Fracture Flow Working Group research project to better identify this process is currently underway with leadership by Frank Calhoun, Tom Zimmerman, and James Bauder (Weatherington-Rice and others 2006a). A paper summarizing their findings is anticipated for publication in a later special issue of *The Ohio Journal of Science*.

Regulatory Use of DRASTIC in Ohio

Although the current county-based Ground Water Pollution Potential mapping program is funded primarily by the Clean Water Act Section 319 grants administered by Ohio EPA, there is currently only one Ohio/US EPA program in Ohio that statutorily requires input from the DRASTIC mapping effort. That program is Ohio EPA's Voluntary Action Program or "VAP." Under this program, industries that choose to voluntarily remediate contamination on their property perform the remediation and can apply to obtain a covenant not-to-sue with Ohio EPA or with Ohio EPA and US EPA (depending upon the process). Certified professional geologists, hydrogeologists, and engineers who have been approved by Ohio EPA, undertake the investigations and clean-ups. Contaminated facilities located in areas with limited potential for the use of ground water, such as urban settings, may be able to limit the extent of site remediation if it is determined that there are no potable users of the ground water. In this situation, under VAP rules, it is determined that the current contaminated

status does not present a risk to the community where the facility resides. DRASTIC maps are important sources of information that are consulted when Ohio EPA approves an "Urban Setting" designation.

While the Ohio EPA does not require the use of GWPP maps or the DRASTIC process for Source Water Protection (SWAP) delineations, these maps have been widely used in this process as well. The maps help provide insight as to the degree of vulnerability and, therefore, the amount of protection that various sites may require.

With the transfer of Confined Animal Feeding Operations (CAFO)s from Ohio EPA to the Ohio Department of Agriculture's (ODA) Livestock Environmental Permitting Program the review of county DRASTIC maps are required, where available, as part of the siting and construction criteria for liquid manure animal waste pits. As currently created however, DRASTIC maps are not able to fully predict the potential for ground-water contamination from this practice. There are several modifications that need to be made to the individual DRASTIC score of a specific site for this application. DRASTIC was designed to record conditions at the earth's surface for a contaminant applied to the ground surface, moving with water. Manure storage ponds and lagoons are usually constructed by evacuation. Therefore, the DRASTIC number must be recalculated by removing the protection of the overlying soil, lowering the vadose zone by the depth of the lagoon, and flattening the topographic slope to zero. These three modifications will raise the effective DRASTIC number to more realistically reflect the actual conditions in an intermittently saturated and dry holding pond. However, DRASTIC was not designed to measure the impacts of a continually saturated setting, so common in today's CAFO settings, so the long-term impact of a continually filled lagoon cannot be determined by the DRASTIC methodology alone. Even modified, the DRASTIC rating numbers will most probably underestimate the potential for ground-water contamination.

Summary and Conclusions

Ohio's Ground Water Pollution Potential mapping program offers quickly accessible, defendable, preliminary evaluations of the potential for ground-water contamination. These DRASTIC maps provide a valuable screening tool for land uses that present a potential for surface or near-surface sources to contaminate ground water. DRASTIC maps can also be a useful tool when considering locations for land application of sewage sludge or animal manures. The original DRASTIC methodology included a separate ranking process that predicted pesticide pollution potential. In the early 1990s, Ohio completed and published Pesticide-DRASTIC evaluations for four counties. Pesticide DRASTIC evaluations are automatically included in the attribute tables of the ArcInfo, GIS-based GWPP maps. Another rural use of DRASTIC and GWPP maps is to help determine areas that are suitable for on-site septic systems. With modification, the data collected by the DRASTIC mapping method can be reviewed to understand the potential threat for subsurface land uses as

well, such as the installation of underground storage tanks or landfills.

GWPP maps have been completed for 76% of the 88 counties in Ohio. Because land-use activities in all counties have the potential for ground water pollution, all of Ohio needs to be mapped. Historically, this effort has been a slow process. However, with the advent of Geographic Information Systems (GIS) applications, compiling a county DRASTIC map has become faster, and publication costs have been significantly reduced.

GIS also provides the tools to review and quickly modify historical mapping efforts that predate the fracture modification developed in 1995. Once the seven layers of the DRASTIC overlays are digitized, it is relatively easy to reassign a value to specific polygons which, when reassembled with the other layers, creates a new numbering system for each polygon. The new numbers will more closely reflect current understanding of ground-water recharge and associated contaminant transport. This GIS application makes it possible to continually upgrade the county-level DRASTIC maps as new information is obtained from site-specific research efforts at various locations and/or as the science grows and scientists are better able to understand more of the limitations to ground-water protection.

DRASTIC maps have applications other than in statewide programs. Counties across Ohio are incorporating Ground Water Pollution Potential maps into countywide or local ground-water protection programs or zoning codes. Maps completed for the counties within the Great Miami River Buried Valley Aquifer have long been referred to as part of the regional ground-water protection programs within the basin. New efforts in Williams County will tie the newly completed Williams County Ground Water Pollution Potential Map to the city of Bryan's Source Water Protection effort and the greater interest in establishing a Sole Source Aquifer designation for the region. Specific DRASTIC modifications are discussed in Weatherington-Rice and others (2006b). A broader discussion of the potential use of DRASTIC for regulatory applications can be found in Weatherington-Rice and others (2006c).

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