

Data related uncertainties in the definition of wellhead capture zones

STEPHEN E. SILLIMAN & GLORIA MANTZ

University of Notre Dame, Notre Dame, Indiana 46556, USA

e-mail: silliman.1@nd.edu

Abstract The Local Gradient Estimate Technique (LGET) is extended to delineation of capture zones: (a) the LGET is extended to provide a reliable test for measurement errors, and (b) the LGET is also extended to delineation of uncertainty in the geometry and orientation of a capture zone. It is demonstrated that the LGET, in combination with monitoring wells, allows elimination of major measurement errors and estimation of capture zones, including uncertainty, with better performance than that obtained using two other common approaches to capture zone delineation.

INTRODUCTION

The impact of heterogeneity on a capture zone is an important factor in delineating the region around a wellhead which must be protected in order to ensure a safe water supply. Full assessment of heterogeneity and its impact on flow in the vicinity of a well is a complex hydrological problem which involves large characterization efforts. Silliman & Frost (1998) have developed a new technique, termed the Local Gradient Estimate Technique (LGET), for the assessment of the local hydraulic gradient. Extended by Mantz (1997), the LGET is a tool whereby simple water level data are used to provide insight into local and regional variations in groundwater flow and direct evidence of the presence of measurement errors.

In the present paper, two extensions of the LGET are briefly considered for application to wellhead capture zone assessment. This form of assessment is critical to protection of water supplies, particularly in rural areas, or for application in developing countries where resources for characterization of groundwater systems are limited. The first application is the identification of sampling error. The second is the characterization of uncertainty in a capture zone.

THE LGET

Groundwater moves in response to the hydraulic gradient. The LGET involves estimating the local hydraulic gradient *via* a local gradient estimate (LGE) derived from water levels (hydraulic heads) measured at three wells. As such, the LGET is based on a very simple, and inexpensive, field measurement.

Provided with more than three wells, a set of LGEs can be obtained by deriving one LGE for each combination of three wells. Sets of LGEs behave as illustrated in Figs 1(a) and 1(b), which show magnitude and orientation of the LGE plotted against the area enclosed by the three wells used to estimate the LGE. These plots converge to

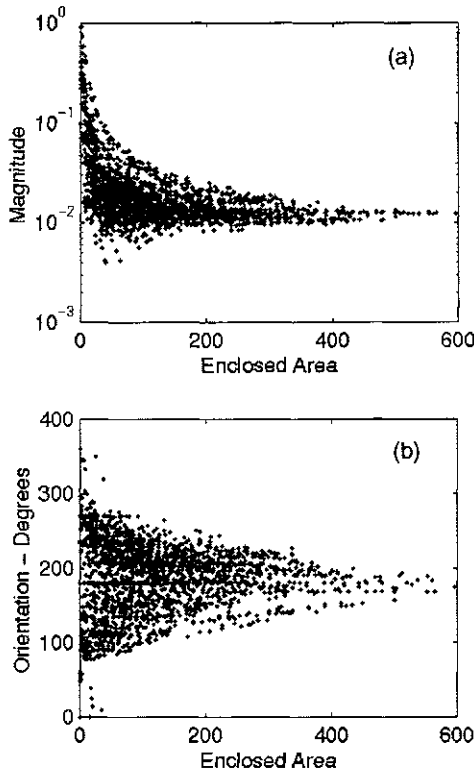


Fig. 1 Variation in the LGEs with area enclosed by the wells: (a) estimated magnitude, (b) estimated orientation.

the mean regional gradient. Background on the mathematical basis of the LGET can be found in Silliman & Frost (1998) and Mantz (1997).

THE LGET FOR IDENTIFYING MEASUREMENT ERROR

Mantz (1997) showed that many data sets published in the literature contain measurement errors which are so large that the associated estimates of the hydraulic gradient are effectively meaningless. As a result, Mantz suggests a statistical test to identify measurement errors, which is based on analysis of the LGEs as outcomes of a binomial process. Separate tests are conducted for both the magnitude and orientation estimates. For these tests, the data shown in Fig. 1 are subdivided by area and the distribution of the data along the vertical axis is interpreted in terms of a binomial distribution. “Success” in the classic sense of a binomial test (e.g. Ostle & Malone, 1988) is here defined as an LGE being within a specified range around the median (Mantz suggests bounds on the orientation equal to the median orientation $\pm 25^\circ$, and bounds on the magnitude of 0.65–1.35 times the median magnitude). Using standard statistical tests, each well is assessed to see if it has a disproportionately low number of successes, in which case the well is considered suspect.

Mantz (1997) describes a blind test involving addition of transcription and random errors to a database. Results, indicating the utility of this approach for eliminating measurement errors, include: (a) all transcription errors were identified; and (b) the LGET consistently identified locations with high measurement errors. In terms of capture zone identification, this method aids in eliminating significant measurement error (which can impact our estimation of the hydraulic gradient).

IDENTIFYING HETEROGENEITY NEAR THE PUMPING WELL

A second question which arises is whether the LGET provides a means of characterizing uncertainty in flow in the vicinity of a well. Figure 2 shows a wellhead surrounded by a group of 10 monitoring wells. Based on this design, 10 LGEs with equal area can be estimated and ranked (prior to the onset of pumping) to determine the maximum and minimum estimates of the magnitude and orientation of the gradient. Four individual capture zones can be estimated using the standard groundwater flow equation in conjunction with the following combination of estimates: (a) maximum orientation and minimum gradient, (b) maximum orientation and maximum gradient, (c) minimum orientation and minimum gradient, and (d) minimum orientation and maximum gradient. The final capture zone, incorporating local uncertainty, is the union of these four capture zones (Fig. 2).

The behaviour of this approach was compared with two classic capture zone delineation approaches: (a) measuring the mean gradient using three wells, and (b) estimating the capture zone as a circle of 1000 m radius. Two measures of behaviour were identified: (a) the “shared area”, equal to the percentage of the real capture zone which is enclosed by the estimated capture zone, and (b) the “wasted area”, equal to the area enclosed within the estimated capture zone which is not included in the real capture zone (as a percentage of the area of the real capture zone). The shared area is a measure of how well we have protected the wellhead. The wasted area is a measure of how overly restrictive the identified area is as compared to what was actually needed to protect the water supply.

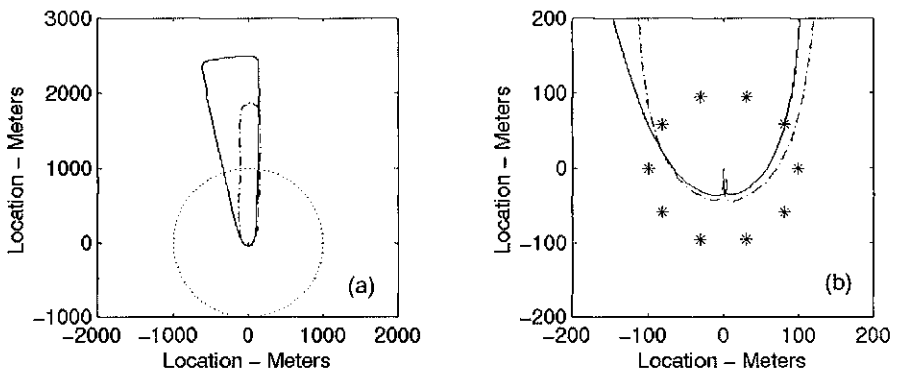


Fig. 2 Comparison of the LGET capture zones with the fixed radius and three well methods: (a) dotted line is fixed radius, dashed line is the 3-well method, and the solid line is the LGET capture zone; (b) location of the 10 monitoring wells (*) relative to the pumping well (o) and the central portion of the capture zones in (a).

Table 1 Summary of Monte Carlo results for estimation of capture area.

Estimator	% Shared area	% Wasted area
Fixed radius	85.9	553
3 Wells	52.0	47
LGET	67.5	182

The three methods were tested within numerically simulated aquifers. The mean performance is summarized in Table 1. The observation that the fixed radius provides the highest shared percentage is a direct result of stopping the capture zones after only five years of travel. This percentage would drop dramatically if the time period considered for the capture zone was increased. In terms of shared percentage, the LGET method provided much better performance than the three-well method.

In terms of wasted areas, the fixed radius performed poorly (as expected). In contrast, using the three-well method provided for the best performance. This latter result is related to the narrow capture zones produced by the three-well method. As a result, even though these plumes provided only slightly better than 50% shared area, there was little wasted area (~47%). Once again, the LGET provided results which fell between the other two methods as the LGET provides oriented plumes (as compared to the fixed radius method), but wider plumes (as compared to the three-well method) due to inclusion of the uncertainty in the hydraulic gradient (Fig. 2).

These results show that the LGET will allow capture zones to be estimated with higher shared areas than will be achieved with simple estimates of the regional gradient, and with lower wasted areas than will be observed with fixed radius methods. These improvements over the other techniques come at low cost as the LGET is based only on measured water levels and a reasonable number of monitoring wells.

Acknowledgements This work was partially supported through grants from the US Geological Survey and the National Science Foundation (through the Research Experience for Undergraduates programme).

REFERENCES

- Mantz, G. M. (1997) Assessment of the local gradient estimator technique under non-uniform gradients and measurement error. MSc Thesis, University of Notre Dame, Notre Dame, Indiana, USA.
- Ostle, B. & Malone, L. (1988) *Statistics in Research: Basic Concepts and Techniques for Research Workers*. Iowa State University Press, Ames, Iowa, USA.
- Silliman, S. E. & Frost, C. (1998) Monitoring hydraulic gradient using three-point estimator. *J. Environ. Eng.* 124(6), 517-523.