INTEGRATED USE OF VADOSE ZONE CHARACTERIZATION METHODS TO EVALUATE ARTIFICIAL GROUNDWATER RECHARGE SITES

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An estimation of long-term achievable recharge rates is necessary to evaluate proposed spreading basin recharge projects, and is often not obtained until full-scale or at least pilot project operations occur. The potential effect of subsurface heterogeneities on downward flow is usually based on data from a few point measurements of near-surface infiltration and geologic logging of vadose zone exploration boreholes. These limited data are often insufficient to accurately estimate large-scale recharge rates. The judicious use of in-situ vadose zone testing methods, however, can provide robust data that greatly improves initial estimates of groundwater recharge rates and can eliminate the need for a pilot test, resulting in significant cost savings. The proposed approach integrates near-surface infiltration testing, exploratory drilling, geological logging, and multiple-scale in-situ vadose zone testing. In-situ testing in instrumented exploratory boreholes quantifies vadose zone hydraulic properties in much the same way that aquifer tests quantify hydraulic properties of the saturated zone. Testing at multiple scales provides a better understanding of subsurface heterogeneities and the efficiency of vadose zone sediments to transmit groundwater recharge. This approach maximizes field-based data collection, resulting in a more cost-effective investigative program. In addition, in-situ testing is well suited for comparing relative recharge characteristics between proposed sites.

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INTRODUCTION

The ability of a spreading basin recharge site to transmit water through the vadose zone is highly dependent on the morphology and distribution of the vadose zone sediments. In most alluvial basins, the near-surface and subsurface sediments consist of highly variable inter-bedded layers that are a result of the changing fluvial processes over the basin's depositional history. The lateral extent and vertical inter-connectivity of the various sedimentary layers ultimately determine the hydraulic capacity of the vadose zone. Thus a groundwater recharge site investigation must answer the following questions:

1) Are the infiltration rates of the near surface sufficiently high for the project needs?

2) Do laterally extensive low-permeability layers exist within the shallow vadose zone? What is the saturated hydraulic conductivity (Ksat) of the(se) layer(s)?

3) What are the hydrologic properties of the predominant layer type? How vertically interconnected are these hydrologic units?

The first question is by far the most important: adequate infiltration must be demonstrated at the surface. It is then necessary to demonstrate that fine-grained or cemented layers, or even thick layers of well-graded materials deeper in the vadose zone, will not reduce long-term recharge rates and the economic viability of the project. If preliminary site investigations raise questions about deeper subsurface permeabilities, permitting and construction of pilot basins are the typical “next phase”. In the case of a successful pilot test, the full project costs are mostly recouped. However, some pilot projects have shown marginal long-term recharge rates and the full recharge projects were never implemented. We suggest that relatively inexpensive additional subsurface testing in exploration boreholes combined with general principles of sedimentology can result in great cost savings if a pilot project can be avoided. This type of recharge site characterization effort focuses on assessing the spatial variability and hydrologic properties of near-surface and subsurface sedimentary layers.

The spatial distribution of geologic facies provides a “template” for defining the spatial distribution of Ksat (Carle and Fogg, 1998). This approach presumes that a relationship between geologic facies and Ksat exists and can be estimated, and that the spatial distribution of the modeled geologic facies adequately represents the spatial distribution of Ksat. Application of this approach to alluvial basins relies on the correlation between the Ksats of different soils and geologic units with particle-size distribution parameters, such as the percentages of fines (i.e., silt plus clay) (Todd, 1980). Consequently, if the Ksat of the observed near-surface and sub-surface layers can be measured, other layers having similar textural similarities can be assigned similar Ksat values. The question remains: how laterally extensive are the observed fine-grained layers and how inter-connected are the high permeability layers?

The lateral extent, or horizontal length, of a sediment layer can be assumed to be directly proportional to the observed layer thickness (Miall, 1984). This assumption is based on Walther’s law, or the “rule of succession of facies,” which means that lateral distribution of strata can be predicted by studying them in a vertical direction. For example, observed sediment layers at a proposed recharge site in southeastern Arizona showed mean thickness-to-length ratios of 1:100 and 1:60, for the Recent Alluvium and Fort Lowell geologic units, respectively (GSA, 2000a). In a recharge site investigation, observation of potential thickness to length ratios in a few closely spaced (i.e. 500 feet) exploration boreholes can be used to estimate the lateral extent of observed layers where borehole data are sparse.

The final piece of the puzzle is to estimate the heterogeneity or hydraulic inter-connectivity within the subsurface sediments. High permeability sediments inter-bedded in low permeability layers may result in a higher overall permeability than can be measured by small or intermediate-scale tests. Mohanty and others (1998) cite numerous soil and vadose zone studies that demonstrated an increase in Ksat with sample volume. More recently, Schulze-Makuch and others (1999) were able to quantify a direct relation between scale of measurement and Ksat data in a variety of saturated formations. Therefore, more than one type and scale of field based Ksat measurement should used to assess sub-surface permeabilities. Our approach incorporates the use of small-scale laboratory tests, intermediate scale in-situ tests to assess the permeability of fine-grained units and the predominant soil layer type, and the use of a large-scale in-situ test to assess the vertical inter-connectivity of high permeability sediments.

INVESTIGATIVE APPROACH

We recommend a phased approach for site characterization in order to maximize cost-effectiveness. Individual site characteristics and project needs determine whether only some or all the methods described below should be implemented.

Phase I - Near-Surface Investigation

The near-surface investigation is focused on the upper 20 feet of soils. Backhoe trenching or shallow drilling with geologic logging will identify any near-surface fine-grained or cemented soils that potentially represent a “fatal flaw” as well as the depth and extent of favorable coarse-grained hydrologic units. Shallow test pits provide a large sample volume and the ability to visually map the test pit. Auger drilling or other boring techniques provides deeper samples for this first investigative phase. Geologic logging is highly detailed and focuses on textural data (percent fines) needed for correlating with measured hydrologic properties. Selected representative test pit samples undergo laboratory particle size distribution testing to confirm field-based estimates.

Assuming that favorable soils are identified somewhere within five feet of the surface, the cylinder infiltrometer (CI) testing method provides an intermediate-scale Ksat measurement of the near surface soils. Here, a short-term, single-ring infiltration test is recommended to estimate the effective field Ksat as described in Bouwer, et al. (1999). A sufficient number of CI tests should be performed to provide adequate spatial coverage and support statistical analysis. Numerous authors (e.g., Nielsen et al., 1973) have shown the Ksat of similar soils and sediments to be log-normally distributed. Consequently, the geometric mean of the CI test results is believed to provide a good approximation for achievable infiltration rates during recharge operations. In some cases where Ksat appears to be randomly distributed, the harmonic mean is preferable (Bouwer, 1978).

Surface infiltration rates can then be estimated based on the distribution of surface soils and the CI results. The spatial consistency of the surface soils encountered and the geometric (or harmonic) mean of the CI tests provide support for deciding whether to proceed to Phase II. If suitable soils are not identified (i.e., infiltration rates less than one foot per day) then further investigation may not be warranted.

Phase II - Deeper Subsurface Investigation

The Phase II investigation focuses on identifying and quantifying potential low-permeability layers that could result in groundwater perching and thereby reduce near-surface infiltration rates. Design of a borehole exploration program follows inspection of existing hydrogeologic data, including geologic logs or drillers’ logs from nearby wells. Borehole depths are typically less than 100 feet below ground surface, although deeper boreholes may be considered if fine-grained or cemented hydrologic units that could potentially impede groundwater recharge are expected. If warranted a few selected boreholes are then instrumented and tested to quantify the subsurface hydraulic properties. Subsurface investigation work plans are specific to each site (and recharge project goals), but generally employ the following approach:

Exploration drilling and decision on further testing. Boreholes are drilled and geologically logged with selected representative samples are sent for laboratory testing. To reduce costs a majority of boreholes can be drilled with inexpensive drilling methods (i.e., reverse-circulation air-rotary drilling), with a limited number of boreholes drilled using more expensive Rota-Sonic drilling to collect core samples. Field geologic logging provides the basis for classifying the predominant sediment layer type and determining whether there are deeper fine-grained (low permeability) layers that could restrict recharge. The criteria for deciding the need for in-situ subsurface testing are necessarily qualitative. If the presence of fine-grained or cemented layers is either minimal or extensive, further in-situ testing is probably not warranted. However, if frequent fine-grained or cemented layers are interbedded with more favorable sediments, then in-situ testing can help assess the permeability and inter-connectivity of the layers.

Instrumentation of selected boreholes. One or several selected boreholes are instrumented with nested water and air piezometers for conducting in-situ vadose zone testing. Typically, the last borehole(s) in the drilling program is instrumented, or in the case of multiple site investigations, at least one at each site is instrumented for comparison purposes. Testing intervals are selected to measure Ksat of the predominant sediment layer and any thick fine-grained layers that may be present. Nested piezometer design consists of several one- or two-inch diameter PVC well casings with sealed slotted intervals for borehole permeameter testing. Multiple air-piezometers are small, inexpensive, easily installed and are used for atmospheric pressure wave testing.

Constant-head borehole permeameter (BP) testing. The BP method provides an intermediate-scale Ksat measurement of specific sediment horizons surrounding a short-screened piezometer interval (i.e. 1- to 5- foot). The BP methodology used is similar to that described by the U.S. Bureau of Reclamation for testing formation permeabilities above a deep water table using an open-hole packer-injection system (USBR, 1974) and a perforated-casing gravity-test system (USBR, 1977). Our use of the BP method focuses on measuring the hydraulic conductivity of selected sediment layers (hydrologic units) representative of the observed fine-grained layers and the predominant sediment material types. These data quantify the permeability of fine-grained units which could result in excessive groundwater perching if the units are laterally extensive, and also provide an estimate of the overall Ksat of the subsurface assuming that the predominant hydrologic unit(s) are interconnected.

Atmospheric pressure wave (APW) testing. The APW method provides a large-scale measurement of the vadose zone hydraulic conductivity. Field testing follows the method described by Weeks (1978) and consists of monitoring the atmospheric barometric pressure decline that occurs most afternoons at the ground surface of each instrumented borehole. At the same time, subsurface air pressures are monitored at sealed air-piezometers placed at selected depths in the borehole. The time lag and pressure attenuation observed between the surface and subsurface pressures at a particular depth is a function of the pneumatic air permeability and thickness, porosity and water content of overlying sediments. Vertical saturated hydraulic conductivity is then estimated using one-dimensional modeling, although our own experience and data cited by Weeks (1978) indicate that calculated Ksats are probably several times greater than actual Ksat values due to the failure of the 1-D approach to accurately model heterogeneity (*i.e.,* high velocity pathways). More importantly, the APW method indicates whether permeable pathways will allow recharged water to move around fine-grained or cemented low-permeability units.

Integration of the data set is as follows: Sediment layers observed in the borehole cuttings/core are classified into distinct hydrologic units based on the textural estimates that have been corroborated with laboratory particle-size analyses, and the extent of consolidation and cementation. Hydrogeologic cross sections are prepared to estimate the lateral continuity of hydrologic units using estimated thickness-to-length ratios as inferred from adjacent boreholes or the site-specific conceptual model of sediment deposition. In-situ Ksat estimates are then applied to the various hydrologic units and potential long-term infiltration rates are estimated for the various areas available for recharge basins identified from the preliminary planning phase.

CASE STUDIES

We have performed six recharge site investigations using the described approach. Two projects, located in Nevada and Arizona, are presented as examples of the investigation process, data interpretation, and results. Both sites revealed extensive sequences of fine-grained and cemented layers within 100 feet of the subsurface that could have necessitated the need for pilot projects. In-situ Ksat testing showed that although low permeability strata would impede recharge, high recharge rates at the surface could be maintained.

Case Study 1

A hydrogeologic study was performed to determine the feasibility of converting existing effluent evaporation pond(s) into recharge basins (GSA, 2000b). The field investigation consisted of two phases: a near-surface infiltration study and a focused, highly-detailed subsurface investigation. Existing hydrogeologic data indicated that extensive low permeability layers may be present, consequently, three exploration boreholes were planned to depths of 250 feet. Specific investigations consisted of:

- Excavation of 11 test pits and performing geologic logging of near-surface soils.
- Fourteen cylinder infiltrometer tests on near-surface soils.
- Dual rotary drilling and geologic logging of eight exploration boreholes in potential effluent-recharge areas.
- Laboratory testing on test pit and drill cuttings samples from representative locations in the boreholes.

- Instrumentation of three exploration boreholes with water and air piezometers for intermediate- and large-scale Ksat testing.
- Constant head BP tests in low permeability layers to determine a bounding “lower” permeability value for restricting layers.
- APW tests in air piezometers located below low permeability layers to assess the lateral extent of these layers.
- Constant head injection and slug recovery tests in nearby monitor wells to estimate the saturated hydraulic conductivity of the aquifer.

Textural classes of near-surface soils (i.e., 0-15 feet) were fairly consistent, ranging from silty sands to cobbly sands. Effective Ksat estimates from CI testing in undisturbed areas were an order of magnitude greater (5 feet vs. 0.5 feet per day) than CI tests in existing ponds where sediment accumulation had been removed. Drill cuttings were correlated to laboratory particle size distributions and classified into four lithologic/hydrologic units:

- Unit 1: 5 percent or less fines (silt plus clay); includes well- and poorly graded gravels and sands.
- Unit 2: 5 to 15 percent fines; includes well- and poorly-graded gravels and sands with silt and clay.
- Unit 3: 15 to 50 percent fines; includes silty and clayey gravels and sands.
- Unit 4: more than 50 percent fines; includes silts and clays.

Geologic logging showed the subsurface to highly stratified, with hydrologic Units 3 and 4 predominating in the subsurface to depths of 200 feet in layers ranging from 2 to 45 feet thick.

Figure 1. Observed and Simulated APW Data for DB-3

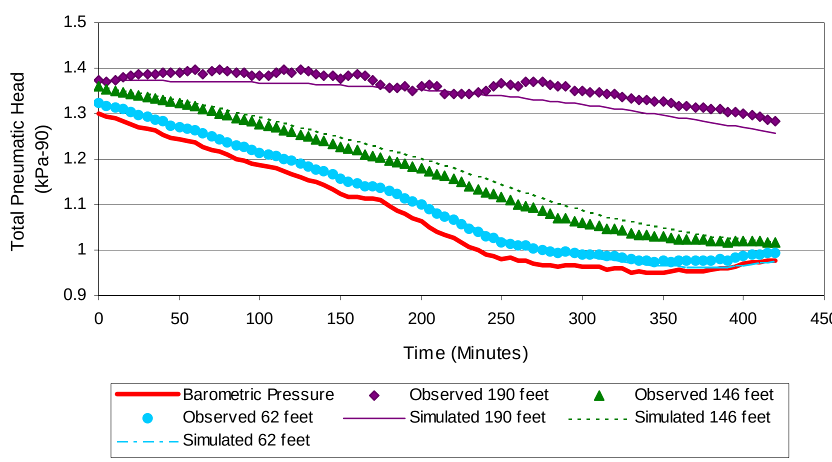

Figure 1 shows the observed and simulated APW data in borehole DB-3. The red line shows the atmospheric pressure change observed on the afternoon of April 22, 1999. The relatively minor difference in pressure observed in air piezometers located at various depths between the surface and 146 feet bgs indicates that inter-connectivity of high permeability layers is high to that depth. The subsequent increase in differential pressure at 190 feet indicates the presence of an impeding layer between 140 and 190 feet bgs.

Figure 2 shows the observed and simulated APW data in borehole DB-1 in the afternoon of April 28, 1999. These data are very similar to DB-3, though the differential pressures observed at 200 feet indicate that the subsurface at DB-1, approximately 2500 feet away from DB-3, is more permeable.

Figure 2. Observed and Simulated APW Data for DB-1

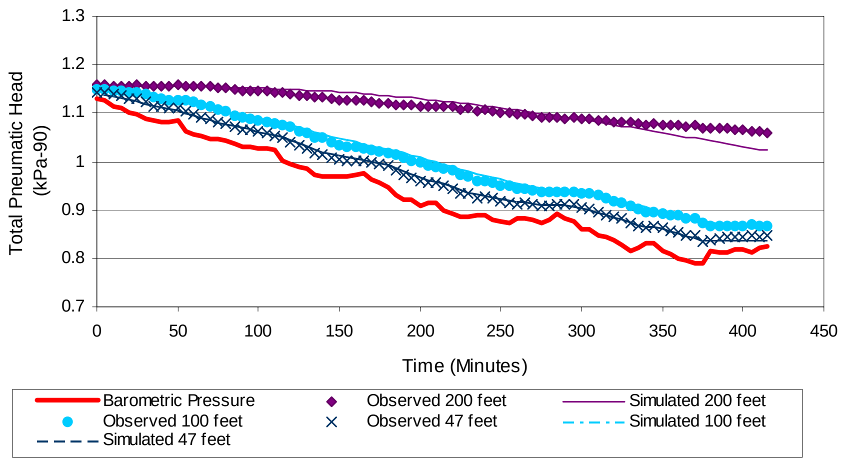

Table 1 compares the estimated vertical Ksat results for the intermediate- and large-scale tests. The APW tests showed high saturated hydraulic conductivity to depths of less than 50 feet bgs, but decreasing hydraulic conductivity with increasing depth. BP tests showed generally low saturated hydraulic conductivity for the targeted layers (i.e., less than 1 foot/day). As previously mentioned, the APW modeling method tends to overestimate Ksat values, though, APW results converged towards the intermediate scale BP tests at depth.

Table 1. Case Study 1, Summary of Field Ksat Test Results

		Atmospheric Pressure Wave Tests		Borehole Permeameter Tests		
Borehole No.	Predominant Hydrologic Unit(s) tested	Depth Interval Tested (feet bgs)	Estimated Ksat (feet/day)	Predominant Hydrologic Unit(s) tested	Depth Interval Tested (feet bgs)	Estimated Ksat (feet/day)
DB-1	3	0 – 47	23.4	3	26.5 – 29.5	1.8
	1 and 3	47 – 100	21.0	4	66.5-69.5	0.4
	2	100 – 150	5.3		NT	NT
	2	150 – 200	1.9	3	174.5 – 177.5	0.3
				2	237.0 – 239.7	0.4
DB-2	3	0 –38	103.6	4	10.5 – 13.5	1.4
	3	38 – 70			NT	NT
	3	70 – 150	1.9	4	83.5 – 86.5	0.3
	4	150-240	NT	3	157.2 – 160.2	0.7
				2	247.1 – 250.0	0.2
DB-3	3	0 – 36	46.0		NT	NT
	2	36 – 62		4	83.5 – 86.5	0.3
	3	62 – 146	11.6	4	111.0 – 114.1	0.7
	2	146 – 190	0.2	2	162.5 – 165.5	1.6

NT = Not Tested

Based on the APW evidence and measured BP Ksat values showing low Ksat values for Units 3 and 4, the long-term estimated groundwater recharge rates in the subsurface were anticipated to be approximately 0.5 feet per day. These Ksat values are also consistent with constant head injection and slug recovery tests in saturated sediments in two nearby existing wells that showed estimated Ksat values of 0.3 to 0.7 feet/day.

Nonetheless, because the CI-measured Ksats at the near-surface sediments were high (geometric mean = 5 feet/day), and the APW testing showed that the sediment layers were generally permeable to depths of 150 feet bgs, narrow basins spread out over a large area were recommended. The implemented design allows groundwater mounding to dissipate, thereby maintaining high surface infiltration rates. Current recharge rates at the facility are in excess of design parameters.

<u>Case Study 2</u>

A hydrogeologic characterization study was performed on three sites to assess their potential for use as groundwater recharge basins (GSA, 1999). Five to six approximately 10-foot-deep test pits were excavated at each site and composite samples from 2-foot depth intervals were geologically logged. Continuous Rota-Sonic core was collected and geologically logged from five or more exploratory boreholes at each site to depths averaging approximately 75 feet bgs. Observed sediment layers were categorized into the following four hydrologic units:

- Unit 1: Thick sequence of clayey and silty gravel and/or clayey and silty sand layers, with less than 30 percent fines.
- Unit 2: Gravelly silts and/or sandy silts; thin layers located in the near surface.
- Unit 3: Single relatively thin layer of densely compacted and cemented sediment with generally more than 30 percent fines.
- Unit 4: Several relatively thin, densely compacted and cemented layers with generally more than 30 percent fines, separated by thicker, coarse-grained layers.

One borehole per site was instrumented with air and water piezometers located at depth intervals corresponding to the major hydrologic units at the site. The instrumented boreholes were located in the most favorable areas for recharge at each site, based on geologic logs. In-situ field measurements of air and water permeability at the different depth intervals were made using APW tests and constant head BP tests. Laboratory Ksat and various recharge-related measurements on unsaturated flow, bulk density, porosity and leaching of soluble salts were also conducted on subsamples representing each of the major lithologic layers.

Table 2 compares the vertical Ksat results for the small-, intermediate- and large-scale tests. The measured Ksat values clearly show the effect of scale on the test results, with the smallest values exhibited by the remolded core laboratory samples, and the largest values shown by the APW tests. Generally, the lowest Ksat values for each test are at depth and roughly correspond to Unit 4. As shown in the APW tests, the observed fine-grained and compacted Unit 4 layers clearly reduce the bulk vertical Ksat, but do not eliminate the downward movement of fluid.

Table 2. Case Study 2, Summary of Field and Laboratory Ksat Tests

Borehole No.	Predominant Hydrologic Unit(s) Tested	Atmospheric Pressure Wave Tests		Borehole Permeameter Tests		Remolded Laboratory Constant Head Tests	
		Depth Interval Tested	Estimated Ksat	Depth Interval Tested	Estimated Ksat	Depth Interval Tested	Estimated Ksat
		(feet bgs)	(feet/day)	(feet bgs)	(feet/day)	(feet bgs)	(feet/day)
SB-4	Units 1&2	0 – 16	22.3	NT	NT	NT	NT
	Unit 1	16 – 36	54.0	20.5 – 27	0.8	NT	NT
	Unit 1	36 – 49	6.0	52.7 – 59	1.0	NT	NT
HSB-5	Units 1&2	0 – 29	10.0	NT	NT	NT	NT
	Unit 4	29 – 47	21.7	34.0 – 39.0	2.8	34 -39	0.1
	Unit 1	47 – 63	4.6	54.1 – 59.2	2.0	55 - 58	0.3
	Units 1&4	63 – 82	1.5	86.1 – 91.0	0.4	87 - 91	0.6
NSB-1	Units 1&2	0 –24	32.1	NT	NT	NT	NT
	Units 1&3	24 – 42	37.5	30.1 – 35.0	4.3	32 - 36.5	0.2
	Unit 1	42 – 64	14.6	48.1 – 53.0	9.9	50 - 53	0.06
	Units 1&4	64 – 78	7.7	66.9 – 72.3	1.2	NT	NT

NT = Not Tested

Based on the observed range of 1.2 to 9.9 feet per day in the BP tests for the predominant hydrologic units, and the higher estimated Ksat values at depth in the APW tests, the site represented by borehole NSB-1 was recommended as the best site for future recharge operations. Although groundwater perching resulting from low permeability layers at depth has been noted, recharge operations at this property average 1 to 2 feet per day.

CONCLUSIONS

Integrated vadose zone characterization and testing quantifies vadose zone hydraulic properties, much the same as aquifer testing quantifies hydraulic properties of the saturated zone. In conjunction with detailed geologic logging, these data can be used in-lieu of expensive pilot project recharge basin testing. In-situ hydraulic testing at various scales provides information on flow-path heterogeneities associated with scale. Cylinder infiltrometer testing provides reliable estimates of surface infiltration rates; borehole permeameter testing provides a means to assess the permeability of predominant and low permeability layer types, and; the atmospheric pressure wave test provides a method to assess the inter-connectivity of sedimentary layers.

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