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METHODOLOGY FOR
MAPPING GROUND-WATER RECHARGE AREAS
IN DELAWARE'S COASTAL PLAIN

by

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INTRODUCTION

Purpose and Scope
This one-year project, funded by a U. S. Environmental Protection Agency (USEPA) grant administered by the Delaware Department of Natural Resources and Environmental Control (DNREC), began in May 1990. The purpose was to test procedures for delineating ground-water recharge areas, with the expectation that recharge areas may be subject to land-use controls to safeguard areas for future water-supply development. The pilot study was conducted in the area covered by the Fairmount and Frankford 7.5-minute topographic maps (Fig. 1). This area was agreed upon by representatives of the DNREC and Delaware Geological Survey (DGS) because it is part of the Delaware Inland Bays National Estuary Program study area and because a large amount of geologic and hydrologic data had been collected and published (Andres, 1986, 1987a, 1987b, 1991a, 1991b; Denver, 1989; Talley, 1987, 1988; Talley and Andres, 1987; Ramsey and Schenck, 1990).

This report documents the development of a methodology for mapping ground-water recharge areas in Delaware's Coastal Plain. It is anticipated that the methodology presented herein will evolve as it is applied to other areas in the State and as computerized geographic information systems become more widely available. This report deals with methodology; the recharge area maps generated in the course of the research are available for review at the DGS.

Previous and Current Work
Following are summaries of selected ground-water recharge mapping projects that have been completed or are currently underway.

New Castle County, Delaware (NCC) has designated Water Resource Protection Areas (WRANCC, 1987) based on work done by the DGS (Petty, Miller, and Lanan, 1983, 1985). This work is currently being revised for the southern NCC area by the Delaware Geological Survey.

USEPA (1987) documents similar work that has been completed in some small areas. It is documented in USEPA (1987) under "Hydrogeologic Mapping Methods."

The New Jersey Geological Survey (NJ) was directed by statute to develop methods to map ground-water recharge areas. The methodology being developed is based on water-budget analysis. The water-budget includes terms for soils infiltration potential (from digitized county soil survey maps), potential overland runoff (from a U.S. Soil Conservation Service model), and potential evapotranspiration (Emmanuel G. Charles, pers. comm.).

The Illinois State Geological Survey (IL) was directed by statute to develop methods to map ground-water recharge areas and to map such areas throughout the State. A map showing potential for ground-water recharge was constructed using geologic, soils (infiltration potential), and aquifer maps (Keefer and Berg, 1990).

The St. Johns River Water Management District, Florida (SJR) has published maps of ground-water recharge potential that were derived from head differences between the water-table and confined aquifers, confining layer permeability, and soils infiltration potential (Bonio et al., 1990).

A Kansas Geological Survey and U.S. Geological Survey joint-program in the Rattlesnake River basin uses a detailed water-budget to map ground-water recharge areas. The budget accounts for crop type and irrigation method in addition to more standard climatic and soils factors (Sophocles and McAllister, 1990).

Discussions were held with the principal investigators of the DGS-NCC, NJ, IL, and SJR projects. The common theme in all these discussions was that the methodology must be tailored to the geologic and hydrogeologic conditions of the areas to be mapped.
Figure 1. Location of area of investigation.
EVALUATION OF RECHARGE AREA MAPPING METHODS

In developing a methodology to map or rate the hydraulic properties of ground-water recharge areas, it should be recognized that in most drainage basins 70 to 95 percent of land area can be considered recharge area as determined by flow-net analysis (Freeze and Cherry, 1979). Given the difficulties in enacting and managing land-use regulations, it would not be practical to manage 75 to 90 percent of the land. Rather, it would be more useful to identify the best recharge areas for some degree of protection.

The different methods for mapping and rating recharge areas that were evaluated for possible application in Delaware are described as follows.

Water Budget

The water-budget method uses the water-budget equation:

\[ R = PPT - ET - Ro - S \]

where:

- \( R \) = ground-water recharge (\( l^1 \), \( l \) = length)
- \( PPT \) = precipitation (\( l^1 \))
- \( Ro \) = overland runoff (\( l^1 \))
- \( ET \) = evapotranspiration (\( l^1 \))
- \( S \) = storage (in the unsaturated zone, \( l^1 \))

to solve for \( R \) on an area by area basis. A variety of methods can be used to estimate each component of this equation. The estimation methods can be simple steady-state empirical as applied in New Jersey or complex numerical time-dependent models used in Kansas. There often is great uncertainty in the estimates because of approximations and assumptions inherent in the models or because of a lack of reliable input data. A sophisticated geographic information system is required to manage the results of the model as well as to keep track of areal differences in the components of the equation.

To investigate the applicability of the water-budget method to mapping recharge areas in Delaware, a simple water-budget model was made for the study area. The climatic water-budget described by Mather (1978) was used to estimate water surplus or \( R \) for a variety of soil and plant cover types. Soils data are from Ireland and Matthews (1974). Plant cover was determined from aerial photographs and knowledge of the crops and natural plants typical of the area. Monthly temperature and precipitation data are from National Oceanic and Atmospheric Administration (1982). Given even the most drastic differences in soil moisture capacity and cover types there is about a 10 percent difference in the estimated \( R \) between the highest and the lowest soils and cover types using this method. Considering the assumptions used in the model, a 10 percent difference is not large enough to be a useful discriminatory tool. There also is a problem with the overland runoff component of the water budget. In the study area, rapid lateral variability in soil type and small slopes are typical (Ireland and Matthews, 1974). This presents a practical problem with devising a method to route runoff from one area to another for a relatively large map area. Further, using hydrograph separation techniques, Johnston (1976) found that overland runoff is a relatively small part of the water budget in the Coastal Plain of Delaware, comprising less than 20 percent of the water budget. For these reasons ranking recharge areas based on a water-budget model does not appear to be a useful method for Delaware's Coastal Plain.

Water-budget analysis is being used in New Jersey and Kansas. The method works well in the New Jersey Piedmont and Highlands physiographic provinces where soils are potentially much less permeable and
the overland runoff component of the water budget is more significant than in the Coastal Plain of Delaware. The method works well in Kansas where precipitation is roughly one-third that in Delaware and evapotranspiration is a much larger component of the water budget. As used in New Jersey and Kansas, this method is heavily dependent on geographic information system (GIS) technology. A GIS was not available for this study.

**Soils Infiltration Potential**

The U. S. Department of Agriculture soil surveys could be used to rate the infiltration potential of materials between 0 and approximately 5 feet below land surface. Soils infiltration potential could be a useful screening tool, but has several drawbacks. Where the water table occurs within 5 feet of land surface this method would rate the ease with which water could move to the water table, but in many areas the water table occurs below five feet. Further, the upper five feet is generally less than five percent of the thickness of the aquifer. In some areas the upper 5 feet might have excellent recharge capability, but if a thicker layer was evaluated the area could be considered a poor recharge area because of low permeability materials below the mapped horizon.

Soils infiltration potential is one of the criteria used to rate recharge potential in Illinois, New Jersey, Kansas, and Florida. It is a primary rating factor in New Jersey and Kansas but not in Florida or Illinois.

**Flow-Net Analysis**

Flow-net analysis depicts ground-water flow in the vertical plane and allows for visual differentiation between areas where the net flow is downward (recharge area) and areas where the net flow is upward (discharge area). Flow-net analyses done for this project of a number of cross-sections in the study area show that more than 75 percent of the study area would be a recharge area if this were the sole criterion for recharge mapping.

The St. Johns River Water Management District used a form of flow-net analysis as a criterion for determining aquifer recharge areas. In the St. Johns River basin, however, the aquifer being recharged is a confined aquifer, and therefore the direction of ground-water flow is critical to determining ground-water recharge potential.

**Stack-Unit Mapping**

Stack-unit mapping, a form of three-dimensional geologic mapping, was developed by the Illinois Geological Survey (Kempton, 1981). Stack-unit mapping is a means by which the geologic units occurring in a specified interval below land surface are depicted on a map. Stack-unit maps also show the spatial relations between geologic units. Stack-unit maps have had application to a variety of problems in Illinois such as susceptibility to contamination by waste-disposal practices, land-use planning, evaluation of construction conditions, and development of mineral and water resources (Berg et al., 1984; Kempton and Cartwright, 1984). A study to evaluate ground-water recharge areas has been completed (Keefer and Berg, 1990). Stack-unit mapping was a primary rating factor.

**METHOD SELECTION**

Ground-water recharge areas are components in a hydrologic system that includes aquifers and ground water, as well as bodies of surface water. A method to map and rate ground-water recharge areas should be able to differentiate recharge areas on their abilities to contribute water to the aquifer and also provide a means to identify an area's potential impact on adjacent components in the hydrologic system as well as the aquifer.

In the study area, the primary ground-water resource is the near-surface Columbia aquifer, a relatively thick (75 feet or more) and permeable hydrologic unit. On a regional scale, the Columbia aquifer is an unconfined aquifer. On a local scale, it may be confined or be stratified into unconfined and confined sections. Water-table depth is variable but almost always occurs within 20 feet of land surface.

The Columbia aquifer is an important multi-purpose resource. Almost all water entering Delaware's ground water must first pass through the Columbia aquifer. It serves as the source of stream baseflow and is the main source of water for potable, agricultural, and irrigation purposes. The depth range 20 to 75 feet below land surface is the part of the aquifer most often used for drinking water and agricultural supply wells.
Many individual, community, and industrial waste water disposal systems also discharge into the aquifer.

Ground-water flow is a three-dimensional process, and thus, evaluation of recharge potential should depict the three-dimensional distribution of geologic units. Given that the hydraulic properties of rocks can be systematically related to their geological properties, I believe that stack-unit mapping can be a powerful tool in the evaluation and delineation of recharge areas.

**METHOD DEVELOPMENT**

**Application of Stack-Unit Mapping to Recharge Area Mapping in Delaware**

Results of this project show that stack-unit mapping can be adapted to map and rate recharge areas in the Coastal Plain of Delaware. In this study, the stack-unit mapping method is used to categorize and show the areal distribution of three-dimensional units having specified hydrologic characteristics. The resulting maps are to be used along with maps of recharge and discharge areas determined by flow-net analysis.

To determine the best means for applying the stack-unit mapping technique to delineating and rating recharge areas, a variety of combinations of layer thickness, number of layers, numbers and types of lithologic and map units, and recharge rating categories were tested. The mapping criteria chosen (Fig. 2 and tables 1 and 2) included three material thickness categories, three lithologic types, and four recharge categories. Because the hydrogeology of the study area does not differ greatly from the rest of the Coastal Plain, it is likely that the methods determined by this work should be applicable to all of Delaware's Coastal Plain.

Tables 1 and 2 show the lithologic and recharge rating categories. The lithologic categories were based on the expected permeabilities of the rock types found in the area and were derived from interpretations of the geology of the area (i.e., depositional environment, common associations of lithologies, and models of three-dimensional distribution of lithologic units). Tables and graphs of permeability ranges for different rock, sediment, and soil types may be found in most ground-water and soils textbooks. In general, the more coarse-grained and uniform the rock, the higher the recharge rating. The problems associated with rating agricultural soils are discussed in the section "Effects of Agricultural Soil Horizons on Ratings."

The map depicting recharge potential represents a layer extending from land surface to 20 feet below land surface. This layer is named the recharge layer. It is important to note that a map of the recharge layer would be sufficient for evaluating recharge potential in most areas of Delaware. This layer thickness and name were chosen because:

1. Almost all water that recharges the ground water moves through this layer.
2. This interval almost always contains the water table, and therefore, ground-water recharge occurs in this layer.
3. This thickness is great enough to filter some local-scale heterogeneity and allow for correlation, but not so large as to filter out sub-regional heterogeneity or local trends. This factor is discussed in more detail in a following section.

The criteria for determining recharge potential units (0 to 20 foot layer) focus on the ability of the rocks to transmit water vertically through the unsaturated zone to the water table. Note that only the most uniformly coarse-grained categories (20S and 20S(I)) are included in the excellent rating for the recharge layer. In effect, this rating scheme limits the amount of land area that could be rated as excellent. An example of a recharge map is shown in Figure 3.

In order to determine the effectiveness of stack-unit mapping to resource evaluation, a second layer extending from 20 to 60 feet below land surface was mapped. This layer is named the resource layer because many water supply wells in this area obtain water from this section. Resource layer mapping provides valuable data in that it also can be also be used to show the relationship between the recharge layer and the remainder of the underlying aquifer. It was not, however, included in the original scope of work for this project. As mentioned previously, the map of the recharge layer is sufficient for evaluating recharge potential.

The thickness of the resource layer was chosen so that a significant portion of the aquifer could be rated. In addition, the thickness of the resource layer reflects the amount of available data. The criterion for
Figure 2. Lithologic and recharge rating example.
Table 1. Definitions of lithologic rating symbols. An illustrative example is shown in Figure 2. Additional details regarding material classification should be consulted and are contained in the Appendix.

**LITHOLOGIC RATING UNITS**

**Lithologic Category Symbols**

- **S** = Sand with trace (0 to 10%) of silt or clay and coarser, including: gravel, sandy silty; sand, gravelly silty*; and gravel, silty*
- **L** = Silty sand - sand with 10% to 35% silt
- **M** = Mud - all finer than silty sand.

* When stratified into sorted layers; when unstratified then L.

**Thickness Category Symbols**

- 0 to < 5 ft = (lower case)*
- 5 to 10 ft = 10
- 11 to 20 ft = 20
- 21 to 30 ft = 30
- 31 to 40 ft = 40

* Lithologies with a total thickness of less than 1 ft may be combined with another lithologic category.

Table 2. Definition of recharge and resource rating symbols.

**RECHARGE AND RESOURCE RATING UNITS**

**0 to 20 ft Interval**

**Recharge Layer**

- **EXCELLENT** (E)
  - 20S / 20S(I)
- **GOOD** (G and G(e))
  - 20S 10L (+m) / 10S 10L (+m) / 20L(±s) / 20S (m±)
- **FAIR** (F)
  - 20L (m ±s) / 20S 10M ±(l) / 10S 10M (+l) / 10M 10L 10S / 20L 10S 10M / 20L 10M ±(s)
- **POOR** (P)
  - 20M 10S (±l) / 10M 10L (+s) / 20M 10L (+s) / 20M (+s,l)

**EXCELLENT** (E)

- 40S / 40S(I) / 40S(±) / 40S 10L / 40S 10L(m) / 40S(±m)
- **GOOD** (G)
  - 30S 20L / 30S 20L(m) / 30S 20L(m) / 30S 10L 10M / 30S 10L(m) / 20S 20L / 20S 10L 10M / 40S 10M / 30S 10M 20S 20L(m) / 30L 20S / 30S 10L / 40L 10S / 40S 10L
- **FAIR** (F)
- **POOR** (P)
  - 20M 20L / 30M 10L 10S / 30M 10L / 30M 10L(s) / 30M 10S(l) / 40M 30M 10S / 30M 20S / 40M 10S / 30M 20L(s) 30M 20S 10L / 40M 10L
Figure 3. Example of recharge potential map. This map is provided for illustrative purposes only.
determining resource potential units (20 to 60 foot layer) is the capability of the rocks to transmit water horizontally as well as vertically. Because of the greater layer thickness and the emphasis on horizontal permeability, a small thickness of material classified as mud is allowed in the excellent rating category (table 2).

Alternatives for a resource layer include saturated thickness of the aquifer, presence of underlying aquifers, and thicknesses of their overlying confining layers. In parts of New Castle and Kent counties, where the Columbia aquifer is not as highly productive as in Sussex County, the criterion for mapping a resource layer could be the estimated transmissivity of the aquifer.

Table 3 shows the results of the rating method for the recharge and resource layers in terms of land areas. The large differences in areas characterized by rating categories, both between maps and between layers, are a result of changes in both the geology and the rating criteria. For example, on the Fairmount sheet the difference between layers in the amount of area rated excellent partly results from the fact that the relatively fine-grained Omar Formation occurs only in the uppermost 20 ft whereas the underlying Beaverdam Formation is relatively coarse-grained. Further, the excellent rating category for the resource layer includes small thicknesses of materials classified as mud.

The relation between the recharge and resource layers can be evaluated by laying one map over the other. This procedure can be used to identify the areas having the potential for transmitting the most water from land surface deep into the aquifer, such as where excellent or good recharge areas overlie excellent or good resource areas. The maps can also be used to identify areas where the aquifer is likely to be partially protected by poor or fair recharge areas from potentially polluting activities occurring on land surface. However, it is possible that pollution originating at land surface in an area rated as poor or fair could eventually affect the underlying aquifer.

Table 3. Results of recharge rating in terms of land areas.

<table>
<thead>
<tr>
<th>Recharge Category</th>
<th>Fairmount Quadrangle</th>
<th>Frankford Quadrangle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Land area (sq. mi.)</td>
<td>Percentage (land only)</td>
</tr>
<tr>
<td>0 to 20 ft layer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excellent</td>
<td>2.27</td>
<td>4.4</td>
</tr>
<tr>
<td>Good</td>
<td>20.66</td>
<td>40.4</td>
</tr>
<tr>
<td>Fair</td>
<td>22.36</td>
<td>43.7</td>
</tr>
<tr>
<td>Poor</td>
<td>5.84</td>
<td>11.4</td>
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<tr>
<td>Number of data points</td>
<td>164</td>
<td></td>
</tr>
<tr>
<td>20 to 60 ft layer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excellent</td>
<td>23.58</td>
<td>46.1</td>
</tr>
<tr>
<td>Good</td>
<td>21.78</td>
<td>42.6</td>
</tr>
<tr>
<td>Fair</td>
<td>5.17</td>
<td>10.1</td>
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<tr>
<td>Poor</td>
<td>0.60</td>
<td>1.2</td>
</tr>
<tr>
<td>Number of data points</td>
<td>138</td>
<td></td>
</tr>
</tbody>
</table>
Recharge and Resource Rating and Mapping Procedures

The first step in recharge area mapping is to collect accurate lithologic logs and location information from engineering test borings, water well completion reports, geologic test borings, and outcrop descriptions. The need for accurate lithologic logs cannot be overstated, because both inaccurate logs and an inadequate number of logs may lead to inaccurate maps. The determination of what is or is not adequate is judged on the basis of experience, and should be done by a qualified geologist after review of all available data. Experience in the pilot area shows that most water well drillers' logs are not detailed enough to be used.

The procedure for determining lithologic and recharge category ratings is illustrated on Figure 3. First, each log is evaluated by placing the lithologies described in the layer of interest into their respective lithologic categories as described in Table 1 and then adding up the thicknesses of each category. The resulting numbers are placed into thickness categories and a lithologic rating consisting of a number and a letter is assigned for each category present in the layer for that log. The recharge rating is then determined from Table 2.

Drawing the boundaries on a map requires some means of identifying the subsurface distribution of materials of similar characteristics and the locations where the materials are different. If data were available for every square foot of the area this would be a simple task. However, data points are often located thousands of feet apart, requiring that the person drawing the boundary lines have a systematic and defensible means of determining locations of boundary lines. This step is a form of geologic correlation and is the principal reason for having a qualified geologist do the mapping. Locating boundary lines is subjective, it is, however, based on analysis of all available data.

A number of tools can be used to aid correlation including paleontologic data, cross-sections, structure-contour maps, sand-percentage maps, and isopach maps. These tools enable the geologist to construct models of subsurface geology (including depositional environments, common associations of lithologies, and three-dimensional distribution of lithologic units) that can then be used to infer subsurface conditions between control points.

Recharge and Discharge Areas and Flow-Net Analysis

One of the maps produced in the recharge mapping procedure is a map of ground-water recharge and discharge areas. Recharge and discharge areas were determined by flow-net analysis. The flow nets are models of ground-water flow conditions and also are models of the relationships between ground water and surface water. Because a detailed water-level measurement network is not available for the entire study area, the flow nets are somewhat generalized. However, it is believed that the use of generalized flow nets is justified because they are based on application of basic hydrologic principles and established flow-net construction practices.

The flow nets were constructed using the cross-sections produced by the stack-unit mapping procedure. In the study area, flow-net construction was aided by having water-level data from several small drainage basins that had been equipped with numerous monitoring wells (Andres, 1991a, 1991b; unpublished data). Flow-net construction outside of these drainage basins was based on water-table elevation data from Hydrologic Atlas Series maps (Adams et al., 1964; Boggess et al., 1964), by correlation with the basins with monitoring wells, and by analogy to flow nets presented in numerous ground-water text books and journal articles. Hydrologic Atlas Series maps are available for all of Delaware's Coastal Plain. It is anticipated that site-specific water level data that will aid flow-net construction can be obtained for other areas of the State from hydrogeologic investigations done for ground-water contamination incidents.

Testing of Rating Categories

In order to relate the hydraulic properties of rocks to the different rating categories a number of single-well aquifer tests (i.e., slug tests) were completed and analyzed using the method described in Bouwer (1989). Data were collected for both rising and falling head tests using a data logger and pressure transducer system. These tests provide information about the permeability of the saturated portion of the aquifer within a few feet of the well being tested. The results are typical of the types of materials encountered in the study area. They are summarized in Figure 4. Note that there is some overlap in permeability values between the different lithologic types and that some of the tests of wells completed in materials rated as sand yield permeability values less than 50 feet per day. The values of less than 50 feet per day for materials rated as clean sand could be valid or may result from problems with the well such as small screen slot size (0.01 in or
Figure 4. Results of permeability testing. Units are feet per day. Test method of Bouwer (1989).
less) or incomplete well development, errors in logging the well, and/or lithologic variability within a few feet of the well. In any case, all the materials rated as clean sand have permeability values in the range of what can be considered aquifer material.

Effects of Agricultural Soil Horizons on Ratings

In almost all instances, lithologic logs describe the uppermost layers as soil or topsoil and engineering test boring logs describe materials that can only be the agricultural A and B soil horizons. Almost all recharge will pass through these materials, hence there should be some means of rating their hydrologic characteristics within the context of stack-unit mapping. There are several factors that affect the evaluation of potential recharge of these materials.

1. In the case of materials described only as "soil" or "topsoil," no judgement can be made on the recharge capacity of the layer and the material is excluded from the rating procedure.

2. Soil permeability is not only controlled by grain size distribution, but also by animal and root burrows, cracks, structural development, and microspatial variability (Bouwer, 1991). These features usually are not visible in samples collected during engineering test borings, and are not described in drillers' logs.

3. The B horizon often is composed of silty sand and finer-grained materials that if evaluated solely on grain-size distribution may cause the rating to be lower than it would be if the permeability of the soil were known.

4. Many drillers' logs often do not adequately describe the upper five feet of the drill hole, which is the interval that contains both the A and B horizons. For example, some silty sands that may contain a trace of clay are often described as "clay" whereas, silty sands without clay are often described as "sand."

The solution to the problem of evaluating soil permeability is not easily obtained. One possibility is to ignore the A and B horizons and consider the first material below the soil layer as the top of the recharge layer. The effect of this procedure changes the ratings of roughly one-third of the data points in the Fairmount and Frankford quadrangles for which the B-horizon could be identified. Almost all of the changes increase the recharge rating. On the Fairmount Quadrangle, 20 percent of the points changed from good to excellent. Most of these points are clustered in two areas resulting in a change in the map in those areas. The change in additional excellent area as a percentage of the map area was less than 3 percent. On the Frankford Quadrangle, only 2 points (5 percent) changed from good to excellent. Removal of the soil layer prior to evaluation has implications for the use of the maps, in that the effect of the soil layer on the rate and chemical quality of recharge is ignored. This may not be justified for activities occurring at land surface such as agriculture, spray irrigation, composting, and sludge spreading, but probably is justified for activities occurring more than one to two feet below land surface (e.g., septic systems) and where development plans call for the removal of material from land surface. In this study the recharge potential of the soil layer was determined from the lithologic description of the soil layer. However, the recharge rating category G(e) is used to display the condition where the soil layer causes the recharge rating to be good rather than excellent.

MAP USE

Scale Effects and Resource Protection

In applying stack-unit mapping methodology to recharge area mapping or any other type of mapping, the mapper and users of the map must realize that geology varies, both on regional and local scales (often over distances smaller than the distances between most data points). The problem of geologic heterogeneity affects the perceived accuracy of map units and boundary locations.

The mapping completed in this study produces maps at a scale of 1:24,000, which will be referred to as sub-regional scale. The sub-regional scale is one of the most common scales used for geologic mapping, environmental studies, and land planning purposes, in part because U.S. Geological Survey topographic maps are produced at this scale. In resource evaluation and protection applications in Delaware, sub-regional scale maps are the most useful for displaying, organizing, and evaluating data.

Sub-regional scale maps show regional and sub-regional scale heterogeneities and local scale trends
but, because of the spacing of data points, they can not depict all local-scale heterogeneities. Local-scale heterogeneity is very apparent in an outcrop where individual beds extend distances of tens to hundreds of feet. Local-scale heterogeneity is also apparent in areas with closely spaced data points, where sizes and shapes of stack or recharge units become highly variable.

It is important to note that the stack-mapping technique used in this study could also be used for larger or smaller scale mapping projects. The level of detail depicted in the resulting maps should reflect the amount of data and spacing of data points in the map area.

Challenges to Locations of Recharge Areas

Often land-use decisions must be made on local-scale projects. An anticipated problem related to map scale is one where a land developer objects to the restrictions placed on its land because the map shows all or part of the property is part of a sensitive area (e.g., excellent recharge or extremely susceptible to contamination). In New Castle County (NCC) developers have challenged the County's Resource Protection Area (RPA) maps by gathering data from their properties to refute the map. The RPA maps are sub-regional scale maps of the recharge potential of the aquifer based on evaluations of numerous lithologic logs and data from a few long-term pump tests. In some cases, interpretation of new data indicates a conflict with the RPA map designation, but on inspection of the methods used to collect the new data, the conflicts are often the result of inappropriate sampling techniques and/or laboratory methodologies. For example, at several sites samples have been collected from the unsaturated zone, from the B soil horizon and/or less than 10 feet below land surface, and tested in a laboratory permeameter or by evaluation of the sample grain-size distribution. In these cases, the sampling and testing procedures are not appropriate because the type and scale of the tests differ greatly from the type and scale of data used to generate the RPA maps. Evaluation of the properties of an aquifer should instead be developed from representative aquifer-scale tests (Freeze and Cherry, 1979).

To challenge a map, methods similar to those used to produce the map should be used. This means installing test borings, accurately and completely describing the lithology, and then evaluating the recharge potential. The design of the investigation and the final report should be completed according to prescribed methods (Appendix 1) under the supervision of a geologist or engineer qualified in hydrogeology and licensed to work in the State of Delaware. The results of an investigation are submitted to the regulatory agency for review.

The scale of investigation is an important consideration, in that during a site-specific investigation local scale heterogeneity will most likely be discovered. Methods to reasonably accommodate new data into the existing map are needed. There are several options to accommodate new data:

1. Each new data point could be used to redraw map boundaries. This will, no doubt, create a never ending cycle of redefining map boundaries to accommodate a number of areally small map units. This is not a reasonable option because the resource will not be protected if the most sensitive areas are split into smaller and smaller areas and incompatible land use occurs all around them. The issue of who redraws the map boundaries also becomes a factor.

2. Buffer zones could be defined around the most sensitive areas. In terms of resource protection, buffer zones are reasonable and defensible because activities occurring adjacent to a sensitive area frequently impact the sensitive area. This is commonly the case when dealing with water. Water does not stop flowing because of a line on a map.

3. A means to filter local scale heterogeneity from the new data can be applied. A procedure to do this is contained in the Appendix.

A combination of the second and third options should provide adequate resource protection, reduce the need to redraw map boundaries, and provide an equitable method to challenge the map.
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Talley, J. H., 1987, Geohydrology of the southern coastal area, Delaware - Sheet 1, Basic geohydrologic data: Delaware Geological Survey Hydrologic Map Series No. 7.


Water Resources Agency for New Castle County (WRANCC), 1987, Water Resource Protection Areas: WRANCC, 3 sheets, scale 1:24,000.
The following American Society for Testing and Materials (ASTM) methods are listed as being acceptable for ground-water recharge mapping. Alternative methods may be acceptable but are not listed below. If alternative methods are to be employed, they should be approved before commencement of the project.

Test Boring and Logging Methods

Test borings should be completed according to ASTM D1452 to a depth of at least 25 feet. This allows for the soil horizon, down to the top of the "C" horizon, to be removed from the determination of the recharge potential rating. Removal of the soil layer from the recharge potential rating is a reasonable procedure because soil permeability is not only controlled by grain size distribution but is also greatly affected by soil structures (Bouwer, 1991). Split barrel (ASTM D1586) or thin walled tube (ASTM D1587) samples should be collected at five foot intervals. The test boring report should include the information collected during drilling and the descriptions and classifications of all materials penetrated in each boring.

All materials occurring in the depth interval of interest, even those not sampled by split barrel or thin-walled tube methods, are to be fully described, including the information recorded during drilling, according to method ASTM D2488, parts 1, 2, 3.11, 3.13 through 3.15, and 3.17 through 13, or an equivalent. Acceptable alternate classification methods include ASTM D2487 parts 1 through 4 and 5.13 through 15 (Unified System), American Society for Engineering Education (Burmeister) system, or other visual or laboratory methods that accurately describe the grain size distribution, grain shapes, composition, compactness, consistency, homogeneity, and degree of cementation of the sample.

Sieve analyses may be employed (ASTM D422) to assist the description of individual core samples. It should be noted that the sample preparation procedures used for sieve analysis can homogenize a sample and therefore may not accurately describe the materials as they occur in the ground or in the core.

The dimensions of sand are 0.074 mm (or U. S. Sieve No. 200) to 2.0 mm (or U. S. Sieve No. 60). The minimum dimension of gravel is 2.0 mm (or U. S. Sieve No. 60) (Hunt, 1984, p. 342, 355 [e.g. Burmeister System]). The dimensions for gravel and sand given in ASTM D2487-5.11 and -5.12, and D2488-3.12 and -3.16 (Unified System) are not acceptable.

The system for describing sand and gravel sizes given above is a hybrid of the Udden-Wentworth scale (Ehlers and Blatt, 1982, p. 325) and the Unified System, the two grain size scales most commonly used by geologists and engineers in the United States. These sand and gravel sizes are used in order to accommodate the considerable volume of research on the hydraulic properties of materials done by engineers and to recognize the importance of gravel in geologic interpretation. In addition, it is recognized that most drillers' logs are made using the Unified System and that drillers' logs constitute the bulk of subsurface information used in recharge mapping. In terms of evaluating logs for the recharge mapping process, materials described as very coarse sand by the Unified System would be classified as granules or fine gravel by the Udden-Wentworth scale.

Boring Locations and Statistical Filter

For sites up to 20 acres a minimum of two test borings per site should be required. If borings used to construct the existing recharge map are located on the site, then those borings should be used in the evaluation and can be substituted for one of the required additional borings. In addition, if borings used to construct the existing recharge map are located within 500 feet of the site boundaries, then those borings should be included in the evaluation. For sites between 20 and 200 acres an additional boring per 20 acres should be required for the total acreage between 20 and 200 acres. The maximum number of borings for sites 200 acres and smaller is 10. For sites larger than 200 acres an additional boring per 40 acres should be required for the total acreage exceeding 200 acres. In all cases the borings should be arranged, as much as possible, to be evenly distributed over the site and conform to a rectangular grid.

Averaged lithologic ratings are determined (using table 1 from the text) for each pair of adjacent
borings by adding together the thicknesses of each lithology (e.g., sand, silty sand, or mud) and dividing the result by two. This procedure averages the results of borings and smooths local scale heterogeneity. Averaged recharge potential ratings are then determined (using table 2 from the text) from the averaged lithologic rating and plotted on the map at the mid-point between the adjacent borings (see Fig. A1). If the resultant recharge rating(s) at the mid-point rating position differs by less than two ranks (e.g., excellent to good) from the original map, then the existing map rating for that location should be considered valid. If new data (the average recharge ratings) show that a recharge rating or ratings at the mid-point rating position(s) differ by two or more ranks (e.g., excellent to fair) from the existing map, then the map should be revised by the agency responsible for managing recharge areas. The revision should consider only the data points from the existing recharge map and the averaged recharge potential ratings. The revision should also be guided by cross-sections, isopach maps, or other tools commonly used in geologic mapping.
Figure 1. Illustration of boring plan for map challenges. Site size is approximately 200 acres.