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CONTRASTS IN REGIONAL AND LOCAL-SCALE HETEROGENEITY IN RELATION TO GROUND-WATER SUPPLY AND CONTAMINATION IN THE ALBUQUERQUE BASIN

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Abstract—This paper discusses the multiscale nature of geologic heterogeneities in the context of ground-water supply and ground-water contamination problems. Following a discussion of general issues related to heterogeneity scale in water resource problems, two datasets developed as part of characterization efforts on the Albuquerque basin's West Mesa are described. One of the datasets was generated as part of the ongoing water supply hydrogeoelogic characterization of the basin. The other dataset resulted from characterization associated with a shallow ground-water contamination problem resulting from solvent releases near the ground surface. Comparing and contrasting the two datasets clearly demonstrates the differences inherent in the relevant geologic heterogeneity scales, which hydrogeologists must consider when addressing such problems. For regional ground-water supply resource evaluations, the relevant scales of heterogeneity are at least an order of magnitude larger than the heterogeneity scales important to localized ground-water contamination problems.

INTRODUCTION

Geologic media typically exhibit heterogeneity on a variety of scales, from laboratory to outcrop to regional scales (Dagan, 1986; Gelhar, 1993). These different scales of heterogeneity can greatly affect the transport of fluids and solutes. With regard to ground-water contamination and water supply development problems, the important scales of geologic heterogeneity generally differ.

In this paper, we consider deposits found in the Albuquerque basin to illustrate the relevant heterogeneity scale to consider in ground-water-resource problems. The Upper Santa Fe Group and younger deposits found in the vicinity of Calabacillas Arroyo west of the Rio Grande provide an example to demonstrate clearly the heterogeneity scale issue with sufficient data for both a water supply problem and a ground-water contamination problem. Before moving into the Albuquerque basin-specific example, we provide a brief overview of the role of geological heterogeneity in ground-water supply and ground-water contamination problems.

Geological heterogeneity in water-supply problems

When one is interested in developing a sustainable water supply from a ground-water reservoir, or aquifer, one typically plans on pumping water from a well for a period of a decade or more. An estimate of the spatial scale of relevance here can be obtained by assessing the volume of the aquifer from which the water will be extracted over a variety of time scales, and the travel time for a water particle within the well's cone of depression. The greater the duration of sustained pumping at any given discharge rate, the larger the cone of depression, and the larger will be the relevant spatial scale of heterogeneity.

Consider first a domestic well for a single private residence. A four- or five-person family with moderate landscaping may pump on the order of 500 gallons per day (gpd), or 66.8 ft^3/day. This pumping rate leads to extraction volumes of roughly 15,000 gallons per month, and over 180,000 gallons per year. Assuming negligible groundwater recharge, confined conditions, a 10-foot-thick aquifer, and a typical aquifer hydraulic conductivity (on the order of 3 ft/day) and effective porosity (0.05), water produced at a well today would have been over 50 ft away from the well 30 days earlier, and over 200 ft away one year earlier. Next, consider a large-diameter municipal well. For a 400 ft thick confined aquifer exploited by a well that is serving 2000 households, water produced at a well today would have been over 500 ft away from the well 30 days earlier, and nearly 2000 ft away one year earlier. These pumping scenarios result in two very different scales at which heterogeneities must be evaluated.

One of the primary factors that affects the ability of a permeable geologic unit to deliver water to a well is the total, integrated thickness of all laterally extensive permeable horizons in the vertical section spanned by the well intake screen. Even a braided deposit with significant fine-grained lenses can behave as a laterally extensive permeable unit. Consider a highly permeable lens in a braided-channel deposit. So long as that lens exhibits significant hydraulic connection with another highly permeable lens, and that lens is in turn connected to yet another lens, and this pattern is repeated again and again, then this series of connected lenses can serve as an essentially continuous permeable layer. The intervening fine-grained layers exert a minor impact on the aquifer's ability to transmit water horizontally to an extraction well. While these fine layers will inhibit the vertical movement of water, their net affect in the well supply problem is they will cause the aquifer to behave anisotropically, with the effective vertical conductance of the aquifer some small fraction of the effective horizontal conductance. They also cause a net reduction in the effective thickness of a permeable unit roughly proportional to their relative predominance in a vertical section (e.g., if over a 100-ft-thick section of aquifer 20% is fine-grained layers, then the effective thickness is approximately 80 ft).

In summary, for the water supply problem, one should attempt to characterize permeable units with lateral continuity/connectedness on the order of several hundred, or thousands of feet. Furthermore, thin fine-grained horizons embedded within an aquifer reduce the aquifer's overall horizontal transmissivity (the parameter controlling water flow toward the well) roughly linearly with their relative thickness (integrated thickness of fine-grained layers divided by the total aquifer thickness).

Geological heterogeneity in ground-water contamination problems

With respect to contaminant transport in ground-water systems, even thin, fine-grained layers can have a significant impact on the evolution of a contaminant plume. When a contaminant source is located in the vadose zone, fine-grained layers can contribute to a lateral spreading of the contamination (Crosby et al., 1971; Yeh et al., 1985; McCord et al., 1991) before it reaches the water table. Within the saturated zone, thin fine-grained layers may prevent contamination from penetrating deep into an aquifer. It is well recognized that the subsurface migration of dense non-aqueous phase liquids (DNAPLs) is profoundly influenced by the topographic configuration of fine-grained layers (Cohen and Mercer, 1993; Pankow and Cherry, 1996). Analogous to an upside down hydrocarbon reservoir, the migration of sinking DNAPLs is largely controlled by stratigraphic and structural features in the subsurface environment. In a hydrocarbon reservious, lighter-than-water gases and oils migrate upward to stratigraphic and structural traps.

Generally, one can define the critical scale of heterogeneity for a groundwater contaminant transport problem as heterogeneities with areal spatial dimensions of roughly the same order as the size of the contaminant source (Dagan, 1989; McCord and Goodrich, 1994; Harter and Yeh, 1996). Heterogeneities much smaller than the source (<10%) cause a dispersive spreading of a plume, and they do not need to be considered as separate, discrete features. Heterogeneities at a scale much larger (>1000%) than the source, on the other hand, behave as homogeneous discrete features. It is the intermediate-scale heterogeneities that impart significant local influences on contaminant transport, and, therefore, characterization efforts need to focus on clearly defining geologic features at these scales and larger.

Given this dependence on contaminant source size, one can infer that the relevant heterogeneity scale for a landfill problem is much different than that for a leaking storage tank. When attempting to understand the migration of a contaminant plume from leaking tanks or pipelines, one should characterize geological heterogeneities with vertical scales on the order of feet, and horizontal scales on the order of tens or hundreds of feet. Furthermore, for DNAPL problems, the dip of lithologic contacts over small spatial scales may be an important charaterization target.

ILLUSTRATION OF HETEROGENEITY SCALE ISSUES: ALBUQUERQUE'S WEST SIDE

Shallow deposits (<300 ft below ground surface [bgs]) on Albuquerque's west side near Calabacillas Arroyo provide an opportunity to consider geological heterogeneity scales in the context of both water supply and ground-water contamination problems. The area examined in this paper (Fig. 1) has been the subject of fairly detailed subsurface investigations for both Albuquerque's ground-water-supply problem (Hawley and Haase, 1992) and for a ground-water-contamination problem involving the release of DNAPLs from an industrial manufacturing site (HLA et al., 1992).

Hydrogeologic setting

The area considered lies in the northern Albuquerque basin. Ground water occurs in recent alluvium and in older basin-fill sediments of the Santa Fe Group. The recent alluvium is a thin (0–200 ft thick) veneer of sediments (sand, gravel, silt/clay) associated with piedmont slope, alluvial fan, and river terrace deposits (Kelley, 1977; Thorn et al., 1993).

From a water-supply perspective, the permeable geologic materials that yield most of the ground water in the Albuquerque basin consist of the coarse-grained upper Santa Fe Group deposits, which range in thickness from less than 500 to more than 1500 ft across the basin. Underlying the upper Santa Fe deposits are the less permeable deposits of the middle Santa Fe Group, which are 1000–10,000 ft thick. These in turn overlie low-permeability playa floor deposits of the Lower Santa Fe Group. A generalized geologic cross-section which includes the study area is shown in Figure 2a (adapted from Hawley and Haase, 1992).

Early hydrogeologic studies of the Albuquerque basin (e.g., Bjorklund and Maxwell, 1961) failed to recognize the poor water bearing characteristics and relative predominance of the middle and lower Santa Fe Group deposits (Fig. 2b), creating an overly optimistic estimate of the ground-water supply. Bjorklund and Maxwell (1961) perhaps employed an inappropriately large scale in their basin characterization, causing them to overlook structural and stratigraphic limitations in the extent of the more permeable horizons of the middle and upper Santa Fe Group. Rapidly dropping water levels coupled with a reanalysis of the hydrogeologic characteristics (e.g., Hawley and Haase, 1992) has led to a large, ongoing subsurface investigation to better understand the basin's ground-water resource.

Ground-water supply problem: Hunter Ridge Park boring log

As part of the ongoing regional ground-water resource characteriza-

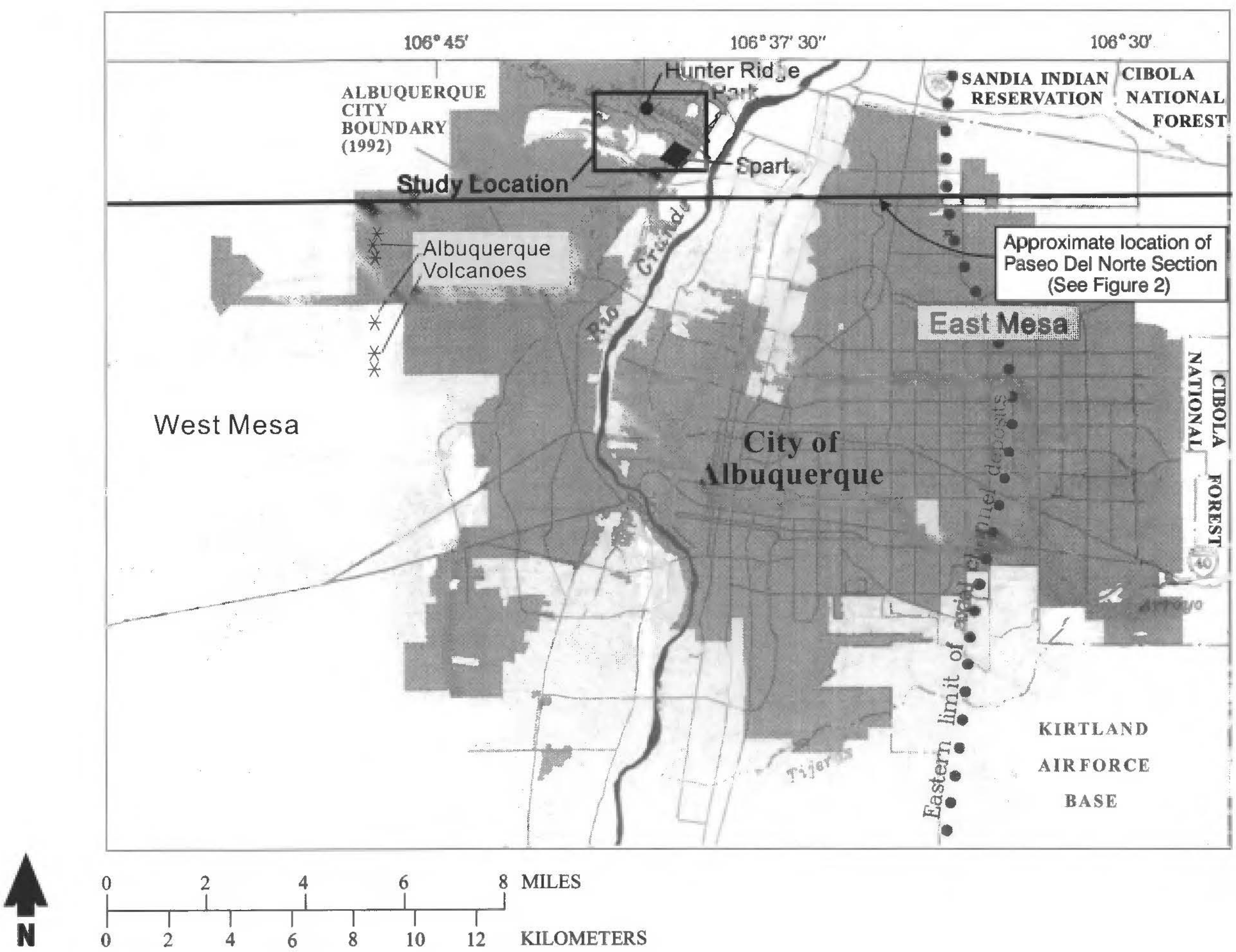

Figure 1. Location of study area in central Albuquerque basin.

tion effort, the U.S. Geological Survey (USGS) and the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) installed a deep multilevel piezometer (known as the Hunter Ridge Park 1 piezometer nest) on the north side of Calabacillas Arroyo (Fig. 1). NMBMMR personnel developed a detailed geologic log of the borehole (Johnson et al., 1996) based on mud-rotary cuttings taken at 5-ft intervals.

A summary of the hydrogeologic interpretation for the Hunter Ridge Park 1 (HRP1) borehole (Table 1) indicates predominately sand and gravel deposits in the top 280 ft of the borehole. The nomenclature and definitions for the lithofacies presented in the right hand column of Table 1 were developed to characterize the ground-water production potential of the various units (Hawley and Haase, 1992). Table 2 summarizes these Santa Fe Group lithofacies as developed by Hawley and Haase (1992). According to these definitions, we expect the Type I coarse-grained lithofacies encountered in the top 280 ft of the HRP1 borehole to exhibit bed thicknesses greater than 5 ft and horizontal bed continuities greater than 500 ft. The inherently multiscale nature to geologic heterogeneity is clearly evident in the Hawley and Haase (1992) hydrogeologic conceptual model; their cross sections (e.g., Figure 2a) show the Type I units to be laterally continuous over length scales on the order of miles.

Exposures of the geologic profile in the Hunter Ridge Park vicinity can be found immediately south of the borehole location in a cut bank on the north side of Calabacillas Arroyo. Consonant with the HRP1 borehole log, this 40-foot-high exposure shows predominately coarse-grained materials. In contrast to the definitions of this material in Table 2, several thin (on the order of 1–2 ft thick) fine-grained horizons of significant lateral extent (on the order of 100 ft) could be observed in the outcrop. Based on discussions with NMBMMR personnel responsible for the geologic logging of the drill cuttings (S. Connell, 1999, personal commun.), it is likely that the mud rotary drilling technique cloaked the presence minor fractions of, or occasional thin lenses of, fine-grained materials. As discussed in earlier, such minor occurrences of fine-grained materials are likely to be of only secondary importance in ground-water-supply problems, consistent with the lithofacies definitions presented in Table 2.

The USGS and NMBMMR investigations are focussed on character-

Table 1. Hydrogeologic interpretation of Hunter Ridge Park 1 borehole (from Johnson et al., 1996)

Depth (ft)	Hydrostratigraphic Unit	Lithofacies
0–105	Modern arroyo-valley alluvium associated with Calabacillas Arroyo; sand and pebble to cobble gravel with clasts having a Nacimiento Mountains source (VA)	A1 (formerly Vv)
105–147	Undifferentiated river channel alluvium; densely-packed cobble gravel associated with terrace deposits of uncertain stratigraphic position (TA or USF-2)	A1 or I
147–280	Ancestral river channel alluvium; sand and gravel dominated (≥50%) with minor silt/clay (USF-2)	I
280–1105	Basin-floor fluvial facies and local eolian deposits; sand and pebbly sand with variably mixed clay and silt (USF-2)	II
105–1210	Ancestral river channel and basin-floor alluvium; sand and gravel dominated (≥50%) with minor silt clay (USF-2, 4)	I
1210–1505	Basin-floor fluvial facies and local eolian deposits; sand and pebbly sand with variably mixed clay and silt (USF-2)	II

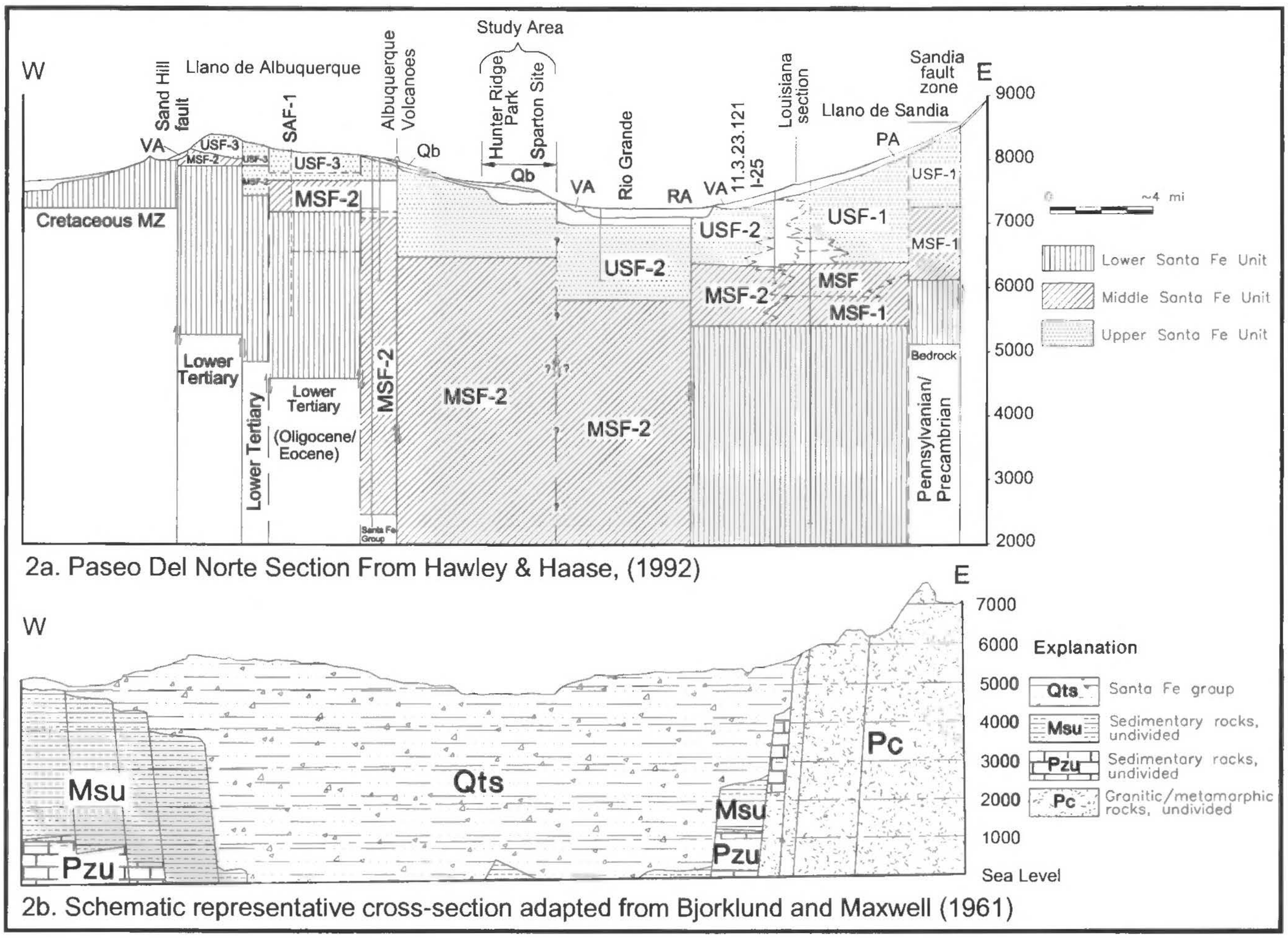

Figure 2. East-west geologic sections in central Albuquerque basin as published by investigators in 1961 and 1992.

Table 2. Summary of lithofacies properties that influence ground-water-production potential (modified from Hawley and Haase, 1992).

Lithofacies	Sand and gravel/silt and clay[1]	Bedding thickness (ft)	Bedding configuration[2]	Bedding continuity (ft)	Bedding connectivity[3]	Hydraulic conductivity (ft/day)
I	>2–0.5	5	Elongate	>500	High to moderate	>30–0.3
Iv	>2–0.5	>5	Elongate	>500	High to moderate	>30–0.3
Ib	>2	>5	Elongate	>500	High	>30
II	>2–0.5	>5	Elongate	>500	High to moderate	>30 to 0.3
III	<0.5	1–5	Planar	>500	Low	<0.3
IV	<0.5–2	1–5	Planar to elongate	100–500	Moderate to low	30– <0.3
V	0.5–2	1–5	Elongate to lobate	100–500	Moderate	0.3–30
Vf	0.5–2	1–5	Elongate to lobate	100–500	Moderate to low	30– <0.3
Vd	0.5– >2	>5	Elongate to lobate	100–500	Moderate to high	0.3– >30
VI	>2	>5	Lobate	<100	Moderate to high	0.3– >30
VII	0.5–2	1–5	Elongate to lobate	100–500	Moderate to low	30– <0.3
VIII	>2	>5	Lobate	<100	Moderate to low	30– <0.3
IX	<0.5	<1	Planar	>500	Low	<0.3
X	<0.5	<1	Planar	>500	Low	<0.3

[1] Ratio of sand and gravel to silt and clay
[2] Length-to-width ratio:
Elongate = >5
Planar = 1–5
Lobate = asymmetrical or incomplete planar beds
[3] Estimation of ease with which ground-water can flow between individual beds within lithofacies

izing the geology to provide a framework for understanding water-supply development for municipal wells, with each well serving thousands of users. Inasmuch as large-scale features are most relevant to predicting long-term aquifer performance, it is entirely appropriate that their efforts focus on characterizing features on the order of thousands of feet in length and tens (or scores) of feet in thickness. Therefore, neglecting thin lenticular units is not a serious problem in their characterization program.

Ground-water contamination problem: the Sparton site

Approximately 0.5 mi southeast of the HRP1 location on the south side of Calbacillas Arroyo is the Sparton site (Fig. 1). Manufacturing activities at the Sparton site between the early 1960s and the early 1980s have been associated with the release of significant quantities of dense industrial solvents (Black and Veatch, 1996), including trichlorethylene (TCE).

The Sparton site is situated on Albuquerque's West Mesa near the corner of Coors Road and Irving Boulevard. It is located near the eastern edge of a bluff roughly 50 ft above the inner valley of the Rio Grande, approximately 3000 ft west of the river's main channel. Geologic material underlying the site includes poorly consolidated to unconsolidated alluvial gravels, sands, and clays associated with an inset river terrace and the Los Duranes post-Santa Fe depositional units. The water table is encountered at approximately 70 ft bgs, and upper Santa Fe Group deposits lie at depths of roughly 200 ft beneath the site.

Figure 3 presents stratigraphic sections at the site as interpreted from samples of the materials encountered during ground-water monitoring well installation. Primarily sandy materials with frequent gravel and fine-grained interbeds occur from the ground surface to a depth of approximately 10 ft below the water table. At that depth (within the alluvial aquifer), a low-permeability fine-grained horizon with thicknesses ranging from less than 1 ft to greater than 10 ft extends approximately from the eastern site boundary to several hundred feet west of the western site boundary. Recall that these cross sections were developed based on borehole logs and subsurface sampling associated with the installation of ground-water monitoring wells to characterize a contamination problem. The shallow depth, large number, and close spacing of these monitoring wells (while entirely appropriate for characterizing the contamination area of concern), is clearly in contrast to the depth, number, and spacing of the characterization wells employed for the Albuquerque basin water-supply studies. Furthermore, if one had only this small-scale, high-density data for a regional water-supply study, it likely would be averaged to yield information of relevance for that purpose.

Heterogeneity and hydraulic head distributions

A notable difference in elevation of water levels exists in wells completed above and below this low-permeability horizon in the vicinity of the site, leading to a local distinction between an upper flow zone and a lower flow zone within the recent alluvium (HLA, 1990; Black and Veatch, 1996). Figure 4 shows potentiometric surface contours and inferred ground-water flow directions in the upper and lower flow zones; note the different migration directions evident in the two zones. Despite this local site-scale distinction, this low permeability feature is unlikely to be detected in the regional water-supply investigation. From a regional perspective, the ground water in the recent alluvium and that in the Santa Fe Group is hydrologically interconnected, and the entire section beneath the Sparton site can be considered as a Type I lithofacies unit (Table 2). Conversely, from a local perspective, these heterogeneities are key to understanding the DNAPL migration at the Sparton site.

Heterogeneity and contaminant transport

Heterogeneities also appear to affect strongly contaminant plume migration. Isoconcentration contours of the TCE plume in groundwater based on January 1992 monitoring (Fig. 5) exhibit a kink in the vicinity of the presumed source. This apparent dog leg in the plume would be difficult to explain if one relied on a homogeneous medium (e.g., Type I lithofacies), uniform flow conceptual model of groundwater conditions beneath the site. However, the observed plume is consistent with the upper and lower flow zone conceptual model discussed above. When the DNAPL TCE reaches the water table, it first migrates to the west-southwest in the upper flow zone. As the TCE migrates laterally, some of it sinks into the lower flow zone, where it takes on a west-northwest flow trajectory. Knowledge of the presence of the thin, low- permeability layer, which would have been largely ignored in a regional water supply study, is critical to understanding the contaminant migration behavior at the site.

An additional control on the TCE migration may be related to the surface slope of this fine-grained horizon. Using 45 boring logs from the 10-acre site, a contour map of the top surface of the low-permeability horizon was developed (Fig. 6; adapted from HLA, 1990). This map shows a trough in the surface of the low-permeability unit. The trough trends from beneath the presumed source area to the southwest, and from there to the west, similar to the configuration of the kink in the plume near the source. If DNAPLs reached this horizon, they would tend to accumulate in the trough. These high concentrations are evident in Figure 5. Even if separate, liquid-phase contaminants did not percolate all the way down to the low-permeability horizon, sufficiently high

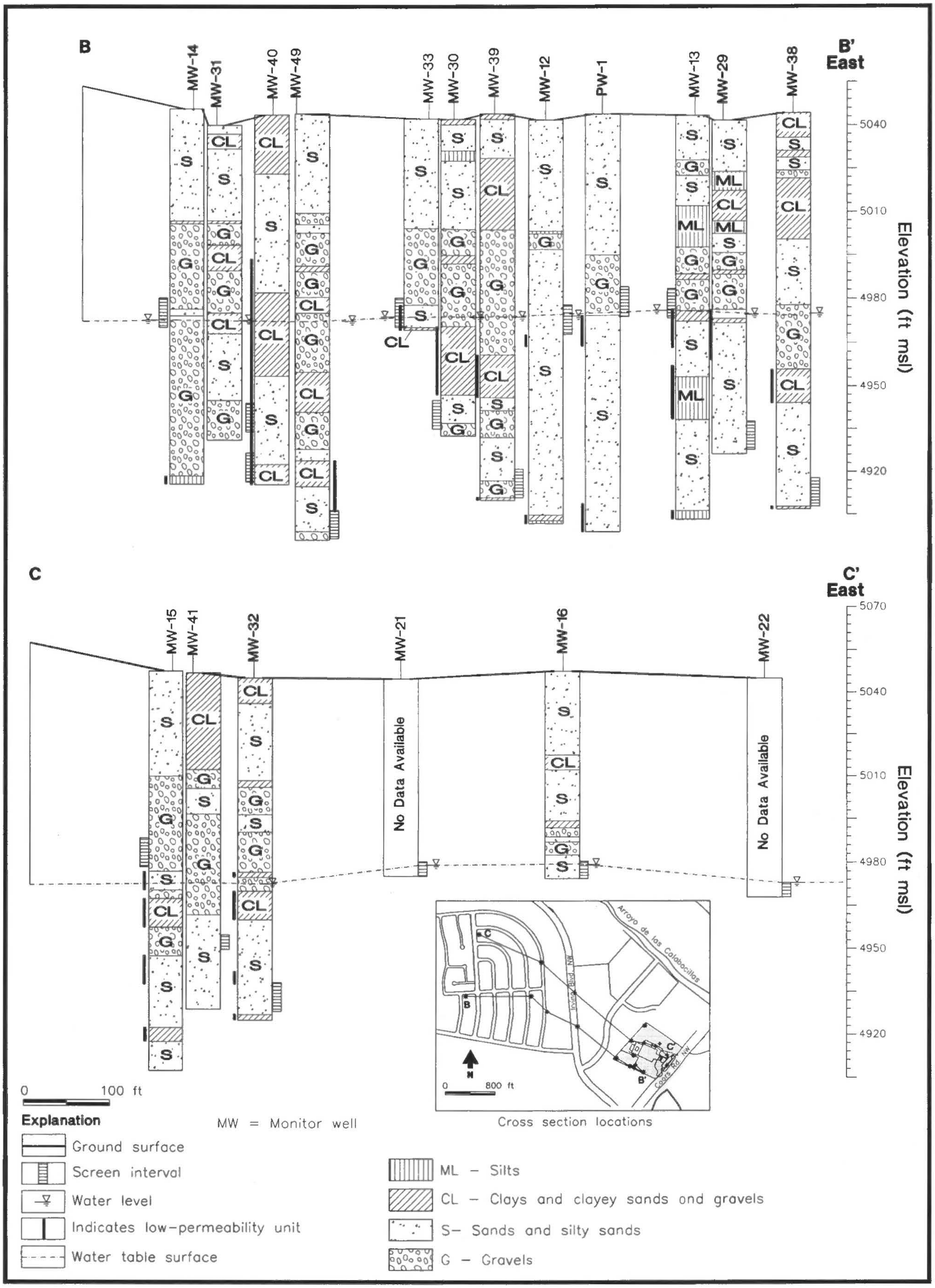

Figure 3. Hydrogeologic cross sections at Sparton site.

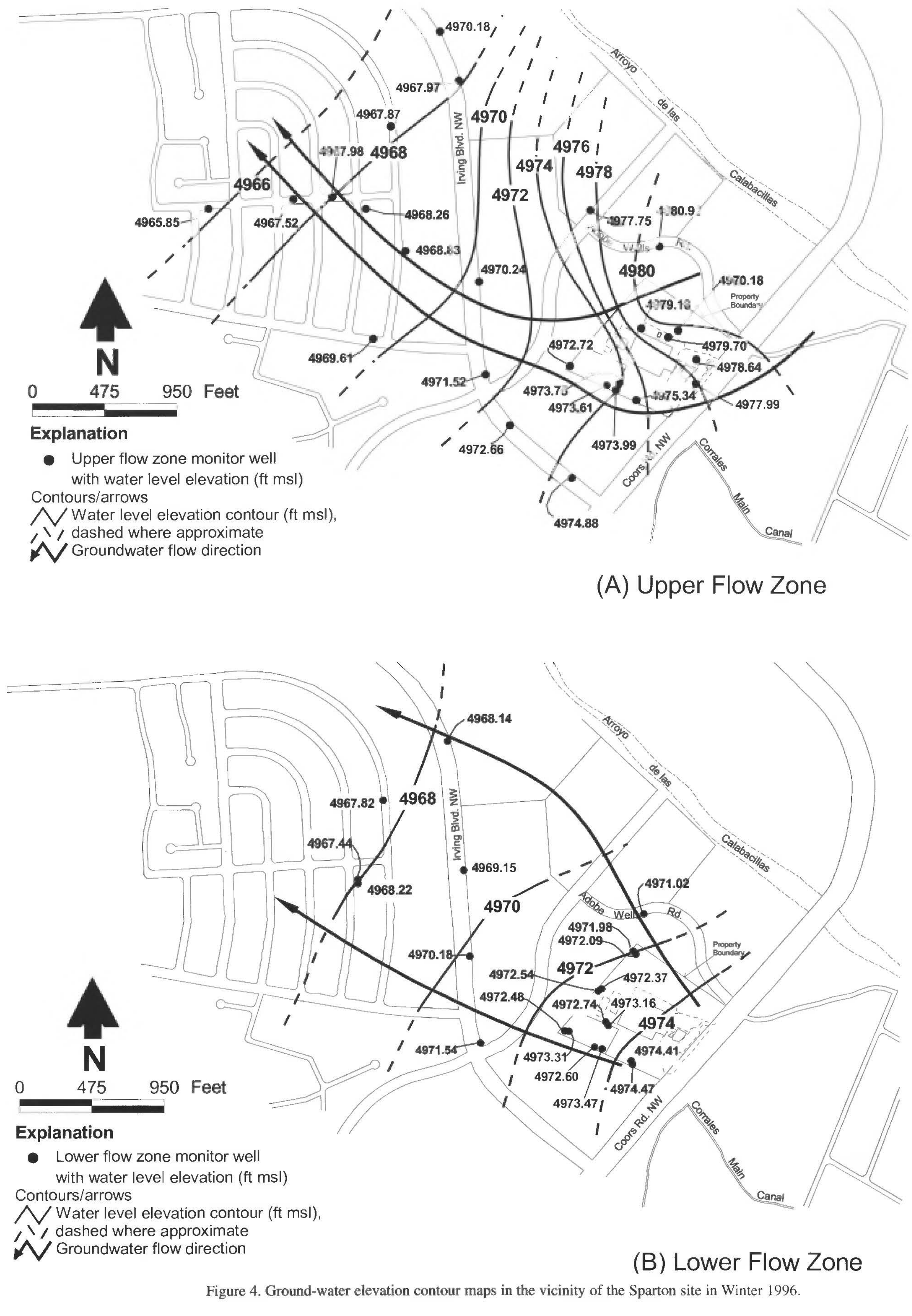

Figure 4. Ground-water elevation contour maps in the vicinity of the Sparton site in Winter 1996.

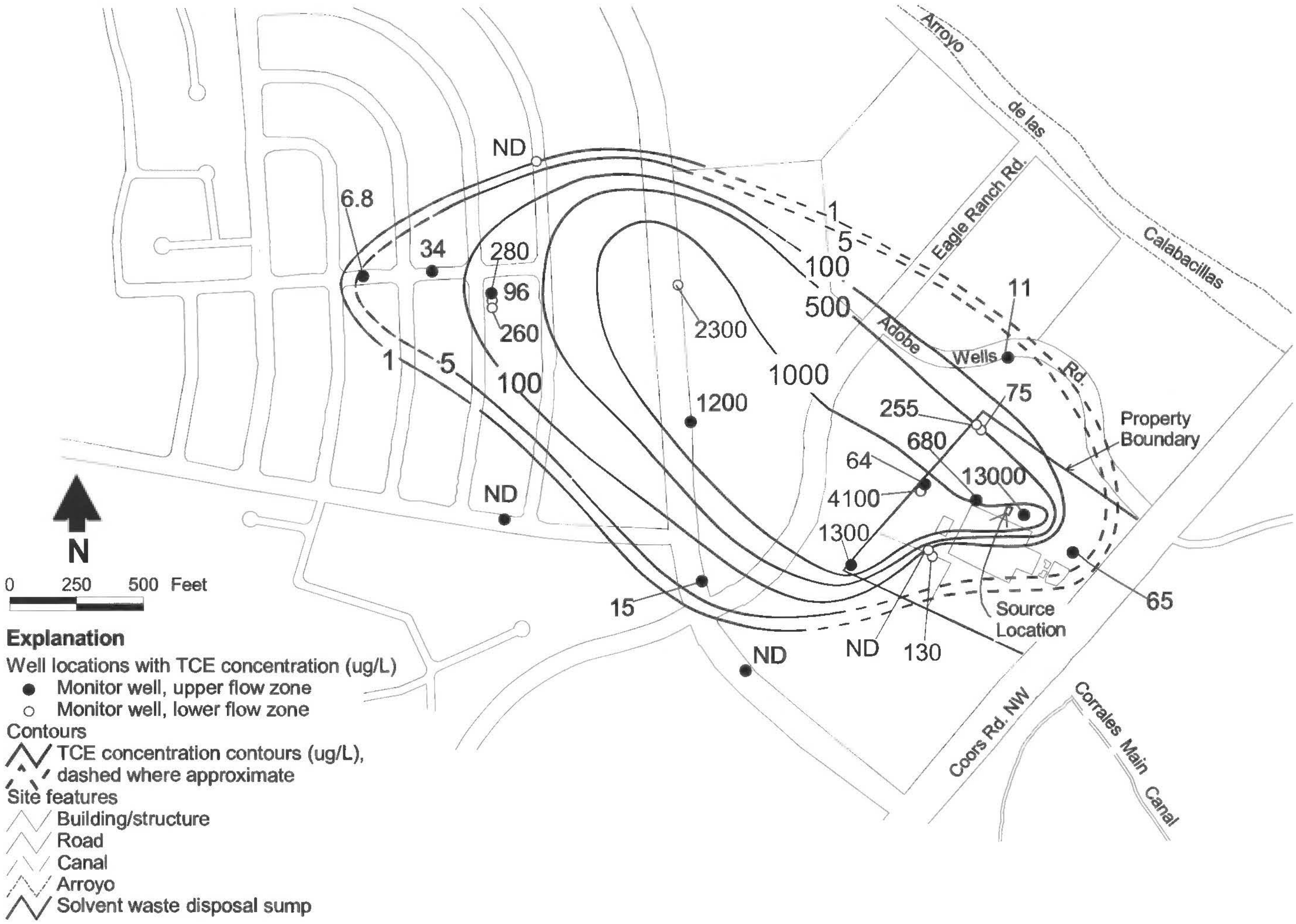

Figure 5. TCE plume in ground-water in the vicinity of the Sparton site in January 1992.

dissolved concentrations could exhibit density effects (Istok and Humphrey, 1995), and this higher density (higher concentration) part of the plume would be affected by the topography of the low permeability unit surface.

SUMMARY AND CONCLUSIONS

Recognizing that geologic media exhibit heterogeneity on a variety of scales, we examine how different scales of heterogeneity can affect the transport of fluids and solutes in the context of ground-water contamination and water-supply-development problems. In this paper, we consider deposits found in the vicinity of Calabacillas Arroyo west of the Rio Grande in the Albuquerque basin to provide an example with sufficient data to demonstrate clearly the heterogeneity scale issue for both a water-supply problem and a ground-water-contamination problem.

With respect to the municipal water-supply problem, the geological characterization effort should focus on defining the extent, thickness, structure, and interrelationships between features with length scales on the order of thousands of feet and vertical scales on the order of tens (or scores) of feet. With respect to a localized ground-water contamination-problem, a hydrogeologic field program needs to focus on much smaller features, with length scales on the order of tens or hundreds of feet and thicknesses on the order of a foot.

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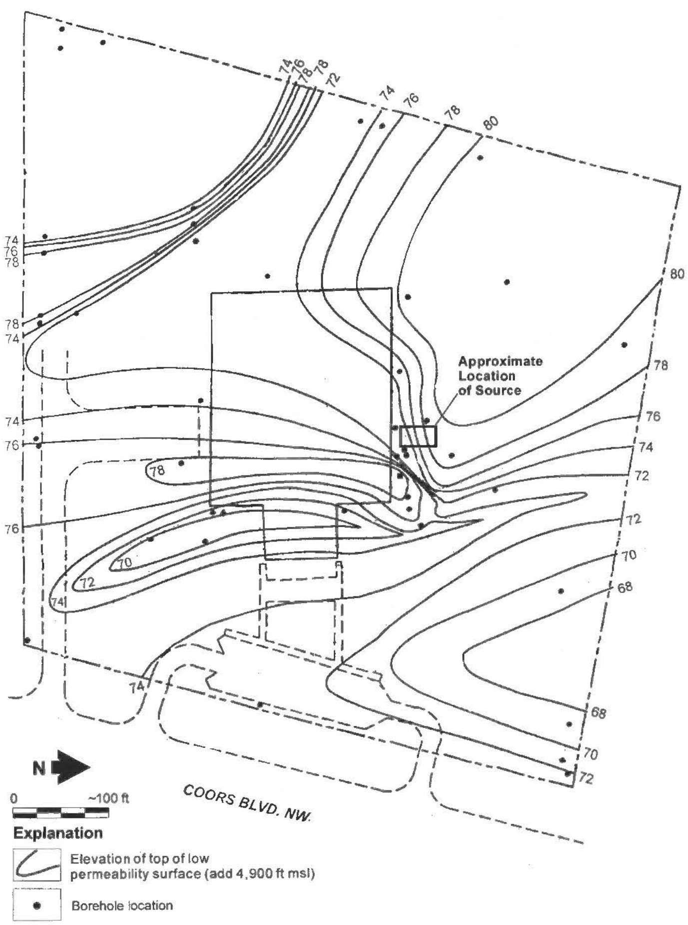

Figure 6. Elevation of the surface of the low-permeability horizon beneath the Sparton site (adapted from Harding Lawson Associates (unpubl. report for Sparton Technology, Inc., 1990).

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