Report for 2001CO261G: Use of Low-Cost Data to Simulate Fractured-Aquifer Watersheds for Management of Water Quality and Quantity

- Book Chapters:
  - Poeter, E., G. Thyne, G. VanderBeek, and C. Güler, 2003, Ground water in the Turkey Creek Basin of the Rocky Mountain Front Range in Colorado, in press in Engineering Geology in Colorado: Contributions, Trends, and Case Histories, ed. Douglas Boyer, Paul Santi, and Pat Rogers, Association of Engineering Geologists Special Publication 15 and Colorado Geological Survey Special Publication 55.
- Conference Proceedings:
  - Poeter, E., G. Thyne, J. McCray, J. Lee and G. VanderBeek, 2002, Low-Cost Data for Chyaracterization and Management of Fractured-Crystalline Aquifers, Proceedings of Fractured Rock Aquifers 2002, National Ground Water Association.
  - Vanderbeek, Greg, Eileen Poeter, Geoff Thyne, and John McCray, 2003, "Ground-water availability in Turkey Creek Basin, Colorado," Geol. Soc. Amer., Abstracts with Programs, 35 (5).
- Articles in Refereed Scientific Journals:
  - Wellman, Tristan, and Eileen Poeter, 2005, "Estimating spatially variable representative elementary scales in fractured architecture using hydraulic head observations," Water Resources Research, Vol. 41, No. 3.
  - Thyne, Geoff, Cuneyt Guler, and Eileen Poeter, 2004, "Sequential analysis of hydrochemical data for watershed characterization," Ground Water, v. 42, no. 5, pp 711-723.
- Other Publications:
  - Day, S., G. Thyne and E. Poeter, 2003, Using statistical analyses to characterize effects of population growth on water quality, Geol. Soc. Amer., Abstracts with Programs, 35(5), p. 30.
  - Thyne, G., S. Day, J.E. McCray, and E. Poeter, 2002, Evaluation of the effects of population growth in mountain watershed water quality, EPA Fractured Rock Aquifers 2002 Focus Conference, Denver, Colorado.
  - Wellman, Tristan and Eileen Poeter, 2004 in press, Optimizing the Predictive Accuracy of Hydraulic Head Observations to Delineate Continuum Scales in Phreatic Fractured Rock Aquifers, The Finite-Element Models, MODFLOW, and More 2004 conference, Carlsbad, Czech Republic.
  - Wellman, T. and E. Poeter, 2004, Evaluating Hydraulic Head Data as an Estimator for Spatially Variable Equivalent Continuum Scales in Fractured Architecture Using Discrete Feature Analysis, Dynamics of Fluids in Fractured Rock Conference, Sponsored by Lawrence Berkeley National Laboratory, February.
  - VanderBeek, G., Poeter, E.P., Thyne, G.D., and McCray, J.E., 2003. Ground-water availability in Turkey Creek Basin, Colorado, Geol. Soc. Amer., Abstracts with Programs, 35(5).

    - Dano, K., Poeter, E. and Thyne G., 2002, Geochemical and geophysical determination of the fate of septic tank effluent in a mountain watershed. Colorado. Geol. Soc. Am. Abstracts with Programs, 34(6).
    - VanderBeek G, Poeter E, Thyne G, McCray J.E., 2002, Ground-water Availability in Turkey Creek Basin, CO. GSA Abstracts with Programs, 33(4).
- Dissertations:
    - VanderBeek, Greg, 2003, Masters Thesis: "Estimating recharge and storage coefficient in a fractured rock aquifer, Turkey Creek Basin, Jefferson County, Colorado," Colorado School of Mines, Department of Geology and Geological Engineering, Masters Thesis.
- unclassified:
    - Day, S., G. Thyne, E. Poeter, and J.E. McCray, 2002, Effects of population growth on water quality in a mountain watershed, Geol. Soc. Amer. Abstracts with Programs, 34(6).
    - Day, Sharon, Geoff Thyne, John McCray, and Eileen Poeter, 2002, Evaluation of the effects of population growth on water quality in a mountainous watershed, Geol. Soc. Amer. Abstracts with Programs, 33(4).
    - Guler, C., and G. Thyne, 2002, Hydrochemical evolution model and characterization of flow in a fractured crystalline rock aquifer, Turkey Creek, Colorado, Geol. Soc. Amer. Abstracts with Programs, 34(6).
    - VanderBeek, Greg and Eileen Poeter, 2004, Water Resource Evaluation in Fractured Rock Aquifers Using Low-Cost Data, in preparation for Ground Water.
    - Thyne, G. D., C. Guler, and Poeter, E., 2004, in press for Ground Water Sequential Analysis of Hydrochemical Data for Watershed Characterization, Ground Water.
    - Wellman, TP and EP Poeter, 2003, Estimating Equivalent Continuum Scales in Fractured Aquifer Watersheds Using Discrete Feature Network Simulation, Fall AGU Meeting, Eos, 84 (46) abstract H42B-1071.

Report Follows

Problem and research objectives:

Mountain watersheds are primary water resources in the western United States, but we lack a scientific basis for making credible decisions regarding mountain land use. The rapid growth of population and development in mountain watersheds caused Jefferson County of Colorado to begin collecting data in a pilot study of ground-water resources in the Turkey Creek Watershed, a fractured-crystalline rock aquifer, typical of those that support individual domestic wells and sewage disposal systems for residents of the county and similar areas throughout Rocky Mountains, United States, and the world. A number of agencies funded data collection in the watershed, but the data are in different forms at many locations and have not been integrated into a model for a management tool. Although a ground-water model of the watershed is not expected to predict conditions in a particular well, it can provide information about future conditions in specific areas of the watershed. The proposed research utilizes a rare database from the watershed to complement and extend the work of the USGS by integrating data from many sources and developing models to: 1) better understand the flow system, 2) determine which low-cost data are instrumental in describing the system and which data reduce uncertainty, and 3) simulate the impacts of alternative development scenarios on ground-water levels, quality, and its to the total maximum daily load in streams. The value of the low-cost data will be confirmed using the more unusual data. The methods developed in this research will be useful for assessing the effects of population growth and development in other fractured-aquifer watersheds. The most difficult portion of this task is evaluating the fracture character of the aquifer. At this time, society cannot afford to characterize every detail of the subsurface water-bearing fractures to manage ground water. This project will use an elaborate database to determine the value of low-cost, holistic measures for evaluating the character of three-dimensional fracture flow and the scale at which equivalent porous media models can be used to predict impacts of management scenarios. Before collecting additional field data, modeling studies can glean information from existing data and determine which data will decrease uncertainty.

Methodology:

Task 1) compile and organize available data in a manner that will facilitate its dissemination;
Task 2) evaluate the data by viewing their distribution from a variety of perspectives;
Task 3) utilize the data to develop representative synthetic equivalent-porous-media and fracture flow models, with characteristics similar to that of Turkey Creek Watershed, to evaluate attributes generally believed to differentiate porous media and fracture flow systems and compare the character of hydraulic head and water quality observed in Turkey Creek Watershed to synthetic model behavior to estimate the scale at which Turkey Creek Watershed can be represented as equivalent porous media;
Task 4) use results of task 3 to generate models of Turkey Creek Watershed applicable to the management scale, calibrate the models using multiple regression techniques, and identify the data that are instrumental in describing the flow system, as well as, the type and location of new data that will improve the calibration or confirm the value of the low-cost data
Task 5) collect data identified in task 4 and incorporate the data into the model calibration to modify and improve the representative models;

Task 6) use the representative models to predict the impact, and associated uncertainty, of increased development on the quantity and quality of water resources;
Task 7) identify the data that are instrumental in making accurate predictions and evaluate the type and location of new data that would reduce prediction uncertainty or confirm the value of the low cost data;
Task 8) prepare a report and provide project findings to the public; and
Task 9) train future geological engineers while accomplishing the previous objectives.

Research Results:

Evaluation of front-range aquifers is only beginning and this project will continue to refine conceptual models and limit the possible range of interpretation through data mining, data collection, and analysis. Current analysis of the available data reveals:

- Water bearing fracture frequency is fairly uniform among rock types (~0.01 water-bearing fractures per foot) but fault zones and coarse granitic rocks have higher yields per fracture, thus are likely to have larger apertures and/or better connectivity.
- Fracture frequency (and yield) is uniform between 100 and 700 feet below ground surface.
- Well yields are higher in the fault zones and coarse granite, which occupy limited area in the upper portion of the basin.
- Depth to water averages less than 100 feet (30m).
- Water levels in wells mimic the topography, with coincident surface and ground-water divides.
- Water levels are responsive to spring recharge and generally exhibit a recession each water year.
- Precipitation is on the order of 20 in/yr (508 mm/yr) while evapotranspiration is on the order of 18 in/yr (457 mm/yr). Both are variable and known from a short period of limited spatial distribution, and thus introduce much uncertainty in the water budget.
- Water levels are declining.
- Storage in the basin is poorly characterized.
- Volume of annual recharge is uncertain but is currently estimated on the order of an inch per year, with 75% pumped, but only 7% consumed because of ISDS recharge.
- Estimates of recharge are uncertain due to the short period of record and limited spatial distribution, consequently the estimate may be somewhat more or substantially less.
- The uncertainty associated with the water budget renders assessment of the sustainable population difficult.
- Surface water chemistry appears to have been adversely impacted by population growth during and after the 1970s.
- Ground-water chemistry has been impacted by anthropogenic effects that include high nitrate and chloride and lower pH, primarily in areas of high population density.
- Limited duration and spatial distribution of data prevents determination of whether the system has reached equilibrium concentrations.
- Ongoing studies will reduce current uncertainties.

- Hydrochemical data, water levels, and response of wells to recharge suggest an equivalent porous medium can represent the watershed for large-scale evaluations.
- Equivalent porous media models can be used to integrate the data, design further data collection and provide predictions of the hydrologic response to further development with ever decreasing uncertainty as additional data are accumulated.

Uncertainty associated with the Turkey Creek Basin water budget is large, making it difficult to determine the population that can be reasonably supported in the basin. Short-term records can be misleading, and must be used with caution. Water quality has been impacted by development, but the limited period of record prevents us from knowing whether concentrations have reached a steady condition or are reflecting only the beginning of a long-term increase. Continued collection of hydrologic records and assessment modeling is necessary to reduce uncertainty.

Low-cost data are useful for characterizing the spatial distribution and magnitude of recharge, hydraulic conductivity, storage, and water consumption, in support of sustainability evaluation. For a system to be sustainable, long term recharge to the system must exceed long term consumption, and storage volume must be sufficient and its rate of decline slow enough to provide water during times of drought when use exceeds recharge.

In TCB, water use and return flow fractions are uncertain yielding a broad range of possible consumption on the order of 113,000 to 670,000 m^3/yr, with a likely value on the order of 340,000 m^3/yr (~90, 275, and 550 AFY for low, intermediate and high consumption rates). Recharge varies with location with a long-term spatially average rate between 0.3 in/yr and 2+ in/yr (750 to 5664 AFY), but is likely less than 1 in/yr and closer to the lower value. Hydraulic conductivity in TCB is low, ranging from 0.0001 to 0.003 ft/day. Consequently, drainage from the basin will be relatively slow, which should enhance sustainability through droughts. This is confirmed by the slow decline of water levels during the drought of 2001. Although different approaches to estimating specific yield produce wide variation, overall system behavior, given aquifer tests and water level declines during drought, suggest a specific yield is on the order of 0.6%. However this may reflect shallow conditions and specific yield may decrease with depth, which may cause the level of sustainability during droughts to decrease if averages use increases and lowers regional water levels.

Water use ranges from 100 to 200 AFY, assuming a 90% return, or from 300 AFY to 600 AFY for a 70% return. The long-term average recharge rate in the Turkey Creek Basin is expected to exceed 0.3 in/yr (~750 AFY), thus current water use in TCB appears to be sustainable on average. However, if the high estimate of use is more representative of current use, then sustainability of further growth is questionable. Additional monitoring of pumpage and return flow is warranted to obtain a better representation of consumptive water use.

Given that the current use is likely near the low estimate of the possible range of recharge to TCB, the long-term water level declines likely reflect a transition to a new equilibrium condition. In a fractured environment this may result in individual wells going dry (well yield below sustainable use), but deepening or relocating wells should yield a sufficient supply once a well-connected fracture is tapped by the well**.** Given that 1) the long-term average recharge is likely greater than average water consumption in TCB, and 2) available storage relatively high and

declines slowly (for a fractured rock aquifer), the current population of TCB is expected to be sustainable. However, specific yield is likely to decrease as water levels decline, and the maximum estimated current water use exceeds the minimum estimated recharge, thus continued refinement of these estimates is prudent.

Theoretical development of a method for estimating spatially variable representative elementary scale (RES) from low-cost data for the purpose of estimating the potential minimum scale of water resource management in a fractured aquifer led us to the following conclusions:

1. Porous media theory requires that the minimum scale of RES is constant in geometry and magnitude throughout a model domain. In naturally fractured media there is wide variation of connectivity, which we argue must lead to spatially variable RES. We have developed the HYRES approach to estimate spatially variable RES using readily-available low-cost field data.
2. Requiring absolute scale invariance of a parameter to define RES likely is not reasonable and arguably impossible for many fractured aquifers. We use scale derivatives of effective hydraulic head to estimate an appropriate tolerance, which we determine by dividing the global head gradient by the model area. Other tolerances may be appropriate and can be evaluated by plotting scale derivatives as a function of sampling area, in the manner described above. In practice an appropriate tolerance should be determined for each fractured aquifer.
3. We demonstrate the utility of estimating spatially variable RES using hydraulic head observations. HYRES is consistent with hydraulic head contours and fracture structure. Rather than analyzing structural behavior as a function of sampling volume, HYRES measures the variability of volume-normalized fluid energy. We argue HYRES is a more direct measure of flow behavior.
4. RES estimated via porosity indicates major regions where fractures have become disconnected, but exhibits significant noise in regions which are relatively homogeneous, as indicated by head contours and fracture structure. While RES determined from porosity can sense the structure of a discontinuity it does not account for fluid diversion around impermeable or low conductivity regions.
5. There is strong agreement between RES predicted by hydraulic conductivity and HYRES. Difficulty with using effective hydraulic conductivity results from its scale dependency, spatial variability, and the difficulty of measuring hydraulic conductivity relative to measure hydraulic head. Our analysis cannot distinguish which predictor is more accurate.
6. HYRES distinguishes disconnected regions with improved accuracy for larger data sets.
7. HYRES distinguishes clustered regions via varying tolerances. Varying tolerances in an iterative manner can identify clustering and regions with similar permeability. Regardless of the tolerance used for evaluating clustering, an appropriate tolerance should be employed for the HYRES analysis.
8. Varying hydraulic gradient does not affect HYRES. RES in a fracture flow system is independent of the fluid energy gradient, but dependent on spatial variability of fluid energy.
9. Varying flow direction causes a significant difference in predicted RES. These results do not contradict porous media theory but highlight the fact that discretely fractured systems will

seldom, if ever, approach theoretical porous media behavior. Subsequently a structural measure of continuum for fractured aquifers may not be appropriate, at least with respect to a flow continuum.

10. Multiple realizations are conducted using different numbers of observations. Accuracy and consistency of RES estimations improve with increasing number of observations.

We cannot determine nor numerically honor the true fracture architecture over large scales. Therefore determining a direct relation between complex, spatially variable fracture structure and RES may not be possible. We hypothesize RES can be determined by examining fluid behavior in an unknown fracture network by spatially analyzing hydraulic head observations. Our analyses compare HYRES to structural indicators of RES, and HYRES behavior under varying boundary conditions and fracture architecture. Our results indicate HYRES is an appropriate fluid-based approach to estimate spatially variable RES.

HYRES is an estimation of RES for fluid flow and provides some indication of subsurface structure, which may not completely coincide with transport RES. HYRES maps indicate areas with low fracture connectivity, thereby delineating zones where flow is channeled. In these regions it is reasonable to expect that transport is also channeled, possibly with a stronger control by the fracture network geometry. Therefore, HYRES maps provide some understanding of subsurface structure which is most pertinent to flow continuum but may have some first order applicability for transport.

HYRES improves with increasing data observations, in accordance with most analyses involving spatial data. Hydraulic head measurements are optimal because they are readily available and relatively inexpensive to collect. HYRES accuracy is likely a function of the number of data observations, the distribution of these points, and fracture architecture. In systems that are essentially homogeneous few points may characterize continuum behavior, whereas in highly heterogeneous zones more points may be required to adequately constrain spatially variable RES.

We argue that because HYRES analyzes variability of fluid energy it is a direct measure of flow behavior. Analyses support our hypothesis, indicating HYRES may provide the best estimation of large-scale flow continuum in fracture aquifers.

We have published the HYRES methodology to estimate spatially variable RES in fractured architecture in Water Resources Research.