DESIGN OF RESEARCH WELLFIELD FOR CALIBRATING GEOPHYSICAL METHODS AGAINST HYDROLOGIC PARAMETERS

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ABSTRACT

A wellfield (Boise Hydrogeophysical Research Site or BHRS) is being developed in Boise, Idaho, for hydrologic and geophysical research in a shallow, coarse (cobble-and-sand), alluvial aquifer. Our goal is to develop cost-effective methods for quantitatively characterizing the distribution of permeability in heterogeneous alluvial aquifers using hydrologic and geophysical techniques. Responses to surface geophysical techniques (e.g., seismic, radar, and transient electromagnetics) will be calibrated against a highly characterized volume (the wellfield) with determined three-dimensional distributions of geologic, hydrologic, and geophysical properties. Well coring and construction methods, and the well arrangement in the field, are designed to provide detailed control on lithology (facies distribution and sediment properties), and to support a variety of single-well tests (e.g., borehole geophysical logging, permeability logging, and vertical seismic and radar profiling), crosshole tests (e.g., seismic, radar, and resistivity tomography), and multiwell tests (e.g., pumping and tracer tests). The wellfield has a central well surrounded by two rings of six wells each, and five outer "boundary" wells. Wells are screened through the cobble-and-sand aquifer to a clay that underlies the BHRS at about 20 m depth. Permeability will be measured with the flowmeter and pumping method in each well, and with a series of tests where successive discrete intervals will be pumped in a given well while multiple zones will be monitored in surrounding wells. Wellfield dimensions (e.g., ~20 m diameter of central well cluster) and design specifics are based on experience at the nearby Capital Station remediation site in the same aquifer material, and are designed to provide detailed control on the variation of properties over a range of volume scales (<1 m^3 to ~6000 m^3). A Monte Carlo search was used to refine the wellfield design to optimize well-pair distances and azimuths for determination of geostatistical parameters and anisotropy.

Key words: *permeability, heterogeneity, geophysics, wellfield design, geostatistics*

INTRODUCTION

It is widely acknowledged that permeability is the most significant aquifer parameter for quantitatively describing or modeling groundwater flow and contaminant transport, and for designing remediation systems. One rarely has sufficient funds to emplace and test enough wells or collect enough permeability data to characterize heterogeneity of permeability (especially in three dimensions [3-D]), although such information is needed to simulate groundwater flow and contaminant transport in many aquifers (e.g., Guven et al., 1992; Rehfeldt et al., 1992; Mas-Pla et al., 1992). And at hazardous waste sites in particular, it may be prohibitively expensive or unsafe to emplace many wells and test them in ways that will yield data on permeability variations at scales useful for modeling and design of remediation systems. Methods that supplement well data are needed to characterize the 3-D distribution of permeability in heterogeneous aquifers.

A number of workers have shown the potential of supplementing sparse, expensive, direct subsurface data with geophysical data that can be collected relatively rapidly and inexpensively at the surface and between existing wells (e.g., Rubin et al., 1992; McKenna and Poeter, 1995; Hyndman and Gorelick, 1996). Recent work in this direction at the Capital Station groundwater remediation site in downtown Boise, Idaho, has investigated a variety of geophysical and hydrologic techniques in a coarse, unconsolidated, alluvial aquifer (Barrash et al., 1995, 1997a,b; Barrash and Morin, 1997; Michaels and Barrash, 1996; Michaels, in press). Based on results at Capital Station, a wellfield is being developed as a 3-D control volume to support research on methods for using non-invasive geophysical techniques in conjunction with hydrologic measurements to map variations in permeability in shallow alluvial aquifers (Barrash and Knoll, 1997). This research wellfield (Boise Hydrogeophysical Research Site, or BHRS) is located adjacent to the Boise River (Figure 1) at an uncontaminated site in unconsolidated, coarse (cobble-and-sand), braided-stream deposits similar to those at Capital Station.

The BHRS is designed to support a variety of tests to thoroughly characterize the distributions of geologic, geophysical, and hydrologic parameters in a 3-D volume where "the truth" will then be known for calibrating responses from non-invasive geophysical methods against hydrologic parameters. The design is influenced by a number of general and site-specific considerations including the need to have the appropriate density and configuration of wells for the wide range of tests anticipated and for the physical characteristics of the alluvial aquifer at the site. Also, the development of wells at the site is guided by the need to maximize the amount and quality of information gained from the subsurface (both from the drilling process and subsequent use of the wells in tests) while minimizing the disturbance to the subsurface.

WELLFIELD DESIGN OBJECTIVES

General design considerations incorporated into the BHRS are as follows: (1) the range of tests planned or reasonably anticipated; (2) the basic configuration of wells that will support this range of tests; and (3) the resulting requirements for individual well dimensions, installation, and materials.

Characterization Methods

The range of tests planned include hydrologic and geophysical tests in individual wells (1-D), between wells (2-D and 3-D), and at the surface; and tests that combine excitation and sensing both at the surface and in wells. Also, laboratory analysis of core collected during the drilling process will provide additional support for field measurements. A list of planned field tests is given in Table 1. This list is derived from (a) the need to provide direct measurements of hydrologic and geophysical parameters at several scales (submeter-to-meter scale immediately adjacent to the borehole, and submeter-to-several meter scale between wells) throughout the wellfield or "calibration volume," and (b) the range of methods that show promise for measuring parameters of interest or for reliably sensing variations in material properties (i.e., aquifer structure or zonation) at the scales of interest.

Figure 2 is a schematic diagram showing some of the types of measurements and tests planned at the BHRS. Apparent redundancy in methods or parameters measured is intended to investigate scale effects in the aquifer, to provide control or calibration for a given parameter that can be measured at successive scales (e.g., borehole measurements calibrate crosshole measurements which calibrate surface profile measurements along a transect between boreholes), and to investigate means to quantitatively relate results from different methods of measuring similar parameters (e.g., apparent resistivity from instruments using electromagnetic induction in boreholes and in soundings from the surface).

Configuration of Wells

The wellfield includes a concentration of wells in a central area for detailed testing and thorough characterization, and wells at some distance from the central area to provide information on hydraulic gradient and boundary conditions during tests and to provide "targets" for testing predictions beyond the central area (Figure 1). The configuration of wells in the central area is meant to provide adequate density and arrangement of wells to support "deterministic" characterization of 3-D parameter distributions (i.e., wellfield volume as calibration standard). The chosen configuration is a double-ring pattern having a central well surrounded by two rings of six wells each, with wells in each ring offset from each other at 60° radial angle spacings, and with wells offset 30° between rings (Figure 3). This pattern allows for reasonable areal density as well as a high density of interwell transects. Also, this pattern supports thorough hydrologic characterization with multiple-well pumping tests and tracer tests. Multiple-well pumping tests can be run in overlapping subvolumes, where the central well has six wells immediately surrounding it in the inner ring that can be monitored during a test, and where each of the six wells in the inner ring has five wells surrounding it that can be monitored during a test (including series of tests where successive discrete intervals will be pumped in a given well while multiple zones will be monitored in surrounding wells). A variety of forced-gradient tracer tests can be run (e.g., Gelhar et al., 1992) including radial injection tests for 3-D characterization and injection-withdrawal tests between well pairs in a variety of orientations relative to material anisotropy and gradient.

Well Design

Design considerations for individual wells include the following: (1) collecting complete core samples to the extent possible, including collection of sand matrix associated with cobbles; (2) drilling and emplacing the wells with minimal disturbance to the formation while ensuring good mechanical and hydrologic coupling to the formation after the well is installed; (3) having the smallest well diameter that accommodates the range of instruments needed to support the range of planned tests (Table 1); (4) having the maximum possible thickness of the aquifer screened in the well; and (5) using materials that do not interfere with planned tests.

DEVELOPMENT OF THE BOISE HYDROGEOPHYSICAL RESEARCH SITE (BHRS)

Site Description

The BHRS is located nine miles east of downtown Boise on property acquired by the Idaho Transportation Department (ITD) in conjunction with the construction of a bridge across the Boise River (Figure 1). The site is on a gravel bar immediately adjacent to the Boise River where the river leaves a canyon and enters the broad western Snake River Plain. Approximately 1 km upstream from the site is Diversion Dam which regulates flow in the Boise River and distributes water to two irrigation canals (New York canal and Penitentiary canal). Overall, the property is managed by ITD as wetlands mitigation for construction of the bridge and as winter habitat for bald eagles. The site is relatively pristine, and outside hydrologic influences (e.g., changes in river level and leakage from the Penitentiary canal) are relatively predictable (Figure 4) and/or measurable.

Location of the central area of 13 wells coincides with a minimally vegetated region; five boundary wells are distributed around the central area (Figure 1) and are located at or above the wetted perimeter when flow in the Boise River is at 7000 cfs (nominal flood stage). The aquifer in the cobbles and sands is unconfined; depth to water below land surface (BLS) varies with topography (about 1 m of relief between wells at the site) and with river stage. In the wellfield area, the water table is 0 to 1 m BLS at high river stage, and 2 to 3 m BLS during summer irrigation and winter low flow seasons (Figure 4).

Coring and drilling information indicate that the cobble-and-sand alluvial sediments are present from land surface to 18.5 to 21.5 m BLS, and are underlain by a red clay that is continuous beneath the site and at least 3 m thick. Preliminary ground penetrating radar (GPR) profiling indicates that the cobble-and-sand unit at the site consists of a sequence of deposits separated by subhorizontal bounding surfaces (Figure 5). The scale and architecture of the radar stratigraphy appears to be similar to slightly older Quaternary, coarse, braided-stream, deposits (Othberg, 1992; Othberg and Stanford, 1994) observed in nearby outcrops and quarries (e.g., Figure 6), and to coarse braided-stream deposits that have been studied intensively in outcrop and with GPR in Switzerland (Huggenberger, 1993; Seigenthaler and Huggenberger, 1993; Jussel et al., 1994).

Symmetric and Asymmetric Wellfield Designs

The central area of 13 wells was designed originally in a symmetric pattern of two concentric rings of six wells each around a central well (Figure 3). This pattern meets the objectives of providing a high density of wells for direct measurement of geophysical and hydrologic parameters, establishing control for crosshole and surface geophysics, and providing many well pairs (78 possible) that can be used for crosshole tomography and control for surface profiles along the same transects. This pattern also provides seven overlapping volumes that can be investigated with multiple-well pumping tests, including 3-D hydrologic tomography where successive discrete intervals will be pumped in a given well while multiple zones can be monitored in five or six surrounding wells in each of those seven volumes (Figure 7).

However, there is a significant limitation with the original design. Because the inner ring wells were all the same distance from the central well and from each other, and outer ring wells were of two alternating distances from the central well and each other, this design resulted in a patchy histogram of well-pair distances (Figure 8). That is, the original design resulted in a poor distribution of wells for capturing geostatistical information.

To improve the design for capturing geostatistical information, experimental variograms in the horizontal and vertical directions were generated for porosity in the Quaternary cobble-and-sand alluvial unit at the Capital Station site (Figure 9) based on the petrophysical transform of epithermal neutron log data to porosity values (Hearst and Nelson, 1985; Barrash et al., 1997b). Porosity was used because far too few permeability values are available at the Capital Station site to perform a geostatistical analysis directly for permeability. In this regard, some previous work (Phillips and Wilson, 1989; Rehfeldt et al., 1992) suggests that porosity may be a proxy parameter for log permeability in some sedimentary aquifers (Clarke, 1979; Tomatsu et al., 1986; Nelson, 1994).

Model variograms were fit to the experimental vertical and horizontal variograms of porosity data by trial and error. A nested Gaussian and spherical model provided a reasonable visual fit (Figure 9). Vertical relationships are well defined: range is ~1.5 m and a hole effect is observed. Horizontal relationships are less well defined; the horizontal range with this model is about 6-7 m. If an exponential model is fit to the experimental variograms, the horizontal range is ~5 m. These horizontal range values are similar to those estimated in coarse braided-stream deposits in Switzerland (Jussel et al., 1994).

A new design was developed for the 13-well central area of the BHRS with the added objective of determining geostatistical relationships and parameters over the rising-limb portions of horizontal variograms for hydraulic and geophysical properties, without sacrificing design objectives listed previously. Criteria for the new design include (a) 13 wells in two rings around a central well, with wells in the two rings at regular but offset radial angles; (b) a smooth distribution of numbers of well-pair distances through the rising limb of horizontal variograms for hydraulic parameters; (c) a smooth azimuthal distribution of numbers of well pairs in each lag grouping of well pairs; and (d) a minimum of one well pair in each azimuthal octant (i.e., each 45^{o} sector) for lag groupings in the rising limb of horizontal variograms for hydraulic parameters. The latter two criteria are included to improve our ability to characterize anisotropy.

Based on the results of geostatistical analysis of porosity data from the Capital Station site (Figure 9), it was assumed that the range for hydraulic parameters (porosity, log permeability) likely would be in the interval of 7 ± 2 m. Revised wellfield characteristics prescribed for the 13-well, two-ring design are (1) the six wells in the inner ring must be in the distance range of 2.5 m to 5.5 m from the central well and at 60° radial angles from each other; and (2) the six wells in the outer ring must be in the distance range of 7.5 m to 10 m from the central well, at 60° radial angles from each other, and at 30° radial angles from the inner-ring wells.

A Monte Carlo search technique was used to find a wellfield design that would meet the new requirements. Search criteria used to determine the best design for geostatistical characterization are (1) even distribution of numbers of well pairs at 1-m lag intervals throughout the rising limb of the horizontal variogram (i.e., minimize the sum of squared differences between the average number of well pairs per meter lag between 2.5 m and 9.5 m and the number of well pairs in each lag); (2) even distribution of well-pair azimuths at 1-m lags for all well-pair distances in the central area (i.e., minimize the sum of squared differences between the average number of well-pair azimuths in each octant per meter lag from 2.5 m to 20.5 m, and the number of well-pair azimuths in each octant per meter lag); and (3) ensure at least one well pair is present in each azimuthal octant per meter lag interval throughout the rising limb of the horizontal variogram (i.e., from 2.5 m to 9.5 m). An additional design feature was to orient the well configuration with anticipated axes of anisotropy (longer axis parallel to river flow and shorter axis perpendicular to river flow).

The well configuration that best met the search criteria out of 3000 Monte Carlo runs was selected and staked on the ground at the BHRS. After three of the central area wells had been installed according to this configuration, the new design had to be revised because a drive-casing failure left 20 ft (6.1 m) of steel casing in the subsurface at an outer-ring well location which, fortunately, was the outer-ring well at the greatest radial distance from the central well. The search criteria were applied once more with the added constraints that (1) the central well and the three other wells already installed were at given locations, and (2) the outer ring well at the azimuth of the failed well must be at least 2 m closer to the central well than the failed well. Figures 10A and B show the relative positions and the histogram of well-pair distances, respectively, for the revised well configuration that best meets the new search criteria (out of 3000 Monte Carlo runs). With the revised configuration, the 13 wells in the central area are not aligned so well with anticipated principal axes of material anisotropy. However, the Monte Carlo search criteria requiring even azimuthal distribution of well pairs makes it likely that anisotropy will be recognizable with the number of wells available.

The five boundary wells at the BHRS serve the purposes of (1) defining the hydraulic gradient across the site; (2) determining if and when hydrologic influences from tests in the central area have reached these "boundaries;" (3) providing control locations or "targets" for geophysical transects away from the thoroughly characterized central area; and (4) determining if and when hydrologic influences from off the site have reached the site. Placement of boundary wells at the BHRS is largely determined by site-specific natural, cultural, and regulatory conditions. Available locations for boundary wells are limited by topography at the BHRS (sand ridges with abrupt relief east and north of the central area) and by proximity to the Boise River and a flood bypass slough (to the west and east of the central area, respectively) (Figure 1). In particular, wells could not be placed riverward or sloughward of waterlines when the Boise River is flowing at 7000 cfs-the common controlled high-discharge rate during late winter and early spring run-off (Figure 4). The fifth boundary well is necessary because of the close proximity of the central well area to the Boise River (i.e., constant head boundary 22 m from the central well when the Boise River flows at 7000 cfs). Boundary well distances from the central well range from 22 m to 45 m (Figure 1).

Well Construction

The basic principal underlying well construction for the BHRS is as follows: maximum information with minimum disturbance. Design considerations for the individual wells include (1) using the smallest well diameter that accommodates the range of instruments needed to perform the planned borehole tests (Table 1); (2) collecting continuous core samples to the extent possible including collection of sand matrix associated with cobbles; (3) drilling and emplacing the wells with minimal disturbance to the formation while ensuring good mechanical and hydrologic coupling to the formation after the well is installed; (4) having the maximum possible thickness of the aquifer screened in the well; and (5) using materials that do not interfere with planned tests.

Coring and Drilling

Coring and drilling methods used at the BHRS largely follow methods developed in our work at the Capital Station remediation site in downtown Boise (Barrash et al., 1997a). At Capital Station, coring attempts with a diamond drill bit were unsuccessful at capturing matrix with the cobbles (either with or without using a plastic sleeve in the core barrel above the bit). However, high-percentage recovery of cobbles (or cobble segments) with associated sand matrix was achieved at Capital Station and the BHRS by driving a 2.5-inch (6.3-cm) ID by 1.5- or 2-ft (0.46- or 0.61-m) long, split spoon with a hydraulic hammer. This method cuts cobbles that are either larger than the diameter of the spoon mouth or that straddle the spoon mouth; broken cobble segments are relatively easy to identify in the core (Figure 11; see also Figure 6 in Barrash et al., 1997b). Greater than 80% of the cored length was recovered from the 18 wells drilled at the BHRS.

The well drilling process is a repeated sequence of coring, drilling, and driving temporary casing (Figure 12). Generally two spoons are driven in succession followed by drilling to the cored depth with a rock bit. Then 5-inch (12.7-cm) ID, 5.25-inch (13.3-cm) OD steel casing with a welded-on 6-inch (15.2 cm) drive shoe is driven to the cored depth followed by a second drilling cycle to clean out the hole. This sequence of core-drill-drive-drill is repeated throughout the unconsolidated cobble-and-sand unit to 60-70 ft (18.5-20.5 m) BLS where the red clay is intercepted. The wells are completed either 5 or 10 ft (1.5 or 3 m) into the clay to provide room for downhole testing equipment so that direct measurements can be taken through the full thickness of the cobble-and-sand unit and the upper portion of the clay. A synthetic drilling "mud" is used to lift drill cuttings without adding mineral solids (e.g., bentonite) that would be difficult to remove from the formation and would lower permeability adjacent to wells. The synthetic "mud" is decomposed with addition of 5.25% sodium-hypochlorite solution (common bleach) after the well is completed.

Well Completion

After total depth is reached, the hole is flushed until it flows clear with clean water. Then the 4-inch (10.2-cm) schedule 40 PVC casing and screen is placed into the hole (Figure 12). For most wells, 5 or 10 ft (1.5 or 3 m) of blank casing is installed in the clay and then 55 ft (16.8 m) of 0.020-slot PVC screen is placed against the cobbles and sands to about 5 ft (1.5 m) BLS. With judicious sequencing of 5- and 10 ft-long screen sections, effort is made to avoid locating the joints between screen sections adjacent to sand lenses that are recognized during coring. This is important because sand lenses generally are the most permeable units in the cobble-and-sand deposits (Jussel et al., 1994; Barrash et al., 1997b), and many sand lenses are comparable in thickness to the 1-ft (0.3-m) thickness of blank casing at the joints between screen sections. The smallest well diameter that will accommodate the range of instruments needed to perform borehole tests (Table 1) is 4 inches (10.2 cm). The types of equipment which would be difficult to fit in smaller diameter wells are down-hole seismic sources and straddle-packer systems with multiple transducers and multiple-zone sampling capabilities. No planned or anticipated tests are eliminated or compromised with 4-inch (10-cm) wells, especially since the disturbed zone, including the well, is limited to a diameter of 6 inches (15.2 cm) with the drilling and well-emplacement methods used at the BHRS.

The annular space between the 4.5-inch (11.4-cm) OD of the PVC casing and screen and the 5-inch (12.7-cm) ID of the temporary drive casing is too small to allow the emplacement of a filter pack. However, when the drive casing is removed, the unconsolidated cobbles and sands collapse against the PVC casing and screen without leaving large gaps or loose regions adjacent to the well. A similar well-construction method was used in unconsolidated sands at Cape Cod and was found to be superior to augering or mud-rotary drilling for minimizing the disturbed region around the well as determined by statistical analysis of geophysical logging responses (Morin et al., 1988).

Surface completion is designed for protection against vandalism and contamination, while minimizing the use of metal components which interfere with electrical geophysical methods such as TEM and GPR. Thick-walled, high-density polyethylene pipe is used for the protective casing and cap around the PVC well-casing riser. A removable steel bar is slid through holes in the cap and locked to deter vandalism. Inside the protective casing, another cap with a brass tightener provides the water-tight seal at the well. The only permanent metal associated with a given well is a small identification tag from the Idaho Department of Water Resources that is fixed in the concrete surface seal and plug at each well.

CURRENT STATUS

Eighteen wells are now in place at the BHRS according to the revised design (Figure 10A). Initial tests conducted to date in some of the wells include borehole geophysical logging (in conjunction with the USGS), vertical seismic profiling (VSP), vertical radar profiling, and seismic and radar tomography (in collaboration with Lawrence Berkeley Laboratory). TEM soundings have been taken at well locations before and after wells were emplaced, and initial surface seismic and radar profiles have been run across portions of the site.

Data analysis for site characterization is still in preliminary stages but results to date indicate that design features are supporting wellfield testing objectives. In particular, mechanical and hydrologic coupling between well screen and casing and the formation is good. No gaps or loose regions are evident from VSPs in six wells using SH waves which require a high-degree of mechanical coupling between the formation and wells. Also, preliminary analysis of permeability logging with the flowmeter-and-pumping method (Molz et al., 1989) in four wells at the BHRS (in collaboration with the USGS) show no indication of high-permeability bypass regions. Benefits in improved data quality of TEM soundings and surface GPR profiles are evident with the use of high-density polyethylene protective casing instead of metal at the surface. Compared with data collected at Capital Station where the wells have metal protective surface casing, resolution is improved with TEM and interference is decreased with GPR at the BHRS. Crosshole seismic and radar experiments between three wells indicate that, for seismic tomography, a high-frequency piezoceramic bender source operates well in the 4-inch (10-cm) diameter borehole, and the upper portion of the cobble-and-sand aquifer at the BHRS is highly attenuative (John Peterson, written communication). GPR tomography yields high-resolution images (e.g., Figure 13, courtesy of LBL) that provide data on variation of properties such as porosity which may, with other data sets, improve interpretations of the distribution of lithologic units or facies.

SUMMARY

A research wellfield (BHRS) is being developed in Boise, Idaho, to provide a 3-D calibration volume for geophysical and hydrologic research aimed at developing methods for using non-invasive geophysical techniques to map variations in permeability in shallow alluvial aquifers. The BHRS is located on a gravel bar adjacent to the Boise River where the shallow aquifer consists of ~20 m of coarse, unconsolidated, alluvial sediments underlain by clay. The wellfield has been designed to accommodate a wide range of geophysical and hydrologic tests including single well, crosshole, and multiple-well tests. The configuration of wells is optimized to capture geostatistical information at short separation distances, to define the range and structure of hydrologic and geophysical parameters, and to recognize anisotropy. To date, coring results and preliminary geophysical measurements (e.g., VSPs, borehole geophysical logs, radar and seismic tomography, GPR reflection profiles) confirm that the wellfield design supports a variety of characterization methods, and that the wellfield is located over a sequence of cobble-and-sand (braided stream) deposits that exhibit lateral and vertical variations underneath the site. Further testing is planned over the next several years to thoroughly characterize the 3-D volume encompassed by 13 wells in the central wellfield area, to determine relationships between geophysical and hydrologic parameters, and to develop methods for mapping permeability variations by combining geophysical and hydrologic data.

ACKNOWLEDGMENTS

The following are gratefully acknowledged: funding by U.S. Army Research Office grants DAAH04-94-G-0271 (Capital Station) and DAAH04-96-1-0318 (BHRS); access to the Capital Station site by S-Sixteen Inc. and Anderson Associates, Inc; access to BHRS by Idaho Transportation Department, U.S. Bureau of Reclamation, and Ada County; collaboration with Dr. Ernie Majer, John Peterson, Tom Daley, and Ken Williams (Lawrence Berkeley Laboratory), Dr. Roger Morin (USGS), and Dr. Harry Jol (University of Wisconsin at Eau Claire); and innovative drilling by Haz-Tech Drilling.

REFERENCES

Barrash, W., and M.D. Knoll, 1997. Research Wellfield for Calibrating Geophysical Measurements Against Hydrologic Parameters (abs.), Fall AGU Meeting, San Francisco, CA, EOS, 78 (46), pp. F319.

Barrash, W., and R.H. Morin, 1997. Recognition of Units in Coarse, Unconsolidated Braided-Stream Deposits from Geophysical Log Data with Principal Components Analysis, Geology, 25, pp. 687-690.

Barrash, W., P. Donaldson, K. Huang, M. Knoll, P. Michaels, and J. Pelton, 1997a. Toward Joint Inversion of Hydrologic and Geophysical Data for Permeability Distribution in an Alluvial Aquifer. Selected Res. in Env. Quality FY1996, Proc. Joint USAF/Army Contractor/ Grantee Mtg., Jan. 14-17, 1997, Panama City, FL, pp. 9-17.

Barrash, W., P. Donaldson, P. Michaels, J. Pelton, and S. Urban, 1995. Joint Inversion of Hydrologic and Geophysical Data for Permeability Distribution in an Alluvial Aquifer: Proc. Env. Site Char. and Mon. Basic Program 1995 Contractor/Grantee Mtg., May 11-12, 1995, Hanscom AFB, MA, Air Force Office of Scientific Research, pp. 1-9.

Barrash, W., R.H. Morin, and D.M. Gallegos, 1997b. Lithologic, Hydrologic and Petrophysical Characterization of an Unconsolidated Cobble-and-Sand Aquifer, Capital Station Site, Boise, Idaho, Proc. 32nd Symp. on Eng. Geol. and Geotech. Eng., Mar. 26-28, 1997, Boise, ID, pp. 307-323.

Clarke, R.H., 1979. Reservoir Properties of Conglomerates and Conglomeratic Sandstones, AAPG Bull., 63, pp. 799-803.

Gelhar, L.W., C. Welty, and K.R. Rehfeldt, 1992. A Critical Review of Data on Field-Scale Dispersion in Aquifers, Water Res. Res., 28, pp. 1955-1974.

Guven, O., F.J. Molz, J.G. Melville, S. El Didy, and G.K. Boman, 1992. Three-Dimensional Modeling of a Two-Well Tracer Test, Ground Water, 30, pp. 945-957.

Hearst, J.R., and P.H. Nelson, 1985. Well Logging for Physical Properties, McGraw-Hill, New York, p. 571.

Huggenberger, P., 1993. Radar Facies: Recognition of Facies Patterns and Heterogeneities within Pleistocene Rhine Gravels, NE Switzerland, In Best, J.L. and C.S Bristow (Eds.), Braided Rivers, Geol. Soc. Sp. Publ. 75, pp. 163-176.

Hyndman, D.W., and S.M. Gorelick, 1996. Estimating Lithologic and Transport Properties in Three Dimensions Using Seismic and Tracer Data: The Kesterson Aquifer, Water Res. Res., 32, pp. 2659-2670.

Jussel, P., F. Stauffer, and T. Dracos, 1994. Transport Modeling in Heterogeneous Aquifers, 1. Statistical Description and Numerical Generation of Gravel Deposits, Water Res. Res., 30, pp. 1803-1817.

Mas-Pla, J., T.-C.J. Yeh, J.F. McCarthy, and T.M. Williams, 1992. A Forced Gradient Tracer Experiment in a Coastal Sandy Aquifer, Georgetown Site, South Carolina, Ground Water, 30, pp. 958-964.

McKenna, S.A., and E.P. Poeter, 1995. Field Example of Data Fusion in Site Characterization, Water Res. Res. 31, pp. 3229-3240.

Michaels, P., in press, *In Situ* Measurement of Soil Stiffness and Damping, J.Geotech. Eng.

Michaels, P., and W. Barrash, 1996. The Anomalous Behavior of SH-Waves across the Water Table, Proc. Symp. on the Appl. of Geophys. to Eng. and Env. Problems, Keystone, CO, Apr. 28-May 2, 1996, pp. 137-145.

Molz, F.J., R.H. Morin, A.E. Hess, J.G. Melville, and O. Guven, 1989. The Impeller Meter for Measuring Aquifer Permeability Variations: Evaluation and Comparison with Other Tests, Water Res. Res., 22, pp. 1677-1683.

Morin, R.H., D.R. LeBlanc, and W.E. Teasdale, 1988. A Statistical Evaluation of Formation Disturbance Produced by Well-Casing Installation Methods, Ground Water, 26, pp. 207-217.

Nelson, P.H., 1994. Permeability-Porosity Relationships in Sedimentary Rocks. Log Analyst, May-June, pp. 38-62.

Othberg, K.L., 1994. Geology and Geomorphology of the Boise Valley and Adjoining Areas, Western Snake River Plain, Idaho: Idaho Geol. Surv. Bull. 29, p. 54.

Othberg, K.L., and L. R. Stanford, 1992. Geologic Map of the Boise Valley and Adjoining Area, Ada and Canyon Counties, Idaho: Idaho Geol. Surv. Map Ser. scale 1:100,000.

Phillips, F.M., and J.L. Wilson, 1989. An Approach to Estimating Hydraulic Conductivity Spatial Correlation Scales Using Geologic Characteristics, Water Res. Res., 28, pp. 141-143.

Rehfeldt, K.R., J.M. Boggs, and L.W. Gelhar, 1992. Field Study of Dispersion in a Heterogeneous

Aquifer 3. Geostatistical Analysis of Hydraulic Conductivity, Water Res. Res., 28, pp. 3309-3324.

Rubin, Y., G. Mavko, and N. Copty, 1992. Mapping Permeability in Heterogeneous Aquifers Using Hydrologic and Seismic Data, Water Res. Res., 28, pp. 1809-1816.

Seigenthaler, C., and P. Huggenberger, 1993. Pleistocene Rhine Gravel: Deposits of a Braided River System with Dominant Pool Preservation, In Best, J.L. and C.S. Bristow (Eds.), Braided Rivers, Geol. Soc. Sp. Publ. 75, pp. 147-162.

Tomutsa, T., S.R. Jackson, and M. Szpakiewicz, 1986. Geostatistical Characterization and Comparison of Outcrop and Subsurface Facies: Shannon Shelf Sand Ridges: Proc. 56th Ann. California Reg.Mtg., Soc. Petr. Eng., SPE Paper 15127, pp. 317-328.

U.S. Geological Survey, 1998. http://waterdata.usgs.gov/nwis-w/ID/data.components/hist.cgi? statnum =13203510 (—>Retrieve historical daily streamflow data as graph).

Weeks, E.P., 1969. Determining the Ration of Horizontal to Vertical Permeability by Aquifer-Test Analysis, Water Res. Res., 5, pp. 196-214.

Figure 1. Photomap of the Boise Hydrogeophysical Research Site (BHRS) showing locations of 13 wells in the central portion of the field and five boundary wells. 7000 cfs line is wetted perimeter when Boise River is flowing at that rate. Slough is wet east of dotted line at high river stages, but is dry during normal irrigation and winters season flows of the Boise River. Flow in the Boise River at this location is to the northwest.

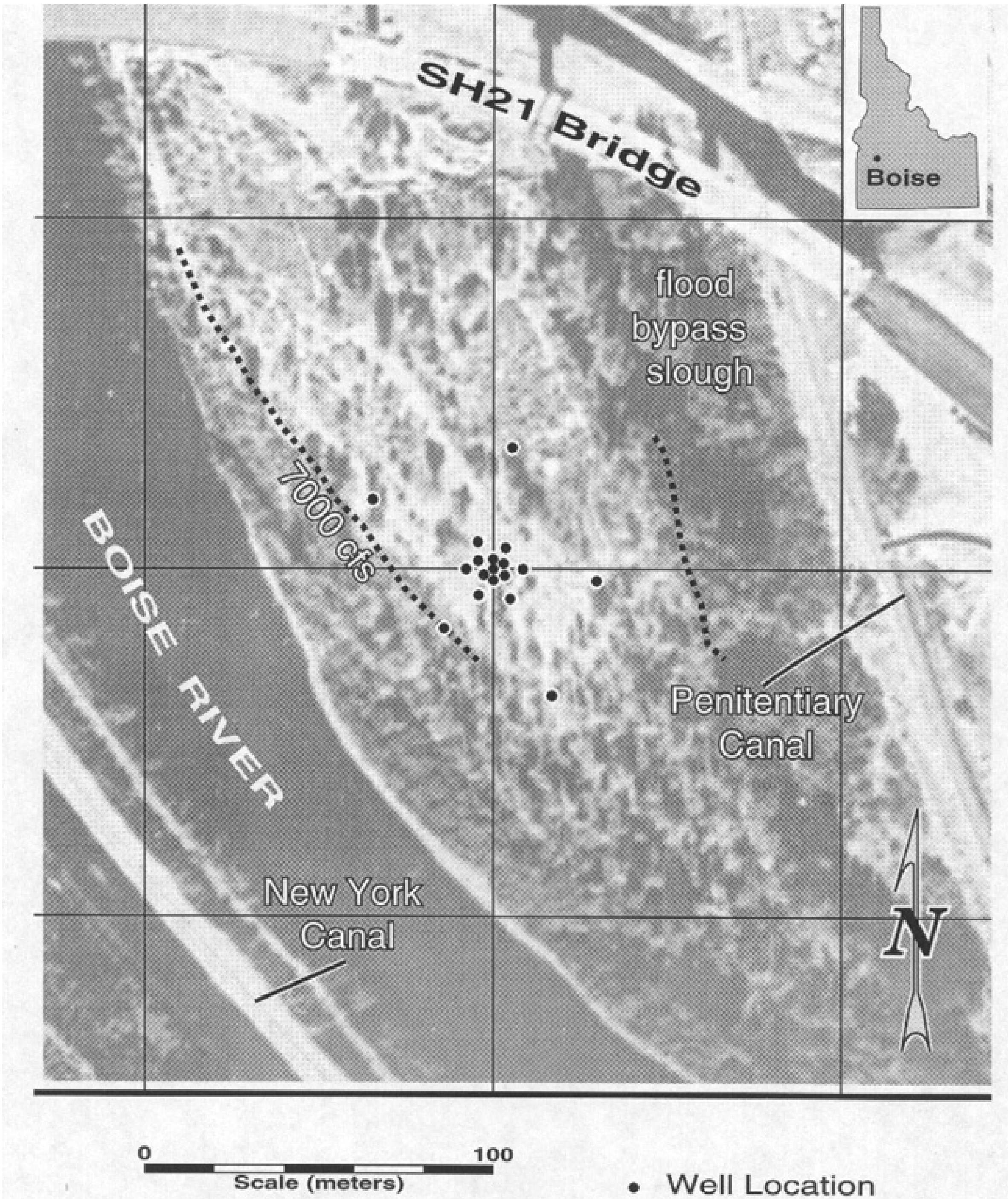

Figure 2. Schematic diagram of testing methods in individual wells, between wells, and at the surface. For GPR and seismic methods, borehole measurements calibrate crosshold measurements, and borehold and crosshole measurements calibrate surface measurements. For the transient electromagnetic method (TEM), apparent resistivity soundings were made a well locations prior to coring and installation (and elsewhere in a grid pattern over the wellfield), and will be compared with induction resistiveity borehole geophysical logs in the wells.

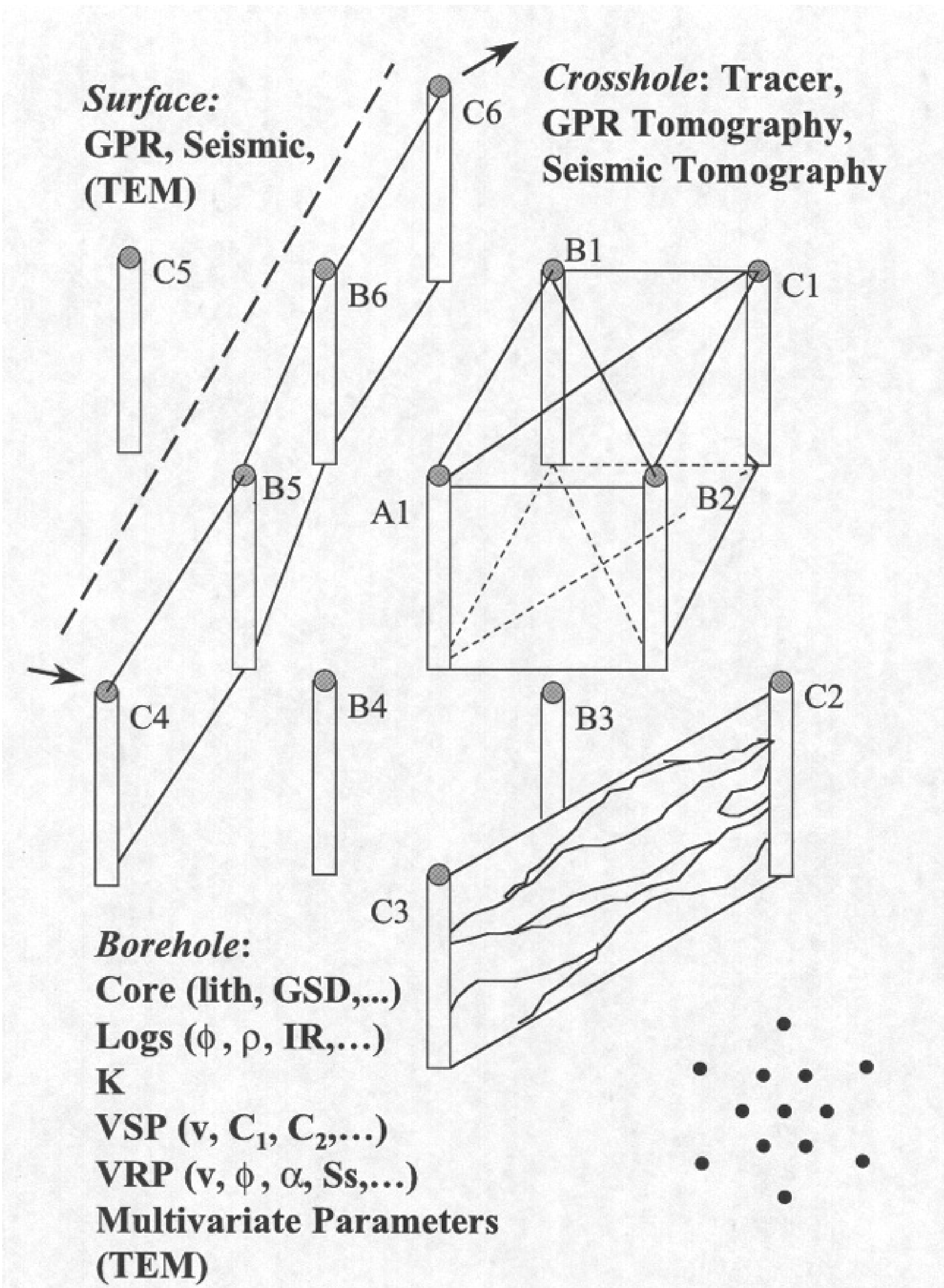

Figure 3. Original design of 13-well central area for the BHRS is a double-ring pattern having a central well surrounded by two rings of six wells each, with wells in each ring offset from each other at 60° radial angle spacings, and with wells offset 30° between rings. Wells are at two alternating radial distances from the central well in the outer ring.

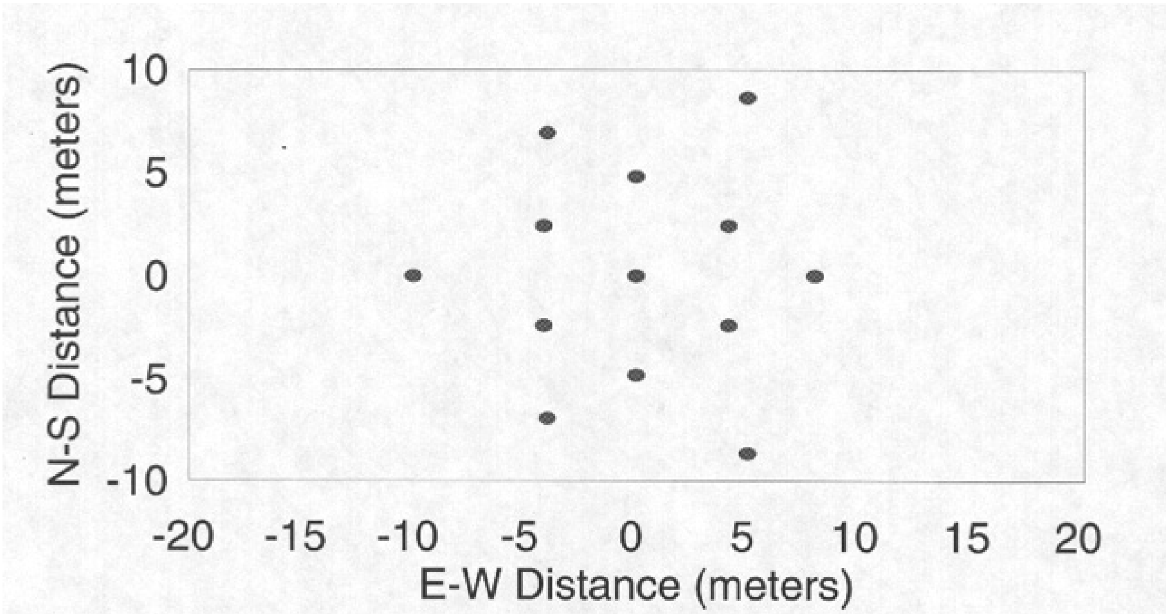

Figure 4. Hydrograph of Boise River stage from gaging station 0.5 km upstream of the BHRS (from USGS website: http://waterdata.usgs.gov/nwis-w/ID/data.components/hist.cgi?statnum= 13203510). At this location, the annual cycle is dominataed by two or three stages associated with late winter or spring high water (~7000 cfs), irrigation season flows (~1500±500 cfs), and fall-winter low flows (~200±100 cfs).

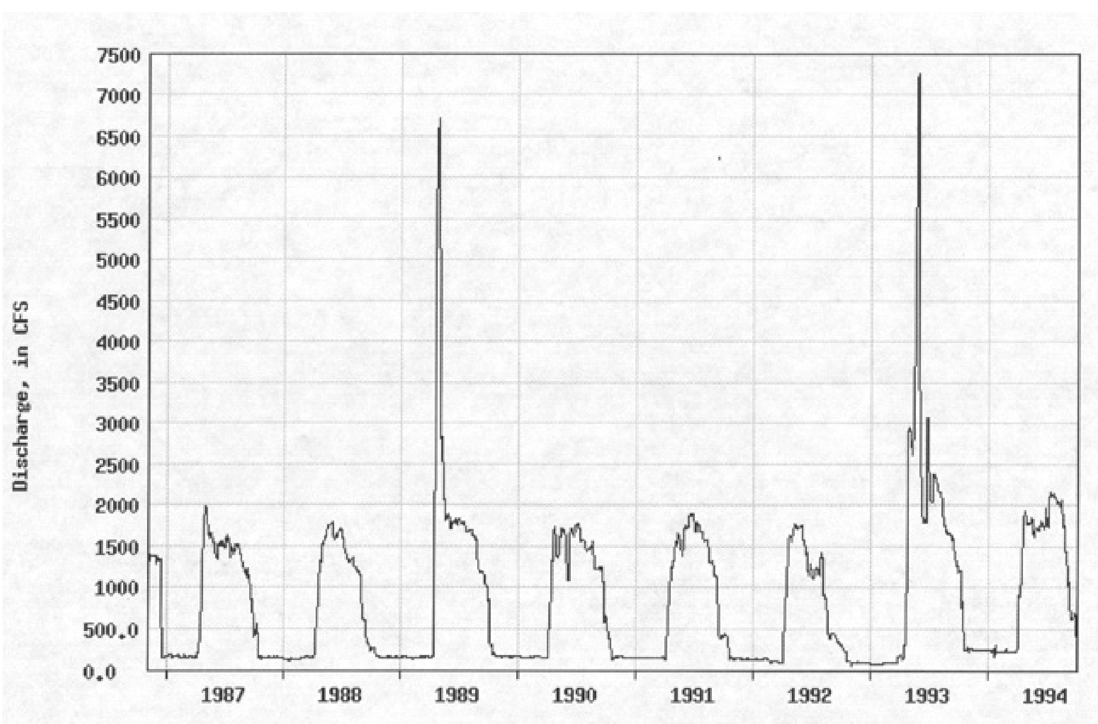

Figure 5. Ground-penetrating radar (GPR) reflection profile at the BHRS (taken with 100 MHz antennas) showing subhorizontal bounding surfaces and lateral and vertical variation in sedimentary structure that can be associated with different cobble-dominated facies (Huggenberger, 1993). Location of central portion of BHRS straddles much of the variability avident in this profile. Note different horizontal and vertical scales.

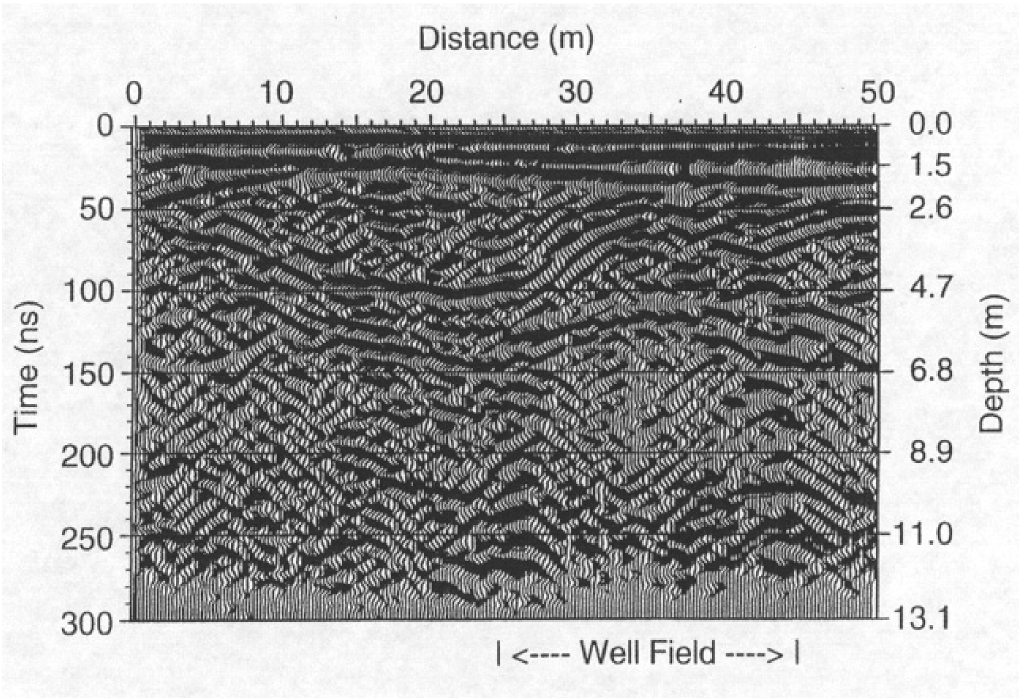

Figure 6. Quarry exposure of analogous coarse, braided-stream deposits showing disconnected sand lenses (S) and a variety of cobble-dominated facies ranging from poorly sorted massive unites (Gm), to moderate sorted horizontally-bedded units (Gh) and trough crossbedded units (Gt). Heavy lines indentify bounding surfaces between depositional sequences. Prime Earth quarry northwest of Boise, Idaho. For scale, quarry face is approximately 12 m high.

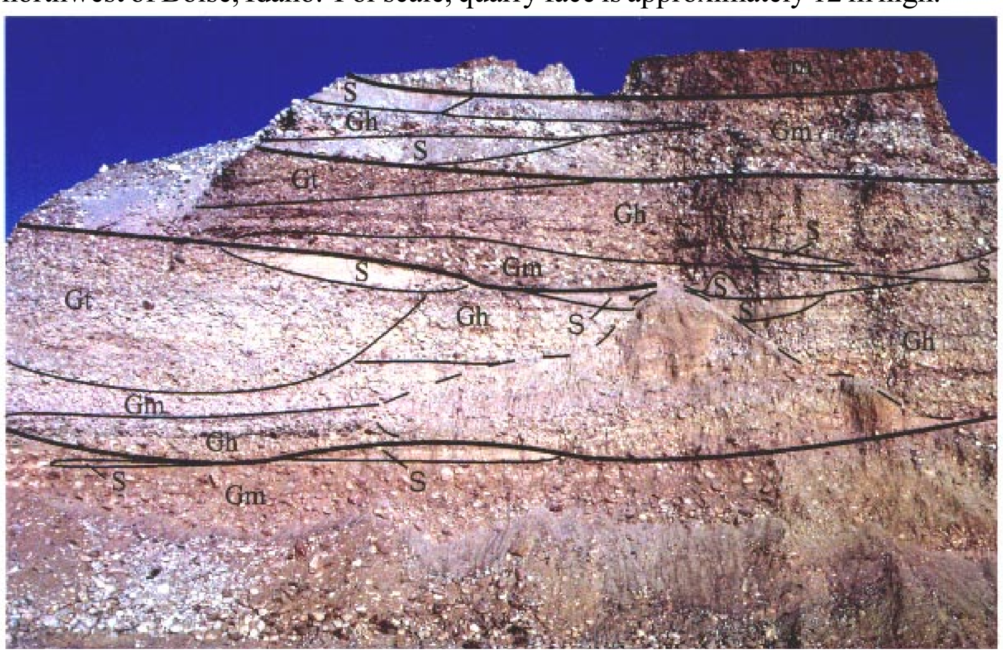

Figure 7. Schematic diagram of "hydrologic tomography" method for characterizing 3-D distribution of permeability. Discrete intervals are pumped at a given well (here the central well) while head responses are monitored at multiple discrete intervals in surrounding observation wells. Similar, but less densely controlled, experiments at the Capital Station groundwater remediation site in downtown Boise (Barrash et al., 1995, 1997a) showed the potential for this method to identify permeability variations in 3-D. Seven sets of overlapping 3-D hydrologic tomography experiments can be run at the BHRS.

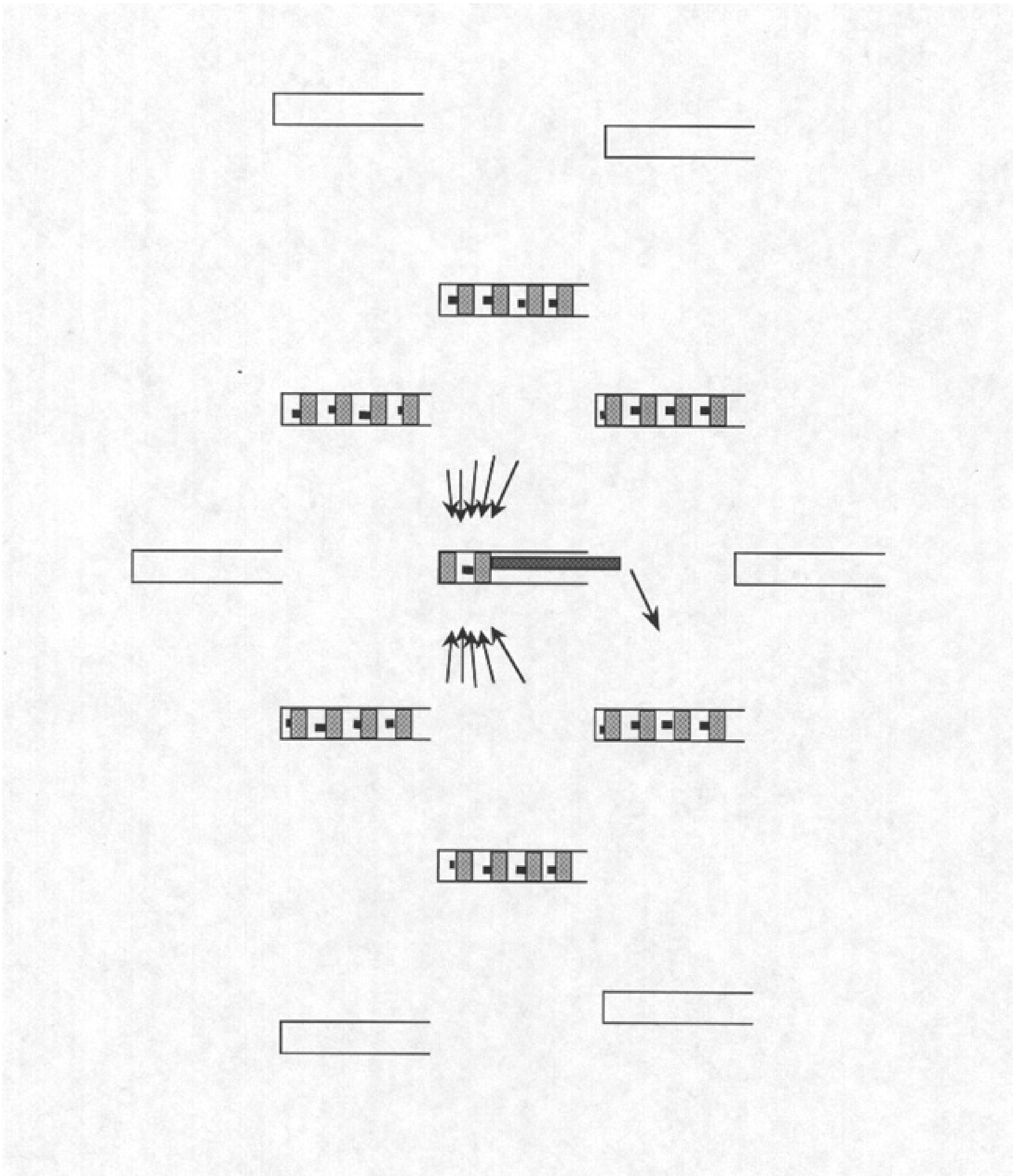

Figure 8. Histogram of well-pair distances at 1 m lags for original wellfield design shows that the highly symmetrical arrangement of wells in two rings about a central well does not provide a good distribution of well-pair distances for geostatistical analysis.

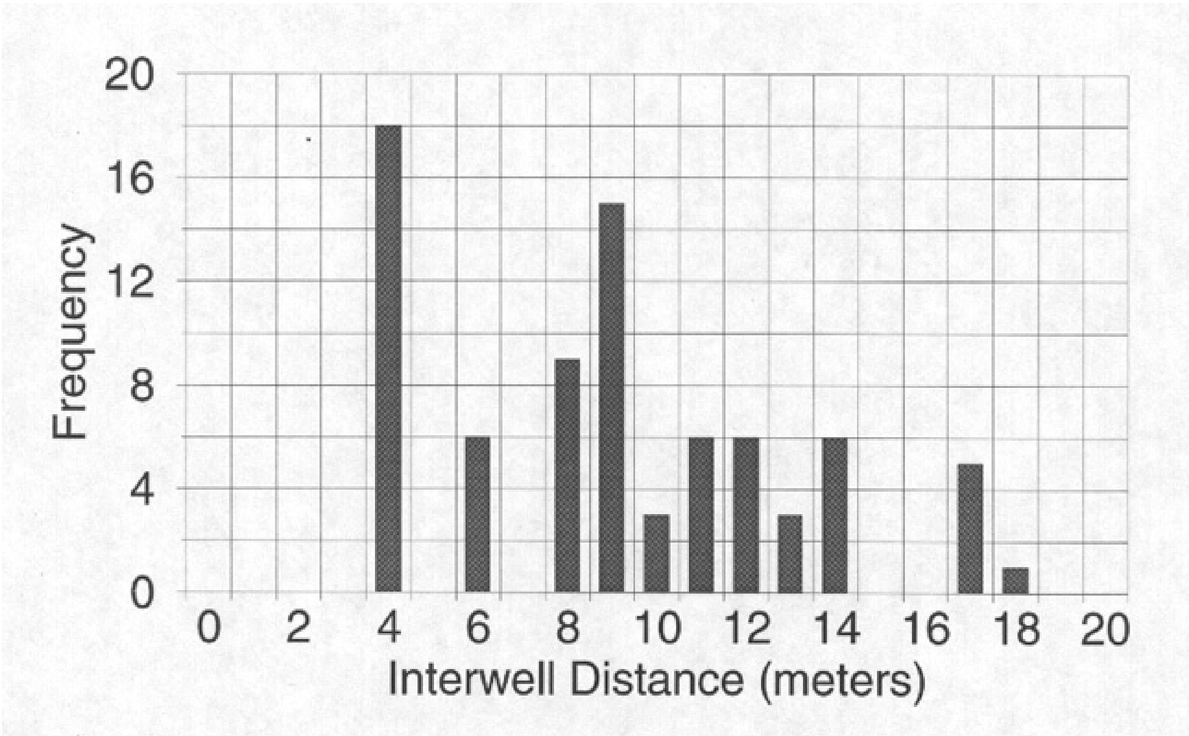

Figure 9. (A) Vertical and (B) horizontal variograms of porosity (based on neutron geophysical log data at Capital Station) can be fit with nested Gaussian and spherical models with vertical and horizontal ranges of about 1.5 m and 6-7 m, respectively. This information was used to revise the design of well spacings and locations at the BHRS.

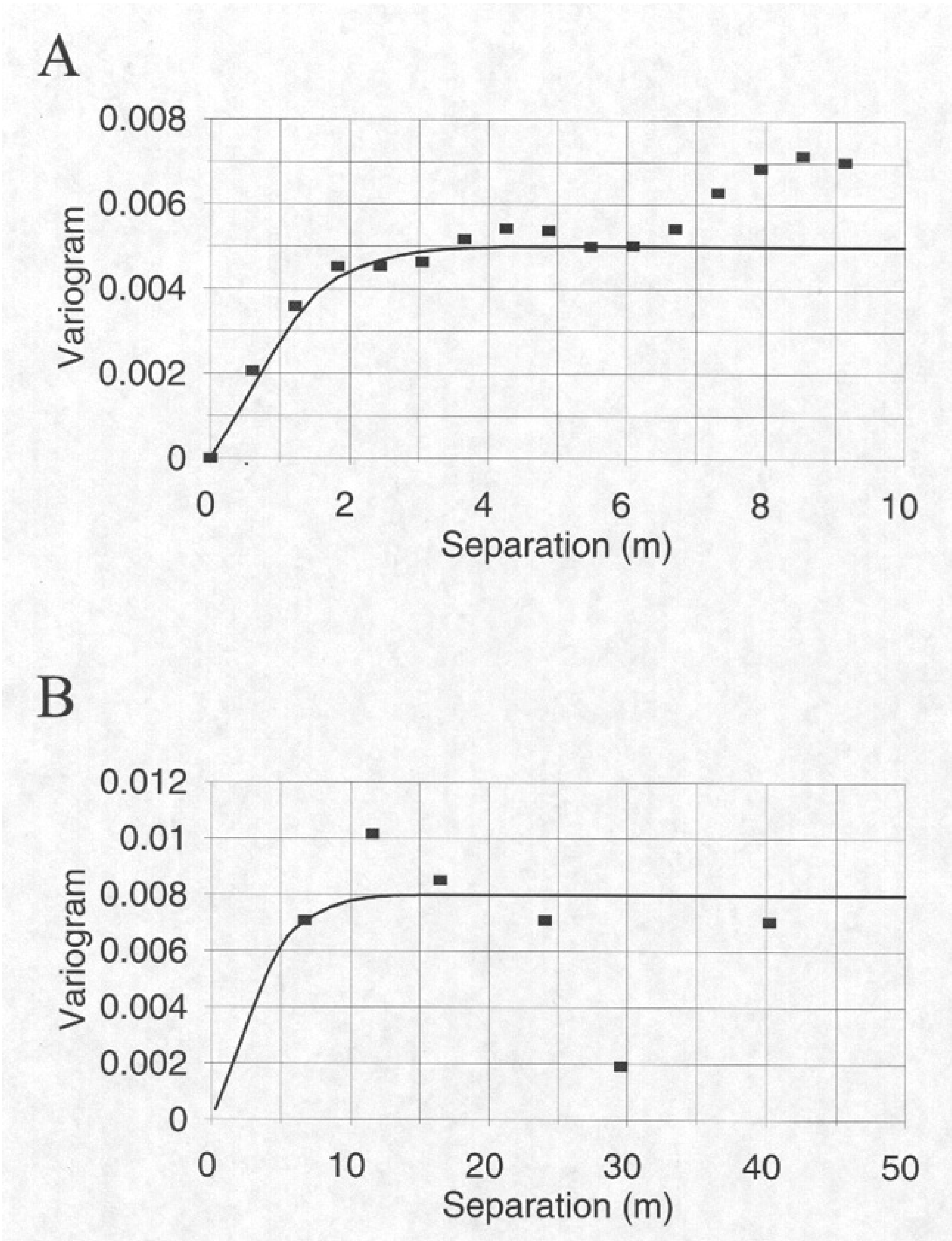

Figure 10. (A) Revised design of central well area based on a Monte Carlo search (3000 runs) for a tw-ring configuration. Wells are identified by ring and position. (B) Histogram of well-pair distances at 1-m lags shows more even distribution through the 6-7 m expected length of the rising limb portion (range) of the horizontal variogram for porosity or log permeability.

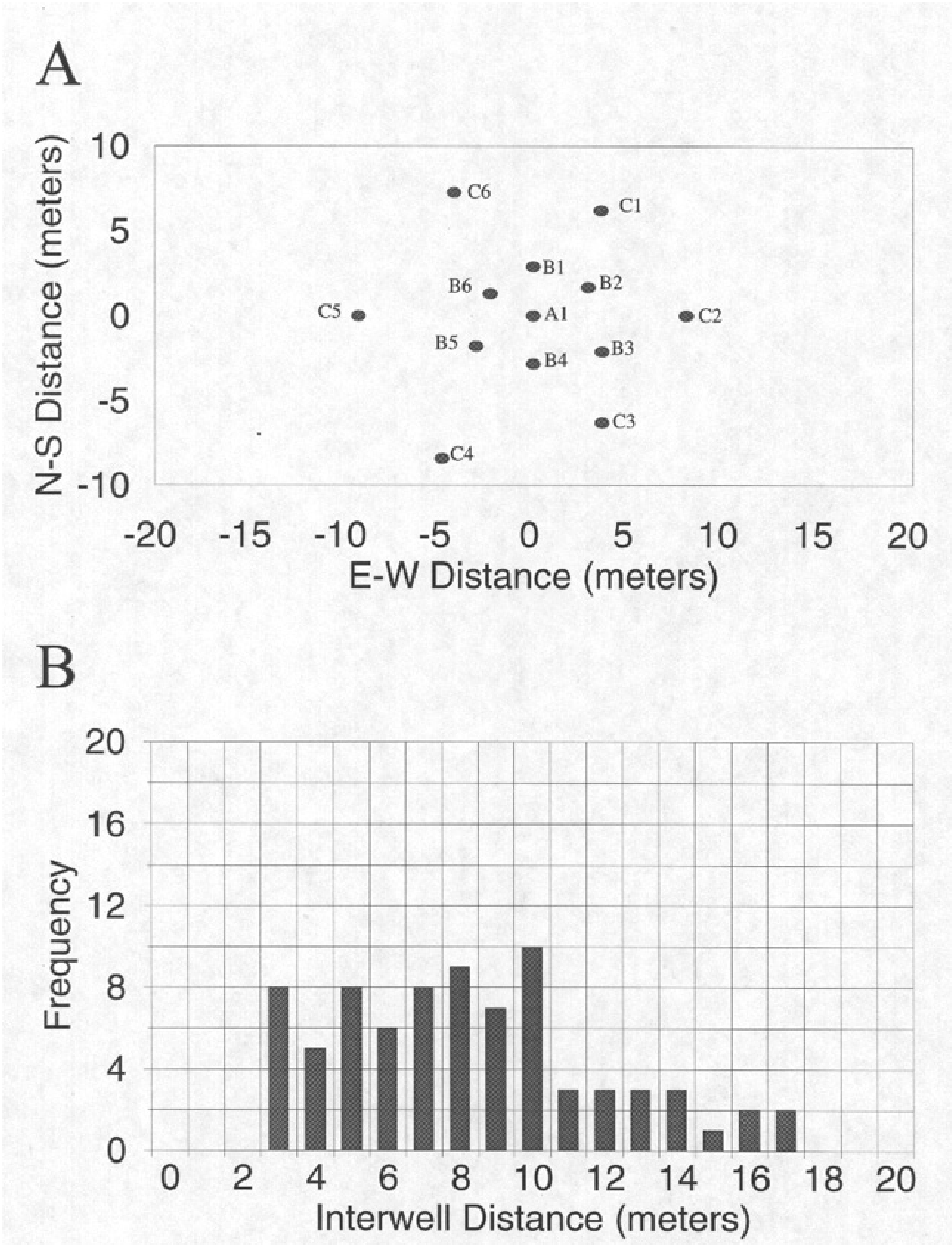

Figure 11. Example of core recovery from 34 to 42 ft BLS in well X1 at the BHRS. Changes in cobble size are evident. Large cobbles may be mostly intact (e.g., at 35 ft) or broken to variying degrees (e.g., at 40-40.5 ft). Sand lenses (e.g., at ~37.6-38.4 ft) and sand matrix with cobbles are captured in place. Unrecovered intervals (places held by foam with X marks) are arbitrarily assigned to the top of a given cored section during collection in the field.

Figure 12. Wells at the BHRS are cored by driving a split spoon. Core recovery is greater than 80%. The unconsolidated formation is held back with drive casing (13.3-cm OD). Residual material is removed by rotary drilling using a synthetic mud. PVC screen (10-cm ID, 11.4 cm OD) is set inside the 12.7-cm ID drive casing. The formation collapses flush against the screen when the drive casing is removed. A tight red clay is continuous beneath the site at about 20 m below land surface.

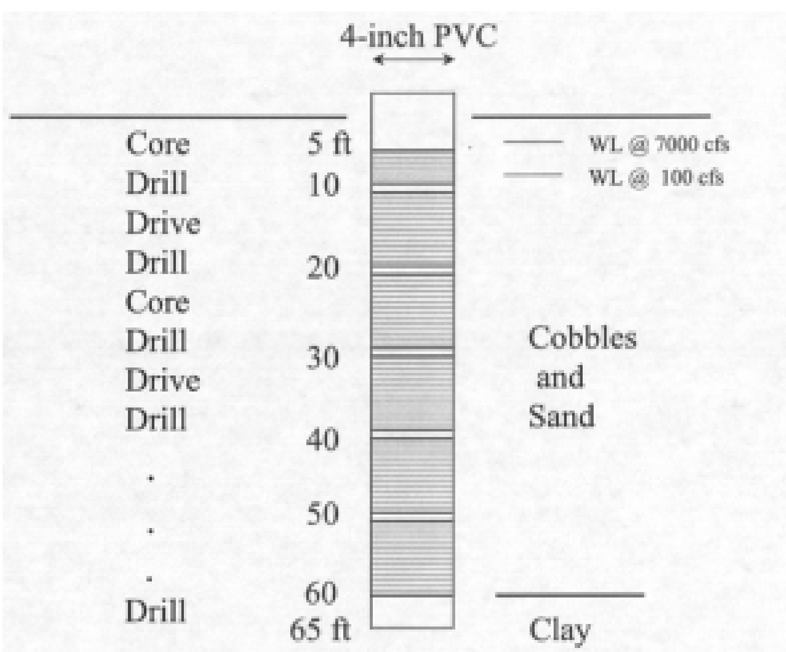

Figure 13. Radar velocity tomogram produced from crosshole data collected between wells B2 and C1 at the BHRS by BSU and Lawrence Berkeley Laboratory investigators in October 1997. Fine detail of velocity variation is indicative of porosity variations between the wells. Water table is about 3 m below land surface. Figure courtesy of LBL.

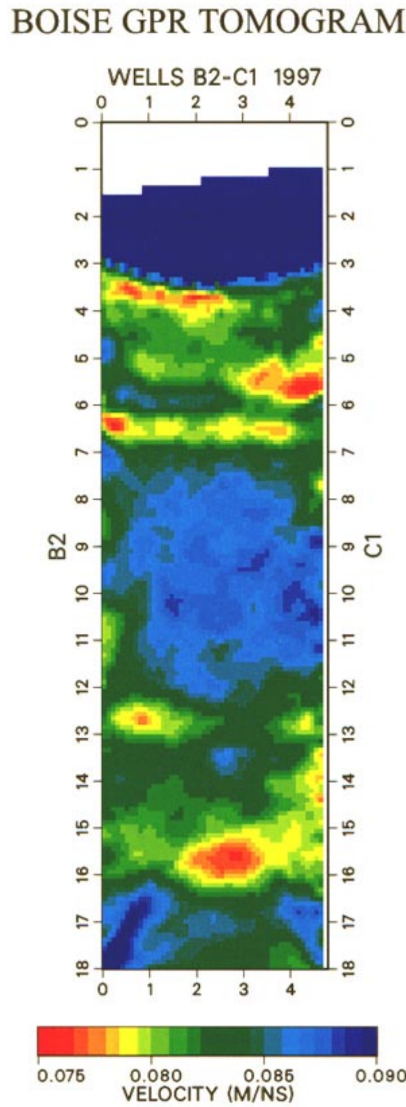

Table 1. Tests planned for the Boise Hydrogeophysical Research Site

Single-Well Tests
Neutron (porosity) logs
Natural gamma logs
Gamma-gamma (density) logs
Temperature logs
Fluid resistivity logs
Induction conductivity logs
Flowmeter logs
Flowmeter-and-pumping (permeability) profiles
Borehole deviation logs
Vertical seismic profiles
Vertical radar profiles
Head profiles (in discrete intervals)
Slug tests (in wells and discrete intervals)
Water chemistry profiles (in wells and discrete intervals)

Crosshole Tests
Seismic tomography
Radar tomography
Resistivity tomography

Multiple-Well Tests
Pumping test with fully penetrating pumping and observation wells (step, constant rate)
Pumping test with partially penetrating pumping well, fully penetrating observation wells
Series of tests pumping from and observing in discrete zones
Radial injection tracer test including observation and sampling in discrete zones of multiple observation wells
Pumping-injection, forced-gradient tracer test including observation and sampling in discrete zones of multiple observation wells
Monitoring head changes in discrete intervals of wells during rapid change in river stage

Surface Tests
TEM and resistivity soundings
Seismic reflection, refraction, and surface wave
Ground-penetrating radar

Borehole and Surface Tests
Borehole seismic source and array of receivers at the surface
Seismic monitoring of a pumping test
Radar monitoring of a pumping test