MODELING RECHARGE ZONES IN FRACTURED BEDROCK FOR MAINE'S SOURCE WATER ASSESSMENT PROGRAM

Gail Lipfert[1], Andrews Tolman[2], Marc Loiselle[1]
[1]Maine Geological Survey, 22 State House Station, Augusta, ME 04333.
[2]Maine Department of Human Services, Drinking Water Program, 10 State House Station, Augusta, ME 04333.

INTRODUCTION

It is commonly believed that determining the recharge area to a bedrock well is so fraught with the potential for error that a fixed radius circle is the best solution for most sites unless extensive site-specific hydrogeologic data is available. However, several workers have successfully estimated the recharge to fractured-rock wells at sites with varying amounts and quality of data (e.g., Bradbury et al., 1991; Heath, 1995; Barton et al., 1999). All of the above studies stress the importance of developing a conceptual model of the site.

This study is the second phase of a project of the Maine Drinking Water Program (DHE) to evaluate and refine delineations of the contributing areas to public and community ground-water supply sources. The goal of this project is to develop and implement a methodology for delineating the area that contributes significant recharge to the wellfields of 26 water districts utilizing bedrock aquifers. A previous project delineated zones for municipal supplies utilizing sand and gravel aquifers based on 200- and 2500-day travel times (Tolman et al., 2000). A particular challenge to this study is the limited available hydrogeologic data given that most of the water districts serve small communities and lack the resources to invest in extensive hydraulic testing and investigations of their water supply wells.

A pilot study conducted on five sites determined that for bedrock wells, (1) a fixed-radius circle is extremely poor representation of the capture zones, (2) time of travel estimates are not feasible given the level of information available, (3) capture zones for wells at "simple" sites may be adequately determined using a combination of hydrogeologic mapping and analytical flow system modeling, (4) capture zones for wells at "complex" sites can only be determined using numerical ground-water modeling, (5) capture zone delineation is an iterative process with one methodology (e.g., Q/R mass balance) providing a check on another method (Tolman et al., 2000).

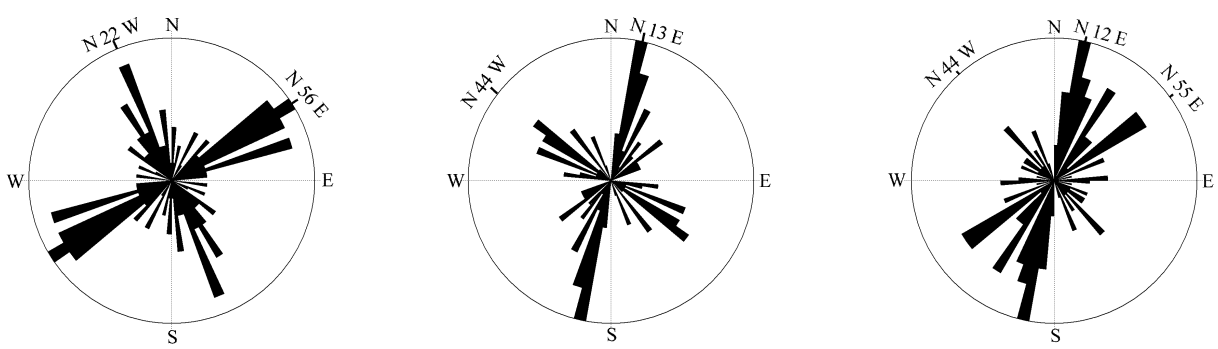
METHODOLOGY

The methodology is based on the Heath (1995) approach with contributions from other studies including Bradbury et al. (1991) and Barton et al. (1999). For each site, we compiled existing data such as topographic maps, bedrock and surficial geology maps, previous hydrogeologic reports, pump test data, geophysical data, pumping records. A photo-lineament analysis of each site was conducted at two scales from two sets of aerial photos. Every site was inspected and fracture data collected from nearby outcrops. A conceptual model was created that involved characterization of the bedrock and overburden and classification of the system as "simple" or "complex" based on factors such as overburden thickness, presence of fracture zones, etc. An example of a "simple" system is thinly covered bedrock with essentially homogenous hydraulic conductivity and recharge. A "simple" system could be anisotropic as long as it was consistent across the site. A "complex" site is one where the overburden significantly influence the hydrology, the hydraulic parameters are heterogeneous across the model area or the boundary conditions are complex. A preliminary delineation of the capture zone was drawn based on the data compiled so far and the conceptual model. Anisotropy was determined by examining near-vertical fracture orientation, dominant lineament orientation, and available drawdown data. Porous-media equivalence was tested based on the following criteria: lack of nearby major lineaments, a minimum delineation dimension that is 100 times the average fracture spacing, and, where pump test data were

available, smooth drawdown curves and a linear relationship between drawdown and pumping rate (Bradbury et al., 1999). Initially, a system classified as "simple" was modeled using EPA's WhAEM, an analytical element model. A "complex" system was modeled using Groundwater Modeling Systems (GMS), a front end for MODFLOW, a finite difference model. However, most of the "simple" systems have since been modeled using GMS, allowing us to compare the two model results. For all the sites, sensitivity analyses were conducted by varying model parameters such as hydraulic conductivity, recharge and anisotropy, about the base case parameters. The modeling results were displayed as confidence zones based on the number of overlapping capture-zone polygons from all the simulations.

RESULTS AND DISCUSSION

The usefulness of the fracture and lineament data for characterizing the fracture style of a site's underlying bedrock depends on the complexity and consistency of the bedrock's structural style throughout the area. An example of a structurally consistent site is a site underlain by metamorphic rock where the foliation of the bedrock consistently and pervasively controls the fracture orientations throughout the area. At structurally inconsistent sites, rose diagrams of fracture orientations vary from outcrop to outcrop and correlate poorly with the lineament data. However, at almost every site, even those with consistent and pervasive structure, there was at least one dominant fracture orientation that was poorly represented in the lineament data or vice versa. Sites in granitic plutons commonly show an inconsistency in the fracture data and a lack of correlation between fracture and lineament data that is similar to the more geologically complicated sites (Figure 1), indicating that fracture network characteristics are variable across a pluton. At some structurally inconsistent sites, contours of the drawdowns show an elongation along an axis whose orientation does not match either the dominant fracture or lineament orientations. As a result a system with inconsistent structure may indeed be anisotropic at the model scale, the fracture and lineament data may be insufficient to determine it.



A. **B.** **C.**

Figure 1. Rose diagrams of: (A) fracture planes with a dip greater than 50, (B) lineaments from 1:40,000 scale aerial photos, (C) lineaments from 1:20,000 aerial photos for a site in granite

At almost every site where we have pump test data and more than one observation well, we can demonstrate a greater porous-media response with increasing distance from the pumping well thus strengthening the validity of using porous-media models. Figure 2 shows a log-log graph of the drawdowns of a pumping well, PW, and three observation wells at a granitic site. A log-log plot of drawdown over time will have a half-unit slope if the borehole intersects a high-yielding fracture (Gringarten, 1982). In Figure 2, the data from the pumping well closely matches the line with a half-unit slope, but none of the observation wells do. Note that Obs1, the well closest to PW, shows the least drawdown response, indicating anisotropy and lack of fracture interconnectivity with the rest of the wells.

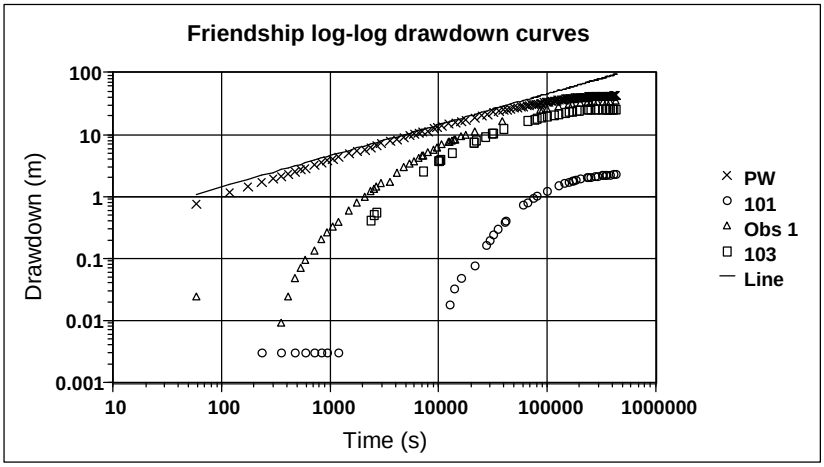


Figure 2. A log-log plot of the drawdown over the time for the pumping well and three observation wells, 103, Obs1, and 101 that are 82, 107, and 126 meters from the pumping well, PW. The solid line has a slope of 0.5.

A simple analytical model (WhAEM) and a finite difference model (MODFLOW) were compared for sites where the system was classified as "simple". For a given travel time at the same site, the pathlines from the WhAEM simulations delineated a contributing area similar to that of the MODFLOW simulations. A pilot study concluded that WhAEM was sufficient for delineating recharge areas at "simple" sites that could be modeled as a single layer of homogeneous material, of either isotropic or anisotropic nature. Further research has led us to the realization that there are very few truly "simple" sites where WhAEM was able to accurately simulate the flow system, however. A variable-parameter model, such as MODFLOW, more accurately simulates the conditions and boundaries of the conceptual model. It was determined that travel times were a poor choice for defining the extent of the delineation because of the uncertainty in the value of porosity of the bedrock in the area due to lack of data. Hence, the method that was used in the delineation of the sand and gravel aquifer supplies of depicting wellhead protection zones as 200- and 2500-day travel times was deemed inappropriate for the wells in fractured bedrock. In GMS particles track pathlines from the well to the surface, but in WhAEM particles continue until a boundary in the flow field is reached. With readily available hydrologic and topographic data of each site that could be easily imported into GMS (MODFLOW), it was determined that time savings using WhAEM did not warrant the uncertainty in the model results.

It was important in this study to account for the uncertainties involved in modeling fractured bedrock. We have incorporated all the sensitivity analysis simulations in our final delineation zones. The final capture zones are identified as zones of low, moderate, and high confidence based on the increasing amount of overlapping areas of the individual simulations. Figure 3 shows the confidence zones of the site for which the rose diagrams are shown in Figure 1. The confidence zones are based on the MODFLOW simulations, but the zones derived from WhAEM (not shown) are very similar. Also shown in Figure 3 are the fixed-radius circles, preliminary delineation, and a hydrogeologic mapping delineation for one well based on the drawdown contours. This site is in granite and has a complex pattern of hydraulic connection among the wells on a scale of tens of meters and less. However, except for wells in close proximity to the pumping well, all the log-log plots of the observation wells showed radial flow similar to that in Figure 2, indicating that a porous-media equivalence is likely valid at the scale of the delineation. The site is classified as a "simple" system because of the minimal overburden. The granite at this site showed some structural consistency, and anisotropy was assigned by correlating the dominant fracture orientations with the elongation of the drawdown contours.

Our work to date indicates that the above methodology defines a more plausible and defensible capture zone than the fixed-radius circle method. Porous-media models can be used to delineate contributing areas of fracture-flow systems even at sites with a minimal data set provided conservative measures are taken in constructing the delineation.

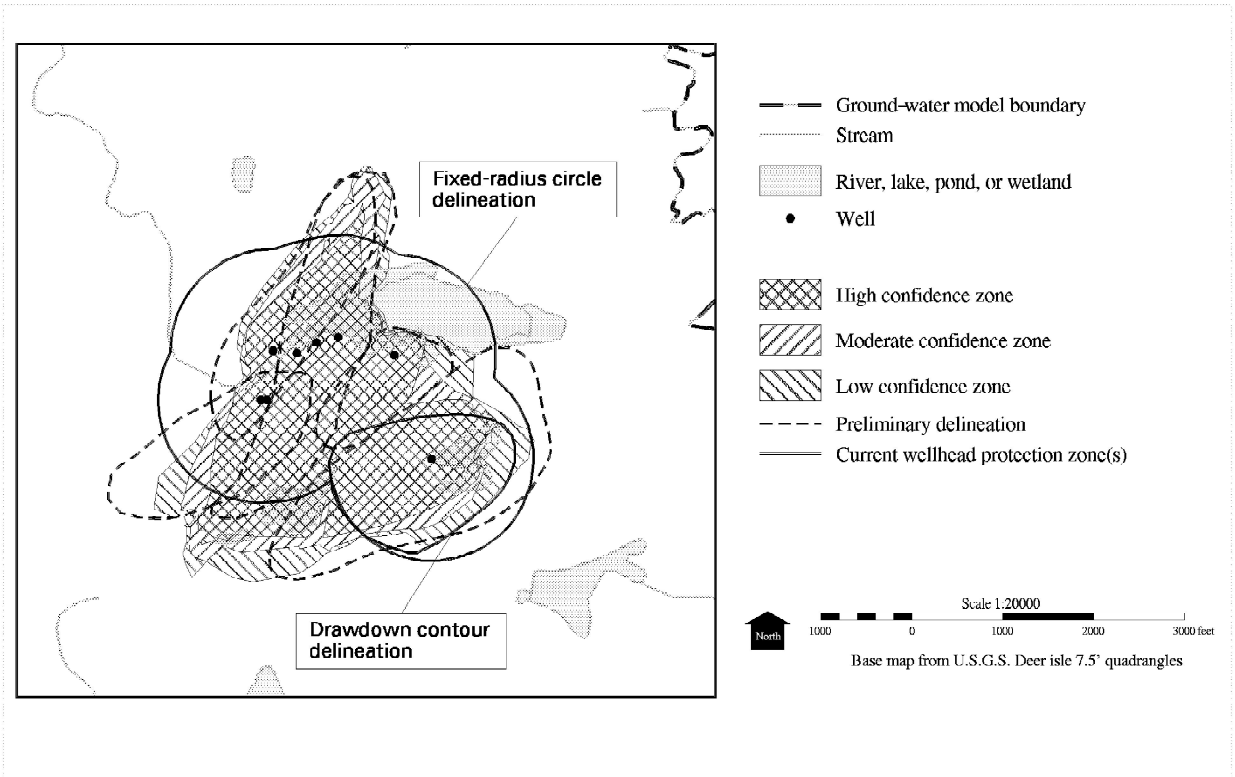


Figure 3. Map comparing confidence zones, fixed-radius circle delineations, preliminary delineations, and a delineation of one well based on drawdown contours for a site in granite.

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