Effective Groundwater Model Calibration, with Analysis of Data, Sensitivities, Predictions, and Uncertainty

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Corrections and additional references

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The listed corrections are relative to the first printing of the book. Later printings were altered to include many of these corrections.

Corrections

Page	Correction
xviii	Norm Jones' affiliation should be Brigham Young University.
8	Section 1.3.1, line 1 and 2. Reword to "…produce model predictions that are accurate enough to be useful in assessing the consequences…"
18	Line 6. The problem can also be simulated using earlier versions of MODFLOW.
28	On line 7, the variable defined is the residual. Omit the word "weighted".
29	The more common form of the maximum-likelihood objective function is obtained by substituting in the maximum likelihood estimate of σ^2, which equals $(e^T\omega e)/n$. Making this substitution into equation 3.3 and eliminating constant terms yields $S'(b') = n \times \ln[(e^T\omega e)/n]$. Here, n = NOBS+NPR.
31	In the last line of equation 3.4, the square root should be omitted so that the relation is $\omega \propto V(\varepsilon)^{-1}$
33	First line of second paragraph. "models" should be "layers".
33	The last sentence of the third paragraph should read "The variance of the error can be derived from geostatistical arguments; see, for example, the option available in PEST (Doherty, 2005)."
49	- End of line 4. The equation number should be 4.3a. - Third line after eq. 4.3b. "section 3.4.4" should be "section 3.4.2"
50	- Line 10. "section 7.5.2" should be "section 7.3.2" - Section 4.3.4, first line. Replace "total" with "average". Division by ND in equation 4.6 results in this being an average. - In Equation 4.6, on the right-hand-side, the bracket should precede the summation. The summation precedes taking the square root.
70	In figure 5.1a, the results shown are for r = 1.
99	AICc, AIC, and BIC (equations 6.3 and 6.4) are more commonly calculated with $S'(b') = n \times \ln[(e^T\omega e)/n]$, where n = NOBS+NPR. See also the correction for page 29.
100	Four lines from the bottom. Replace the last word, "residuals" by "simulated values"

Page	Correction
102-103	In figures 6.1 and 6.2, using the standard error of the regression to label the vertical axes labeled "Weighted residuals" allows for a quick statistical check. If the weighted residuals are independent and normally distributed, only about 5 of 100 weighted residuals would be exceed two standard errors in absolute value. About 3 of 1000 would exceed three standard errors. Significant deviations indicate (a) correlations produced by the fitting of the regression (see section 6.4.6), improper weighting (see Guideline 6), nonrandom observation error, or model error.
103	Caption 6.2: The standard deviation ~~are~~ of the…
108	Figure 6.4: CALCUALTED to CALCULATED
116	Caption 6.7, line 3: "vertical grid lines are placed at" to "vertical axis has"
128	Line 4. Section 7.2.1 also should be listed.
157	The critical values for total and intrinsic model nonlinearity measure are: Greater than 1.0, highly nonlinear 0.01 to 0.9, moderately nonlinear 0.9 to 1.0, nonlinear Less than 0.01, effectively linear
136	Eq. 7.9. Definition for c_{ji} at bottom of the page. In the equation, the square root of the weight matrix $\boldsymbol{\omega}^{1/2}$ should be at the end of the equation, after the last $\mathbf{X}^{\mathrm{T}}$.
167	The definition of the identity matrix following equation 8.6 should be "(diagonal elements equal 1.0; others are 0.0)"
172	The reference for Good (2001) is listed below in this document.
191	In the middle of the page the definition of sensitivity should read as follows: "…with respect to the parameters, calculated at the optimal…"
196	In the heading labeled (b), "prediction scaled sensitivities" should be changed to "scaled sensitivities"
206	Toward the bottom of the page, the first line of the Problem should refer to Question 4 instead of 3.
208	Second line from the bottom of the page should refer to Question 5 instead of 4.
212	Third line from the bottom of the page should refer to Question 5 instead of 4.
236	Figure 9.5, heading of last column: W**EI**GHTED RESIDUAL
358	The first equation should be "$1/(sd_1^2 + sd_2^2 + sd_3^2 + \ldots)$"
392	Equation C.1. The first X should be the same as the other X's in this equation.
408	For Barlebo et al. (1996), the order of the two editors should be reversed and the name of the second editor should be spelled Heijde.
414	The following reference is missing: Good PI (2001). Resampling Methods- a practical guide to data analysis. Birkhauser.
420	For Poeter et al. (2005), the fifth author is missing. It should be Christensen S.

Additional References

While over 300 references are cited in the book, the topics covered have been the subject of considerable activity over more than three decades, and there are many additional works that could have been referenced. We do not expect to maintain a complete reference list for the topics of interest, but as we become aware of publications that might

be helpful to readers, we include them here with an indication of their relevance. We invite readers to contact us with suggestions of references to include here.

Banta, E.R., Hill, M.C., E.P. Poeter, J.E. Doherty, and J. Babendreier (2008). Building model analysis applications with the joint universal parameter identification and evaluation of reliability application programming interface (JUPITER API): Computers and Geoscience, 34: 310–319. doi:10.1016/j.cageo.2007.03.016. Journal article describing the JUPITER API mentioned on page 342.

Beven, Keith, Freer, Jim (2001). Equifinility, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. Journal of Hydrology, 249: 11-29. Related to references to Beven and Binley (1992) and Binley and Beven (2003), pages 11, 140,187, and 188.

Bohling, G. C. (2009), Sensitivity and resolution of tomographic pumping tests in an alluvial aquifer, Water Resour. Res., 45, W02420, doi:10.1029/2008WR007249. Reference for table 15.1.

Boyle, D. P., H. V. Gupta, and S. Sorooshian (2000), Toward Improved Calibration of Hydrologic Models: Combining the Strengths of Manual and Automatic Methods, Water Resour. Res., 36(12), 3663–3674, doi:10.1029/2000WR900207. Relates to section 3.2.3.

Chen, J., S. Hubbard, J. Peterson, K. Williams, M. Fienen, P. Jardine, and D. Watson (2006), Development of a joint hydrogeophysical inversion approach and application to a contaminated fractured aquifer, Water Resour. Res., 42, W06425, doi:10.1029/2005WR004694. Example for table 11.2.

Christensen, S., Doherty, J. (2008). Predictive error dependencies when using pilot points and singular value decomposition in groundwater model calibration. Advances in Water Resources 31 (4), 674–700. Related to chapter 6.

Cirpka, O. A., C. M. Bürger, W. Nowak, M. Finkel (2004). Uncertainty and data worth analysis for the hydraulic design of funnel-and-gate systems in heterogeneous aquifers, Water Resour. Res., 40, W11502, doi:10.1029/2004WR003352. Includes the effects of small-scale heterogeneity.

Dai, Z., Samper, J. (2006). Inverse modeling of water flow and multicomponent reactive transport in coastal aquifer systems, Journal of Hydrology, 327(3-4), 447-461. Additional example for Section 9.2.7.

Dausman, A.M., Doherty, J., Langevin, C.D., Sukop, M.C. (2008). Quantifying data contributions toward reducing predictive uncertainty in a variable-density flow and solute/heat transport model. In: MODFLOW and More: Ground Water and Public Policy, Proceedings of the International Conference of the International Ground Water Modeling Center. Colorado School of Mines, Golden, CO, pp. 320–324. Related to section 8.3.2. The statistic described is a variation of the OPR statistic.

Deng , H., M. Ye, M. G. Schaap, and R. Khaleel (2009), Quantification of uncertainty in pedotransfer function-based parameter estimation for unsaturated flow modeling, Water Resour. Res., 45, W04409, doi:10.1029/2008WR007477. Related to page 10.

Doherty, J., Hunt, R.J. (2009). Two statistics for evaluating parameter identifiability and error reduction. Journal of Hydrology 366, 119–127. Relates to chapter 4.

Doherty, John and R. J. Hunt (2010). Response to Comment on ''Two statistics for evaluating parameter identifiability and error reduction": Relates to chapter 4.

Doherty, J., Johnston, J.M., 2003. Methodologies for calibration and predictive analysis of a watershed model. Journal of American Water Resources Association 39 (2), 251–265. Related to chapter 5 and section 8.4.3 (The PEST prediction analysis capability calculated the nonlinear intervals described in section 8.4.3)

Fienen, M. N., J. Luo, and P. K. Kitanidis (2006), A Bayesian geostatistical transfer function approach to tracer test analysis, Water Resour. Res., 42, W07426, doi:10.1029/2005WR004576. Relates to page 10.

Fienen, M. N., T. Clemo, and P. K. Kitanidis (2008), An interactive Bayesian geostatistical inverse protocol for hydraulic tomography, Water Resour. Res., 44, W00B01, doi:10.1029/2007WR006730. Relates to p. 10.

Fienen, M.N., Muffles, C.T., Hunt, R.J. (2009). On constraining pilot point calibration with regularization in PEST. Ground Water. doi:10.1111/j.1745-6584.2009.00579. Relates to section G5.2. Includes criticism of Hill (2008)

Finsterle, S. (2000). Using the continuum approach to model unsaturated flow in fractured rock: Water Resour. Res., 36, 8, doi:10.1029/2000WR900122. The analysis of scale issues relates to section 9.2.3.

Finsterle, Stefan and Julie Najita (1998) Robust estimation of hydrogeologic model parameters: Water Resources Research, 34(11): 2939-2947. Relates to objective functions discussed in Chapter 3. Demonstrates advantage of robust regression for errors that are random and slightly systemic. Related to section G6.2.

Finsterle, S. and P. Persoff (1997). Determining Permeability of Tight Rock Samples using Inverse Modeling: Water Resour. Res., 33, 8, doi:10.1029/97WR01200, 1997. Methods are similar to those described by Hill and Tiedeman. Related to table 15.1 or 15.2.

Finsterle, S. and K. Pruess (1995). Solving the Estimation-Identification Problem in Two-Phase Flow Modeling: Water Resour. Res., 31, 4, doi:10.1029/94WR03038. The approach is very similar to the methods of Hill and Tiedeman. Exceptions include that an L1 norm is used to identify important parameters instead of an L2 norm like CSS.

Foglia, L., S.W.Mehl, M.C. Hill, Perona, P., Burlando, P. (2007). Testing alternative ground water models using cross validation and other methods: Ground Water, 45(5): 627-641, doi: 10.1111/j.1745-6584.2007.00341.x. Update of existing reference. Relates to chapter 4.

Foglia, L., M.C. Hill, S. W. Mehl, and P. Burlando (2009), Sensitivity analysis, calibration, and testing of a distributed hydrological model using error-based weighting and one objective function, Water Resour. Res., 45, W06427, doi:10.1029/2008WR007255. Example for table 15.1.

Gaganis, P., Smith, L. (2006). Evaluation of the uncertainty of groundwater model predictions associated with conceptual errors: A per-datum approach to model calibration, Advances in Water Resources, 29(4), 503-514. Relates to prediction uncertainty in Chapter 8 and Guideline 14, and discussion of model error uncertainties in Guideline 6.

Gallagher , M. R. and J. Doherty (2007), Parameter interdependence and uncertainty induced by lumping in a hydrologic model, Water Resour. Res., 43, W05421, doi:10.1029/2006WR005347. Relates to section 7.6 and Guideline 1.

Good PI (2001). Resampling Methods- a practical guide to data analysis. Birkhauser. Referenced on page 172 of the book.

Hill, M.C. (2008). Data error and highly parameterized groundwater models, *in* eds. Jens Christian Refsgaard and others, Calibration and reliability in groundwater modeling, Credibility of Modeling, Proceeding of the ModelCARE2007 Conference, Copenhagen, Denmark: IAHS Publication 320, p. 316-321. Relates to section G5.2. Criticisms by Fiene et al (2009) were addressed in Hill (2010) to the extent possible given the scope of Hill (2010). Additional criticisms are similarly subject to debate.

Hill, M.C. (2010). Comment on ''Two statistics for evaluating parameter identifiability and error reduction" by John Doherty and Randall J. Hunt: Journal of Hydrology, 380, p. 481-488. Relates to chapter 4.

Hill, M.C., Barlebo, H.C., and Rosbjerg, Dan (2006). Reply to Comment on "Investigating the Macrodispersion Experiment (MADE) site in Columbus, Mississippi, using a three-dimensional inverse flow and transport model" by Fred J. Molz, Chunmiao Zheng, Steven M. Gorelick, and Charles F. Harvey: Water Resources Research, 42, W06604, doi:10.1029/2005WR004624. Reference on page 45 with Barlebo et al. (2004).

Hunt, R.J., Doherty, J., 2006. A strategy of constructing models to minimize prediction uncertainty. In: MODFLOW and More 2006 – Managing Ground Water Systems: Proceedings of the 7th International Conference of the International Ground Water Modeling Center. Colorado School of Mines, Golden, CO, pp. 56–60. A rebuttal of Hill (2006). Relates to guideline 1 and section G5.2.

Hunt, R.J., Doherty, J., Tonkin, M.J., 2007. Are models too simple? Arguments for increased parameterization. Ground Water 45 (3), 254–262. Relates to guideline 1 and section G5.2.

Kavetski, D., and G. Kuczera (2007), Model smoothing strategies to remove microscale discontinuities and spurious secondary optima in objective functions in hydrological calibration, Water Resour. Res., 43, W03411, doi:10.1029/2006WR005195. Displays and discusses the effect of model nonlinearity on objective function surfaces for hydrologic models. Relates to section 3.5.

Kim , S. M., B. L. Benham, K. M. Brannan, R. W. Zeckoski, and J. Doherty (2007), Comparison of hydrologic calibration of HSPF using automatic and manual methods, Water Resour. Res., 43, W01402, doi:10.1029/2006WR004883. Relates to chapter 5.

Kowalsky, M. B., S. Finsterle, J. Peterson, S. Hubbard, Y. Rubin, E. Majer, A. Ward, and G. Gee (2005). Estimation of field-scale soil hydraulic and dielectric parameters through joint inversion of GPR and hydrological data: Water Resour. Res., 41, W11425, doi:10.1029/2005WR004237. A method is described for the joint use of time-lapse ground-penetrating radar (GPR) travel times and hydrological data to estimate field-scale soil hydraulic parameters. Good example of using geophysical data; relates to table 11.2.

Kunstmann, H., W. Kinzelbach, and T. Siegfried, (2002). Conditional first-order second-moment method and its application to the quantification of uncertainty in groundwater modeling, Water Resour. Res., 38(4):10.1029/2000WR000022. Example of first-order-second moment uncertainty analysis applied to a ground-water model and comparison with Monte Carlo analysis.

Kunstmann, H, Kastens, M. (2006) Determination of stochastic well head protection zones by direct propagation of uncertainties of particle tracks, Journal of Hydrology, 323(1-4), 215-229. Example for Guideline 14: comparison of using inferential statistics and Monte Carlo methods to quantify uncertainty in predicted capture zones.

LeFrancois, Michael and Eileen Poeter (2009). Use of observations below detection limit for model calibration: Ground Water, 47(2):228-236. Demonstration of SIM_ADJUST (Poeter and Hill, 2008). Relates to section 3.5.

Lehikoinen, A., J. M. J. Huttunen, S. Finsterle, M. B. Kowalsky, and J. P. Kaipio (2010). Dynamic inversion for hydrological process monitoring with electrical resistance tomography under model uncertainties: Water Resour. Res., 46, W04513, doi:10.1029/2009WR008470, 2010. Relates to table 11.2.

Li , X. and F. T.-C. Tsai (2009), Bayesian model averaging for groundwater head prediction and uncertainty analysis using multimodel and multimethod, Water Resour. Res., 45, W09403, doi:10.1029/2008WR007488. Relates to section 8.6.

Linde, N., S. Finsterle, and S. Hubbard, 2006, Inversion of tracer test data using tomographic constraints: Water Resour. Res., 42, W04410, doi:10.1029/2004WR003806. A method is described to invert tracer test data using zonation information obtained from two-dimensional radar tomograms to improve the (typically overly smooth) hydraulic conductivity fields obtained from conventional inversion of tracer test data. Synthetic test case. Relates to tables 11.2 and 15.2.

Mays, D.C., B. A. Faybishenko, and S. Finsterle (2002). Information entropy to measure temporal and spatial complexity of unsaturated flow in heterogeneous media: WaterResour.Res., 38, 1313, doi:10.1029/2001WR001185, 2002. The investigation of marginal value of additional data collection using randomly selected "virtual wells" is related to Hill and Tiedeman chapter 13.

Mehl, Steffen (2007). Forward Model Nonlinearity versus Inverse Model Nonlinearity Ground Water 45 (6) , 791–794 doi:10.1111/j.1745-6584.2007.00372.x. Investigates relation of forward and inverse model nonlinearity. Relates to section 1.4.1, p. 12-13.

Mishra, Srikanta (2004). Sensitivity analysis with correlated inputs – and environmental risk assessment example: Proceedings of the 2004 Crystal Ball User Conference, Print ISBN: 0-7803-8787-2, 8p. Example of using partial correlation coefficients from a Monte Carlo analysis. Relates to chapter 4 and guideline 3.

Mishra, Srikanta (2009). Uncertainty and sensitivity analysis techniques for hydrologic modeling: Journal of Hydroinformatics, 11(3). Compares global and local sensitivity and uncertainty methods. Relates to chapters 4 and 8 and guidelines 3 and 14.

Moridis, G., S. Finsterle, and J. Heiser, 1999, Evaluation of Alternative Designs for an Injectable Subsurface Barrier at the Brookhaven National Laboratory Site, Long

Island, New York: Water Resour. Res., 35, 10, doi:10.1029/1999WR900184. Innovative application of inverse methods similar to those of Hill and Tiedeman. Relates to table 15.1.

Mugunthan, P., and C. A. Shoemaker (2006). Assessing the impacts of parameter uncertainty for computationally expensive groundwater models, Water Resour. Res., 42, W10428, doi:10.1029/2005WR004640, A computationally efficient global optimization method and alternative to Monte Carlo for quantifying prediction uncertainty. Relates to Section 5.2 and Guideline 14.

Mukhopadhyay, S., Y. W. Tsang, and S. Finsterle (2009). Parameter estimation from flowing fluid temperature logging data in unsaturated fractured rock using multiphase inverse modeling: Water Resour. Res., 45, W04414, doi:10.1029/2008WR006869. A method is proposed to estimate fracture permeability from flowing fluid temperature log (FFTL) data. Good example of using temperature data; relates to section G4.4.

Pappenberger, F., K. J. Beven (2006). Ignorance is bliss: Or seven reasons not to use uncertainty analysis, Water Resour. Res., 42, W05302, doi:10.1029/2005WR004820. Discussion of arguments against conducting uncertainty analysis, and why the arguments are untenable.

Poeter, E.P., and M.C. Hill (2007). MMA, A computer code for Multi-Model Analysis: U.S. Geological Survey Techniques and Methods 6-E3, 113 p. http://typhoon.mines.edu/freeware/mma/. Updated reference for publications already cited.

Poeter, Eileen P. and M.C. Hill (2008). SIM_ADJUST -- A Computer Code that Adjusts Simulated Equivalents for Observations or Predictions: International Ground Water Modeling Center, Golden, Colorado, Report GWMI 2008-01, 28p. Provides a method for addressing abrupt model nonlinearities, such as observed heads for which the associated model cell goes dry. Relates to section 3.5.

Post, Vincent, Henk Kooi, Craig Simmons (2007) Using Hydraulic Head Measurements in Variable-Density Ground Water Flow Analyses Ground Water 45 (6) , 664–671 doi:10.1111/j.1745-6584.2007.00339.x. Use hydraulic tests and tidal effects, and pilot points without and with geologic structure.

Sanz, E. and Voss, C.I., 2006, Inverse modeling for seawater intrusion in coastal aquifers: Insights about parameter sensitivities, variances, correlations and estimation Procedures derived from the Henry problem: Advances in Water Resources v. 29, no. 3, p. 439-457.

Šimunek, J., and Nimmo, J.R., 2005, Estimating soil hydraulic parameters from transient flow experiments in a centrifuge using parameter optimization technique: Water Resources Research, v. 41, no. 4, doi:10.1029/2004WR003379.

Sun, A. Y., S. L. Painter, and G. W. Wittmeyer (2006), A constrained robust least squares approach for contaminant release history identification, Water Resour. Res., 42, W04414, doi:10.1029/2005WR004312. Additional example for Section 9.2.2.

Tiedeman, C.R., Hill. M.C. (2006). Tools for ground-water flow and transport model calibration, sensitivity analysis, error and uncertainty evaluation, and assessment of prediction data needs, in Thangarajan, M., ed., Groundwater: Resource Evaluation,

Augmentation, Contamination, Restoration, Modeling and Management: New Delhi, Capital Publishing, p. 237-282. Relates to section 9.2.

Tonkin , M. and J. Doherty (2009), Calibration-constrained Monte Carlo analysis of highly parameterized models using subspace techniques, Water Resour. Res., 45, W00B10, doi:10.1029/2007WR006678. Related to chapter 8 and section G5.2.

Tonkin , M., J. Doherty, and C. Moore (2007), Efficient nonlinear predictive error variance for highly parameterized models, Water Resour. Res., 43, W07429, doi:10.1029/2006WR005348. Related to chapter 8 and section G5.2.

Tonkin, M., C.R. Tiedeman, D.M. Ely, and M.C. Hill (2007). OPR-PPR, a computer program for assessing data importance to model predictions using linear statistics: U.S. Geological Survey Techniques and Methods 6-E2, 115p. http://water.usgs.gov/software/OPR-PPR.html. Updated reference for publications already cited.

Tsai , F. T.-C. (2006), Enhancing random heterogeneity representation by mixing the kriging method with the zonation structure, Water Resour. Res., 42, W08428, doi:10.1029/2005WR004111. Relates to guideline 1.

Tsai , F. T.-C. and X. Li (2008), Inverse groundwater modeling for hydraulic conductivity estimation using Bayesian model averaging and variance window, Water Resour. Res., 44, W09434, doi:10.1029/2007WR006576. Relates to page 10.

Tsai , F. T.-C. and X. Li (2010), Reply to comment by Ming Ye et al. on "Inverse groundwater modeling for hydraulic conductivity estimation using Bayesian model averaging and variance window", Water Resour. Res., 46, W02802, doi:10.1029/2009WR008591. Relates to page 10.

Tsai , F. T.-C. and W. W.-G. Yeh (2004), Characterization and identification of aquifer heterogeneity with generalized parameterization and Bayesian estimation, Water Resour. Res., 40, W10102, doi:10.1029/2003WR002893. Relates to page 10 and Guideline 1

Vasco, D.W. and S. Finsterle (2004). Numerical trajectory calculations for the efficient inversion of transient flow and tracer observations: Water Resour. Res., 40, W01507, doi:10.1029/2003WR002362. This alternative to the modified Gauss Newton method related to Hill and Tiedeman chapter 5.The field example relates to table 15.1.

Vermeulen, P. T. M., C. B. M. te Stroet, A. W. Heemink (2006). Model inversion of transient nonlinear groundwater flow models using model reduction, Water Resour. Res., 42, W09417, doi:10.1029/2005WR004536. Alternative methods for inverse modeling of computationally demanding models. Relates to Section 15.1.

Wagener, Thorsten, H.S. Wheater, and Hoshin V. Gupta (2004). Rainfall-runoff modeling in gauges and ungauged basins: Inperial College Press, London, 271 p. Relates to page 10.

Wagener, Thorsten and Hoshin V. Gupta (2005). Model identification for hydrological forecasting under uncertainty: Stoch Environ Res Risk Assess, 19:378-387.

Yapo, Patrice Ogou, Hoshin Vijai Gupta and Soroosh Sorooshian (1996). Automatic calibration of conceptual rainfall-runoff models – sensitivity to calibration data: Journal of Hydrology, 181(1-4):23-48. Related to section 3.2.3. Related to page 10.

Yapo, Patrice Ogou, Hoshin Vijai Gupta and Soroosh Sorooshian (1998a). Multi-objective global optimization for hydrologic models: Journal of Hydrology 204(1-4):83-97. Related to section 3.2.3.

Yapo, Patrice Ogou, Hoshin Vijai Gupta and Soroosh Sorooshian (1998b). Toward improved calibration of hydrologic models -- Multiple and noncommensurable measures of information: Water Resources Research, 34(4):751-763. Related to section 3.2.3.

Ye , M. and R. Khaleel (2008), A Markov chain model for characterizing medium heterogeneity and sediment layering structure, Water Resour. Res., 44, W09427, doi:10.1029/2008WR006924. Relates to page 10.

Ye , M., R. Khaleel, and T.-C. J. Yeh (2005), Stochastic analysis of moisture plume dynamics of a field injection experiment, Water Resour. Res., 41, W03013, doi:10.1029/2004WR003735. Related to page 10.

Ye , M., R. Khaleel, M. G. Schaap, and J. Zhu (2007), Simulation of field injection experiments in heterogeneous unsaturated media using cokriging and artificial neural network, Water Resour. Res., 43, W07413, doi:10.1029/2006WR005030. Related to page 10.

Ye , M., D. Lu, S. P. Neuman, and P. D. Meyer (2010), Comment on "Inverse groundwater modeling for hydraulic conductivity estimation using Bayesian model averaging and variance window" by Frank T.-C. Tsai and Xiaobao Li, Water Resour. Res., 46, W02801, doi:10.1029/2009WR008501. Related to page 10.

Ye , M., P. D. Meyer, and S. P. Neuman (2008), On model selection criteria in multimodel analysis, Water Resour. Res., 44, W03428, doi:10.1029/2008WR006803. Related to section 8.6.

Ye , M., S. P. Neuman, A. Guadagnini, and D. M. Tartakovsky (2004), Nonlocal and localized analyses of conditional mean transient flow in bounded, randomly heterogeneous porous media, Water Resour. Res., 40, W05104, doi:10.1029/2003WR002099. Related to page 10.

Ye , M., S. P. Neuman, and P. D. Meyer (2004), Maximum likelihood Bayesian averaging of spatial variability models in unsaturated fractured tuff, Water Resour. Res., 40, W05113, doi:10.1029/2003WR002557. Related to section 8.6.

Ye , M., S. P. Neuman, P. D. Meyer, and K. Pohlmann (2005), Sensitivity analysis and assessment of prior model probabilities in MLBMA with application to unsaturated fractured tuff, Water Resour. Res., 41, W12429, doi:10.1029/2005WR004260. Related to section 8.6 and table 15.2.

Yeh , T.-C. J., M. Ye, and R. Khaleel (2005), Estimation of effective unsaturated hydraulic conductivity tensor using spatial moments of observed moisture plume, Water Resour. Res., 41, W03014, doi:10.1029/2004WR003736. Relates to Guideline 4 and table 15.1.

Zhang, Y., H. Liu, Q. Zhou, and S. Finsterle (2006). Effects of diffusive property heterogeneity on effective matrix diffusion coefficient for fractured rock: Water Resour. Res., 42, W04405, doi:10.1029/2005WR004513, 2006. The analysis of scale issues relates to section 9.2.3.

Zimmerman, D.A., Hanson, R.T., and Davis, P.A., 1991, A comparison of parameter estimation and sensitivity analysis techniques and their impact on the uncertainty in ground water flow model predictions: U.S. Nuclear Regulatory Commission NUREG/CR-5522 (Sandia National Laboratories SAND90-0128), vp. An example of using particle tracking to simulate equivalents to observations. Relate to Guideline 4 and Table 15.2.