RECHARGE TO HIGH YIELD WELLS IN THE PIEDMONT

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Abstract. Currently most of the municipal water supplies in the Piedmont are from surface water, although there is increasing interest in developing groundwater sources. The igneous and metamorphic rocks contain little primary porosity and very low primary permeability; flow occurs in fractures. High yield wells require fracture zones such as faults or lithologic contacts. While flow in these zones may be rapid, the volume of water stored in the fractures is limited. Recharge to the fracture zone is principally from the saprolite. High pumping rates can only be sustained by induced recharge from surface water bodies or thick saturated saprolite.

INTRODUCTION

While most of the municipal water supplies in the Piedmont are currently from surface water, there is increasing interest in augmenting these supplies from groundwater sources. To do this it is necessary to understand the limitations of the water supply in the igneous and metamorphic bedrock in light of the fact that such rock contains little primary porosity and very low primary permeability. Even wells supplying single family homes rely on water from fractures (secondary porosity). Studies at a variety of locations in the Piedmont have shown that high yield wells (>50 gpm) are possible in favorable zones. Guthrie and DeJarnette (1989) reported that the majority of the well yields in the Alabama Piedmont were less than 20 gpm; wells with higher yields occur in zones characterized by drainage systems that reflected structural control, or along linear trends that transect different lithologies. Tinkham et al (1989) noted that most of the wells they studied in the Virginia Piedmont were located near streams, but that the high yield wells appeared to be independent of stream order.

Most researchers recognize that the saprolite, the chemically weathered material found above the bedrock in the Piedmont, functions as the reservoir, while the fractures in the bedrock serve as a pipeline (Heath, 1989). The interconnection between the saprolite and bedrock is less well understood. Lineback et al (1989), for example, state that water budget considerations suggest that normal recharge will sustain high well yields over long periods of time without significant lowering of the regional watertable or significantly affecting baseflow in streams or water levels in wetlands. This suggests that the fractures tapped by the high yield well intersect the saprolite over a wide area, and the rate of flow through the fractures is the limiting condition.

Emery and Crawford (1994) suggest a very different picture of Piedmont hydrogeology. They describe bedrock wells in a fault zone in the Piedmont as "confined" or "semiconfined". This terminology implies that water pumped from wells located in these fracture zones comes from this depth, and that the recharge area for the wells is far removed. Further, it implies that the pumping rate for the "aquifer" can be sustained at the short-term rates of a several day pump test.

Table 1. Parameter ranges for fracture zone and volume of water stored expressed as time.

Component	Lower Value	Upper Value
Length	1000 ft	2500 ft
Width	10 ft	100 ft
Depth	50 ft	300 ft
Fracture Porosity	0.1	0.2
Time (250 gpm pump rate)	1 day	312 days

Both views of Piedmont hydrogeology lead to the conclusion that safe yield of bedrock wells is dependent only on the fractures at or near the well. This paper shows that other factors also affect the safe yield, and that these other factors are very important for source-area protection.

FRACTURE STORAGE

Idealized representation of Piedmont hydrogeology is illustrated in Figure 1. Saprolite, ranging from 0 to about 100 feet thick overlies the bedrock, although the transition is not generally sharp. High yield wells are located in faults or along lithologic contacts and the fracture volume is necessarily limited.

The implications of available storage were investigated by assuming a fault zone with two extreme ranges of parameters given in Table 1. If volume is expressed in days using a pumping rate of 250 gpm, this geometry represents a storage range of 1 day to 312 days. This uncertainty can be narrowed by using Monte Carlo analysis. If we assume the parameters in Table 1 (length, width, depth, and fracture porosity of the fault zone) are uniformly distributed between the low value and the high value, we can sample a value, called a realization, from each distribution and determine the days of pumping required to empty the volume. Figure 2 represents the frequency distribution we obtain when we repeat this procedure thousands of times. The *a posteriori* distribution is skewed towards the low end: it is more likely that the volume of water stored in the

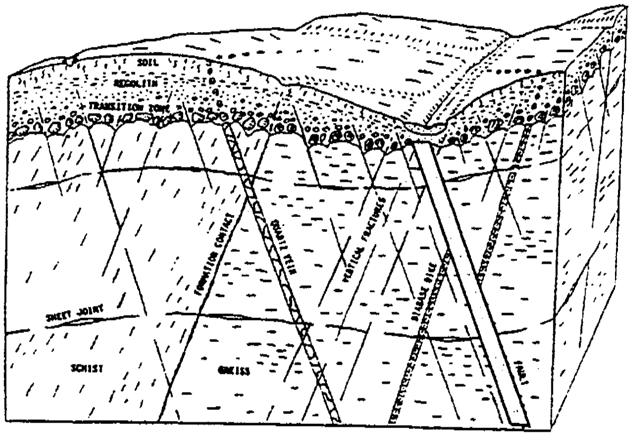

Figure 1. Idealized saprolite-bedrock geology of hydrologic importance. Shaded area represents a highly permeable fault (after Heath, 1989).

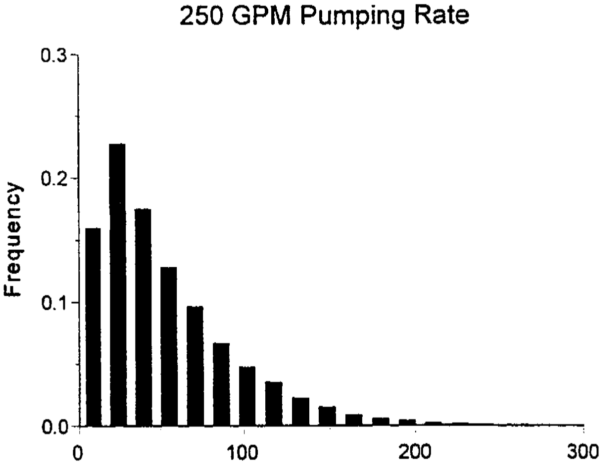

Figure 2. Distribution of expected pumping volumes expressed as time for geometries in Table 1.

fractures of the example fault is less than 100 days, pumping at 250 gpm. These results suggest two important points. First, it is unlikely that a pump test of three or fewer days will actually stress the system sufficiently to determine the recharge rate to the fractures. Second, steady-state pumping of a high yield fracture system will quickly lead to a substantial proportion of the water coming from some recharge zone beyond the primary fractures of the fault.

SAPROLITE GEOMETRY

The previous section demonstrates that the fracture zone must be resupplied with water. Figure 1 illustrates why this recharge must ultimately come from the overlying saprolite. Some recharge will occur down fractures that intersect both the saprolite and the fault, such as the diabase dike in Figure 1, but most of the recharge will occur where the major fractures of the fault intersect the saprolite. This geometry is illustrated in Figure 3, with the saprolite denoted by the shading and the fracture - saprolite interface labeled Boundary 4. This representation is a vertical cross-section at right angles to the fault. The total flux into the fault in this representation is the flow across Boundary 4 times the length of the fault that delivers water to the well.

For modeling purposes, the problem can be simplified by noting that the domain is symmetric. If we place a no-flow boundary in the center of the fracture zone, one half of the flow can be determined by modeling only the left half of the domain. Under steady-state conditions, flow in the saprolite can be described by the differential equation

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial z^2} = 0 \qquad (1)$$

For a unique solution to exist, the boundaries of the domain must be located and specified. For this paper, the fracture zone was assumed to be 100 feet wide with 200 feet of no-flow boundary (Boundary 5) for the rest of the bedrock - saprolite interface. The edge of the problem, Boundary 1, was assumed to have a vertical equipotential equal to the watertable at that point. The watertable can be either a no-flow boundary or a known head boundary. If it is specified as no-flow, its elevation at any point should equal the total head.

Because the flux across the boundary is desired, the Boundary Integral Equation Method (BIEM) is a convenient way to solve the partial differential equation. A modification of a program given in Liggett and Liu (1983) was used. The domain is discretized at nodes on the boundary and either the total head or the gradient is returned as the solution. The fracture - saprolite boundary was assigned a head equal to zero. This represents the maximum gradient in the saprolite that would result from lowering the water level in the fractures below the saprolite - bedrock interface by pumping. The total flow into the fault was determined by integrating the nodal fluxes with the Trapezoidal Rule and multiplying by the length of the fault. Hydraulic conductivity of the saprolite was assumed to be 10^{-4} cm/sec. This hydraulic conductivity is on the high end for saprolite (Champion, 1989; Schumak et al, 1989).

SIMULATIONS RESULTS

The first simulation was for a level watertable and 30 feet of saturated thickness (Scenario A, Figure 4). This yields a recharge estimate of 30 gpm, far less than the 250 gpm assumed to be the pumping rate. Furthermore, this "box" geometry does not have the correct watertable location. Figure 5 shows the difference between the elevation of each node on the boundary and the computed head. If the watertable is correctly located, the difference is equal to zero. Clearly the watertable is too "high". The second simulation was for an assumed watertable with a drawdown at the fractures. This yielded a recharge rate of only 15 gpm but the predicted head nearly equaled the nodal elevations at all points. Because the watertable is more nearly correct, the second simulation yields a more accurate estimate of flux across the saprolite - fractured bedrock boundary. The actual recharge is likely to be higher than this value, however, because some recharge will occur along the other faces of the fault.

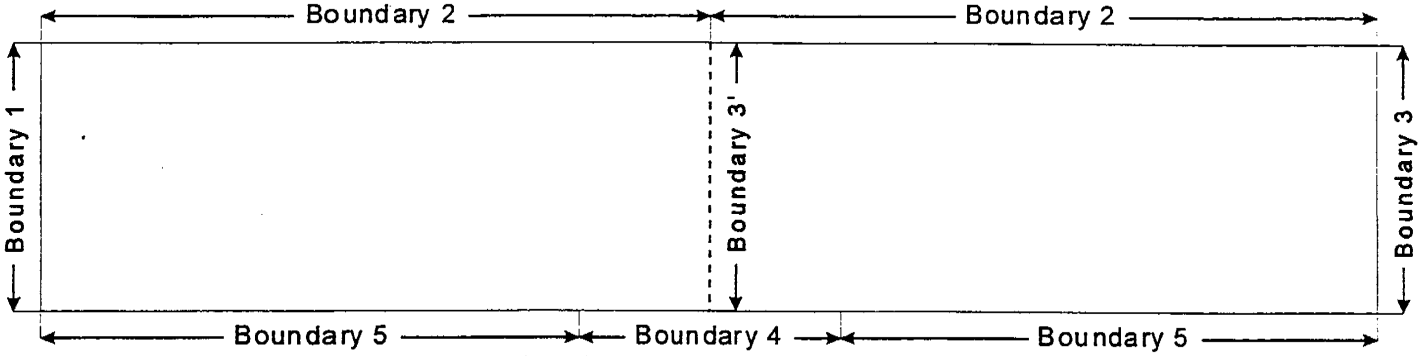

Figure 3. Geometry of modeled saprolite domain and boundaries. Boundary 4 is the top of the fracture zone.

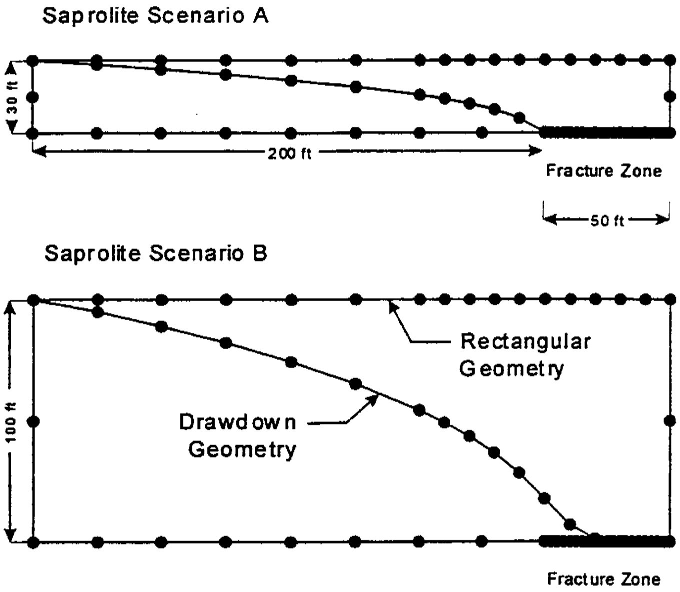

Figure 4. Geometries modeled with BIEM.

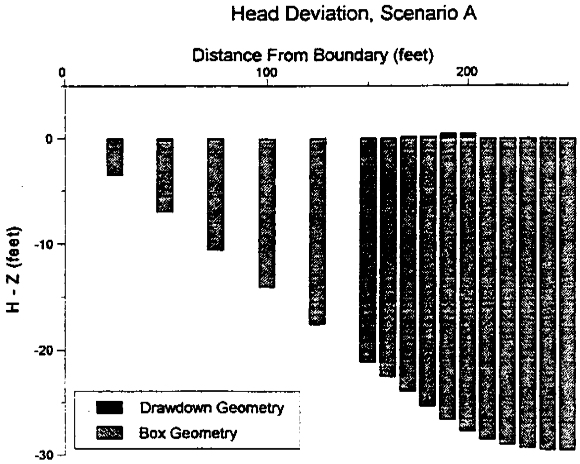

Figure 5. Pressure head deviation from zero, thin saprolite.

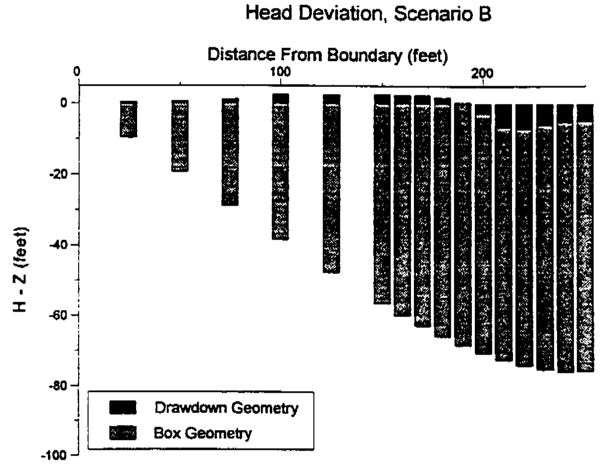

Figure 6. Pressure head deviation from zero, thick saprolite.

A second set of simulations was performed with an assumed saturated saprolite thickness of 100 feet. For the "box" geometry, the recharge was estimated to be 285 gpm. Figure 6 shows that this watertable is also too high. The drawdown shown in Figure 4 (Scenario B) reduced the recharge to 175 gpm, but this is probably still slightly high (note the black bars in Figure 6). Like the previous case, the true recharge probably lies somewhere between the two simulated values.

If a surface water body such as a stream, lake, or reservoir is located above the fault zone, the watertable is represented by a constant head boundary and flux across this boundary is not equal to zero. In the hydrologic literature this is called induced recharge. For Scenario A, the recharge into the fractures would be 475 gpm. Nearly all of the this flow would come from the surface water body. These simulations are summarized in Table 2.

SUMMARY AND CONCLUSIONS

The Monte Carlo analysis demonstrates that the volume of water stored in the large fractures of a fault or linear lithologic contact is

Table 2. Recharge to fracture zone 2500 feet long, 100 feet wide, and a hydraulic conductivity of 10^{-4} cm/sec.

Geometry	Boundary	Recharge to Fractures (gpm)
Box, Scenario A	No-flow	30
Drawdown, Scenario A	No-flow	15
Box, Scenario B	No-flow	285
Drawdown, Scenario B	No-flow	175
Box, Scenario A	Constant Head	475

likely to be quite small, although this may not be evident from a short-term pump test. The water that recharges these fractures comes from the saprolite, but there are conditions where this recharge may be low. High yield wells can be maintained if the saturated saprolite is thick, or more likely, if there is a surface water body above the fracture zone. It is important to understand that if a surface water body exists, much of the water pumped from the well comes from the surface water source. Therefore, there is a potential for adversely affecting small streams or wetlands during drought conditions. Furthermore, water quality conditions of the surface water body might adversely affect the water quality of the well. The recharge rates shown in Table 2 are based upon the assumed size of the modeled fracture zone and hydraulic conductivity of the saprolite. If the hydraulic conductivity were 10^{-5} cm/sec, for example, the values in Table 2 would be reduced by one order of magnitude.

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