Potential for infiltration through the fine-grained surficial deposits of the Bogue Phalia Watershed, Mississippi

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ABSTRACT

The U.S. Geological Survey is conducting a preliminary assessment of the potential for deep infiltration of water and ground-water recharge through fine-grained Mississippi embayment deposits. Findings of this study will provide insight into the potential for transport of agricultural chemicals to ground water in this and similar humid regions of the United States. During an annular period that began in March 2006, various sediment-physical-property, sediment-hydraulic, ground-water, streamflow, and meteorologic data will be collected at two sites in the Bogue Phalia River watershed. The paired sites allow study of the somewhat varying sediment compositions distributed across the watershed. Relatively sandy soils planted with cotton compose the northern site near Gunnison; relatively sand-free soils planted with soybeans compose the southern site near Leland. Both sites are within 0.1 mile of the Bogue Phalia River. Within the study area, about 13 feet of predominantly silt sediments overlie at least 100 feet of sand deposits. The coarse sediments compose the Mississippi embayment alluvial aquifer, with ground-water levels generally about 15-30 feet below land surface. Instrumentation includes vertically nested piezometers and soil-moisture sensors, as well as a meteorologic station, deep ground-water well, and streamgage. Much of the instrumentation is monitored continuously with data-logging devices and the data served to the World Wide Web.

Preliminary data from the growing season of March-September 2006 indicate infiltration generally is limited to the uppermost 3-4 feet of the soil horizon, or just below the primary root zone of the planted crops. Following rainfall events, no appreciable increase in soil-moisture content was detected at monitored depths approaching 9 feet. Underlying ground-water levels and stream stage responded almost instantaneously to these events, indicating that the aquifer and nearby river are in direct hydraulic connection with ground-water levels affected by stream stage. The fine composition of the surficial sediments (generally containing less than 25 percent fine sand) and their presumably low vertical hydraulic conductivity appear to inhibit the deep infiltration of water. Presently, available data are not adequate to differentiate between the deep-infiltration characteristics of the varying sediment compositions that distinguish the two study sites. Additionally, the reported growing season was unusually dry, with 25 to 50 percent of normal seasonal rainfall (about 18 inches recorded). Infiltration response during a seasonally wet period, when evapotranspiration rates are correspondingly low, will need to be monitored to more fully assess the potential for deep infiltration through these fine-grained sediments.

Keywords: Ground Water, Hydrology, Sediments, Methods

Introduction

The Mississippi Delta region (fig. 1) is a rich agricultural area that is a substantial source of cotton, soybeans, rice, and corn. To help maintain this level of production, approximately 9 million pounds of pesticides are applied annually in Mississippi for control of grasses, weeds, insects, and fungi (U.S. Department of Agriculture, 2006a). With this substantial usage of pesticides, there is a potential risk to the quality of the region's surface and ground waters. To address such questions concerning the sources, transport, and fate of agricultural chemicals, the U.S. Geological Survey (USGS) is undertaking hydrologic-based studies in various agricultural and natural settings across the Nation, including the Bogue Phalia River Basin, Miss. (Erwin and others, 2005). The climate, geology, and hydrology of this basin are considered characteristic of the Mississippi Delta region, as well as other humid, subtropical settings in the southeastern United States. The studies in the various areas will examine how natural factors (including climate, geology, topography, and soils) and management practices (including crop type, chemical use, tillage, vegetated buffering) may affect the fate and transport of agricultural chemicals.

Past studies of agricultural-related ground-water quality in the Mississippi Delta region indicate detections of one or more pesticides in about 13 to 36% of the wells that were sampled (Gonthier, G.J., 2003; Office of Pollution Control, 2004). These wells typically were supply wells that penetrate most of the approximately 135 ft thickness of the uppermost Mississippi River Valley alluvial aquifer. There is limited understanding of how these agricultural chemicals are

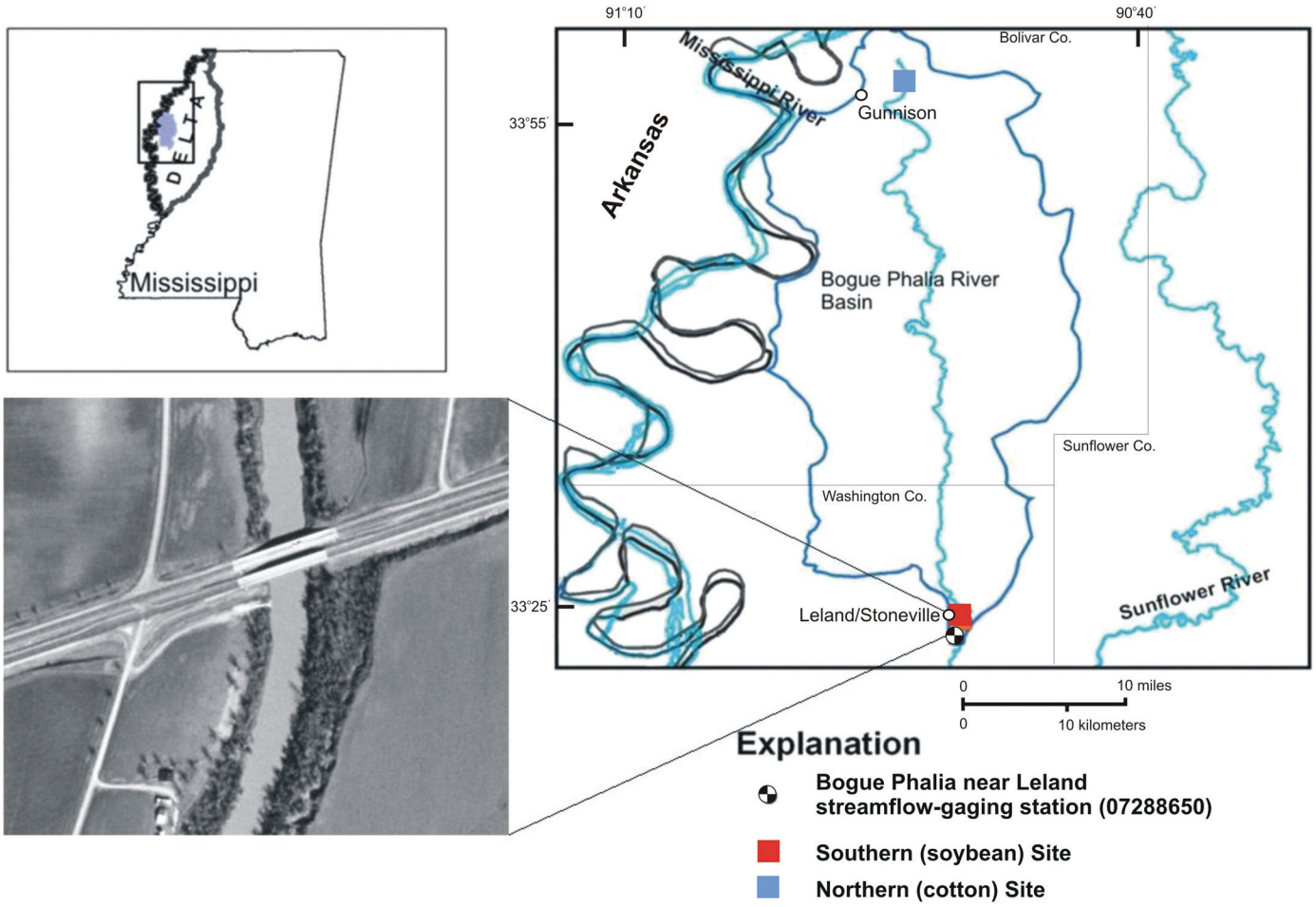


Figure 1. Location of study sites in the Bogue Phalia River Basin, Mississippi.

transported to ground water, particularly because there are few, if any, studies of deep infiltration through the approximately 25 ft thick unsaturated soils that almost fully overlie the aquifer. In addition, there are few, if any, studies of water quality at and near the water table. Water movement below the root zone that is unaffected by near-surface evapotranspiration is a potentially important mechanism for transport of agricultural chemicals to the underlying aquifer. Various estimates of average annual recharge to the aquifer by direct infiltration of precipitation through the overlying soils range from 0.5 (Sumner and Wasson, 1990) to 2.6 in/yr (Author, 2001; Krinitzsky and Wire, 1964). Flow simulation by Author (2006) indicates that direct infiltration represents 86% of total recharge to the aquifer and 5% of annual precipitation. To a lesser extent, vertical leakage from surface-water bodies contributes recharge to the aquifer. The magnitude of this local contribution generally is greatest during wet spring and summer months and where these water bodies deeply incise the fine-grained soils that overlie the aquifer. The present USGS field study in the Bogue Phalia River Basin intends, in part, to assess the relative contribution of various sources of recharge to the Mississippi River Valley alluvial aquifer, and to determine the flux of water and agricultural chemicals through the fine-grained soils that overlie the aquifer.

This paper presents results of a preliminary assessment of the performance and utility for this study of a selected type of dielectric sensor in measuring volumetric soil-moisture content (VMC) and changes in VMC associated with infiltration or evapotranspiration. A brief preliminary conceptualization of the potential for deep infiltration of water through the surficial fine-grained soils of the Bogue Phalia River Basin also is presented and is based on available VMC's and associated data.

Methodology

Two study sites were established in the 484 mi^2 Bogue Phalia River Basin (fig. 1). A southern site was instrumented in the lower part of the basin near Leland (Washington Co.) and a northern site was instrumented in the upper part near Gunnison (Bolivar Co.). The separate sites allowed study of infiltration through different soil-textural compositions and crop types. Predominantly silty clay to clayey silt soils planted with soybeans are present at the southern site; comparatively sandier clayey silt soils planted with cotton are present at the northern site. The fine-grained soils are about 13 ft thick at the southern site and range from about 7.5 ft to greater than 16 ft thick at the northern site (figs. 2, 3). These fine-grained soils overlie fine sands that compose the lower part of the unsaturated zone and upper part of the aquifer. Depth to the water table is about 17 ft at the southern site and 25 ft at the northern site.

Each study site is instrumented to allow monitoring of water movement through the unsaturated zone to the water table. Additionally, precipitation is monitored at or near each site and streamflow is monitored near the southern site. Instruments at the southern site are installed along an 800-ft transect approximately normal to the river channel. Instruments at the northern site are installed in two clusters: in comparatively siltier soils about 200 ft from the river (referred to as the "near-river" site) and comparatively sandier soils about 1,300 ft from the river (referred to as the "west" site) (fig. 3).

To monitor VMC, electronic sensors (Decagon Devices, Inc., 2006) (fig. 4) were installed in vertically nested pairs (fig. 3). A shallow sensor typically was positioned just below the anticipated crop root zone (about 3-4 ft below land surface) and a deep sensor about mid-depth between the

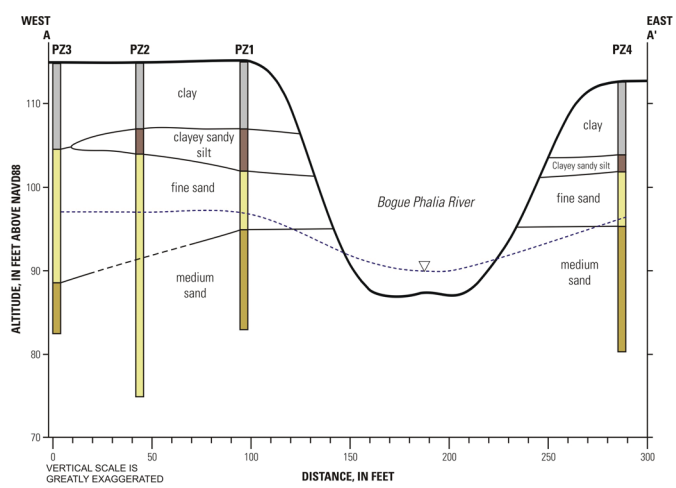


Figure 2. Hydrogeologic cross section of the southern study site in the Bogue Phalia River Basin, Mississippi.

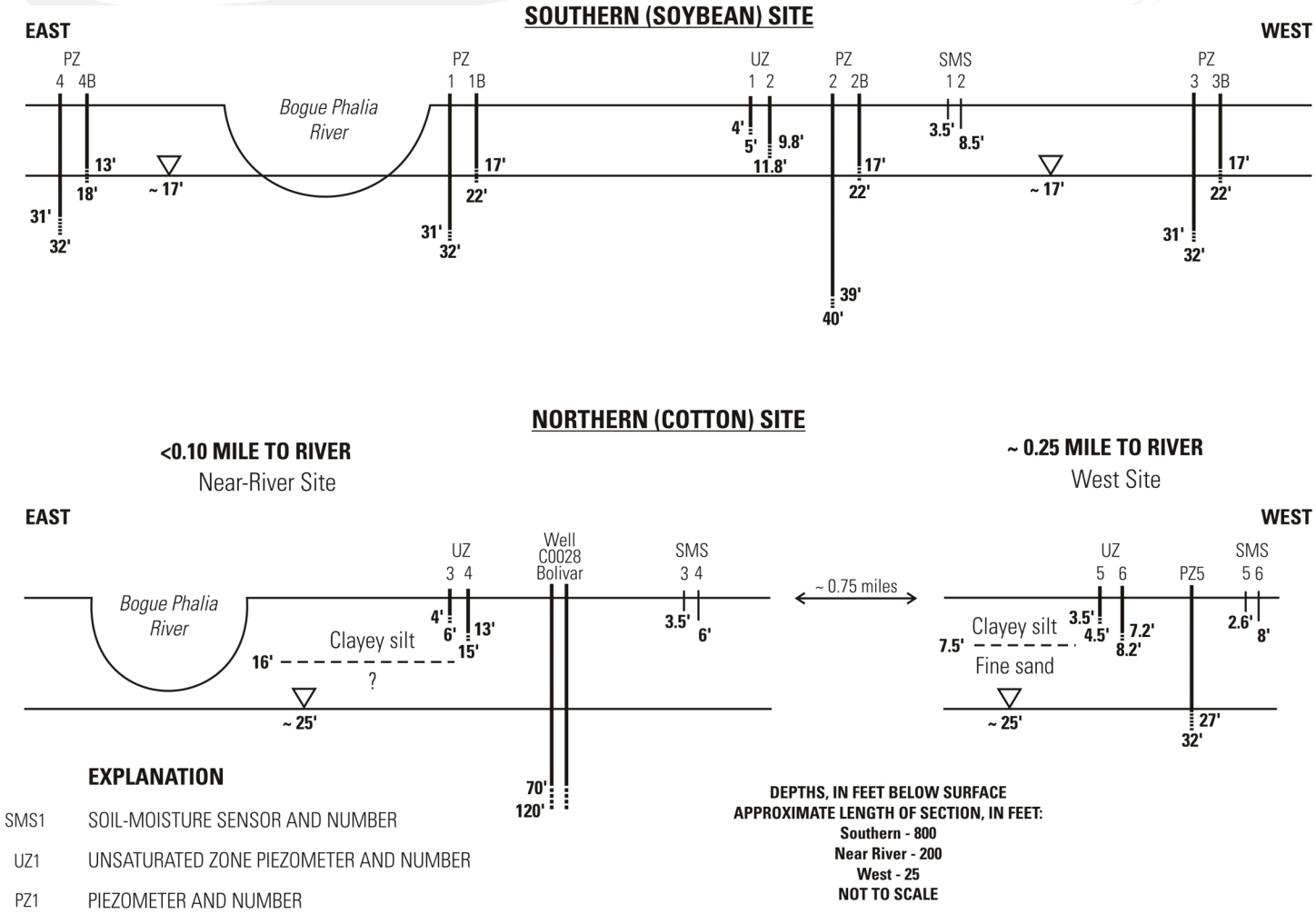
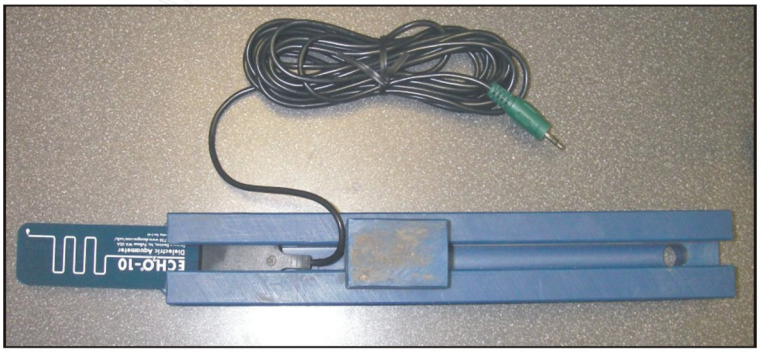


Figure 3. Cross sections showing instrument locations, depth to the water table, and selected stratigraphy at the southern and northern study sites in the Bogue Phalia River Basin, Mississippi.

soil surface and the water table (about 6-10 ft below land surface). The sensors were installed through the base of a 2- or 5-in.-diameter vertical core hole (fig. 5c) and the core hole backfilled with native soils in a manner intended to replicate the stratigraphy and bulk density of the native soils. Additionally, about 1 ft of bentonite was placed as backfill near the top of most core holes to further ensure they do not act as preferential conduits for deep infiltration. The sensors at each study site were connected to a digital data logger, with measurements recorded every 15 minutes.

The VMC sensors are a capacitance device that measures the dielectric constant (permittivity) of the medium (soil, water) in which they are installed. This measurement is made by determining the rate of change of voltage applied to the embedded sensor. The high value of permittivity of water (about 80) relative to that of most soils (about 4) and air (about 1) allows ready detection and measurement of deviations from ambient permittivity (which approximates soil permittivity) (Decagon Devices, Inc., 2007). On this basis, changes in VMC can be readily detected and measured as wetting and drying occurs in association with infiltration or evapotranspiration cycles. From this capacitance measurement, a mathematical model of the linear relation between the output voltage of the sensors, in millivolts (mv), and VMC



A

B

Figure 4. Soil-moisture sensors installed in the fine-grained soils of the Bogue Phalia River Basin, Mississippi study sites: (A) model installed in first phase, April 2006, (B) model installed in second phase, January 2007.

can be resolved (Cobos, 2007). For the sensors used in the study with a 2,500 mv excitation current, the model determined from generic (manufacturer) calibration is:

$$VMC = 0.00093 * mv - 0.376.$$

Capacitance sensors generally are considered to be readily affected by salinity and temperature conditions because of the low frequency (<10MHz) of the applied oscillating voltage. Additionally, electrical properties of soils can vary with soil texture, resulting in comparatively less accurate measurement of the permittivity of coarse-textured soils by the sensors. However, the circuitry design of the sensors used in this study and the soil conditions of the study sites (temperatures between -20 to 50° C, salinity less than 500 µS/cm, and predominantly fine-grained soils) are such that these factors are not expected to appreciably affect the measurement accuracy of the sensors. In fact, the site soil conditions are considered similar enough to the soil conditions used in the generic (manufacturer) calibration of the sensors (table 1) that site-soil-specific calibration was concluded to be unnecessary. Measurement accuracies of about +/- 4% VMC are expected (Decagon Devices, Inc., 2006).

In an attempt to directly capture infiltrating water, unsaturated-zone (UZ) piezometers were installed adjacent to each cluster of soil-moisture sensors. Similar to a gravity lysimeter, the 1-in.-diameter UZ piezometers consisted of a 1- to 2-ft long slotted screen with 1 ft of bottom-sealed casing attached to the base of the screen. Mid-points of the UZ piezometer screens were set at the approximate depths of the sensors (fig. 3). Beginning in June 2006, water levels in the piezometers have been monitored during most site visits. The visits generally have been made weekly to monthly. When standing water has been detected, the height of the

Table 1. Comparison of soils used in generic (manufacturer) calibration of soil-moisture sensors to soils at the study sites in the Bogue Phalia River Basin, Mississippi.

Soil type - source	Sand, in %	Silt, in %	Clay, in %	Electrical conductivity in µS/cm
Sandy silt loam - BF[1]	12-25	68-83	5-90[2]	<500[3]
Loam - G[4]	47	29	24	90
Silt loam - G	3	71	26	120
Silty clay loam - G	3	68	29	90
Silty clay - G	17	41	42	1,480

[1]Bogue Phalia River Basin study sites
[2]Upper value from U.S. Department of Agriculture (2006b)
[3]Estimated
[4]Generic (manufacturer) calibration

Figure 5. Installation of unsaturated-zone monitoring instruments at the Bogue Phalia River Basin, Mississippi study sites: (A) direct-push rig used to collect cores for installation of piezometers and soil-moisture sensors (looking west along piezometer transect at the southern study site); (B) sensor and insertion tool; (C) insertion of sensor; and (D) data-logging station for recording sensor data, and flush-mounted unsaturated-zone and water-table piezometers.

water column has been measured. As planned, the standing water was to be evacuated after each measurement, but to date this has not been done regularly. It is assumed that any flow into the piezometers results from soil moistures at or near saturation levels and not from preferential drainage down the annulus adjacent to the piezometer casing. This assumption is considered valid because the annulus of each piezometer was backfilled with bentonitic clay.

At the southern site, conventional 1-in.-diameter piezometers were installed in the saturated zone in four vertically nested pairs along the instrument transect (figs. 4, 5). Each pair consists of one piezometer with a 5-ft screen positioned near the water table (about 17 ft below land surface) and another with a 1-ft screen about 10 to 20 ft below the water table. During the initial spring-fall 2006 study period, measurement of water levels in all piezometers were made only during site visits; future data-collection plans include installation of pressure transducers for continuous monitoring of levels in some piezometers. Precipitation at this site is measured by a tipping-bucket gage co-located with a USGS streamflow-gaging station (07288650) about 1 mi south of the site (fig. 1). Site precipitation data are supplemented by measurements at the Mississippi Agricultural Experimental Station at Stoneville, Miss., about 4 mi northwest of the study

site (National Weather Service, 2007a).

The instrument cluster at the northern near-river site is co-located with an unused irrigation well and a tipping-bucket rain gage (fig. 3). The well is screened from 70 to 120 ft below land surface. Ground-water levels and rainfall are recorded automatically at 15-minute intervals by a digital data logger. The instrument cluster at the northern west site, located about 0.75 mi west of the near-river site, includes vertically nested soil-moisture sensors, UZ piezometers, and a conventional piezometer positioned near the water table (fig. 3).

Automatically logged data from the northern near-river site and the USGS streamflow-gaging station are transferred by satellite telemetry to the USGS Mississippi Water Science Center Web site (http://ms.water.usgs.gov/). Additionally, soil cores were collected during installation of the monitoring instruments and analyzed for various physical properties including particle-size distribution (soil texture), bulk density, soil-moisture content, and hydraulic conductivity.

Results

Following are the initial assessments of the performance of the soil-moisture sensors and the potential for deep infiltration though the fine-grained soils at the two Bogue Phalia River Basin study sites. These assessments are considered preliminary, pending possible additions to instrumentation along with full data collection and analysis.

Performance of Soil-Moisture Sensors

Soil cores collected near and at the installation depths of the sensors were used for verification of sensor-determined VMC's. Analysis of the VMC of southern study site cores collected about one month before the sensors were installed indicates that initially, most sensor values were acceptably close to existing field values (table 2). Differences between the core and sensor-determined VMC's are attributed primarily to (1) disturbance of ambient soil-moisture conditions during sensor installations, resulting in drier soils as measured by the sensors; and (2) differences in ambient soil-moisture between the March and April collection and measurement dates. In January 2007, additional sensors were installed at both study sites. Cores also were collected at the depths of the sensors to better assess the reliability of the sensor measurements. Results are pending for the VMC analysis of these sensors and cores.

Table 2. Comparison of initial values of volumetric moisture content, as measured by soil-moisture sensors installed at the southern study site in the Bogue Phalia River Basin, Mississippi, and moisture contents of cores collected near or at the depths of the sensors.

Soil-moisture sensor or core	Sensor or core depth, in ft[1]	Representative date of moisture value	VMC[2] in m^3/m^3
SMS1	3.5	04-27-06	0.34
Core1	4.0	03-28-06	.46
SMS2	8.5	04-27-06	.31
Core2	8.0	03-28-06	.37

[1]below land surface
[2]volumetric moisture content

Following the disturbance of sensor installation, several weeks seemed to be required to reestablish near-in situ conditions of soil moisture and compaction (figs. 6, 7, 8). Post-equilibration measurements of VMC by most of the sensors seem reasonable, particularly in late spring through early July. During that period, VMC's ranged from about 0.3 to 0.4 m^3/m^3, which generally is consistent with the measured values in nearby soil cores (table 2; figs. 6, 7, 8). The shallow sensor installed at the northern west site (fig. 3) did not seem to perform acceptably, as its measured VMC's were consistently about 0.06 m^3/m^3. During mid-summer, performance problems developed with many of the sensors. To a varying extent, these problems have limited their usefulness in measuring VMC and monitoring infiltration through the fine-grained soils of the sites.

The expected level of performance of the sensors can be seen best in the record of VMC's from the northern near-river site (fig. 7). These sensors have provided seemingly reliable measurements throughout the study period. Following the early equilibration period, cycles of wetting and drying soils

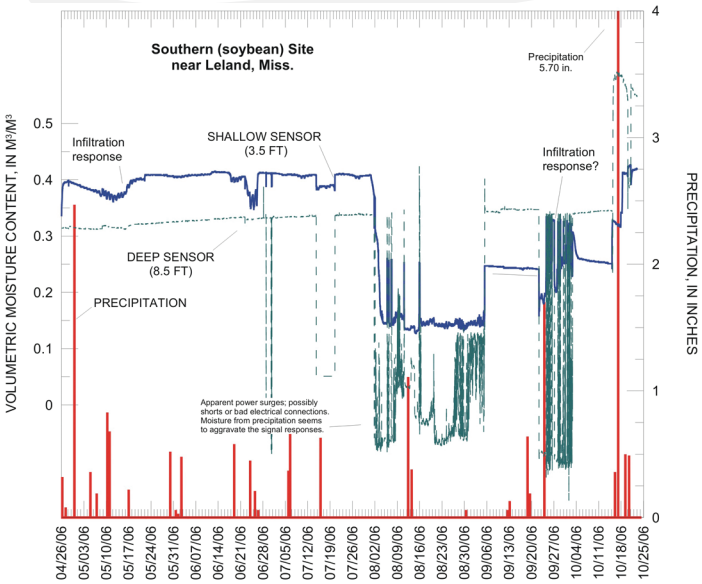


Figure 6. Soil moisture and precipitation at the southern study site in the Bogue Phalia River Basin, Mississippi, April-October, 2006.

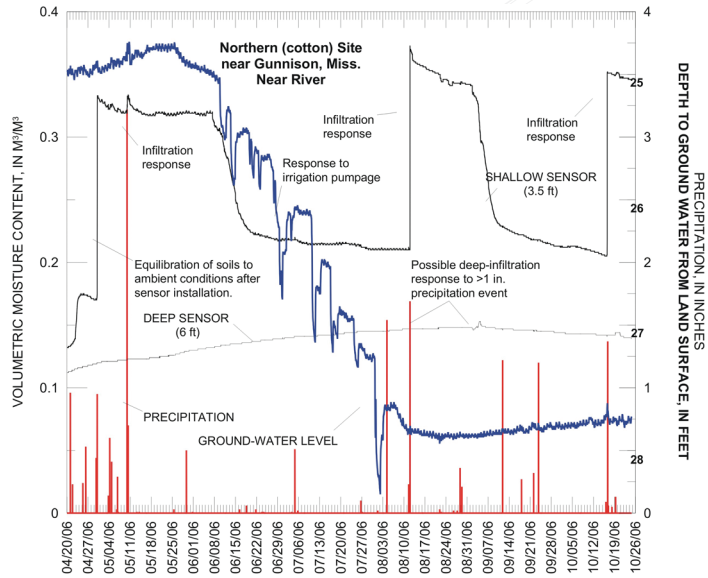


Figure 7. Soil moisture, precipitation, and ground-water levels at the northern near-river study site in the Bogue Phalia River Basin, Mississippi, April-October, 2006.

have been recorded by the shallow sensor in response to precipitation events. VMC's at this site approach a maximum of about 0.35 m^3/m^3. The ambient VMC's measured during periods of limited precipitation seem unexpectedly low for depths below the root zone (about 3 ft below land surface) in fine-grained soils. Measured VMC's were about 0.15 m^3/m^3 for the deep sensor and 0.2 m^3/m^3 for the shallow sensor. However, VMC's determined from cores collected near the respective depths of the sensors (but at different times) were 0.27 m^3/m^3 and 0.08 m^3/m^3. Increasing evapotranspiration related to seasonal warming and crop emergence through the summer months is expected to have limited infiltration to soil depths below the root zone. Additionally, this was the beginning of a period of limited precipitation, with only about 14 in. during May through September (about 11 in. at the southern site). The long-term average for this location is about 18 in. (National Weather Service, 2007a, b). Soils in the vicinity of the deeper sensor also may be sandier than the soils distributed elsewhere at this site, thus accounting for the lower than expected VMC. To assess the accuracy of the deep sensor, additional cores were collected near the sensor in January 2007 for analysis of VMC and particle-size distribution.

In mid-July, near-simultaneous fluctuations and unrealistic decreases in the output signals of both soil-moisture sensors at the southern site began to occur (fig. 6). These fluctuations increased in the following weeks, rendering the measurements unusable. With visual filtering, early portions of the output data signal are extractable for measurement of VMC's. Around the first of July, the shallow sensor at the northern west site rapidly failed, with output values thereafter indicating unrealistic moisture contents (greater than 1.0 m^3/m^3); a similar failure of the deep sensor occurred several weeks later (fig. 8). Both failures occurred during hot, dry periods, with little precipitation during the preceding weeks. Prior to that time, neither sensor responded to the few precipitation events that occurred earlier in the summer; however, most of these events totaled less than 1 in.

It is difficult to specifically determine the cause of the performance problems associated with various soil-moisture sensors. Although not individually tested or calibrated prior to installation to assure against manufacturing problems, their history of effective use in other settings (E.A. Smith, U.S. Geological Survey, oral commun., 2006) and their seem-

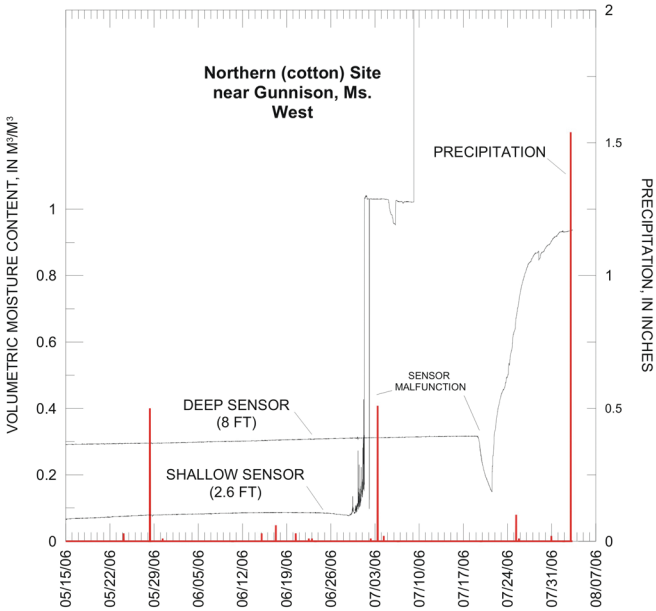


Figure 8. Soil moisture and precipitation at the northern west study site in the Bogue Phalia River Basin, Mississippi, May-August, 2006.

ingly reliable early time performance in this study suggest the problems may be related to one of the following issues.

- The epoxy-impregnated circuit boards that encase the electronic circuitry of the sensors may have been damaged during insertion of the sensors into the dense, clay-rich soils at the study sites. The likelihood of this damage is greatest at the southern site where the Sharkey clay soils are present. Difficulty in aligning the sensors with the insertion slots made at the base of the deep, small-diameter core holes using the bladed sensor-insertion tool further compounded installation problems. Through time, moisture may have come into direct contact with the circuitry of the damaged sensors. However, the near-simultaneous signal surges that occurred in the vertically nested sensors at the southern site are not readily accounted for by this explanation.
- The buried cabling that connects the deeper-buried sensors to the data loggers may have been damaged following sensor installation. Such damage could explain the near-simultaneous surges of the sensor signals at the southern site as well as the apparent sensor failures at northern west site. However, all cables were buried in plastic pipe at a depth of about 2 ft; thus, it seems unlikely that the sensors or cabling were damaged by subsequent plowing or by shrinkage cracks that developed in the near-surface soils during the dry summer months.
- The near-simultaneous signal surges in both shallow- and deep-buried sensors at the southern site suggest a near-surface cause, possibly associated with problems with the power-supply system. Electrical connections may have been loose and(or) moisture may have been present where the sensors and the solar cell/battery assemblies connect with the data loggers. However, no apparent problems have been identified upon inspection of these systems.

One additional limitation of the sensors is that the maximum VMC that can be recorded is 0.40 m^3/m^3. As noted in the VMC measurements by the shallow sensor at the southern site during May though July (fig. 6), the maximum output signal may have been exceeded several times. This limitation can be avoided in future applications by employing an alternative model of capacitance sensor available from the manufacturer. That model can measure moisture VMC's up to 1.0 m^3/m^3. Despite the noted problems, the overall performance of the sensors was considered positive enough to warrant their continued use at the study sites. Their performance will continue to be monitored to ensure the sensors satisfy the data-quality objectives of the study. It is anticipated that installation of the alternative sensor model will be necessary to fully describe and quantify water movement through the unsaturated soils at the sites.

Potential for Deep Infiltration

Soil texture, permeability, moisture-content, and groundwater-level data available from spring through fall 2006 allow preliminary assessment and conceptualization of the potential for deep infiltration of precipitation through the fine-grained soils at the Bogue Phalia River Basin study sites. Soil-texture data collected at various depths indicate an upper soil horizon composed predominately of silts and clays; the horizon ranges from about 7.5 ft to greater than

16 ft thick. Soil data collected at the sites (Rose, 2007) and available from nearby U.S. Department of Agriculture (2006b) surveys indicate clay contents in this horizon range from 5 to 90%. The highest clay content was in the Sharkey Clay soils at the southern site. Silt content typically is greater than 68%. Underlying these fine-grained soils, generally present at least to the depth of the water table, is a horizon consisting of fine to very fine sand. Bulk densities of these soils generally range from about 1.3-1.7 g/cm^3 (R.W. Healy, U.S. Geological Survey, written commun., 2006) (fig. 9) and are greatest, exceeding 1.6 g/cm^3, near mid-depth of the fine-grained horizon (about 8 ft) and in the upper part of the fine-sand horizon (below about 13 ft). Vertical hydraulic conductivities of the fine-grained soils at the southern study site, as determined from laboratory permeameter measurements, range from about 1x10^{-2} to less than 10^{-3} ft/d, with a geometric mean of about 9x10^{-3} ft/d (Rose, 2007). The fine texture, high density, and low vertical hydraulic conductivity of the uppermost fine-grained soil horizon suggest limited potential for infiltration of precipitation to the underlying Mississippi River Valley alluvial aquifer. Evidence of expandable smectitic clays within the fine-grained soils at the southern site (Rose, 2007) furthers suggests a limited potential for deep

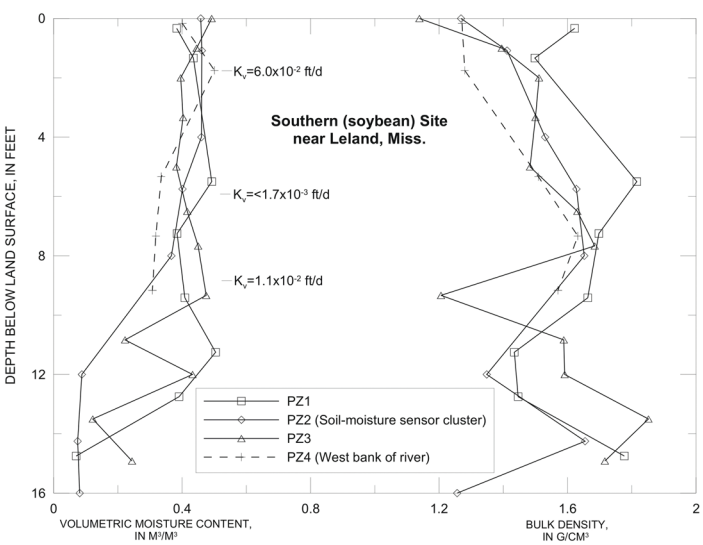


Figure 9. Volumetric moisture content, bulk density, and vertical hydraulic conductivity of soils at the southern study site in the Bogue Phalia River Basin, Mississippi (moisture content and density data from R.W. Healy [U.S. Geological Survey, written commun., 2006]; conductivity data from Rose [2007]).

infiltration through these soils.

The available soil-moisture data from the study sites also suggest limited potential for deep infiltration. At both the southern and northern near-river sites, shallow infiltration to a depth of about 3.5 ft is indicated in response to selected precipitation events that individually or collectively exceed about 1 in.

At the southern site, infiltration responses seem to have occurred following storms in mid-May, late September, and mid-October that produced about 1.5 in., 1.75 in., and 5.7 in. of precipitation, respectively. The responses in the fall months are not certain because of the erratic sensor output (fig. 6). Although the soil-moisture increase associated with the first event appears to be only about 0.05 m^3/m^3, it is likely greater. As previously discussed, the maximum VMC measured by the sensors is 0.40 m^3/m^3. There appears to be an increase in VMC of about 0.1m^3/m^3 associated with the September event and possibly about 0.1 m^3/m^3 or more with the October event. In both these cases, the actual VMC may be higher than the recorded value of about 0.40 m^3/m^3. It is uncertain why there was no apparent response to the approximately 2.5-in. event in late April. Possibly the precipitation total applied here from the Stoneville, Miss., precipitation gage exceeded the actual total at the study site. The recorded total from the site (0.86 in.) was presumed to be underestimated and thus was not used in this evaluation. It also is possible that the apparent infiltration response in mid-May is a delayed response to the two large storms during the previous two weeks.

At the northern site, infiltration responses are observed in late April, mid-May, early August, and mid-September (fig. 7). The response in April followed multiple precipitation events distributed over about one week, each of which produced about 0.5 in. of precipitation. The increase in VMC associated with these events was about 0.18 m^3/m^3. This infiltration primarily contributed to the equilibration of soils to ambient conditions following sensor installation. About two weeks later, following about 3.25 in. of precipitation, there was an additional increase in soil moisture at the 3.5-ft depth. However, the comparatively small increase in VMC of only 0.01 m^3/m^3 suggests the soils were already near

saturation, thus allowing minimal infiltration. Most of the water from that large storm presumably drained from the field as runoff to the nearby river. This assumption is supported by the accompanying rapid and near-simultaneous rise in ground-water levels (fig. 7), which has been attributed to a response to rising river stages (Ackerman, 1989; Sumner and Wasson, 1990). The infiltration response in August followed two storms producing about 1.5 in. of precipitation each, spaced about one week apart. The associated increase in VMC's was about 0.15 m^3/m^3. In September, moisture contents at the depth of the shallow sensor increased by about 0.15 m^3/m^3 following a storm producing about 1.5 in. of precipitation. The varying responses to the storms in August and September, along with the seemingly low ambient soil-moisture content (about 0.22 m^3/m^3) at the depth of the shallow sensor, and the minimal response of the deep sensor to precipitation (as will be discussed subsequently) suggest evapotranspiration is affecting subsurface water movement. More precipitation was required to raise moisture contents at the 3.5-ft depth in early August than in September. During mid-summer the soils were depleted of much of their moisture by lack of precipitation and high rates of evapotranspiration. By late September, evapotranspiration appears to have less effect on sensor response and on limiting infiltration.

Minimal infiltration seems to occur through the fine-grained soils to depths greater than about 6 ft, assuming that all deep sensors were functioning properly into mid-July. VMC's appeared to increase steadily over the recording period by about 0.02 m^3/m^3, but no obvious sensor response to any large individual or clustered precipitation events was observed. The only possible indication of deep infiltration is a slight (less than 0.01 m^3/m^3) increase in VMC as recorded by the sensor at the northern study site in early September (fig. 7). If the sensor reading represents an actual increase in moisture content, the increase possibly is a response to the multiple 1-in. storms that occurred in early August (fig. 7). This response would suggest a travel time for the wetting front of about 0.08 ft/d through the sub-root-zone soils.

Data from the UZ piezometers provide qualitative insight into the potential for deep infiltration at the study sites. However, interpretation of the data is limited by the fact that the piezometers were not regularly evacuated between visits. Furthermore, it is possible that direct drainage into some piezometers occurred when their flush-mounted surface vaults flooded during several large, early spring storms. Preferential flow down the installation annulus also may have occurred prior to full hydration of the bentonite seal. At the first measurement in early June, the 1-ft basal traps of the shallow piezometers at the southern site and northern near-river site (fig. 3) were filled fully with water. Prior to that time there had been more than 5 in. of precipitation at both sites, including 1.5- and 2.5- in. storms about 1 month earlier. In mid-July, about one week after the piezometer had been pumped dry, about 0.1 ft of water was measured in the shallow piezometer at the southern site. Similarly, about 0.9 ft of water was measured in the shallow piezometer at the northern near-river site in late October, about 3 months after the piezometer had been pumped dry. Precipitation totals during these periods were 0.6 in. and 14.5 in., respectively. No drainage to the shallow piezometer at the northern west site was recorded. These observations indicate water can infiltrate through the fine-grained soils to depths of at least 4 ft. The infiltration seemed to occur primarily during late spring and mid-fall, when there is available water for drainage as the result of seasonally high precipitation rates and low evapotranspiration rates. The UZ piezometer data also suggest that infiltration varies spatially, most likely because of variability in soil texture. Drainage to the shallow piezometers seems to be limited to the finer-grained soils at the southern and northern near-river sites. The clay-rich soils tend to inhibit vertical flow, allowing the soil moisture to increase to levels that induce flow into the piezometers. The presumably more permeable soils of the northern west site, along with the comparatively thin fine-grained horizon (about 7.5 ft) at this site, probably allow for more rapid drainage, thus limiting flow into the piezometer.

With one possible exception, no flow was recorded into the deep UZ piezometers. In mid-June, 0.04 ft of water was measured in the piezometer open to the depths of 13-15 ft. However, installation of this piezometer was problematic because of a moist zone at that time near the 6 ft depth. The annulus likely was filled with bentonite only to a depth of

about 6 ft. The recorded drainage to the piezometer is considered unrepresentative of ambient flow conditions at that depth. One possible explanation for the absence of water in the deep UZ piezometers is minimal deep infiltration through these fine-grained soils.

Available ground-water data collected from March through October 2006 at and near the various unsaturated-zone instrument clusters is insufficient for definitive analysis of the potential for deep infiltration and ground-water recharge from precipitation. Periodically measured ground-water levels indicate water levels fluctuate seasonally and in response to selected precipitation events. However, the lack of continuous monitoring makes it difficult to discern if the levels are responding to changes in stream stage or direct recharge from the overlying unsaturated zone. Available data from the deep soil-moisture sensors and UZ piezometers suggest the rise in ground-water levels is associated primarily with rises in stage in the nearby Bogue Phalia River. This is most evident from the continuously collected ground-water-levels at the northern near-river site, as previously discussed. Thus, the river seems to be hydraulically connected to the aquifer and suggests that the river may be an important source of recharge.

Additional Data Collection and Analysis

From the initial period of study during spring through fall 2006, data gaps and instrument needs were identified. In January 2007, additional soil-moisture sensors were installed at the three instrument clusters. Modifications in the installation method, advances in sensor design, and more typical climatic conditions hopefully will result in the newly installed sensors outperforming their predecessors. Newly installed shallow sensors were positioned about one foot deeper than their predecessors to assure that they were below the zero-flux plane, thus, isolated from evapotranspiration effects. With one exception, 2-in. model sensors replaced the original 4-in. sensors (fig. 4). The replacement sensors operate at a higher frequency (70 MHz) than their predecessors (5MHz). This should improve measurement accuracy within a wider range of soil textures (including sand) and allow measurement of VMC's over a wider range (0-100%). The smaller size of the replacement sensors also eases their installation, thus reducing the likelihood of installation-related damage to the sensors.

Along with installation of the replacement sensors, core samples were collected at each of the installation depths for measurement of VMC. These time-synchronous moisture contents will serve as an additional check of sensor accuracy. Finally, particle-size distribution will be determined on selected cores from each of the study sites. This analysis hopefully will provide better delineation of variations in soil texture with depth and between study sites; subsurface water movement is affected, in part, by soil texture.

Future data-collection plans include addressing shortcomings associated with monitoring the UZ piezometers. These instruments seemingly can provide useful information regarding infiltration through the unsaturated zone. To provide accurate information, they must be regularly evacuated of standing water and their sealing caps must be watertight.

It is recognized that the majority of the available data were collected during a period of limited precipitation. The instruments were installed in mid-spring, the seasonal period when most precipitation occurs and most ground-water recharge is expected. During this time, the newly installed instruments seemed, for the most part, to be equilibrating with the subsurface settings that were perturbed by their installation. During the summer months that followed, precipitation was about 60-75% of normal. It is anticipated that data collection during spring 2007 will provide additional insight into the potential for deep infiltration; the wide array of instruments installed between spring 2006 and winter 2007 should be fully equilibrated with the surrounding subsurface conditions and many of the questionably performing instruments have been replaced with technically advanced models.

Conclusions

Initial data obtained during spring through fall 2006 from the two study sites in the Bogue Phalia River Basin, Miss., provided (1) insights regarding the performance and utility of the various monitoring instruments employed and types of data collected for this unsaturated-zone infiltration

study, and (2) the basis for a preliminary conceptual model of the potential for deep infiltration through the fine-grained soils of the basin. Although the performance of the soil-moisture sensors satisfied many of the data-quality objectives of this study, there are remaining questions regarding their utility to the study that necessitate their continued evaluation. When performing optimally, the sensors provided acceptably representative measurements of soil-moisture content. The present soil-physical-property, soil-moisture, and ground-water data suggest only minor amounts of precipitation infiltrate below the approximate depth of the root zone (about 4 ft) in the fine-grained soils of the basin. Soil texture appears to account, in part, for the seemingly greater potential for deep infiltration in the northern part of the basin compared to the southern part. In general, the northern soils are more coarse grained. During spring and fall months, ground-water levels and stream stage responded similarly after large precipitation events (exceeding about 1 in.), indicating that the aquifer and river most likely are hydraulically connected. Thus, the river may be an important source of aquifer recharge.

The additional data from technically advanced soil-moisture sensors installed during January 2007 and the soil-texture analyses of cores collected at each of the study sites hopefully will improve understanding of the potential for deep infiltration and allow quantification of water flux through the fine-grained soils of the Bogue Phalia River Basin. This information, along with water-chemistry and continuously monitored water-level and temperature data from an associated network of streambed and ground-water piezometers, and analyses of the basin's shallow ground water and streams for agricultural chemicals, hopefully will advance understanding of the factors that may account for the presence (or absence) of agricultural chemicals in ground waters of the basin.

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