Uncertainty Analysis of Mound Monitoring for Recharged Water from Surface Spreading Basins

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Abstract: This study has conceptually reviewed issues related to implementation of a groundwater mound monitoring well (GMMW) for monitoring recharged water from a surface spreading basin with emphasis on uncertain hydrogeological conditions. For this, we selected a recharge site in the City of Mesa, Ariz., that is characterized with near-surface clay lenses of low permeability. A geostatistical simulation technique was used for generating hydrogeological fields under the recharge basin, using soil boring logs and historical hydrological data. More than 50 hydrogeological fields were generated and used for modeling. Five scenarios were formulated with varying parameter values and different initial and boundary conditions, and each scenario was evaluated with the 50 hydrogeological fields generated. Results of this study indicate that travel times to the mound may vary by over one order of magnitude and the use of a GMMW will only be practical for regulatory compliance in a homogeneous system.

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Introduction

A growing number of communities have been motivated in the last few decades to implement water reuse. The need for additional water resources in some urban areas has made water reclamation for nonpotable reuse more feasible than developing new sources of fresh water. This trend extends to indirect potable reuse in some arid urban areas.

There are many issues to review in indirect potable reuse, due to concerns with possible chemical and microbial contamination. Even if analytical tests and toxicological and epidemiological studies show no significant health risks (NRC 1998), these concerns create uncertainties regarding the potential health risks of drinking reclaimed water. Therefore, the NRC (1998) viewed planned use of reclaimed water to augment potable water supplies as "a solution of last resort," and recommended safety measures such as the use of multiple barriers with strict performance evaluation and monitoring.

Strict guidelines require a minimum horizontal separation of 500 ft and a minimum retention time of 6 months as barriers for indirect potable reuse with surface spreading basins. In a discussion about monitoring (Crook et al. 2000), the use of a groundwater mound monitoring well (GMMW) for surface recharge basins was addressed as follows: "Using the new sampling technology, it is possible to collect water quality samples from the mound above the point at which it mingles with the native groundwater." [The point is defined as the groundwater mound monitoring point (GMMP) for convenience.] There will be many GMMPs in the mound and some of them will be selected as locations for GMMWs. The concept was to allow for compliance with water quality standards just before recharged water mixes with the native groundwater.

The GMMW should be located to sample the earliest waves of infiltration under various operational conditions of surface recharge basins, to take samples from each wet/dry cycle before infiltrating water mixes with the native groundwater. It is quite possible that the infiltrating water paths vary between cycles as initial moisture conditions change. McCord et al. (1997) reported that even where application of water to the ground surface is relatively spatially uniform, unsaturated fluid fluxes in the underlying soils are often highly spatially variable since material parameters usually display spatial variations within a geologic formation. Because of that, Gelhar and Axness (1983) considered a medium heterogeneity with random changes in components. The current practices for determining infiltration, however, rely on limited data to cover such geologic variations, and thus the estimation of the paths inevitably bears a high degree of uncertainty.

The technical issues regarding the field application of the GMMW concept are as follows: Identifying the earliest wave of infiltration from a surface basin to the GMMPs for each cycle of operation; and locating one or multiple GMMPs as GMMWs that will catch the earliest waves with a given probability. To effectively deal with the two technical issues, we need to estimate the uncertainties in flowpaths in relation to heterogeneous hydrogeologic conditions as well as other operational conditions. This study was initiated to estimate the uncertainty of these issues for the application of the GMMW concept. The uncertainty was analyzed with emphasis on heterogeneous hydrogeologic conditions

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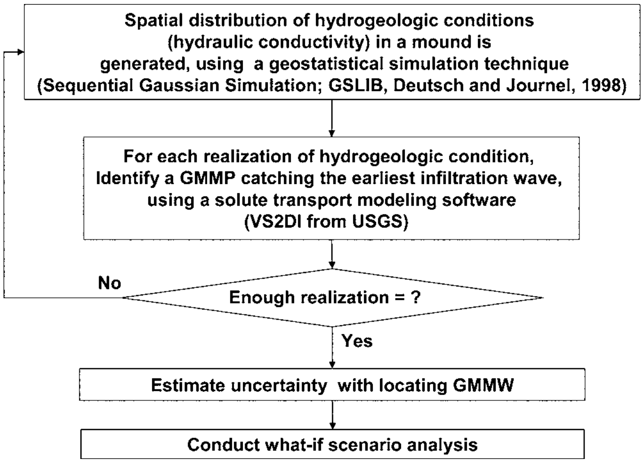


Fig. 1. Analysis methods and procedures

below a surface recharge basin, recognizing there are uncertainties from other sources.

Methods and Procedures

The methodology that this study adopts to estimate the uncertainties discussed above is represented in Fig. 1 and briefly introduced as follows:

1. Simulation of infiltration waves for a solute under various hydrogeologic conditions that were generated with geostatistical simulation techniques using real field data.
2. For each simulation, travel time estimations were made for a solute to points just above native groundwater. Selection of the points was based on compliance with the GMMW concept (Crook et al. 2000).
3. A point was selected with the shortest travel time as a GMMP for the realization.
4. Hundreds of simulations were done to locate an array of GMMPs and select some of them as GMMWs with a certain level of probability of sampling the earliest infiltration waves.
5. What-if scenarios were done to gain insight into related issues. For example, evaluation of hydrogeologic conditions, of initial and boundary conditions, and of modeling parameters for the location of GMMW and sampling requirements (for estimating soil and other hydrogeologic conditions). In addition, the cost effectiveness of the field application of the GMMW concept was considered.

Geostatistical Simulation

To generate hydrogeologic conditions from limited data, geostatistical simulation techniques were used in this study. Geostatistics are a collection of statistical methods for describing the spatial continuity by adopting classical regression techniques. It is a useful tool to analyze and interpret the uncertainty caused by limited sampling data and for providing a prediction of the probable or possible spatial distribution of the subsurface. The geostatistical methods selected for this study are as follows:

Variogram

Typical methods for describing spatial variation (or continuity) of geoenvironmental data include correlogram (or correlation function) and variogram. A variogram is a plot of the average squared differences between paired data values as a function of separation distance and a correlogram is a plot of the correlation coefficient between paired data values as a function of separation distance. For this research, variograms were used.

Kriging

The word "kriging" is synonymous with "optimal prediction" and kriging is a weighted moving average technique for interpolating unknown values from data observed at known adjacent locations. There are many kriging techniques that include simple kriging, ordinary kriging, factorial kriging, cokriging, nonlinear kriging, indicator kriging, and probability kriging (Deutsch and Journel 1998). Which one to use depends on the quantity and quality of data, types of data, purposes of analysis, and other field conditions. This research uses simple and ordinary krigings with software developed by Deutsch and Journel (1998).

Geostatistical Simulation

The geostatistical simulation used was a Monte Carlo simulation for generating spatial distribution of a property under study, based on a variogram model chosen to represent a probability distribution of the property. Different from geostatistical estimation, geostatistical simulation cannot only reproduce an accurate spatial distribution but also generate many equally probable alternative distributions (Desbarats 1996). This feature allows for a more realistic assessment of uncertainty from sampling in heterogeneous hydrogeologic conditions.

Sequential Gaussian simulation is used in this research and its procedure is briefly outlined as follows (Desbarats 1996; Deutsch and Journel 1998):

1. A set of data values at scattered field locations was simulated with conditional probability models, i.e., variogram models.
2. A random point was selected where there is not yet any simulated or measured data value.
3. Both measured and simulated data values were used to calculate the ordinary kriging estimate and corresponding error variance. These are the mean and variance of the conditional distribution of the unknown value at the point, given the set of known values from the surrounding area.
4. A value was randomly selected from the conditional distribution for the point.
5. This value was added to the set of simulated vales and returned to Step 2 until values at all points are obtained.

Once the values at all points are obtained, a simulation was done. For multiple simulations, this procedure was repeated. From the results of multiple simulations, the uncertainty was estimated. The software package GSLIB developed by Deutsch and Journel (1998) was used for this simulation.

Solute Transport Modeling—VS2DI

VS2DI from USGS (2000) consists of three components: (i) VS2DTI; (ii) VS2DHI, for simulating fluid flow and energy (heat) transport; and (iii) VS2POST, a stand-alone postprocessor, for viewing results saved from previous simulation runs (USGS 2000). VS2DTI is a graphical software package for simulating flow and transport in variably saturated porous media. The model can analyze problems in one or two dimensions using either Cartesian or radial coordinate systems. VS2DTI solves the modified Richard's equation for fluid flow, and the advection–dispersion equation for solute transport. The modified Richard's equation is $S(\partial h/\partial t)=\nabla\bullet[K(p)\nabla h]+Q$, where S=storage term (L^{-1}), repre-

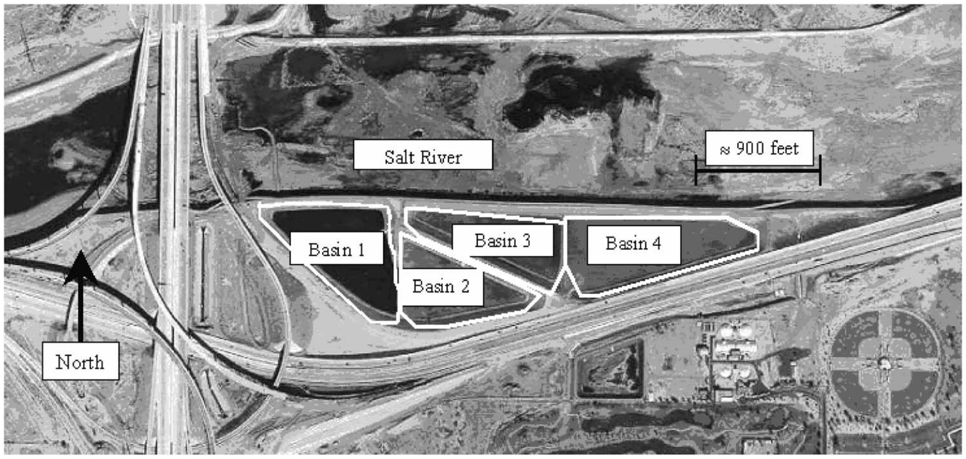


Fig. 2. Northwest Water Reclamation Plant, city of Mesa, Ariz.—example site

senting the specific moisture capacity for unsaturated conditions and specific storage for saturated conditions; $\partial h/\partial t$=change in total hydraulic head (h) with respect to time (t)(LT^{-1}); p=liquid pressure head (L); K=hydraulic conductivity and a function of p(LT^{-1}); ∇=gradient with respect to horizontal (X) and vertical (Z) directions (L^{-1}); and Q=general source/sink flux $[L(LT)^{-1}]$. At each node of the grid, Richard's equation is approximated by a finite-difference equation and solved simultaneously for each time step (Healy 1990).

Modeling and Results

A recharge facility at the Northwest Water Reclamation Plant (NWWRP) operated by the City of Mesa, Ariz., was selected as an example site for this research (Fig. 2). Data necessary for this research were obtained from previous studies that include the works of Johnson (2000), Schönheinz and Drewes (2000), and AWWARF (2001).

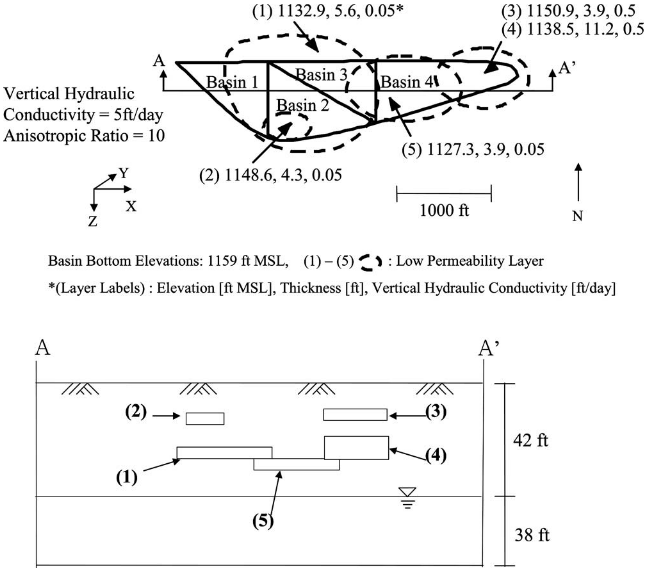


Fig. 3. Spatial distribution of hydraulic conductivity (Johnson 2000, with permission)

For the objectives of this study, i.e., reviewing conceptually the applicability of the GMMW concept, the modeling and analysis approaches are simplified as follows:

- Modeling the site in two dimensions (2D) using only x and z directions ($A-A'$ in Fig. 3), including only a mound under the basins.
- Considering only hydrogeological conditions represented by spatial distribution of horizontal and vertical hydrologic conductivities.

The effects of initial moisture content and surface loading conditions on the GMMW concept was reviewed with sensitivity analysis.

Site Description

The site located in Mesa, Ariz., recharges groundwater to the East Salt River Valley (ESRV) subbasin of the Salt River Valley (SRV) groundwater basin (Johnson 2000). The 27 acres of recharge basins are arranged as shown in Fig. 3. The cross section of $A-A'$, with a width of 6,000 ft and a depth of 80 ft was modeled. The groundwater table was 42 ft deep below the basin surface and, therefore, 42 ft was considered for the unsaturated flow modeling and a layer of 38 ft was included as the saturated zone. All basins had a width of 1,000 ft except Basin 4 with a width of 1,100 ft. In addition, previous studies have shown that using the actual operational data from November 1990 to July 1999, the actual volume of water recharged at the site averaged 3.5 million gallons per day (MGD).

The SRV basin consists of three hydrogeologically distinct units; the Lower Alluvial Unit (LAU), the Middle Alluvial Unit (MAU), and the Upper Alluvial Unit (UAU). A previous study noted that "the UAU underlying the site has a higher fraction of fine-grained material that is generally observed at other areas im-

Table 1. NWWRP Recharge Rates (Johnson 2000, with permission)

Basin	Average observed rate (ft/day)	Simulated rate (ft/day)
1	0.60	0.65
2	0.22	0.21
3	0.26	0.25
4	0.41	0.41

Fig. 4. NWWRP boring logs in 2D (7.5× vertical exaggeration). Note: textural class shown in Fig. 8 has been used.

mediately adjacent to the Salt River channel." Using intensive piezometric data collected during July–August 1999 and March 2000 and FEMWATER model calibration results, Johnson (2000) generated a spatial distribution of the hydraulic conductivity, including low-permeability layers, as shown in Fig. 3. Five layers of low permeability were identified and the remaining layers had a vertical conductivity of 5 ft/day and an anisotropic ratio of 10 throughout.

Modeling Initiation

Initial modeling of the site for this study was done as follows.

Groundwater Table—Static

The duration of infiltration in the mound on which this study focuses was only a couple of days or less. Fluctuations of the native groundwater table were, therefore, assumed negligible.

Initial Moisture Content

Two extreme conditions were assumed for analysis and discussion. The first one was a dry condition that might occur after an extended drying cycle. A moisture content, θ, of 0.23 was used from the surface to the capillary infringe zone (i.e., the tension-saturated zone) located just above the groundwater table. The second one was a wet condition in which the vadose zone was almost saturated (i.e., $\theta \approx 0.4$). Based on field data, the wet condition was most representative of operating conditions. The range of values was used to test the GMMW concept, since it is known that water content can significantly affect unsaturated flow (Yeh et al. 1985; Mantoglou and Gelhar 1987; Green and Freyberg 1995).

Surface Recharge Rates

The simulated recharge rates developed by Johnson (2000) in Table 1 were used in this study, which Johnson (2000).

Wet/Dry Cycles

Many wet/dry cycle variations are conceivable, however, only two cases were simulated to provide a basis for discussion on implementation of the GMMW concept. The first case assumes that all the basins begin to recharge at the same time for periods of 40 and 64 days, with no dry cycle, with the simulated rates shown in Table 1. This was to generate the earliest waves of infiltration if all the basins recharge continuously and simultaneously. The other case used a cycle of 3 days wetting and 5 days drying for each basin for a period of 40 and 64 days with a recharging order of Basins 3, 1, 4, and 2, a day apart from each other. This order was obtained from the July 1999 field observation (Johnson 2000).

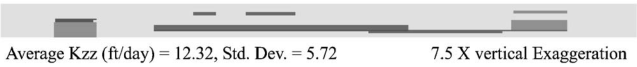


Fig. 5. Spatial distribution of hydraulic conductivity in 2D. Note: textural class shown in Fig. 8 has been used.

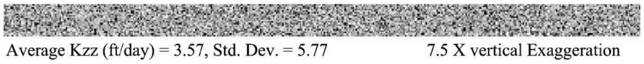


Fig. 6. Spatial distribution of hydraulic conductivity (from soil boring logs). Note: textural class shown in Fig. 8 has been used.

Development of Variogram

A variogram of hydraulic conductivity was developed from a set of field data to generate the probability of its spatial distribution. The field data were obtained from the boring log data and other hydrogeological parameters used in previous studies Corkhill et al. (1993), Hydrosystems (1995), and Dames and Moore (1994). For this research, all these data in 3 dimensions (3D) were transformed into (2D) as follows: The soil boring logs in 3D were excerpted into 2D (Fig. 4). Also, the distribution in Fig. 3 was transformed into the one in 2D in Fig. 5.

From the data in 2D, the variogram model generated spatial distributions of hydraulic conductivity. Vertical hydraulic conductivities were assigned to each soil type (i.e., 0.00467 ft/day to clayey material, 0.25 ft/day to silty material, and 15 ft/day to clean material, as shown in a textural class in Fig. 8) to conduct geostatistical simulation. A distribution generated from the data is shown in Fig. 6, which has an (arithmetic) average of vertical hydraulic conductivity of 3.57 ft/day with a standard deviation of 5.77 ft/day. The values indicate that the distribution from the soil boring logs is out of the range and too dense to be realistic, considering that the average of the vertical hydraulic conductivity in the NWWRP mound was found to vary from 5 to 300 ft/day in the previous studies. It suggested that the data in 2D developed from the soil boring logs cannot be used for generating a variogram model for our analysis.

The average of the distribution shown in Fig. 5, i.e., distribution of Johnson (2000), was 12.32 ft/day. Since it was in the range, the distribution of Johnson (2000) was selected for providing a set of the field data for developing a variogram model as follows. The area was divided into 8,400 grids of 2 ft by 15 ft

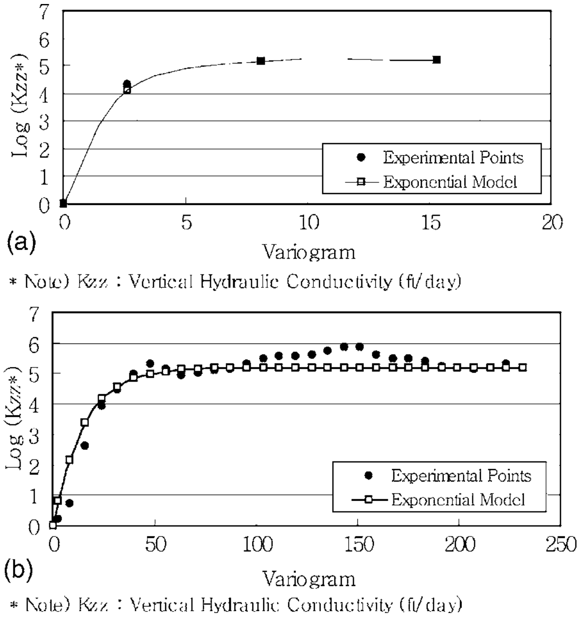
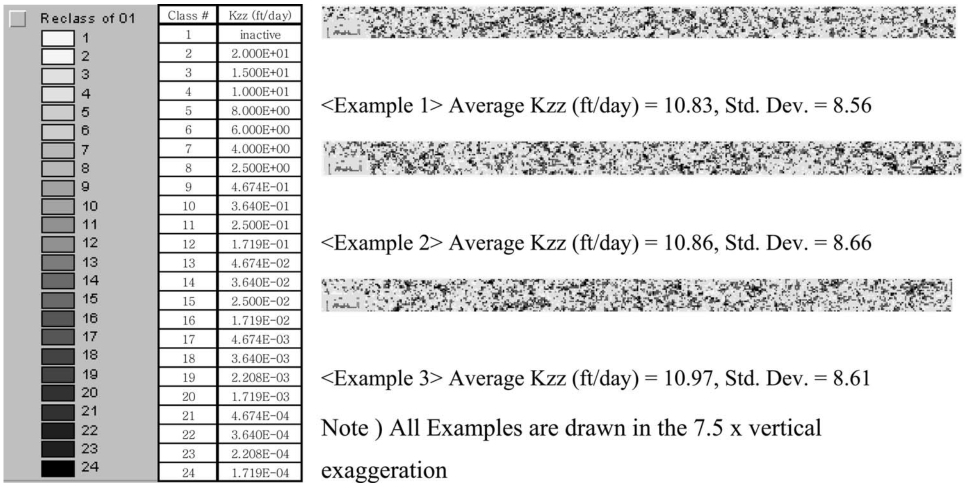


Fig. 7. Variograms for the example site: (a) variogram in the north–south direction; (b) variogram in the east–west direction



Class #	Kzz (ft/day)
1	inactive
2	2.000E+01
3	1.500E+01
4	1.000E+01
5	8.000E+00
6	6.000E+00
7	4.000E+00
8	2.500E+00
9	4.674E-01
10	3.640E-01
11	2.500E-01
12	1.719E-01
13	4.674E-02
14	3.640E-02
15	2.500E-02
16	1.719E-02
17	4.674E-03
18	3.640E-03
19	2.208E-03
20	1.719E-03
21	4.674E-04
22	3.640E-04
23	2.208E-04
24	1.719E-04

<Example 1> Average Kzz (ft/day) = 10.83, Std. Dev. = 8.56

<Example 2> Average Kzz (ft/day) = 10.86, Std. Dev. = 8.66

<Example 3> Average Kzz (ft/day) = 10.97, Std. Dev. = 8.61

Note) All Examples are drawn in the 7.5 x vertical exaggeration

Fig. 8. Example realizations of hydraulic conductivity distribution

with 21 vertical segments and 400 horizontal segments, and 2,000 grids were randomly selected. Their locations and lognormal values of their vertical hydraulic conductivities were used for development of a variogram model. A program called "gamv" from GSLIB was used for the development. (Deutsch and Journel 1998). Fig. 7 shows the variograms developed for the two orthogonal directions: north–south and east–west. The variogram that reaches the sill first (at about 5–6 ft) is in the north–south direction and the variogram with the longer range is in the east–west direction.

Generation of Hydrogeologic Conditions Using Geostatistical Simulation

Geostatistical simulation was done using the variogram developed above and a program called "sgsim" in GSLIB (Deutsch and Journel 1998). The program sgsim conducted a sequential Gaussian simulation. The program was run 50 times, each with simple kriging and ordinary kriging. One hundred realizations of the spatial distribution of the vertical hydraulic conductivity were generated with an anisotropic ratio of 10. Averages and standard deviations of the 100 realizations were 10.87 and 0.21, respectively, for simple kriging and 11.30 and 0.5 for ordinary kriging. The difference between the averages was not significant even when comparing different kriging methods. For illustration, several realizations are shown in Fig. 8.

The distributions are represented with 24 classes of white–black color as shown in the textural class. This classification was also used for VS2DI modeling since VS2DI characterizes hydrogeologic conditions with up to 24 classes of soil texture. As shown in the example realizations, the distribution of low-permeability layers was randomly generated.

Model Calibration

To adjust and determine model parameter values and initial and boundary conditions, the VS2D model was calibrated using the distribution of hydraulic conductivity in Fig. 5 and the piezometer data obtained during a wetting cycle of July 1999 (Johnson 2000). Vertical hydraulic conductivities, recharge rates of the basins, and other boundary conditions used for the calibration are shown in Fig. 9. The two initial water content

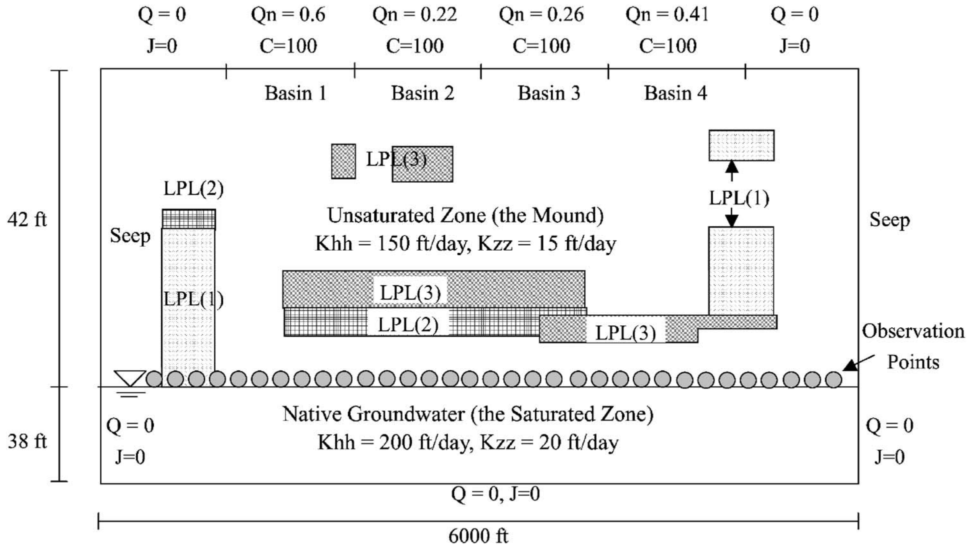
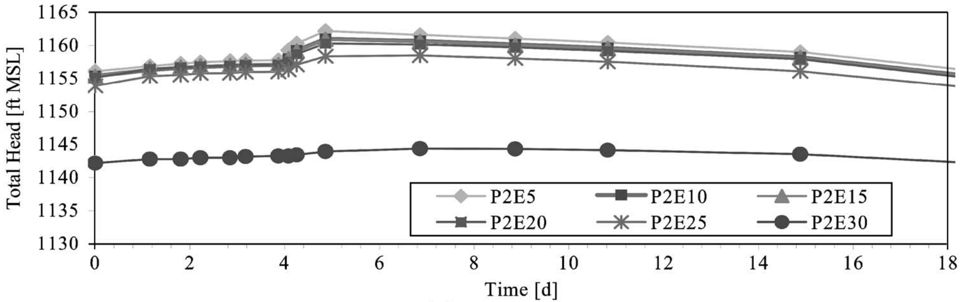
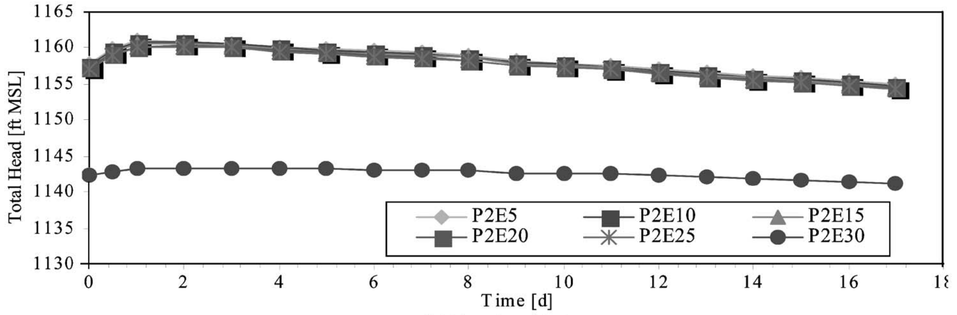


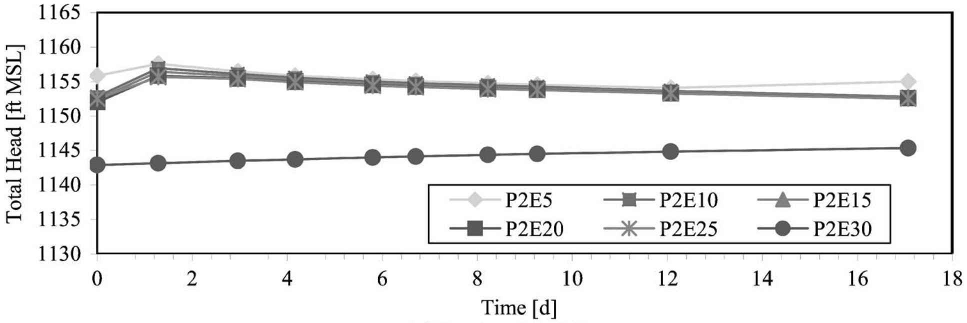
Fig. 9. Parameter values and initial and boundary conditions for model calibration



(a) Field Measured



(b) Simulated in 3D



(c) Simulated in 2-D

Fig. 10. Total heads at NWWRP Piezometer Nest P2E: The set of P2E is described by the depth. For example, the note of "P2E5" is the data recorded at a depth of 5 ft at Piezometer Nest P2E.

conditions, dry and wet, were used as discussed previously.

The final results are shown in Fig. 10, which compares total heads (a) field measured; (b) simulated in 3D using FEMWATER (Johnson 2000); and (c) simulated in 2D using VS2D. As shown in those figures, there is good agreement among the total heads. The calibrated model results using data at six piezometer nests are shown for the P2E nest in Fig. 10.

At a couple of locations, the 2D simulation results show small discrepancies as compared to the other two cases. Considering the difference in dimension, the discrepancies are small enough to be neglected. For all the simulations carried out in the next sections, therefore, the same parameter values and initial and boundary conditions, as shown in Fig. 9, were used.

Five Modeling Scenarios for Uncertainty Evaluation

For reviewing issues with implementation of the GMMW concept in relation to hydrogeological uncertainty, scenarios with different initial and boundary conditions and different kriging methods were developed for sensitivity analysis. Using six different conditions, five scenarios were developed. As shown in Table 2, Scenario 1 is with a combination of continuous recharge, dry initial moisture content, and simple kriging. Each scenario was simulated with each of the 50 realizations of the hydrogeologic conditions. The simulation results were used to estimate the uncertainty for implementation of the GMMW concept and other relevant issues.

Table 2. Five Scenarios with Different Modeling Conditions

	Simple kriging		Ordinary kriging	
	Initial water content		Initial water content	
Recharge condition	Dry	Wet	Dry	Wet
Continuous	Scenario 1	Scenario 2	Scenario 5	—
Wet–dry cycle	Scenario 3	Scenario 4	—	—

Identifying the Earliest Wave of Infiltration with VS2D Modeling

VS2DI is not capable of particle tracking and cannot directly identify the earliest wave of infiltration. To determine the earliest wave, observation wells were placed at certain grids and parameter values such as water content, pressure head, and concentration were recorded at every iteration. The grids and the

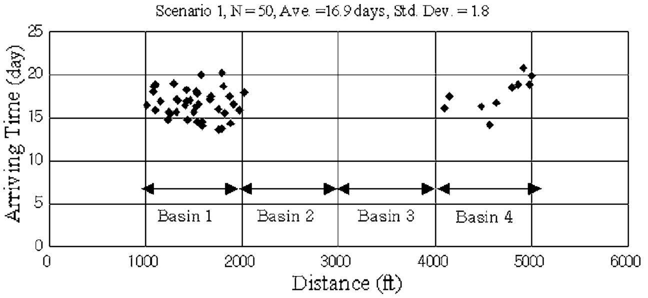


Fig. 11. Distribution of GMMPs catching earliest waves of 50 simulations (Scenario 1)

observation wells were numbered ascending from 1 to 400 from the left-hand side. In this way, the GMMP for the earliest wave was determined without tracing out the pathway of the earliest wave from surface. A certain concentration of tracer was assigned to the recharged water assuming no concentration existed in water before the start of recharge.

Modeling Results of Five Scenarios

Scenario 1, with a combined condition of continuous recharge, dry initial moisture content, and simple kriging, was simulated for a period of 40 days with each of the 50 realizations of hydrogeologic conditions. Figure 11 shows the spatial distribution of the GMMPs of the 50 simulations. As shown in Fig. 11, the locations of the GMMP are different for all the 50 simulations except at the eight observation wells (Nos. 74, 88, 95, 102, 103, 106, 117, and 120) having the earliest wave twice. As shown, the 40 observation wells are located underneath Basin 1 and the remaining 10 underneath Basin 4.

Table 3 shows a summary of the simulation results of the five Scenarios and Table 4 presents the observation wells having the earliest wave more than once in the 250 simulations. From these results, we can discuss the following issues:

Table 4. Observation Wells Having Earliest Waves More than Once in 250 Simulations

Earliest wave frequency	Total number	Well numbers
Two times	31	73, 81, 83, 84, 87, 92, 93, 97, 98, 100, 104, 121, 125, 128, 132, 134, 135, 211, 218, 234, 235, 253, 255, 264, 265, 275, 301, 302, 317, 320, 325
Three times	19	68, 72, 77, 82, 89, 94, 107, 111, 119, 122, 124, 204, 240, 242, 244, 277,286, 322, 332
Four times	6	95, 103, 112, 117, 299, 305
Five times	4	96, 106, 126, 273
Six times	3	74, 88, 120
Seven times	1	102
Sum	64	

Note: Wells 67–133 are underneath Basin 1; Wells 134–300 are underneath Basin 2; Wells 201–267 are underneath Basin 3; and wells 268–340 are underneath Basin 4.

1. Travel time of the earliest wave of infiltration: The travel times of the earliest waves of infiltration from the surface basin to the GMMP are around 1 day under the wet initial water content condition (in Scenarios 2 and 4) and about 17 and 30 days under the dry condition (in Scenarios 1 and 5, and 3, respectively). In fact, the real initial water content condition under the normal and continuous wet/dry operational cycles is closer to the wet initial water content condition. This indicates that the actual travel time of the earliest wave under the real operation of the surface recharge basin will be around 1 day.
2. Location of the GMMPs: From all 250 simulations, there was no observation well that had the earliest wave of infiltration more than seven times. As shown in Table 4, there was only one well having it seven times, three wells six times, and four wells five times. This indicates that the location of a well to catch the earliest wave of infiltration depends largely on the hydrogeologic and operating conditions. It means that we can seldom locate a GMMP or an array of GMMPs to catch most of the earliest waves under normal field conditions of operation and hydrogeology. If we place a GMMW at a GMMP, its highest probability to catch the earliest wave is only seven times out of the 250 simulations, i.e., only 2.8%.

Table 3. Summary of Simulation Results of Five Scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Parameters	Continuous dry initial θ simple	Continuous wet initial θ simple	Wet–dry dry initial θ simple	Wet–dry wet initial θ simple	Continuous dry initial θ simple
Number of observation wells with the earliest wave					
One time	42	42	41	39	41
Two times	8	7	8	8	9
Three times	—	1	1	3	—
Number of observation wells with the earliest wave underneath					
Basin 1	40	7	45	1	41
Basin 2	—	10	—	1	1
Basin 3	—	1	—	48	—
Basin 4	10	32	5	—	8
Travel time of the earliest wave (in days)					
Average	16.89	0.88	30.35	1.57	16.16
Standard deviation	1.78	0.13	3.40	0.49	3.10

3. Insensitivity of data to kriging method: Between the results of Scenarios 1 and 5, noticeable differences were not significant enough to change the above statements. Therefore, other kriging methods were not tested. For this research, the cokriging method with two variables, soil type and hydraulic conductivity (Benson and Rashad 1996) was considered. However, the quantity and quality of the data available for this study were not sufficient for more sophisticated kriging methods. Therefore, the use of simple and ordinary kriging methods was adequate and more sophisticated methods would not provide additional information.

Discussion and Conclusions

From the modeling results and discussions stated above, the applicability of the GMMW concept is summarized as follows:

- The travel time of the earliest wave was approximately 1 day. This alone demonstrates that a GMMW is not appropriate as a point of compliance. Monitoring recharged water at the surface basin combined with monitoring downgradient monitoring wells will provide more accurate information on water quality.
- The depth of a vadose zone could make installation of the GMMW worthy. This depends on many factors, especially related to the physical, chemical, and biological treatment potentials in the vadose zone. Nevertheless, subsurface horizontal transport to a down gradient well will provide more representative samples of product water.
- It is very difficult to practically locate the GMMW or the GMMWs to catch the earliest wave of infiltration with more than a certain level of likelihood. As discussed previously, the best probability of a GMMW catching the earliest wave was 2.8%. The number of GMMWs to catch the earliest wave with a probability of greater than 50% is at least 20 GMMWs and such a large number is not practical.
- Sampling requirements for hydrogeologic conditions must also be considered. For the simulations in this research, we have assumed and used 2,000 data points. Collecting sufficient data on soil type, hydraulic conductivity would not be practical to reduce the uncertainty in locating GMMWs.
- If a monitoring system similar to the GMMW must be implemented, regardless of all the discussions above, this study recommends the following system. A shaft is built and packed with materials of homogeneous hydraulic conductivity to ensure that the a predictable wave passes through this shaft. Then, install sampling devices in this shaft at a point that makes it possible to collect water quality samples from a mound just above the point at which it mingles with the native groundwater. As discussed by Johnson (2000), it would cost around $20,000 to build a shaft at the example site, which seems to be much lower than the cost of the intensive sampling required for the GMMW.
- The geostatistical simulation, VS2DI modeling, and methods for arranging the modeling results, all of which are described in the previous sections, are recommended as an estimation procedure for future field application of the GMMW concept, if necessary.
- In conclusion, this research states that based on all the discussions and simulation results above, implementing the GMMW concept as mentioned has serious practical limitations.

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References

American Water Works Association Research Foundation (AWWARF). (2001). *Soil aquifer treatment for sustainable water reuse*, AWWARF, Denver.

Benson, C. H., and Rashad, S. M. (1996). "Enhanced subsurface characterization for prediction of contaminant transport using cokriging, geostatistics for environmental and geotechnical applications." *ASTM STP 1283*, ASTM, West Conshohocken, Pa.

Corkhill, E. F., Corell, S., Hill, B. M., and Carr, D. A. (1993). "A regional groundwater flow model of the Salt River Valley. Phase I: Hydrologic framework and basic data report." *Modeling Rep. No. 6*, Arizona Dept. of Water Resources, Phoenix.

Crook, J., Hultquist, R., and Sakaji, R. (2000). "New and improved draft groundwater recharge criteria in California." *Proc., Annual Conf. of the American Water Works Association*, Denver.

Dames and Moore. (1994). "City of Mesa Northwest Water Reclamation Plant percolation ponds performance and alternatives evaluation." *Report for City of Mesa, Arizona*, Mesa, Ariz.

Desbarats, J. A. (1996). "Modeling spatial variability using geostatistical simulation, geostatistics for environmental and geotechnical application." *ASTM STP 1283*, ASTM, West Conshohocken, Pa.

Deutsch, C. V., and Journel, A. G. (1998). *GSLIB: Geostatistical software library and user's guide*, 2nd Ed., Oxford Univ. Press, London, 25.

Gelhar, L. W., and Axness, C. L. (1983). "Three-dimensional stochastic analysis of macrodispersion in aquifers." *Water Resour. Res.*, 19(1), 161–180.

Green, T. R., and Freyberg, D. L. (1995). "State-dependent anisotropy: Comparisons of quasianalytical solutions with stochastic results for steady gravity drainage." *Water Resour. Res.*, 31(9), 2201–2211.

Healy, R. W. (1990). "Simulation of solute transport in variably saturated porous media with supplemental information on modifications to the U.S. Geological Survey's computer program VS2D." *Water Resources Investigation Report 90-4025*, U.S. Geological Survey, Reston, Va.

Hydrosystems Inc. (1995). "NWWRP recharge impacts determination report." *Report for City of Mesa*, Mesa, Ariz.

Johnson, M. J. (2000). "Hydraulic improvement of artificial recharge facilities underlain by low conductivity sediments." Ph.D. thesis, Dept. of Civil Engineering, Arizona State Univ., Tempe, Ariz.

Mantoglou, A., and Gelhar, L. W. (1987). "Effective hydraulic conductivities of transient unsaturated flow in stratified soils." *Water Resour. Res.*, 23(1), 57–68.

McCord, J. T., Gotway, C. A., and Conrad, S. H. (1997). "Impact of geologic heterogeneity on recharge estimation using environmental tracers: Numerical modeling investigation." *Water Resour. Res.*, 33(6), 1229–1240.

National Research Council (NRC). (1998). *Issues in potable reuse*, National Academy Press, Washington, D.C., 2.

Schöheinz, D., and Drewes, J. E. (2000). "Groundwater flow modeling for the NWWRP Mesa." Dept. of Civil and Environmental Engineering, Arizona State Univ., Tempe, Ariz.

U.S. Geological Survey (USGS). (2000). VS2DI: "A graphical software package for simulating fluid flow and solute or energy transport in variably saturated porous media." *Water Resources Investigation Report 99–4130*, USGS, Reston, Va.

Yeh, T. C. J., Gelhar, L. W., and Gutjahr, A. L. (1985). "Stochastic analysis of unsaturated flow in heterogeneous soils. 2: Statistically anisotropic media with variable alpha." *Water Resour. Res.*, 21(4), 457–464.