HYDROLOGIC CHARACTERIZATION OF OVERBUDEN SPOIL DEPOSITS : WARRICK COUNTY, SOUTHWESTERN INDIANA[1]

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Abstract: Two sites in overburden spoil were instrumented for hydrologic characterization and intensively monitored through the recharge period of the 1998-99 water year. One site is in an area with no soil cover (Site 1) and the other contains a 50-cm-thick soil cap (Site 2). During the course of the study, the rise of the water table at Site 2 lagged behind that at Site 1, despite the fact that the thickness of the unsaturated zone is about 9 m less at Site 2. Water-level rises are statistically correlated to rainfall at Site 1, whereas at Site 2 the correlation is not statistically significant (95 percent confidence level). At each site, calculated profiles of vertical flux are uniform for each period of measurement, but the range of flux values at different periods is greater at Site 1. Site 1 also has a greater range of vertical flux near the surface than at depth, probably due to increased storage resulting from less compaction in the shallow layer. At Site 2, the range of flux values is smaller and more uniform at depth. Because several of the calculated vertical flux values were measured during recharge periods when gravity drainage was occurring, they are also approximate values of unsaturated conductivity. The values range between 10^{-5} and 10^{-6} and are 1- to 2-orders of magnitude lower than the saturated hydraulic conductivity values determined for the near-surface and underlying saturated zones.

Introduction

Surface coal mining methods involve removal and backfilling of overburden during coal extraction. This backfilled material, called *mine spoil*, is a heterogeneous mixture of rock fragments and pre-existing soil materials with a wide range of texture and lithology.

There are relatively few studies that refer specifically to the hydrology of mine spoil, and most of those that exist are focused on determining values of hydraulic conductivity. Among the latter are Pedersen *et al.* (1980), Cravotta (1998), and Maher and Donovan (1997), who have reported saturated hydraulic conductivity values that range from less than 10^{-8} cm/s to greater than 10^{-3} cm/s. All of these authors have emphasized the inherent heterogeneity of spoil as an hydraulic medium. Consecutive moisture-content measurements of a draining profile by Diodato and Parizek (1994) yielded unsaturated hydraulic conductivity values that ranged from 2.4×10^{-7} to 1.5×10^{-3} cm/s. A tracer study at the same site yielded values between 2.8×10^{-6} and 7.2×10^{-5} cm/s. Data from their study also suggested that water table recharge occurred in short-lived pulses, with the spoil exhibiting dual-permeability characteristics. Taken as a whole, these studies of the hydrologic properties of spoil indicate that it is a highly variable medium, so it would be unwise to over-generalize the results from only a few local studies. This study presents the results of hydrologic monitoring at two sites in Warrick County, Indiana, focusing on the heterogeneity of the hydraulic properties (particularly conductivity) of

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spoil, both within and between the sites, as well as the effect of heterogeneity on vertical flow through the unsaturated zone and resulting ground water recharge. The intention of the work is to reach preliminary conclusions about differences that exist between two broad categories of spoil (ungraded and uncapped *versus* graded and capped). The data collected so far indicate that the hydrologic characteristics of the different spoil landform types are indeed substantially different.

Study Area

Southwestern Indiana, including Warrick County, lies within the eastern portion of the Illinois Basin, a broad structural depression also encompassing western Kentucky and southern Illinois. The Illinois Basin consists of Pennsylvanian Age sandstone, shale, limestone, and coal, which have a general dip to the southwest (7 m/km) in the vicinity of the study. Unconsolidated Quaternary sediments unconformably overlie the Pennsylvanian bedrock. Drilling investigations in the region (including Davis and Walton, 1982) have encountered 15 to 30 m of unconsolidated sediment. The mineable coal in Warrick County exists within the Dugger and Petersburg Groups of the Carbondale Formation.

More than 50 percent of the topography of Warrick County has been altered by surface mining. Before 1967, reclamation of this land involved revegetation, with minimal grading of the spoil deposits. Only the tops of spoil ridges were leveled, leaving a ridge-and-valley topography, and there was no replacement of soil. After 1967, regulations became more stringent, requiring more reshaping of the spoil at cessation of mining. The surface-mined lands of this period have a rolling topography, with fewer areas of steep ridges than the earlier era. The Surface Mining Control and Reclamation Act of 1977 brought national standards for reclamation, including the re-creation of the original contour of the land and replacement of topsoil.

As discussed in our companion paper (Harper *et al.*, this volume) four basic mine reclamation categories, or *spoil landform types*, occur in the study area. These categories are defined by whether or not the deposit was graded and (or) capped with a soil layer. The presence or absence of grading and capping has implications for the performance of a deposit as a hydrologic medium. Two monitoring sites were installed to simultaneously assess and compare the hydrologic regimes of two of the landform categories. Site 1 was installed in Category 1A, which includes deposits that were neither graded nor capped. Site 2 was installed in Category 2, which includes deposits that were both graded and capped (see our companion paper for details about characteristics of individual spoil landform types). The pre-mining overburden at the two sites was very similar: at Site 1, where mining occurred between 1954 and 1964, the overburden was 30 m thick and consisted of unconsolidated material (16 percent), shale (75 percent), and other rock, while at Site 2, where mining occurred between 1980 and 1989, the overburden consisted of unconsolidated material (25 percent), shale (70 percent), and other rock.

Methods

Background Theory

Analysis of the storage and movement of soil water was based on general hydrologic theory and standard methods. The volume of water stored in the vadose zone at a particular moment in time can be determined by integrating the volumetric soil moisture content over the unsaturated profile:

$$S = \int_{z_0}^{z_l} \theta_z \partial z \qquad [1]$$

where z_0 represents the ground surface and z_l the bottom of the profile. Moisture movement in the vadose zone is manifested in the change in moisture content through time, and since flow in the unsaturated zone is dominantly vertical, the continuity equation is expressed as

$$\frac{\partial \theta}{\partial t} = -\frac{\partial v}{\partial z} \qquad [2]$$

where θ is the volumetric soil moisture content, t is time, and v is the specific discharge in the vertical direction z. Approximating the derivatives in equation [2] as finite differences yields:

$$v_z = v_{z+\Delta z} + \frac{\Delta \theta}{\Delta t}\Delta z \qquad [3]$$

where v_z is the specific discharge through depth interval z, Δz is the interval distance, $\Delta\theta$ is the change in soil moisture content in interval z, and $v_{z+\Delta z}$ is the specific discharge determined for the interval directly above z. Concurrently, Darcy's Law states that vertical flow in porous media is given by:

$$v_z = -k\frac{\partial h}{\partial z} \qquad [4]$$

where k is the hydraulic conductivity which depends on the type of soil material and the degree of saturation, h is the total hydraulic head, and z is a vertical coordinate which also represents the elevation head. The total head is the sum of the pressure head and elevation head, or:

$$h = \Psi + z\,. \qquad [5]$$

In the case of an unsaturated porous medium the pressure head, ψ, is negative, representing tension. Substituting equation [5] into equation [4] and expanding the derivative yields:

$$v_z = -k\left[\frac{\Delta\Psi}{\Delta z} + 1\right]. \qquad [6]$$

In the case where $\left\{\frac{\Delta\Psi}{\Delta z}\right\}$ is very small, then

$$k \cong -v_z\,. \qquad [7]$$

Here k is the unsaturated hydraulic conductivity at a volumetric moisture content greater than that corresponding to gravity drainage, but less than saturation. Nielsen *et al.* (1973) first invoked the assumption leading to equation [7], while Diodato and Parizek (1994) used that same assumption and associated methods to estimate the unsaturated hydraulic conductivity of mine spoils.

Instrumentation and Data Analysis

Hydrologic data were collected continuously at each of the two monitoring sites during the study period using electronic sensors connected to digital data loggers. These data were supplemented by unsaturated-zone moisture profiles measured at approximately biweekly intervals using a neutron depth-moisture gauge. The electronic data were analyzed as daily time series, but calculations of flow and hydraulic conductivity for the unsaturated-zone profiles utilized data analyzed according to the neutron gauge measurement intervals. A summary of these intervals is presented in Table 1.

Table 1. Summary of the measurement intervals used for flux and conductivity calculations.

Date of Measurement	Measurement Interval	Interval Length (days)
8/26/98		
9/8/98	A	12
9/21/98	B	13
9/29/98	C	6
10/13/98	D	13
10/20/98	E	6
11/12/98	F	22
12/17/98	G	34
1/12/99	H	25
1/25/99	I	13
2/9/99	J	13
2/25/99	K	15
3/11/99	L	13
3/30/99	M	18
4/20/99	N	20
5/4/99	O	13
5/20/99	P	15
6/10/99	Q	20

Each monitoring installation included a tipping-bucket rain gauge and monitoring well that was equipped with a pressure-sensing transducer to measure fluctuations in the local water table. The instruments were wired to a digital data logger, programmed to sample at ten-second intervals and to record average or total measurements every hour. In addition, the installation at Site 2 included a small weighing-lysimeter to measure infiltration and evaporation. This instrument consisted of a column of soil removed from the surface of the site, confined within a rigid container, and positioned on a load cell. Gains (infiltration) and losses (evaporation) of mass in the soil column were monitored by the load cell and stored by the data logger. Water was allowed to drain through the bottom of the container (percolation), and to flow across the surface of the container (runoff). The percolation and runoff waters were captured in beakers and the volumes of those waters were measured during site maintenance visits.

Soil-moisture profiles were measured using a neutron depth-moisture gauge. Measurements were made at 30.5-cm intervals to a depth of 4.0 m at Site 1 and 8.8 m at Site 2. The neutron gauge employed a factory calibration function for calculating volumetric moisture content as a function of neutron counts. This method of measuring volumetric soil moisture content has been utilized effectively in many different materials, including mine spoil (Hauser, 1984; Diadato and Parizek, 1994).

Changes in soil moisture content, determined from measurements taken during during successive site visits, were input into equation [3] to calculate movement through the unsaturated zone. The solution required an upper boundary flux value (v_z at $z = 0$), which is the net infiltration (wetting period) or net evaporation (drying period) over the measurement interval. This net surface flux was provided by the weighing lysimeter measurements. Site 1 was not equipped with a weighing lysimeter, so net surface flux values for that site were calculated by subtracting the evaporation recorded at Site 2 from the precipitation observed at Site 1.

Flux profiles that corresponded with the period of ground water recharge were segregated for hydraulic conductivity determination. According to the assumptions implicit in equation [7], these were taken to represent profiles of unsaturated conductivity.

Values of *in situ* saturated hydraulic conductivity were also determined from slug tests in each monitoring well, and from Guelph permeameter tests on the near surface soil layer. These data are presented in Table 2.

Table 2. Saturated hydraulic conductivity values measured at each monitoring site.

	Site 1	Site 2
Near Surface[a]	1.5×10^{-4} cm/sec	4.9×10^{-5} cm/sec
Deep[b]	3.0×10^{-5} cm/sec	3.3×10^{-4} cm/sec

[a] Near surface conductivity values were determined using a Guelph Permeameter and associated solutions (Reynolds and Elrick, 1985). At both sites, the shallow well utilized by the instrument was excavated in such a manner as to be in contact with spoil: 0.3 m deep at Site 1, and 1.0 m deep (through the replaced-soil layer) at Site 2.

[b] Deep conductivity values were determined using the Hvorslev slug-test method (Fetter, 1994) in existing monitoring wells.

Results

Precipitation, Infiltration, and Evaporation

During the 9-month period of monitoring reported here, 80.2 cm of precipitation was recorded at Site 1 and 81.2 cm was recorded at Site 2. These totals were only slightly below the National Weather Service average for the same period (82.5 cm for the years 1961-1990). As shown in Figure 1, the daily rainfall totals at the two sites were not identical, but the overall temporal distributions were very similar.

Based on data derived from the weighing lysimeter, only 3.4 cm of the precipitation at Site 1 was partitioned into runoff, and the runoff occurred during two measurement intervals when the ground was frozen. Overall, a total of 37.0 cm infiltrated the surface and 40.8 cm evaporated. The average recorded evaporation rate was 0.16 cm/day, with an extreme value of 0.8 cm/day documented for a sunny day in late April immediately following a rainstorm.

Profiles of Soil Moisture

The wettest and driest soil moisture profiles observed during the course of the study are plotted in Figure 2. At Site 1, the range of moisture was largest near the surface, then decreased with depth. In comparison, the profiles at Site 2 display lower moisture content overall, and the range at the surface does not propagate as deep as observed at Site 1.

The profiles at each site exhibit a characteristic shape, indicative of the vertical heterogeneity. At Site 1, this vertical variability is consistently random through the profile. However, at Site 2 a zone of relatively uniform moisture content occurs in a the interval from 1.6 to 3.6 m.

Unsaturated Vertical Flow and Conductivity

Selected profiles of vertical flux for net drying and net wetting measurement intervals at each site are presented in Figure 4. Note that the profiles at both sites exhibit upward movement during the drying period, with unevenness in the plots indicating the different moisture storage characteristics of each profile. During the wetting period, the profile at Site 1 exhibited a smooth decrease in flux with depth, while Site 2 had zones of increasing flux with depth. Overall, Site 1 displayed greater flux for both evaporative and infiltrative measurement intervals.

A summary of vertical fluxs determined for the entire period of ground water recharge at each site is provided in Figure 4. Again, Site 1 displayed a greater range and a larger maximum flux through most of the upper profile. However, the average recharge flux at the two sites was about the same.

According to the assumption leading to equation [7], the profiles of recharge flux are also profiles of unsaturated vertical hydraulic conductivity. A summary of those data that were judged to meet such an assumption is provided in Table 3. Site 1 exhibited a greater range of extreme values, though the range of average hydraulic conductivity over the entire profile was narrower than at Site 2. At both sites the conductivity values derived from neutron gauge data analysis were significantly less than the saturated conductivity values determined from slug tests and Guelph Permeameter tests (Table 2, 3).

Water Level Changes

Temporal plots of water-level fluctuation in the two monitoring wells are presented in Figure 6. Note that although the unsaturated zone at Site 2 is ten meters thinner than at Site 1, the hydrograph of water level at site 2 exhibits a lag with respect to that of Site 1. In addition, the total range of fluctuation is greater at Site 1. A detailed inspection of the hydrographs for the two study sites indicated that at Site 2 the water-level hydrograph exhibits periodic excursions that did not correlate with storm events, whereas the fluctuations at Site 1 seem to correspond more directly to the rains.

Table 3. Summary of the unsaturated vertical hydraulic conductivity values calculated for the period of ground water recharge at each monitoring site.

	Site 1 (0 - 4.0 m)	Site 2 (0 – 8.8 m)
Range of Average (entire profile)	2.5 – 2.7 x 10^{-6} cm/sec	2.6 – 3.2 x 10^{-6} cm/sec
Maximum (depth)	7.8 x 10^{-6} cm/sec (0.3 m)	5.8 x 10^{-6} cm/sec (0.3 m)
Minimum (depth)	2.7 x 10^{-7} cm/sec (3.7 m)	6.3 x 10^{-7} cm/sec (8.8 m)

Results of statistical analyses relating daily water-level changes to barometric changes and rainfall at the two study sites are presented in Table 4. The results for Site 1 indicate that regression coefficients for barometric change and precipitation are both statistically different from zero. Also, a comparison of the coefficients (they have identical units) indicates that the influence of precipitation on the water table at Site 1was nearly five times greater than the atmospheric pressure effect. Together the two variables combine to account for approximately 45 percent of the observed daily fluctuations in the water level at that site. Conversely, at Site 2 the regression coefficient for rainfall was not significantly different from zero, and the coefficient of barometric change was approximately an order of magnitude larger than at Site 1. Given such a high barometric efficiency (and associated coefficient of determination, $R^2 = 0.98$), one is led to conclude that the saturated zone at Site 2 functions as a "confined aquifer."

Table 4. Multiple regression analysis of the relationship between the daily changes in the water level in the monitoring well (ΔMW), atmospheric pressure changes (ΔB), and precipitation (P) at each study site. Parameter estimation was based on the iterative procedure outlined in Kmenta (1971).

Site 1 model: $\Delta MW1_t = b_0 + b_1\Delta B_t + b_2P_t + (\rho e_{t-1} + v_t)$					
n^b	$B_0{}^c$	$b_1{}^c$	$b_2{}^c$	ρ^d	R^e
330	-0.044 (0.117)	-0.057* (0.009)	0.278* (0.061)	0.60	0.44
Site 2 model: $\Delta MW2_t = b_0 + b_1\Delta B_t + b_2P_t + (\rho e_{t-1} + v_t)$					
n^b	$B_0{}^c$	$b_1{}^c$	$b_2{}^c$	ρ^d	R^e
310	-0.014 (0.082)	-0.338* (0.004)	0.006 (0.030)	0.72	0.98

[a] Variables are expressed in centimeters of water.
[b] Number of observations.
[c] Estimated regression parameters, and standard errors (in parentheses).
[d] Estimated autocorrelation coefficient.
[e] Multiple correlation coefficient.
* Regression parameter is statistically different from zero at 99% confidence level.

Conclusion

Proper management of mine spoil areas requires knowledge about the hydrologic functioning of spoil. Because the hydrologic characteristics of such areas depends upon the mining and reclamation techniques that were deployed in their formation, and because such techniques have evolved through history, there are potentially a great variety of hydrologic regimes that exist within any given mining district. From the operational standpoint, the easiest approach to hydrologic assessment is the mapping of spoil landform types. The results of this investigation provide preliminary support for the conclusion that different landform types function hydrologically in distinctly different ways.

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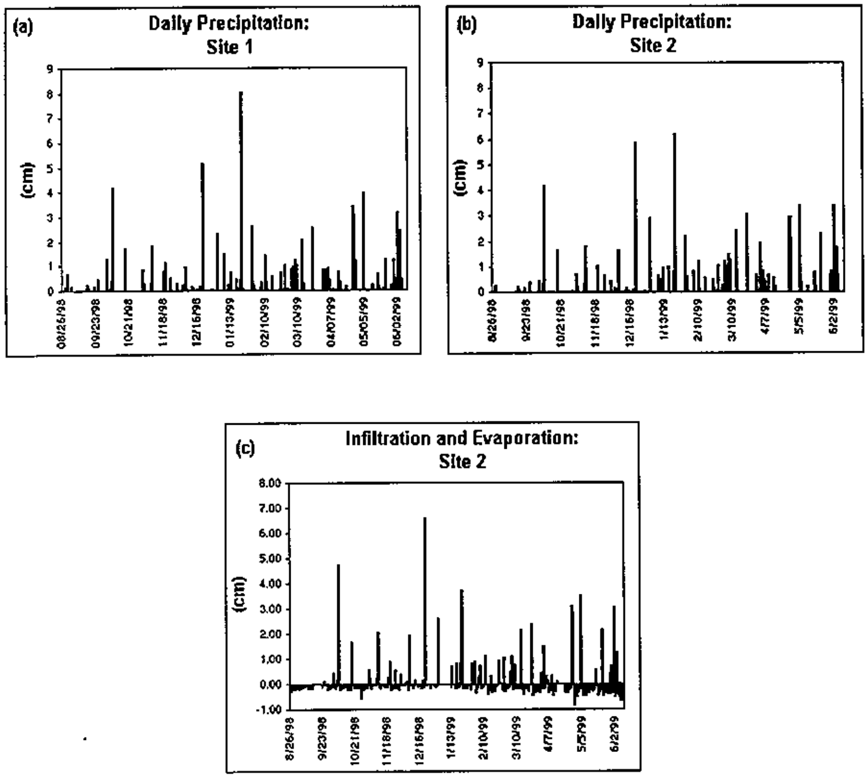


Figure 1. Daily rainfall totals at study site 1 (a) and study site 2 (b), and net daily infiltration and evaporation at site 2 (c).

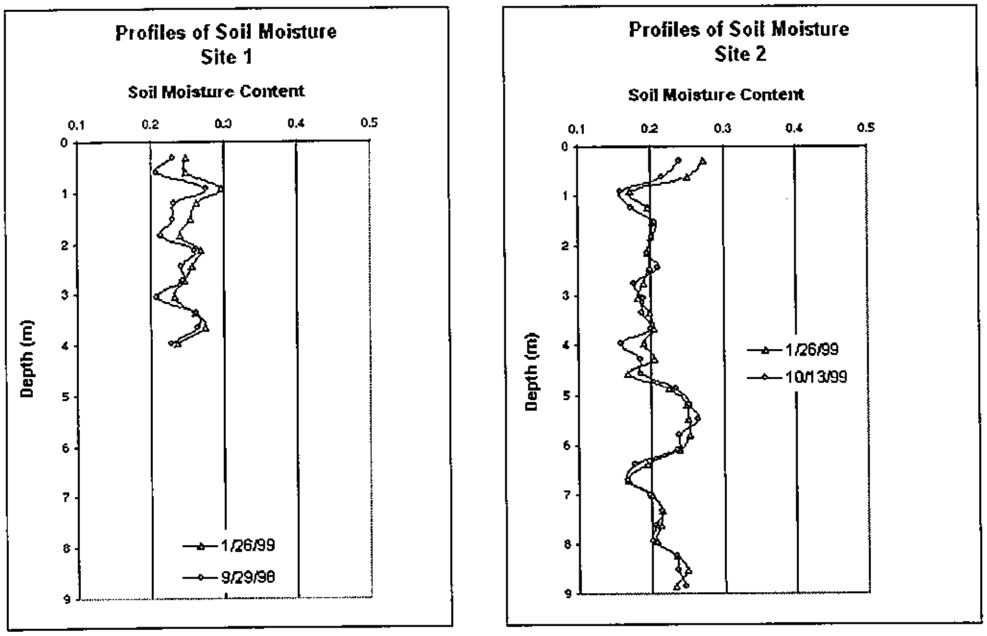
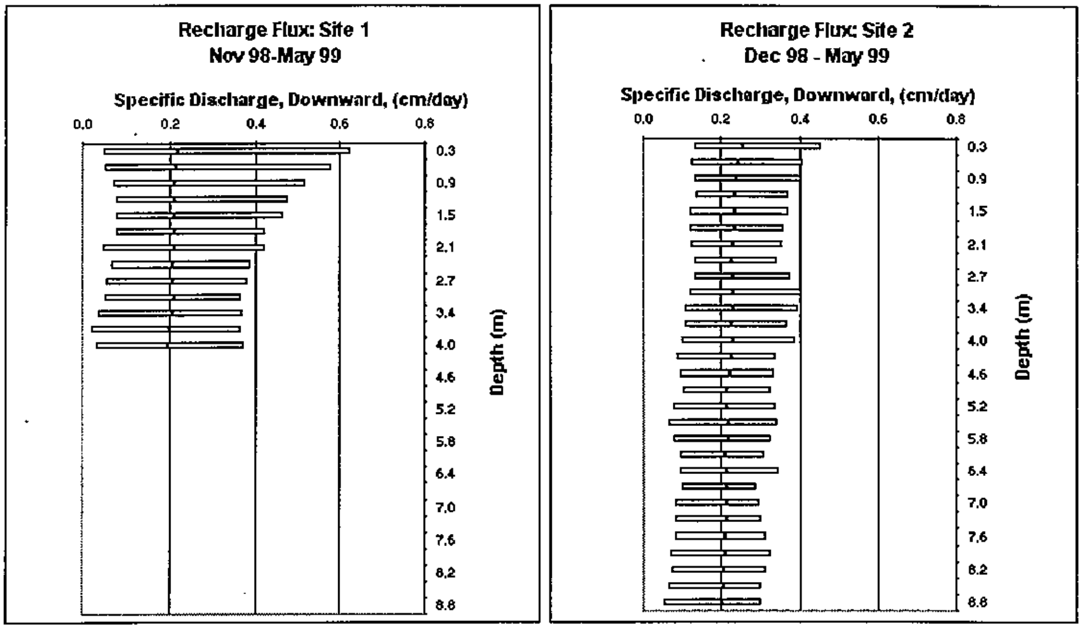


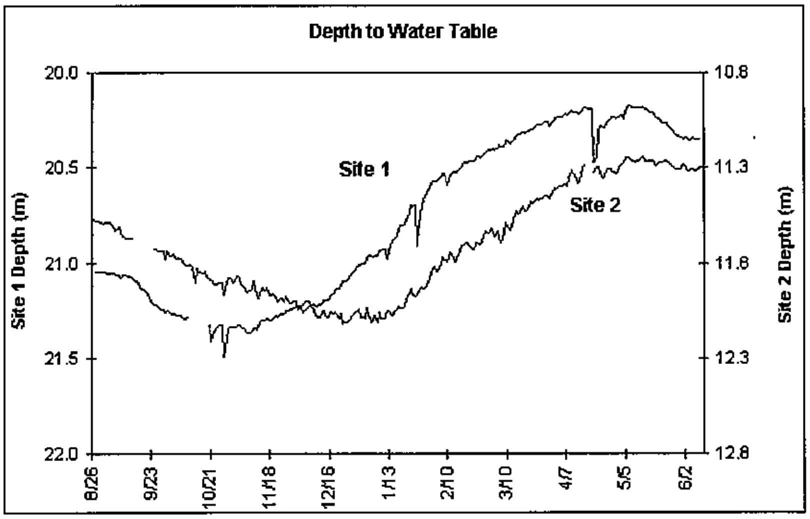
Figure 2. Profiles of wettest and driest soil moisture determined from neutron moisture gauge measurements at each study site



Recharge Flux: Site 1
Nov 98-May 99

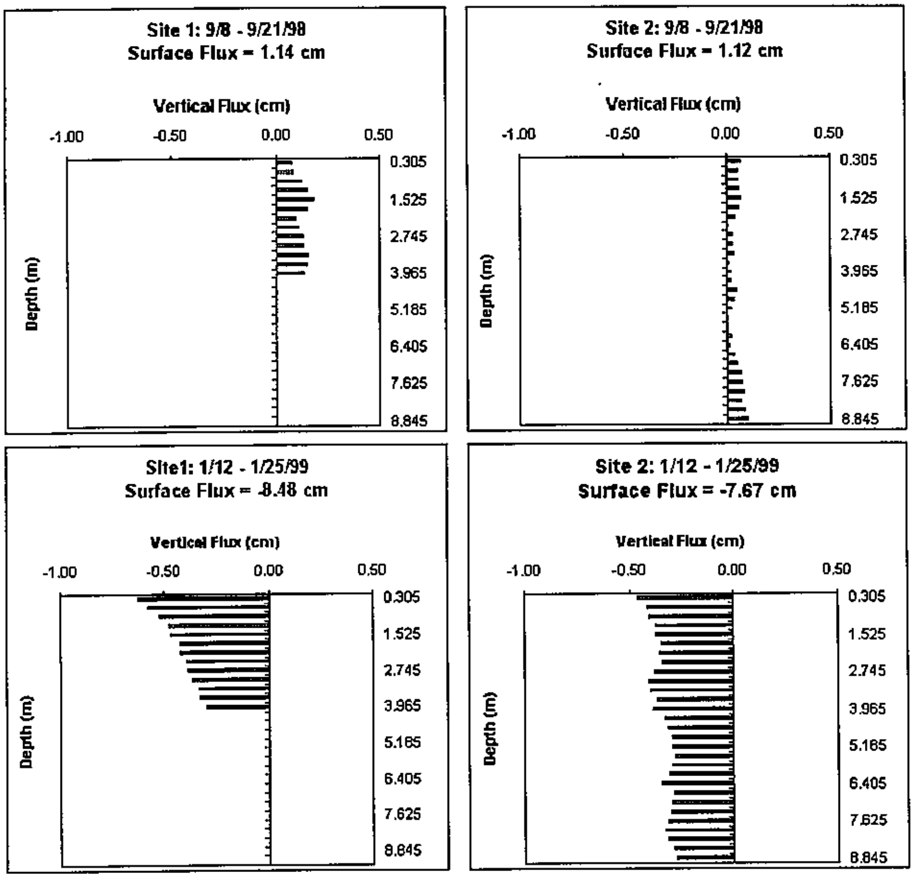
Recharge Flux: Site 2
Dec 98 - May 99

Figure 4. Graphs showing range (bars) and average values (black dots) of computed flux values corresponding to the 17 measurement intervals identified in Table 1.



Depth to Water Table

Figure 5. Hydrographs of water level determined from pressure transducer measurements in monitoring wells at the two study sites.



Site 1: 9/8 - 9/21/98
Surface Flux = 1.14 cm

Site 2: 9/8 - 9/21/98
Surface Flux = 1.12 cm

Site1: 1/12 - 1/25/99
Surface Flux = -8.48 cm

Site 2: 1/12 - 1/25/99
Surface Flux = -7.67 cm

Figure 3. Selected profiles of vertical flux corresponding to periods of net drying (upper graphs), and net wetting (lower graphs). Data plotted in the upper graphs pertain to measurement interval B of Table 1 whereas data plotted in the lower graphs pertain to measurement interval I. Positive surface flux values indicate net evaporation occurred during the measurement interval and negative surface flux values indicate that net infiltration occurred.