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Estimation of Transmissivity using Non-radial Flow Dimensions

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Abstract

Non-radial flow signatures are seen in many hydraulic tests in fractured media. The generalized radial flow approach initially formulated for fracture flow, which uses a variable flow dimension (n), is increasingly used to interpret hydraulic tests to account for non-radial flow. Flow dimension can be estimated directly from the second derivative of pumping test drawdown versus log time and can be described as the power by which cross-sectional area of flow changes with respect to radial distance from the borehole. Representing non-radial flow dimensions in a 2D numerical model has been problematic. As part of an effort to understand how to structure heterogeneous transmissivity to create the type of non-radial flow signatures commonly observed, we generated spatially correlated binary random transmissivity fields with directional anisotropy in the correlation length. Analysis of simulated pumping tests in these fields provided the same types of non-radial diagnostic responses commonly observed in pumping tests in a fractured dolomite at the Waste Isolation Pilot Plant (WIPP) site. Using these simulated tests, we discuss the estimation of transmissivity using flow dimension as a variable versus traditional estimation methods that assume radial flow.

Introduction

Pumping test data derived from tests in fractured aquifers often indicate that flow within these aquifers is non-radial. The generalized radial flow (GRF) model developed by Barker (1988) incorporates a geometric term called flow dimension (n) that accounts for changes in cross-sectional area of a flow system with respect to distance from the borehole, allowing for simulation of non-radial flow. Barker's model has been applied in well-test analysis to characterize fractured media (Bangoy et al., 1992; Kuusela-Lahtinen et al., 2002; Leveinen, 2000), but subsequent use of hydraulic parameters such as transmissivity (T) derived from non-radial analysis has been hampered by an inability to meaningfully incorporate both these hydraulic parameters values and the corresponding geometry in commonly utilized two-dimensional models such as MODFLOW (Harbaugh et al., 2000). Walker et al. (2006) demonstrated that many commonly used heterogeneity models do not reproduce non-radial flow characteristics observed in fractured systems.

In this research, we explore the connection between flow dimension, aquifer geometry, and inferred values of T and storativity (S) using a series of two-dimensional numerical experiments. We simulate and analyze pumping tests in idealized aquifer channels (flow conduits) of various geometries contained within an impermeable host material. The flow dimensions exhibited by our models are determined using diagnostic plots described by Roberts et al. (1999) and Beauheim et al. (2004). We then systematically alter the T of the host material and evaluate diagnostic response changes. We explore the potential utility of the GRF model in less idealistic settings by conducting diagnostic analysis of simulated pumping tests in Gaussian-based binary random fields.

Background

Mathematics and Conduit Simulation Formulation

Barker (1988) defined the GRF one-dimensional model as

$$S_S \frac{\partial h}{\partial t} = \frac{K}{r^{n-1}} \frac{\partial}{\partial r}\left(r^{n-1} \frac{\partial}{\partial r} \right) \qquad (1)$$

where S_S is specific storage [1/L], h is hydraulic head [L], t is elapsed time [T], K is hydraulic conductivity [L/T], r is radial distance from the borehole [L], and n is flow dimension. He described the relationship between distance from pumping well (r) versus cross-sectional area of flow (A) as

$$A(r) = b^{3-n} \frac{2\pi^{\frac{n}{2}}}{\Gamma\left(\frac{n}{2}\right)} r^{n-1} \qquad (2)$$

where b is aquifer thickness [L] and Γ is the gamma function. For our study, we assume that the flow area at the well, $A(r_w)$, is constant and does not change as a function of n as it does in (2). Given this assumption and letting $a=2\pi^{n/2}/\Gamma(n/2)$, b at the distance $r = r_w$ is seen to be

$$b = \left(\frac{A(r_w)}{a r_w^{\,n-1}} \right)^{\frac{1}{3-n}} \tag{3}$$

For any distance r in a constant n system, we can substitute the right-hand side of (3) for b in (2) to get

$$A(r) = \left[\left(\frac{A(r_w)}{a r_w^{\,n-1}} \right)^{\frac{1}{3-n}} \right]^{3-n} a r^{n-1} \tag{4}$$

which simplifies to

$$A(r) = \frac{A(r_w)}{r_w^{\,n-1}} r^{n-1} \tag{5}$$

This relationship defines the cross-sectional area of flow at any distance r from the borehole in terms of the specified area $A(r_w)$. Using equation (5), we are able to create a two-dimensional conduit for any specified value of n.

Conduit Simulations

The first idea we explore is the representation of various flow dimensions in a two-dimensional model through application of equation (5). While familiar geometries such as linear, radial, and spherical flow (n = 1, 2, and 3, respectively) have always been easy for people to visualize, non-integer dimensions have been much more difficult to understand in a two-dimensional context. In this section, we investigate the application of (5) using finite difference simulations and provide visualizations of non-integer flow dimensions.

Field Generation

To create conduits with non-integer geometries, we generate two-dimensional finite difference fields of constant thickness where the width of the conduit at any distance r is defined by (5) for a given initial area. Figure 1 shows four conduits with various geometries.

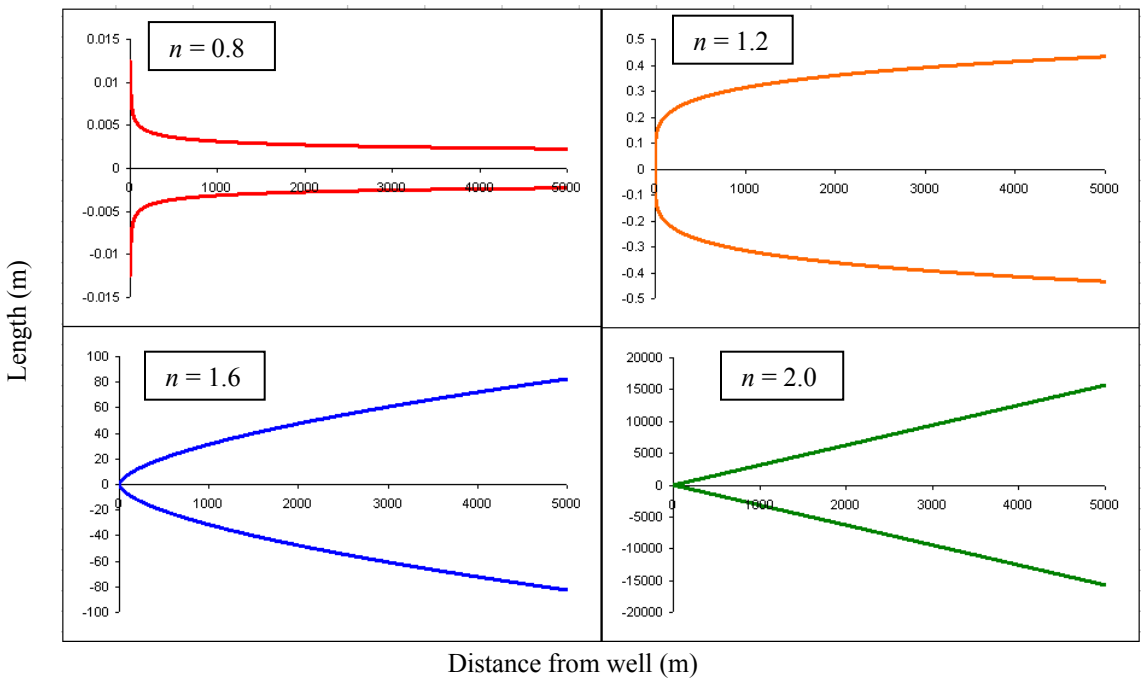

Figure 1: Examples of conduit geometries generated by (5). It is important to note the scale of the y-axis when comparing conduits.

Conduit generation involved transcribing the changing cross-sectional areas of flow described by (5) and Figure 1 into a finite difference context. These fields consisted of a transmissive conduit-shaped flow zone surrounded by an impermeable host material with a pumping well placed at the apex of each conduit (Figure 2). For our simulations, we tested conduits between flow dimension values of linear (n = 1) and radial (n = 2). We assume a fully penetrating, block-centered well with ideal pumping in a saturated, confined aquifer of constant thickness for all simulations. We use a telescoping grid that increased the space between each node as distance from the pumping well increased, similar to the approaches of Willmann et al. (2007), Tumlinson et al. (2006), and Oden and Niemi (2006). This spacing scheme was used to extend flow boundaries to a distance where boundary effects were not evident in the simulated pumping data while maintaining simulation accuracy with a finer grid at the pumping well.

Conduit Simulation Results and Discussion

Using the grids described above, constant-rate pumping tests were simulated in MODFLOW with n = 1.0, 1.2, 1.4, 1.6, and 1.8. Ehlig-Economides et al. (1990), among others, noted that the pressure derivative (p') developed by Bourdet et al. (1989) displays late-time straight lines with slope related to the flow geometry/dimension.

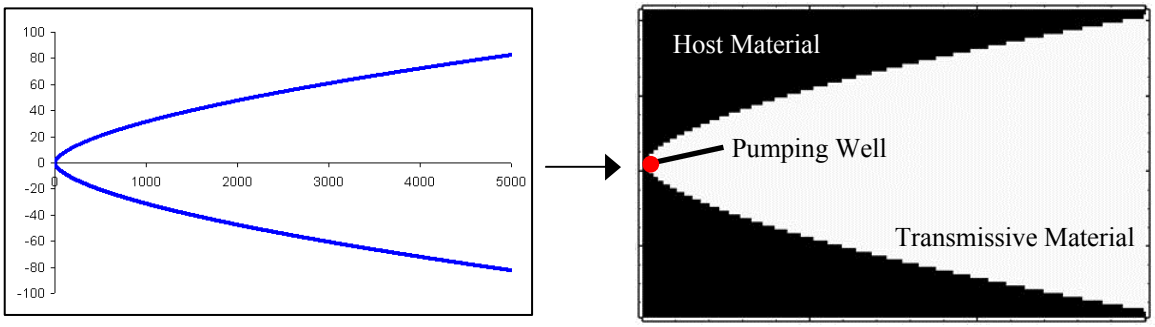

Figure 2: An example of the conversion of a conduit calculated by (5) converted to a map-view finite difference context.

The relationship between the slope of the pressure derivative (m) and n is given by Barker (1988) as:

$$m = 1 - \frac{n}{2} \tag{6}$$

Defining a scaled second derivative as:

$$p'' = -2\frac{\partial \log(p')}{\partial \log(t)} + 2 \tag{7}$$

Roberts et al. (1999) and Beauheim et al. (2004) created a semilog plot of the scaled second derivative versus log time such that the late-time data will plot as a constant value equal to n – a flow-dimension diagnostic plot. Figure 3 shows the flow-dimension diagnostic plots derived from the simulated constant-rate pumping tests in each of our conduits. The late-time values for each of the diagnostic plots correspond well with the input value of n.

Aquifer Property Estimation

To determine how well the input values of T, S, and also the specified value of n used to create the conduit geometry could be estimated from the MODFLOW simulation data described above, we used Sandia National Laboratories' numerical well-test analysis code nSIGHTS (Roberts, 2006) to estimate these three parameters as well as the uncertainty associated with the parameter estimates. nSIGHTS uses non-linear regression to optimize the values of the fitting parameters and thereby obtain the best match to the simulated MODFLOW pressure responses. The uncertainty quantification method applied to the analyses in this report is a process referred to as perturbation analysis. Preliminary analyses are performed in which a reasonable fit is obtained to the simulated pressure data. The resulting values of the fitting parameters are the baseline solution set – a single value for each fitting parameter that provides a satisfactory fit to the data (satisfactory being a judgment call on the part of the analyst).

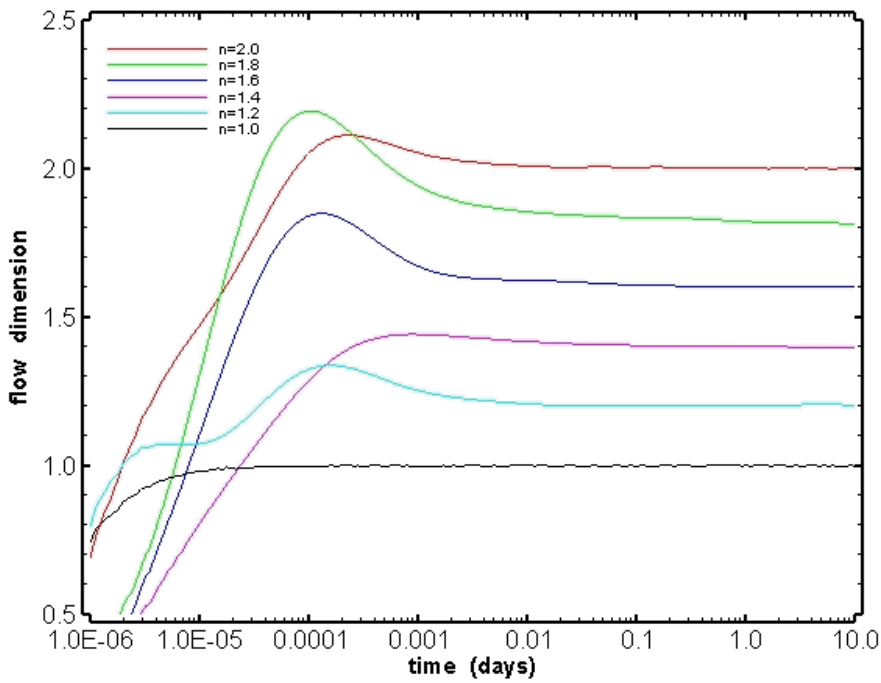

Figure 3: Flow dimension diagnostic plots for constant-rate tests with n = 1.0, 1.2, 1.4, 1.6, and 1.8.

Perturbation analysis begins by assigning a plus/minus range corresponding to the parameter space one wishes to investigate to each of the baseline fitting-parameter values. Starting at the baseline value, the fitting parameters are then randomly perturbed to fall somewhere within their assigned ranges and are then reoptimized from these random starting points. The objective of perturbation analysis is to adequately sample the parameter space and locate all of the minima (possible solutions) within the parameter space, allowing the global minimum (assumed true solution) to be identified. Three hundred perturbation/optimizations were performed to quantify the uncertainty in the T, S, and n estimates. Input T and S values used for the simulations were T = 1E-5 m^2/s and S = 1E-4, and the specified n varied as listed in Table 1 below. This method provided us with mean estimates of S and T that differed from the input values by factors no greater than 3.3 and 0.6, respectively, less than an order of magnitude.

Conduit Simulations with Variable Transmissivity Host Material

We next investigated the effect of altering the transmissivity of the host material (nodes) surrounding each conduit, using n = 1.6 for the conduit geometry and a constant value of T = 1E-5 m^2/s within the conduit. Simulations were run using four different T values for the host material: 1E-9, 1E-8, 1E-7, and 1E-6 m^2/s. Unlike the preliminary analyses from our impermeably bound conduit simulations, the flow dimension was allowed to vary as a function of distance from the borehole ($n(r)$) within nSIGHTS to obtain an adequate fit of our simulated data. As the simulation progressed, leakage through the previously impermeable sides of the conduits effectively increased the cross-sectional flow area, and as a result, increased the apparent flow dimension of the system.

	Minimum Estimated Value				Maximum Estimated Value		
Input *n*	***S***	***T*** **(m²/s)**	***n***	**Input *n***	***S***	***T*** **(m²/s)**	***n***
1.0	2.80E-05	2.03E-06	0.86	1.0	1.25E-03	4.31E-05	1.07
1.2	3.90E-05	8.10E-06	1.20	1.2	1.16E-04	1.65E-05	1.22
1.4	9.55E-07	9.39E-07	1.33	1.4	4.95E-03	8.16E-05	1.51
1.6	1.00E-08	1.04E-06	1.48	1.6	1.00E-03	1.36E-04	1.79
1.8	2.65E-05	1.45E-06	1.66	1.8	5.61E-04	2.78E-05	2.01

	Estimated Mean Value				Estimated Variance		
Input *n*	***S***	***T*** **(m²/s)**	***n***	**Input *n***	***S***	***T*** **(m²/s)**	***n***
1.0	2.02E-04	1.28E-05	1.00	1.0	3.20E-09	8.10E-12	9.33E-05
1.2	8.80E-05	1.02E-05	1.20	1.2	4.84E-10	5.07E-12	1.32E-07
1.4	2.47E-04	1.08E-05	1.40	1.4	2.94E-07	7.19E-11	1.04E-04
1.6	3.29E-04	1.21E-05	1.61	1.6	1.45E-07	1.50E-10	2.83E-04
1.8	1.27E-04	6.44E-06	1.83	1.8	1.06E-09	2.46E-12	4.81E-04

Table 1: Parameter estimates derived from nSIGHTS perturbation analysis.

To implement *n(r)* in nSIGHTS, two to three values of *n* were specified at distance ranges in the model with all values of *n* between the three specified values linearly interpolated. The model then optimized both the value of *n* at the specified points and also the distance between these points to best match the measured data. Figure 4 shows the *n(r)* function used for the simulation in which the conduit and host material T values differed by two orders of magnitude.

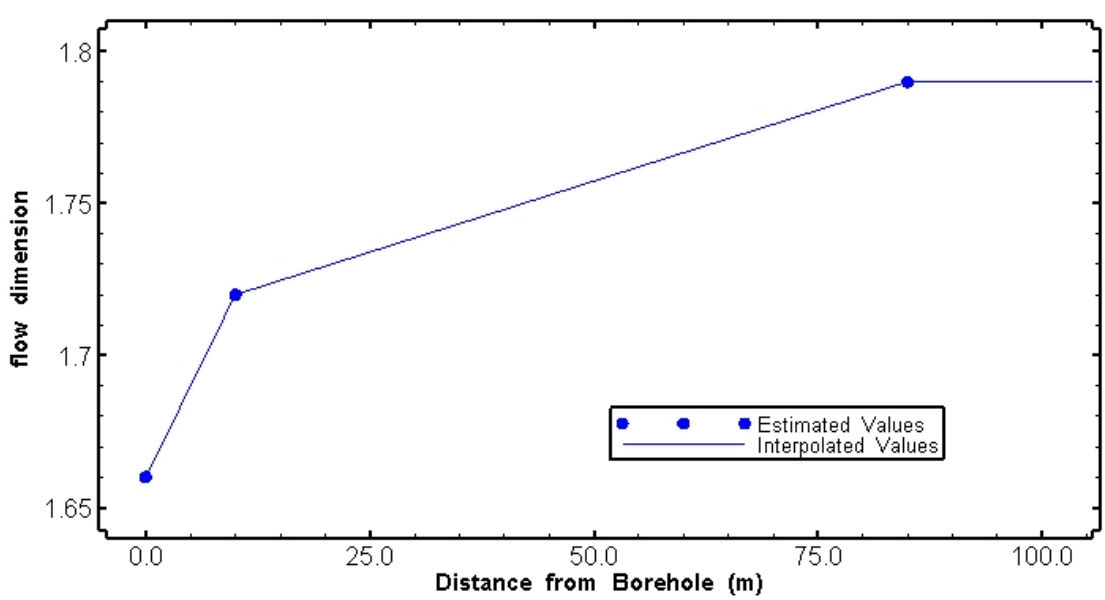

Figure 4: Flow dimension values and corresponding distances from borehole used in the n(r) approach to fit simulated data.

Flow Dimension Analysis

Flow-dimension diagnostic plots for the four simulations, shown in Figure 5, all exhibit a late-time increasing dimension. The positive slope is caused by the gradual increase in flow contribution of the surrounding host material. We believe, given enough time and a large enough field, that the flow dimension of each will stabilize to radial (n = 2) much like the linear strip case demonstrated by Butler and Liu (1991) and the T estimated from a pumping-test response would be equal to that of the host material. When comparing the separate simulations, estimated flow dimension decreases as the transmissivity contrast increases. This is expected, as the system that is most homogeneous results in a more radial flow dimension.

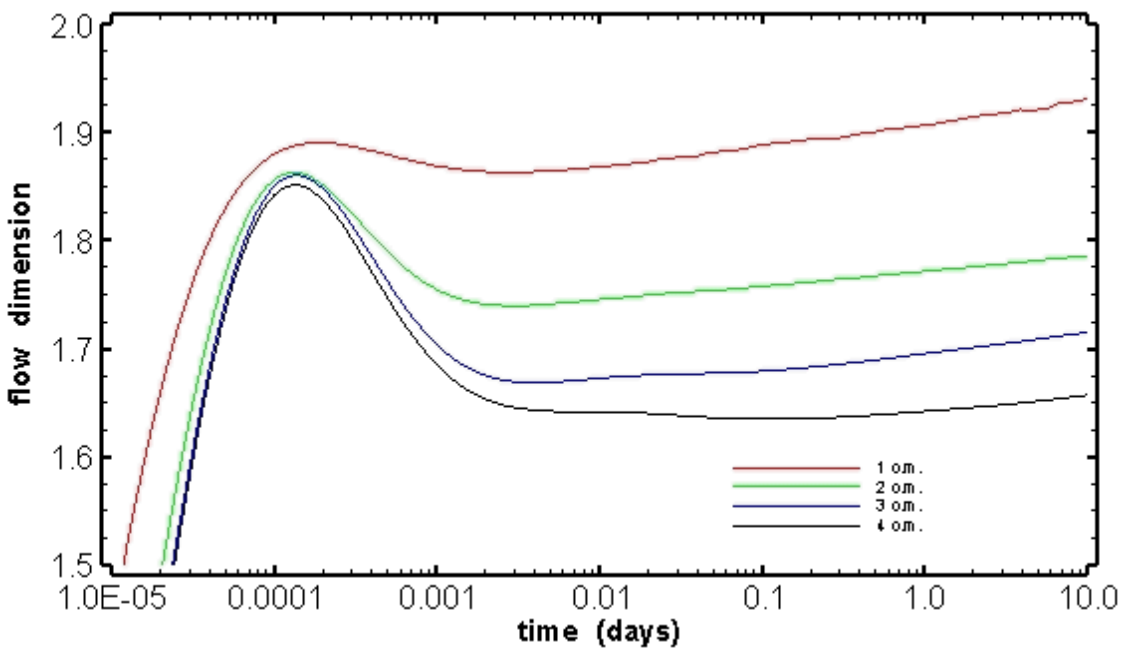

Figure 5: Flow-dimension diagnostic plots for simulated pumping in a conduit of n = 1.6 with host material transmissivity 1, 2, 3, and 4 orders of magnitude (om.) lower than the conduit transmissivity.

Aquifer Property Estimation

The results of our perturbation analysis of the four simulations are detailed in Table 2. We find that flow dimension converges toward the value used to create the conduit as the transmissivities of host and conduit material diverge. Flow dimension at the near n zone is also approximated close to that of the conduit geometry for all but the most homogeneous case. Mean transmissivity estimates were all lower than that of the conduit transmissivity, at most by a factor of 1.35, and mean storativity estimates were all higher than conduit values, at most by a factor of 0.54. These differences reflect the flow through the conduit sides from the host material which results in a lower average transmissivity of the system (compared to the conduit) and allows for greater flow contribution to the conduit.

	Minimum Estimated Value				
Host T (m^2/s)	***S***	***T*** **(m^2/s)**	***n1***	***n2***	***n3***
1E-6	2.05E-06	3.26E-06	1.46	1.88	-
1E-7	1.00E-04	7.65E-06	1.66	1.72	1.79
1E-8	1.14E-04	7.17E-06	1.53	1.71	-
1E-9	1.21E-04	7.92E-06	1.57	1.65	-

	Maximum Estimated Value				
Host T (m^2/s)	***S***	***T*** **(m^2/s)**	***n1***	***n2***	***n3***
1E-6	4.25E-04	1.53E-05	1.9	2.04	-
1E-7	1.14E-04	8.40E-06	1.67	1.73	1.83
1E-8	1.65E-04	9.97E-06	1.65	1.77	-
1E-9	1.55E-04	9.49E-06	1.62	1.68	-

	Estimated Mean Value				
Host T (m^2/s)	***S***	***T*** **(m^2/s)**	***n1***	***n2***	***n3***
1E-6	1.10E-04	5.44E-06	1.82	1.97	-
1E-7	1.10E-04	7.76E-06	1.67	1.72	1.82
1E-8	1.32E-04	7.88E-06	1.63	1.75	-
1E-9	1.35E-04	8.27E-06	1.61	1.67	-

	Estimated Variance				
Host T (m^2/s)	***S***	***T*** **(m^2/s)**	***n1***	***n2***	***n3***
1E-6	1.07E-09	1.57E-12	3.39E-3	1.65E-2	-
1E-7	7.00E-05	3.41E-05	6.01E-6	3.43E-6	3.84E-5
1E-8	1.42E-10	4.18E-13	5.41E-4	1.31E-4	-
1E-9	3.09E-11	5.75E-14	4.42E-5	3.03E-5	-

Table 2: Perturbation analysis results for property estimation of conduits imbedded in variable transmissivity host material. The conduit properties were S = 1E-4 and T = 1E-5 m^2/s.

Binary Random Field Simulations

In our first set of conduit simulations, we explored the connection between flow dimension and geometry and then the effects of variable host transmissivity with constant conduit geometry. For the next section of work, we explore the inverse by simulating pumping in fields with varied geometry, but no transmissivity changes. As a result, we hope to create Gaussian-based fields that reproduce persistent subradial flow characteristics similar to those observed in actual field tests.

Past Works

Several approaches for simulated pumping test analysis in random fields involving flow dimension have already been conducted. Walker et al. (2006) simulated pumping tests in three stochastic model types: percolation networks, fractional Brownian motion, and multivariate Gaussian. They find that multivariate Gaussian fields and fractional Brownian motion fields averaged a radial, $n = 2$, signature while percolation networks averaged a sub-radial signature of approximately $n = 1.5$. Their results suggest that the fields most commonly used for simulated pumping, i.e. Gaussian, are likely to reflect a radial simulation response which is atypical of field data responses.

Simulated pumping responses in fractured media have been investigated by many, but the study most relevant to our work was by Acuna and Yortsos (1995). They use a fractal application of a fracture network to generate their fields. The most notable characteristic of their work is a perpetuating positive slope in their simulated pressure derivatives. Positive slope diagnostics are commonly seen in field data, however, the positive slope diagnostic plots generated by Acuna and Yortsos contain little to no variation, while some variability is common in field data.

Our binary random field simulations are the basis by which we intend to explore a way to generate Gaussian fields that, in contrast to the Gaussian-field simulations of Walker et al. (2006), result in a positive slope diagnostic. We also intend for the positive slope diagnostics to contain variations similar to that of field data, contrary to results displayed in Acuna and Yortsos (1995).

Field Generation

Our first task was to create fields of single transmissivity/storativity amongst units of impermeable media that would result in purely geometric diagnostic analysis effects from simulated pumping. The fields we first investigated were created by generating Gaussian random fields with input mean, variance, and directional correlation length. We then chose a divide in the field values and designated them half transmissive ($T = 1E\text{-}5\ m^2/s$) and half impermeable regions. This methodology mimics that used by Zinn and Harvey (2003) in their reclassifications of transmissivity values using distribution functions. The result is a field where flow will propagate in a single transmissivity and storativity with impermeable regions dictating changes in flow area and direction.

Binary Random Field Simulations

The initial simulations used fields divided into binary components by the mean value of the original Gaussian random field with equal x- and y-directional correlation lengths (isotropic). Diagnostic analyses of these simulations were similar to the findings of Walker et al. (2006). Generally, flow dimension stabilized at approximately radial. The diagnostic analyses of these simulations reinforced the findings of Walker et al. and were dissimilar to diagnostic analysis of WIPP field data.

Our next suite of simulations were conducted in fields with the same mean binary divide, but with anisotropy applied through a 1:10 ratio of the x- to y-directional correlation lengths. Pumping was simulated in fifty of these anisotropic fields with the only variability between each being different seed values used in their generation. Diagnostic analysis of simulated pumping in these fields produces a wide array of varying and stabilized flow dimension values, and showed the desired positive slope (subradial flow) characteristics typically seen in WIPP field data (Figure 6). We also note that several of the simulations that mimicked WIPP data had a final flow area shaped similarly to that of our conduits from the previous section.

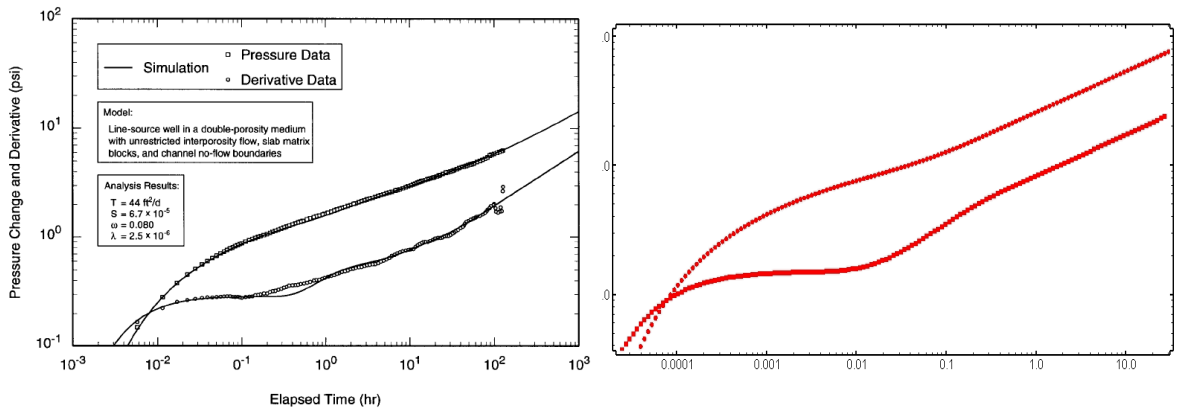

Figure 6: A visual comparison of a diagnostic analysis of a pumping test at the WIPP site (left) from Beauheim and Ruskauff (1998) and the diagnostic analysis of simulated pumping in one of our binary random fields (right).

From this we conclude that the positive slope characteristics often observed in data from the WIPP site and other fractured locations (e.g., Walker et al., 2006) likely reflect the geometry of the fracture networks and the strong transmissivity contrast between the fractures and surrounding host rock.

Conclusions

Field data from pumping tests performed in fractured dolomite in the vicinity of the WIPP site often exhibit subradial flow characteristics. In this paper, we demonstrate a physical connection of flow dimension to simple field geometries using equation (5) that allows us to simulate subradial, non-integer flow dimensions in a two-dimensional finite difference model. Using perturbation analysis combined with standard well-test analysis techniques, we are able to accurately estimate T and S values in these conduit geometries. We explored the effects of leakage into the conduits using various transmissive host materials and demonstrated what one would expect using diagnostic analysis: flow dimension increasing with time toward 2 (radial) and overall system transmissivity decreasing from that of the conduit toward that of the host material. Using anisotropic, binary random fields, we are able to produce a realistic representation of heterogeneity in a fractured medium. Diagnostic analysis of simulated pumping-tests in these fields produced persistent,

non-integer flow dimensions and positive-slope diagnostic characteristics commonly seen in WIPP field data.

We note that our conduits bound in a transmissive material and our binary random fields result in the same type of positive slope diagnostic. Conduits bound in transmissive material should eventually adopt a radial flow dimension as the contribution of the host material is realized unlike binary random fields which will have a flow dimension strictly tied to changes in the geometric system. In the case of field application, knowledge of the geologic material in which one is pumping may allow the analyst to assess the degree to which each is affecting well test response. Future study is needed to quantify and possibly separate the interplay of these two effects. In a fractured medium such as the Culebra Dolomite at the WIPP site where fracture transmissivity is typically no more than two orders of magnitude greater than the matrix transmissivity, the flow dimension inferred from a diagnostic plot is likely somewhat higher than the flow dimension of the fractured network alone due to the contribution of flow from the matrix. In such a case, the inferred value of transmissivity for the entire system is likely less than the transmissivity of the fracture network.

Acknowledgements

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References

Acuna, J.A., and Yortsos, Y.C., 1995, *Application of fractal geometry to the study of networks of fractures and their pressure transient*, Water Resour. Res., 31(3), 527-540.

Bangoy, L.M., Bidaux, P., Drogue, C., Plégat, R., and Pistre, S., 1992, *A new method of characterizing fissured media by pumping tests with observation wells*, J. Hydrol., 138(1-2), 77-88.

Barker, J.A., 1988, *A generalized radial flow model for hydraulic tests in fractured rock*, Water Resour. Res. 24(10), 1796-1804.

Beauheim, R.L., Roberts, R.M., and Avis, J.D., 2004, *Well testing in fractured media: flow dimensions and diagnostic plots*, J. Hydraul. Res., 42, 69-76.

Beauheim, R.L., and Ruskauff, G.J., 1998, *Analysis of Hydraulic Tests of the Culebra and Magenta Dolomites and Dewey Lake Redbeds Conducted at the Waste Isolation Pilot Plant Site*, SAND98-0049, Albuquerque, NM: Sandia National Laboratories.

Bourdet, D., Ayoub, J.A., and Pirard, Y.M., 1989, *Use of Pressure Derivative in Well-Test Interpretation*, SPE Formation Evaluation 4(2), 293-302.

Butler, J.J., and Liu, W.Z., 1991, *Pumping tests in non-uniform aquifers – the linear strip case*, J. Hydrol., 128(1-4), 69-99.

Ehlig-Economides, C.A., Joseph, J.A., Ambrose Jr., R.W., and Norwood, C., 1990, *A Modern Approach to Reservoir Testing*, J. Pet. Tech., 42(12), 1554-1563.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, *MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process*, U.S. Geological Survey Open-File Report 00-92, 121 p.

Kuusela-Lahtinen, A., Niemi, A., and Luukkonen, A., 2002, *Flow dimension as an indicator of hydraulic behavior in site characterization of fractured rock*, Ground Water, 41(3), 333-341.

Leveinen, J., 2000, *Composite model with fractional flow dimensions for well test analysis in fractured rocks*, J. Hydrol., 234(3-4), 116-141.

Oden, M., and Niemi, A., 2006, *From well-test data to input to stochastic continuum models: effect of the variable support scale of the hydraulic data*, Hydrogeol. J. 14(8), 1409-1422, doi: 10.1007/s10040-006-0063-y.

Roberts, R.M., 2006, *User's Manual for nSIGHTS, Version 2.40*, Sandia National Laboratories, Carlsbad, NM, ERMS 544708, 496 p.

Roberts, R.M., Beauheim, R.L., and Domski, P.S., 1999, *Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Final Report*, SAND98-2537, Albuquerque, NM: Sandia National Laboratories.

Tumlinson, L.G., Osiensky, J.L., and Fairley, J.P., 2006, *Numerical evaluation of pumping well transmissivity estimates in laterally heterogeneous formations*, Hydrogeol. J. 14(1-2), 21-30, doi: 10.1007/s10040-004-0386-5.

Walker, D.D., Cello, P.A., Valocchi, A.J., and Loftis, B., 2006, *Flow dimensions corresponding to stochastic models of heterogeneous transmissivity*, Geophy. Res. Lett. 33, L07407, doi:10.1029/2006GL025695.

Willmann, M., Carrera, J., Sánchez-Vila, X., and Vázquez-Suñé, E., 2007, *On the meaning of the transmissivity values obtained from recovery tests*, Hydrogeol. J. 15(5), doi: 10.1007/s10040-006-0147-8.

Zinn, B., and Harvey, C.F., 2003, *When good statistical models of aquifer heterogeneity go bad: A comparison of flow, dispersion, and mass transfer in connected and multivariate Gaussian hydraulic conductivity fields*, Water Resour. Res., 39(3), 1051, doi:10.1029/2001WR001146.

Biographical Information

Dale Bowman is a student intern at Sandia National Laboratories and is currently pursuing a Ph.D. in hydrology. He is investigating the characteristics of fractured systems that exhibit non-radial flow responses. Mr. Bowman received his B.S. in physics from Jacksonville University in 2000, and his M.S. degree in geological engineering from the University of Mississippi in 2002.

Randall Roberts is a Senior Member of Technical Staff at Sandia National Laboratories in Carlsbad, New Mexico. He manages the design and testing of Sandia's numerical well-test analysis code, nSIGHTS, and has 18 years of experience performing well-test analysis for nuclear-waste repository agencies around the world. Mr. Roberts received his B.S. in geology from North Dakota State University in 1986, and his M.S. degree in hydrology from New Mexico Institute of Mining and Technology in 1990.