Water Movement within the Unsaturated Zone in Four Agricultural Areas of the United States

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Millions of tons of agricultural fertilizer and pesticides are applied annually in the USA. Due to the potential for these chemicals to migrate to groundwater, a study was conducted in 2004 using field data to calculate water budgets, rates of groundwater recharge and times of water travel through the unsaturated zone and to identify factors that influence these phenomena. Precipitation was the only water input at sites in Indiana and Maryland; irrigation accounted for about 80% of total water input at sites in California and Washington. Recharge at the Indiana site (47.5 cm) and at the Maryland site (31.5 cm) were equivalent to 51 and 32%, respectively, of annual precipitation and occurred between growing seasons. Recharge at the California site (42.3 cm) and Washington site (11.9 cm) occurred in response to irrigation events and was about 29 and 13% of total water input, respectively. Average residence time of water in the unsaturated zone, calculated using a piston-flow approach, ranged from less than 1 yr at the Indiana site to more than 8 yr at the Washington site. Results of bromide tracer tests indicate that at three of the four sites, a fraction of the water applied at land surface may have traveled to the water table in less than 1 yr. The timing and intensity of precipitation and irrigation were the dominant factors controlling recharge, suggesting that the time of the year at which chemicals are applied may be important for chemical transport through the unsaturated zone.

Approximately 11.1 million tons of farm-fertilizer nitrogen and 5.8 million tons of manure are applied to agricultural fields in the United States each year (Ruddy et al., 2006). Additionally, 0.4 million tons of pesticides are applied annually (Thelin and Gianessi, 2000). These chemicals have boosted agricultural productivity but have raised concerns that their use may adversely affect ecosystems and human health. To minimize the deleterious effects of agricultural chemicals, an understanding of the mechanisms of their transport and of their transformation within the various components of a hydrologic system is an important component of any agricultural management plan.

The transport of agricultural chemicals from the field to groundwater or to surface-water bodies is most commonly facilitated by water movement. Hydrogeology, climate, and agricultural management practices can have important influences on the movement of water and chemicals. For example, best management practices intended to decrease or prevent agricultural surface runoff can reduce sediment and chemical loading to surface-water bodies (Hart et al., 2004), yet retaining water in the field can lead to increased infiltration and chemical loading to aquifers. Water draining through the unsaturated zone can carry along with it nutrients and pesticides. Böhlke (2002) pointed out that common agricultural practices have led to substantial increases in concentrations of agricultural chemicals within the unsaturated and saturated zones. Residence times of these chemicals in the subsurface can be decades or more.

Timing of agricultural chemical applications is important to avoid unnecessary transport of farm chemicals with excess water input. Rapid movement of nitrate through a sandy loam soil to the groundwater after periods of excess water input was observed by Bosch and Truman (2002). Schuh et al. (1997) showed that applied bromide, chloride, and nitrate were detected in trace amounts throughout the unsaturated zone and in the aquifer. They suggested that water is focused within "microtopographically" low areas and transports solutes as the water front infiltrates as a plug flow. They surmised that the shallow unsaturated zone sediments serve as a "feeder zone" for solute transport to greater depths, noting that the elevated concentrations of these chemicals commonly found in the shallow unsaturated zone were observed at greater depths after large precipitation events. Steinheimer and Scoggins (2001) pointed out that the thick loess soils of southwestern Iowa can conduct water and applied agricultural chemicals readily through the unsaturated zone, with

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Abbreviations: S_y, specific yield; WTF, water table fluctuation.

Fig. 1. National map showing agricultural study sites.

the detection and distribution of the chemicals dependent on landscape position and timing of precipitation.

The residence time of water in the subsurface and the geochemical environment control the extent of degradation of chemicals and organic compounds in the subsurface. Rapid transport within the sediment matrix limits the opportunity for the compounds to degrade and thus heightens the potential for contamination of shallow groundwater systems. Under certain conditions, water can bypass the sediment matrix and transport the parent compounds and their degradation products rapidly through the unsaturated zone to groundwater via preferential flow paths. Junior et al. (2004) suggested that preferential flow through permanent macropores was responsible for the high concentrations of applied bromide and pesticides in the first discharge from tile drains after surface application. Brye et al. (2002) suggested that a possible explanation for an increase in mobilization of phosphorus in the unsaturated zone in the presence of nitrogen fertilizer was preferential flow paths created by decaying plant roots.

The Agricultural Chemicals Transport study team of the U.S. Geological Survey's National Water-Quality Assessment Program conducted an investigation to improve our understanding of the processes that govern the fate and transport of agricultural chemicals within the hydrologic compartments of agricultural ecosystems (Capel and McCarthy, 2008). As a part of this investigation, the movement of water through the unsaturated zone was studied in four agricultural settings across the United States (Fig. 1). Detailed water budgets were constructed, and rates and timings of water movement through the unsaturated zone were determined. A unique aspect of this study is the coordination of study designs and efforts over a broad scope of agricultural practices, climates, soil types, hydrogeologies, and geographic locations. The common study design facilitates the estimation of rates of water movement through the unsaturated zone and the identification of factors that influence those rates. This paper describes water budgets, estimates of groundwater recharge rates, and times of water travel through the unsaturated zone for the four sites in 2004. Similarities and differences among the four sites are discussed, as are factors that could be affecting water movement through the unsaturated zone.

Site Descriptions

The study sites are within four important agricultural production areas of the USA (Fig. 1): areas typically planted in corn [*Zea mays* (L)] and soybeans [*Glycine max* (L.) Merr.] in Maryland and in central Indiana, an almond [*Prunus dulcis* (Mill.) Webb] orchard in the San Joaquin Valley of California, and mixed crops in the Yakima Valley of Washington. An intensive monitoring site within each larger study site was equipped with instrumentation to quantify the flux of water and chemicals through the unsaturated zone. Detailed descriptions of each study site can be found in Capel (2008), Gronberg and Kratzer (2006), Hancock and Brayton (2006), Lathrop (2006), and Payne et al. (2007). Selected site attributes, soil characteristics, and soil properties for each study site are listed in Table 1. Annual mean precipitation and monthly mean temperatures were determined from nearby National Weather Service stations.

Indiana

The Indiana study site, in Hancock County, is a flat field planted in soybeans and corn. The crops are rotated annually. Intensive data collection took place along the northern and southern edges of the field. Mean annual precipitation is about 110 cm; mean monthly air temperatures range from 23.8°C in July to −3.8°C in January. The field is conventionally tilled every year before planting. No winter cover crop is planted. An extensive tile drain network exists throughout the field at the study site. These drains promote surface drainage and control the maximum height of the water table. The thickness of the unsaturated zone averaged 1.1 m, primarily because of the depth to the tile drains. Unconsolidated sediments in the unsaturated zone consist of poorly drained, silty clay loam to silt loam soils (Table 1). Water accumulates in ponds on the flat field after heavy rainfall; runoff is slow, and erosion is negligible.

Maryland

The Maryland study site, in Kent County on the Delmarva Peninsula, is in the center of a rolling field with moderate slopes (2–10%). Mean annual precipitation is about 112 cm. Mean monthly air temperatures range from 25.2°C in July to 0.6°C in January. As part of a typical corn/soybean yearly crop rotation, soybeans were planted in 2004. The field was under conservation no-tillage practices. Winter wheat (*Triticum aestivum* L.) was grown as ground cover from October 2003 through April 2004 and from October 2004 through April 2005. The cover crop was killed with herbicide and disked into the shallow soil before planting soybeans. Unsaturated zone sediments, which average 10.6 m in thickness, range in texture from loamy sand to sandy loam. Available water capacity of the soil is moderate to high, with medium runoff potential and moderate soil erosion risk.

California

The California study site is in an almond orchard in Merced County. The intensive study site is on the uphill edge of the orchard. The climate is arid- to semiarid, with a mean annual precipitation of 33 cm and mean monthly air temperatures ranging from 25°C in July to 8°C in January. Because precipitation was

Table 1. Descriptions of study sites in agricultural areas of the United States.

Parameter	Indiana	Maryland	California	Washington
Site attributes				
Crop	soybeans	soybeans	almonds	corn
Irrigation (% of input)	none	none	sprinkler (82)	furrow (80)
Tile drains	~1 m deep	none	none	none
Average unsaturated zone thickness (m)	1.1	10.6	7.2	4.4
Soil classification				
Soil series	Crosby (50%); Brookston (38%)	Sassafrass	Delhi	Warden
Taxonomic class	Crosby: fine, mixed, active, mesic Aeric Epiaqualfs; Brookston: fine-loamy, mixed, superactive, mesic Typic Arqiaquolls	fine-loamy, siliceous, mesic Typic Hapludults	Typic Xeropsamments, mixed, thermic	coarse-silty, mixed, superactive, mesic Xeric Haplocambids
Soil texture	silty clay loam to silt loam	fine sandy loam to medium sand	fine to medium sand (thin silt layer ~3.3 m)	silty clay to fine sand
Soil physical properties				
Depth of samples (m)	0–1.4	0–6.1	0–13.7	0–4.6
Bulk density (g cm^{-3}) [n]	1.65 ± 0.23 [2]	1.78 ± 0.36 [4]	1.71 ± 0.10 [9]	1.39 ± 0.15 [11]
Organic matter (% by mass) [n]	3.6 ± 1.7 [9]	2.2 ± 0.9 [4]	0.4 ± 0.7 [8]	2.0 ± 0.8 [8]
Average % sand [n]	14.0 ± 8.7 [6]	62.1 ± 15.4 [5]	92.4 ± 3.2 [5]†	52.6 ± 4.9 [4]
Average % silt [n]	73.5 ± 7.2 [6]	31.2 ± 12.3 [5]	6.5 ± 2.8 [5]†	42.5 ± 4.5 [4]
Average % clay [n]	12.5 ± 3.6 [6]	6.7 ± 3.3 [5]	1.1 ± 0.4 [5]†	4.9 ± 0.6 [4]

† Particle size analysis data from samples of the uniform medium sand sediments of the unsaturated zone. A sample from a thin silt layer (3.3–3.4 m below land surface) resulted in a particle size analysis of 5.9% sand, 80.8% silt, and 13.3% clay.

insufficient to meet crop water needs, the orchard was irrigated during the growing season. The grower kept the rows between the almond trees free of vegetation by using herbicides or tilling. Irrigation water was imported via rivers and canals from the Sierra Nevada Mountains and applied through sprinklers from early March through August; irrigation was then stopped to induce ripening of the almonds. Before harvest, the trees were irrigated with approximately twice the amount of water that would be applied during a typical growing season application. Unsaturated zone sediments, averaging 7.2 m thick, have a relatively consistent texture (95% fine to medium sand), with a silty sand deposit less than 0.5 m thick at about 3 m below land surface (Gronberg and Kratzer, 2006). The sandy upper soil profile lacked well defined horizons or structure. Runoff and erosion are minimal at this site and were not observed during the 2004 study period.

Washington

The Washington study site is a field in Yakima County with a slope of about 5%. The intensive monitoring site was at the top of the field, at the head of the furrows where irrigation water was applied. In the arid climate in the Yakima Valley, mean annual precipitation is 18 cm, and mean monthly air temperatures range from 22.7°C in July to 0.2°C in January. Precipitation was not sufficient to meet crop requirements, and the field was irrigated during the growing season with water from surface reservoirs that capture snowmelt from the upper reaches of the Yakima River basin. Historically, a variety of crops have been grown on the field, including asparagus (*Asparagus officinalis* L.) before 2001, pumpkins (*Cucurbita pepo* L.) in 2001 and 2003, and corn (*Zea mays* L.) in 2002. Corn was planted in 2004. The field was subtilled to a depth of about 60 cm before planting in 2004. The corn was planted along the top of furrows that channel irrigation water from the head of the furrows to the bottom of the field. Surface runoff at the bottom of the furrows was diverted down drain lines that connect the field to a nearby agricultural surface drain.

Unsaturated zone sediments at the Washington site, averaging 4.4 m thick, consist of layered deposits (rhythmites) accumulated during late Wisconsin outburst floods (Bretz, 1930; Waitt, 1984) overlying greater than 90 m of unconsolidated basin fill (Payne et al., 2007). The rhythmites in the unsaturated zone are fine sand to silty clay in texture (Table 1) and range in thickness from 0.3 to 1 m. Exotic clasts (nonbasaltic pebbles, rocks, boulders) and clastic dikes (vertical "cracks" filled with fine to coarse material) are found within these rhythmites, both of which can affect the movement of water through the unsaturated zone.

Materials and Methods

Data Collection

Data were collected at the four study sites between 2003 and 2005. This paper considers the data only for calendar year 2004 because it is the only year for which a nearly complete data set is available for all four sites. Water content reflectometers, heat-dissipation probes, groundwater wells, weather stations, and suction and pan lysimeters were installed to measure properties that would allow determinations or estimates of soil moisture and matric potential at various depths (Table 2). Details about the instrumentation are provided below and in another paper in this issue (Capel, 2008). Several wells were installed to allow measurement of groundwater levels and collection of groundwater samples. Weather stations were set up to collect meteorologic data needed for estimating evapotranspiration rates. Suction and pan lysimeters were installed at different depths to allow collection of pore-water samples within the unsaturated zone. Before sampling, a vacuum (50–80 centibars) was exerted on the suction lysimeters from 4 to 24 h (depending on unsaturated zone moisture conditions).

Table 2. Instrumentation for soil matric potential (heat dissipation probes), soil moisture (water content reflectometers), unsaturated zone water samples (lysimeters), and groundwater elevation (wells) at each unsaturated zone study site.

Name†	Depth			
	Heat dissipation probes	Water content reflectometers	Suction and pan lysimeters	Well screen interval
	m			
Indiana				
I32a	–	0.6	0.6‡	–
I32b	0.9	0.9	0.9§	–
I32c	1.2	1.2	1.2§	–
I32d	1.5	–	1.5§	–
I32e	1.8	–	1.8§	–
I33r	–	–	–	2.1–2.7
Maryland				
M21a	0.4	0.5	0.5‡/0.6§	–
M21b	–	0.8	–	–
M21c	1.1	1.1	–	–
M21d	–	–	1.2‡/1.3§	–
M21e	–	1.4	–	–
M21f	2.3	–	2.4§	–
M21g	4.1	–	4.3§	–
M21h	5.5	–	5.5§	–
M22p	–	–	–	10.4–11.9
California				
C22a	0.3	0.3	–	–
C22b	–	0.6	–	–
C22c	0.9	0.9	0.9§	–
C22d	3.3	–	–	–
C22e	4.6	–	4.6§	–
C22f	6.1	–	6.1§	–
C22p	–	–	–	6.1–6.7
Washington				
W22a	–	0.6	0.6‡	–
W22b	–	0.9	–	–
W22d	1.1	–	–	–
W22e	–	1.2	1.3§	–
W22f	–	1.5	–	–
W22g	1.7	–	–	–
W22h	–	–	1.9§	–
W22i	2.6	–	–	–
W22j	–	–	2.8§	–
W22k	3.5	–	–	–
W22l	–	–	3.7§	–
W22p	–	–	–	5.2–6.7

† See Capel (in press) for additional details on sampling locations.
‡ Pan lysimeter.
§ Suction lysimeter.

Water content reflectometry probes (Model CS616-L; Campbell Scientific, Logan, UT) were used to monitor the soil moisture profile at a range of depths (Table 2). These probes were inserted horizontally into the soil column from a trench to depths from 0.3 to 1.5 m. The results of gravimetric moisture analyses of sediment samples collected at depths of each probe were used to verify their factory calibration.

Laboratory-calibrated heat-dissipation probes (Model 29-L; Campbell Scientific) were installed at various depths across the full thickness of the unsaturated zone at each site (Table 2). These probes are capable of sensing soil matric potential in the range of 0 to −15 bars; total hydraulic head is then determined by adding elevation head to matric potential. The probes worked relatively well in the arid conditions at the California and Washington sites, but their resolution was insufficient to allow tracking of wetting fronts at the two humid region study sites (Indiana and Maryland). For that reason, matric potential data for those sites are not included here.

Shallow wells were equipped with pressure transducers to continuously monitor changes in groundwater levels (Table 2). Sensor calibration was periodically checked and verified with manual measurements of water level.

A weather station was installed at each study site to continuously record data that were needed to estimate evapotranspiration rates: air temperature and humidity, net radiation, wind speed and direction, soil temperature, and soil heat. Gaps in weather data were filled with data from nearby weather stations: the McDonogh weather station for the Maryland site; the Denair weather station at the University of California, Davis, for the California site; and the Bureau of Reclamation's Harrah weather station for the Washington site. There were no breaks in the data for the on-site weather station at the Indiana site.

Further insights into recharge mechanisms were gained by means of bromide tracer tests conducted at each study site. These tests were designed to determine water travel times from land surface to various depths in the unsaturated zone. Suction and pan lysimeters were installed at various depths within the unsaturated zone at all sites (Table 2) to allow collection of pore-water samples. These samples were analyzed for general water chemistry for another aspect of a larger-scale project (Capel and McCarthy, 2008) and for the bromide tracer. Bromide was applied at a concentration of 15 g m^{-2} to the surface of a 12-m^2 section of land overlying the lysimeter clusters at the Indiana, California, and Washington sites, and at 14 g m^{-2} at the Maryland site. Water samples collected from the lysimeters over time were analyzed by ion chromatography to define bromide breakthrough curves. Analyses of these samples enabled calculation of a range of travel times, velocities, and specific water fluxes for each site. See Capel (2008) for additional details on the study site characteristics and on the collection and analysis of the samples.

Data Analysis

Water Budget Components

The water budget for a column of sediment extending from land surface to the water table can be expressed as:

$$I = ET + R + \Delta S + RO \quad [1]$$

where I is water input (precipitation plus irrigation plus surface runon), ET is evapotranspiration, R is groundwater recharge, ΔS is change in soil water storage, and RO is surface runoff. This equation assumes that there is no lateral subsurface inflow or outflow from the soil column. Components of Eq. [1] were measured or estimated independently. Surface runoff or runon were not measured. They were considered minor components of the water budget at these study sites because of the highly

permeable sediments at the California, Washington, and Maryland sites and the low surface slope and the presence of tile drains at the Indiana site.

Reference evapotranspiration was calculated with the Priestly-Taylor (Priestly and Taylor, 1972) and Penman-Montieth (Allen et al., 1998) methods for the Indiana and Maryland sites. The Kimberly-Penman (Wright, 1982) method was used for the Washington site because of the availability of those calculations from the nearby Bureau of Reclamation weather station. For the California site, reference evapotranspiration was obtained from the University of California weather station estimated with the California Irrigation Management Information System model, which is a combination of the Penman-Montieth equation and a modified version of the Penman equation (Pruitt and Doorenbos, 1977). Crop coefficients used to convert reference to actual evapotranspiration were obtained from Allen et al. (1998) and varied as a function of crop type, growth stage, and irrigation frequency.

Groundwater recharge was estimated using the water-table fluctuation (WTF) method (Delin et al., 2000; Healy and Cook, 2002), in which the water-table rise that was associated with an individual recharge event was determined by comparing groundwater hydrographs with precipitation records and with temperature records for periods of suspected snowmelt. To estimate recharge from the water-table rise, the following equation was applied:

$$R(t_i) = S_y \times \Delta H(t_i) \qquad [2]$$

where $R(t_i)$ is recharge occurring between time t_i and t_{i-1} (cm), S_y is specific yield of the unconfined aquifer (dimensionless), and $\Delta H(t_i)$ is the change in groundwater elevation due to recharge and takes into account the expected water-table recession that would have occurred in the absence of precipitation. This method assumes that water transported laterally into or away from the water table moves at a rate that is substantially slower than the rate at which vertical recharge water reaches the water table.

Specific yield was estimated as the average of the results of three calculation methods for all sites except the Washington site. The first method involved subtracting the specific retention, or field capacity, of the soil from the porosity. In the second method, S_y was set equal to the difference between the field-measured saturated and the average volumetric moisture contents after free drainage. In the third method, a value of S_y was selected from charts contained in Loheide et al. (2005), who computed values of "readily available" specific yield from a collection of water-table hydrographs for a range of sediment textures. For the Washington site, a different approach was used to estimate S_y. In the lower part of this field, the water table is less than 1 m deep and fluctuates diurnally in response to evapotranspiration from plants whose roots extended into the saturated zone. The method of White (1932) was used to estimate evapotranspiration on the basis of these fluctuations. The value of S_y used in the White method was adjusted until the estimates of evapotranspiration matched those determined from the micrometeorologic methods previously described.

Change in soil moisture storage was calculated as the daily difference in moisture content integrated over the depth of measurement of the moisture content reflectometers.

Travel Time and Velocity

Two approaches were used to analyze the travel time and velocity for water moving from land surface to the water table: a "piston-flow" model and a bromide tracer test. The movement of a wetting front through the shallow unsaturated zone, which was tracked by moisture content reflectometry probes and heat-dissipation probes, provided additional information on water movement through the unsaturated zone.

In the piston-flow approach, it is assumed that water draining out the bottom of the root zone displaces water below and that all water within the soil column moves uniformly downward the same distance (additionally assuming homogeneous sediment characteristics). If the amount of water stored in an unsaturated zone column and the average rate of recharge are known, then the following equation can be used to estimate the travel time (or residence time), T:

$$T = \frac{TH_{UZ} \times VMC_{AVG}}{R} \qquad [3]$$

where TH_{UZ} is the unsaturated zone thickness (cm), VMC_{AVG} is the average volumetric moisture content (dimensionless), and R is the annual recharge (cm yr^{-1}). Velocities were calculated as the average unsaturated zone thickness divided by the residence time obtained in Eq. [3].

Moisture content reflectometry probes were useful for determining the movement of wetting fronts from land surface to the various depths within the unsaturated zone, thus providing insight to recharge mechanisms. These probes helped track the wetting fronts at depths shallower than 1.5 m. A wetting front is initially identified as a change in moisture content at the shallowest sensor. Wetting-front velocity was calculated as the change in depth of the front over time from the shallowest sensor to the deepest sensor (Table 2).

Results

Precipitation and Irrigation

At each site in 2004, total precipitation was within 20% of the long-term mean annual precipitation (Fig. 2). The Indiana and Maryland sites received similar amounts of precipitation (Table 3 and Fig. 3), yet both received less in 2004 (about 18 and 12% less, respectively) than the long-term means (Fig. 2). The California study site received about 17% less precipitation in 2004 than the long-term mean, whereas precipitation at the Washington study site was about 6% greater than the long-term mean. Total precipitation at the California and Washington sites was approximately 30 and 20%, respectively, of that received at the nonirrigated sites.

Total irrigation at the California site was estimated by the almond grower to be 120 cm (Table 3) in 2004 on the basis of sprinkler applications of approximately 10 cm per application beginning in March and a final irrigation of about 20 cm in early October, just before harvest (Fig. 4H). Water was not applied between 15 August and 14 October to "stress" the trees and induce ripening of the almonds. Precipitation accounted for only 18% of the total

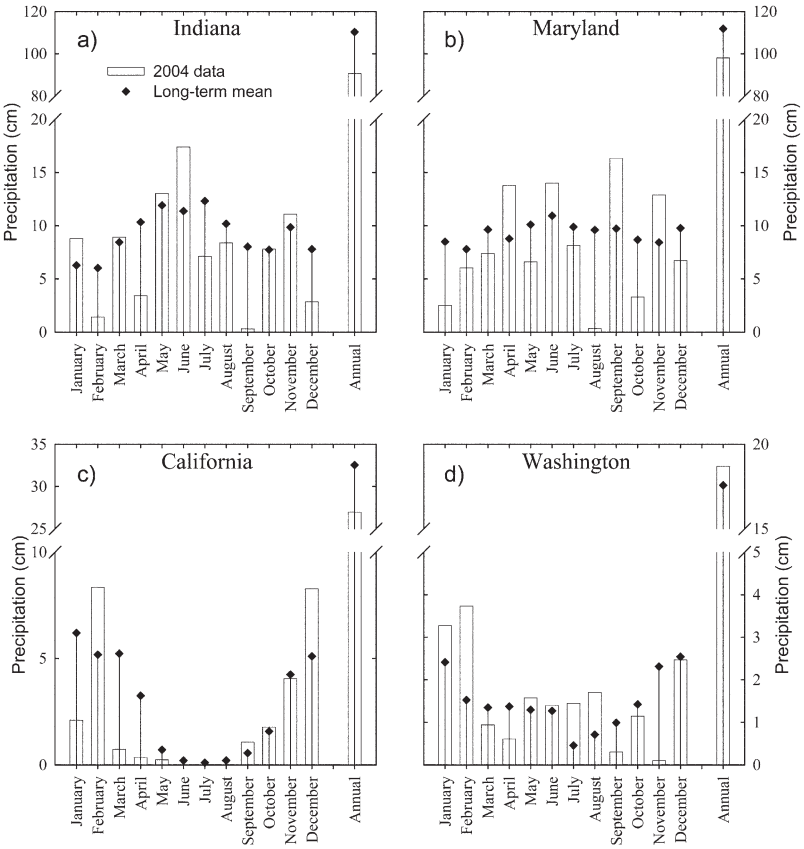

Fig. 2. Long-term mean and monthly and annual precipitation for 2004 for the (a) Indiana, (b) Maryland, (c) California, and (d) Washington study sites.

water input. Most precipitation fell in late fall and winter.

Total irrigation at the Washington site was estimated at 74.4 cm in 2004 on the basis of data obtained from the local irrigation district (Table 3). This amount was applied over the course of four "events" during the growing season, each lasting about 2 d. The volume of each of the four irrigation events shown in Fig. 4L is the sum of two events occurring on two consecutive days. Water was channeled down every other furrow on the first day of irrigation and down the adjacent furrows for the next day. Most (~64%) of the annual water input at the Washington site was irrigation water applied during the summer months (Fig. 5A). Approximately 24% of the annual water input occurred in the spring; this amount included early season irrigation. Precipitation accounted for 20% of the water input to the site. Precipitation was fairly evenly spaced throughout the year, with daily totals seldom exceeding 1 cm.

Table 3. Annual water balance for each unsaturated zone study site, 2004.

	Indiana	Maryland	California	Washington
	cm			
Water input				
Precipitation	90.6	98.1	27.0	18.7
Irrigation	–	–	120	74.4
Recharge	47.5	31.5	42.3	11.9
Evapotranspiration				
Priestly-Taylor	60.2	65.6	–	–
Penman-Montieth	57.3	61.9	89.9	–
Kimberly-Penman	–	–	–	83.7
Change in soil water storage	0.1	−0.1	1.3	0.0
Residual†	−17.2 to −14.2	1.1 to 4.8	13.5	−2.6

† This term is the result of subtracting recharge, evapotranspiration, and the change in soil storage from the total water input.

Evapotranspiration

Early in the year, evapotranspiration was driven by bare-soil evaporation (Allen et al., 1998); a small amount of water was transpired by volunteer plants at the Indiana, California, and Washington sites and by winter wheat at the Maryland site. Evapotranspiration (Fig. 3) increased at the onset of the growing season at all study locations, more so in the irrigated sites (California and Washington) than the nonirrigated. Plant transpiration continued over the growing season until harvest, at which time evapotranspiration rates dropped considerably, again becoming driven by bare-soil evaporation.

Cumulative evapotranspiration at the California site (Table 3) was 29 to 35% greater than that at the Indiana or Maryland sites, even though maximum daily evapotranspiration rates were similar (Indiana, 0.8 cm d^{-1}; Maryland, 0.7 cm d^{-1}; and California, 0.7 cm d^{-1}). The difference was due to the longer growing season for almond trees than for soybeans. Cumulative evapotranspiration at the Washington site (Table 3) was similar to that at the California site, even with the shorter growing season for corn in Washington.

Evapotranspiration rates estimated for this study are similar to published estimates for the Indiana site (57.2 cm yr^{-1}) (USGS, 1990) and the California site (95.9 cm yr^{-1} average) (University of California Cooperative Extension, 2005). Historical evapotranspiration rates for corn in the Pacific Northwest (66.5 cm yr^{-1}) (U.S. Department of the Interior–Bureau of Reclamation, 2006) are about 20% lower than this study's estimate for the Washington site. The disparity may be due to differences in methods of calculating reference evapotranspiration, differences in irrigation techniques, or differences in agricultural management practices throughout Washington. For the Maryland site, these estimates are 10% lower than the 78.4 cm reported by Hancock and Brayton (2006). The evapotranspiration rate reported in this study, however, is specific to soybeans, whereas the evapotranspiration rate reported by Hancock and Brayton (2006) is an aerially distributed average for the study region as a whole.

Recharge

Recharge rates for 2004, as estimated with the WTF method, are shown in Table 3. Specific yield used in these calculations was determined to be 0.045 for the Indiana site, 0.170 for the Maryland site, 0.212 for the California site, and 0.053 for the Washington site. These values are within the expected range on the basis of previously published values (Johnson, 1967).

Recharge at the Indiana site (47.5 cm) was 51% of annual precipitation. About 40% of the annual recharge occurred during the spring (Fig. 5B). Recharge occurred at lower rates in the

fall and winter (22 and 35% of the total recharge, respectively). During summer months, evapotranspiration dominated the water budget (Fig. 5B), but some recharge occurred in response to relatively large rainfall events (Fig. 3A and Fig. 4A). Tile drains enhanced recharge by reducing runoff and inducing infiltration. Figure 4C shows the groundwater elevation and elevation of a tile drain at the Indiana site. The plot shows how the tile drains controlled the shallow groundwater elevation after rainfall. The water level rose above the tile drain relatively quickly in response to precipitation, followed by a rapid recession until the water level approached the elevation of the tile drains. The water level dropped below the elevation of the tile drain after July in response to plant transpiration. The sharp decline in the water table between 1 October and 1 November was due to pumping and sampling of the shallow well at this site. Slow recovery of the water table observed during this period of reduced water input shows that very little soil water was being transported to the groundwater; rather, water was being removed by evapotranspiration or tile drains. An increase in the elevation of the water table followed the onset of fall precipitation, and, as would be expected, harvest reduced crop evapotranspiration to a minimum.

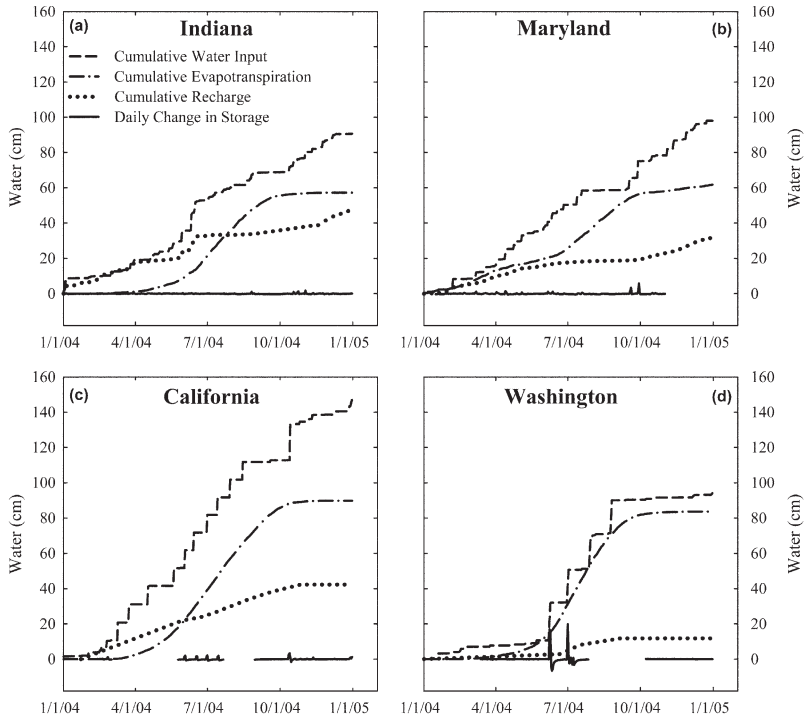

Fig. 3. Water balance for the (a) Indiana, (b) Maryland, (c) California, and (d) Washington study sites including cumulative water input, evapotranspiration, recharge, drainage, and daily change in soil moisture storage.

Estimated recharge for 2004 at the Maryland site (31.5 cm) was 32% of annual precipitation. Precipitation rates during the winter and spring exceeded evapotranspiration rates of the winter wheat cover crop, allowing recharge to occur; 30% of the annual recharge occurred in winter, and 31% occurred in spring (Fig. 5B). Approximately 6% of the total recharge occurred during summer. In the fall, the rate of evapotranspiration decreased, and recharge was again detected; fall accounted for 33% of the annual recharge.

Estimated recharge at the California site (42.3 cm) was 29% of the sum of precipitation and irrigation (and 35% of the total irrigation alone) for 2004. The long growing season for almonds required irrigation from spring to fall. Virtually all recharge occurred during the growing season in response to irrigation. Some minor water-table rises were seen in response to precipitation outside of the growing season, but these produced a negligible amount of recharge. Measurements of total hydraulic head obtained from heat-dissipation probes showed the progression of hydraulic head profiles after the 15 August irrigation event (Fig. 6A). Hydraulic head profiles indicated downward movement of water throughout the profile immediately after irrigation. Close inspection of the total hydraulic head profiles revealed that 1.0 cm of precipitation on 19 Sept. 2004 resulted in only a small change in potential in the shallow unsaturated zone (data not shown). Water in the upper soil profile was scavenged by the tree roots during the subsequent days without irrigation. As shallow soil water was removed by evapotranspiration, the direction of the total hydraulic head gradient was reversed such that water moved upward in the top 3 to 4 m of the unsaturated zone.

Estimated recharge at the Washington site (11.9 cm) for 2004 (Table 3) was 13% of the total water input, 16% of the irrigation applied, and 60% of the yearly precipitation. Recharge occurred almost exclusively during the growing season in response to irrigation. Summer accounted for 76% of annual recharge (Fig. 5B). Approximately 24% of the total recharge occurred in the spring as a result of early irrigation and low evapotranspiration of the developing corn crop. Measurements of groundwater levels indicated no recharge in the fall or winter of 2004. The WTF method, however, revealed a minor recharge event (~0.4 cm) in January 2005 (data not presented), which was a result of precipitation and snow/ice melt. Recharge was estimated to be about 0.5 cm during this event. Thus, large precipitation events, although infrequent, may produce recharge to the groundwater.

Heat-dissipation probe measurements indicated unusual total hydraulic head gradients in the unsaturated zone of the Washington site. The gradient seen on June 7 (Fig. 6B) was observed consistently throughout much of the year. The lower portion of this profile indicated upward water movement from the saturated zone. The shallowest sensor tended to indicate the opposite—water movement in a downward direction—yet no hydrogeologic evidence was available to explain this anomaly. The shallow sensor may not have been functioning properly, or the heat-dissipation probes may not have accurately sensed the true hydraulic head potentials and direction of water movement. The range of total hydraulic head potentials seen at the Washington site (–3.9 to –7.5 m) was less than that at the California site (–0.5 to –87.2 m).

Groundwater elevation at the Washington site (Fig. 4N) varied by 1.2 m over the study period, with increases corre-

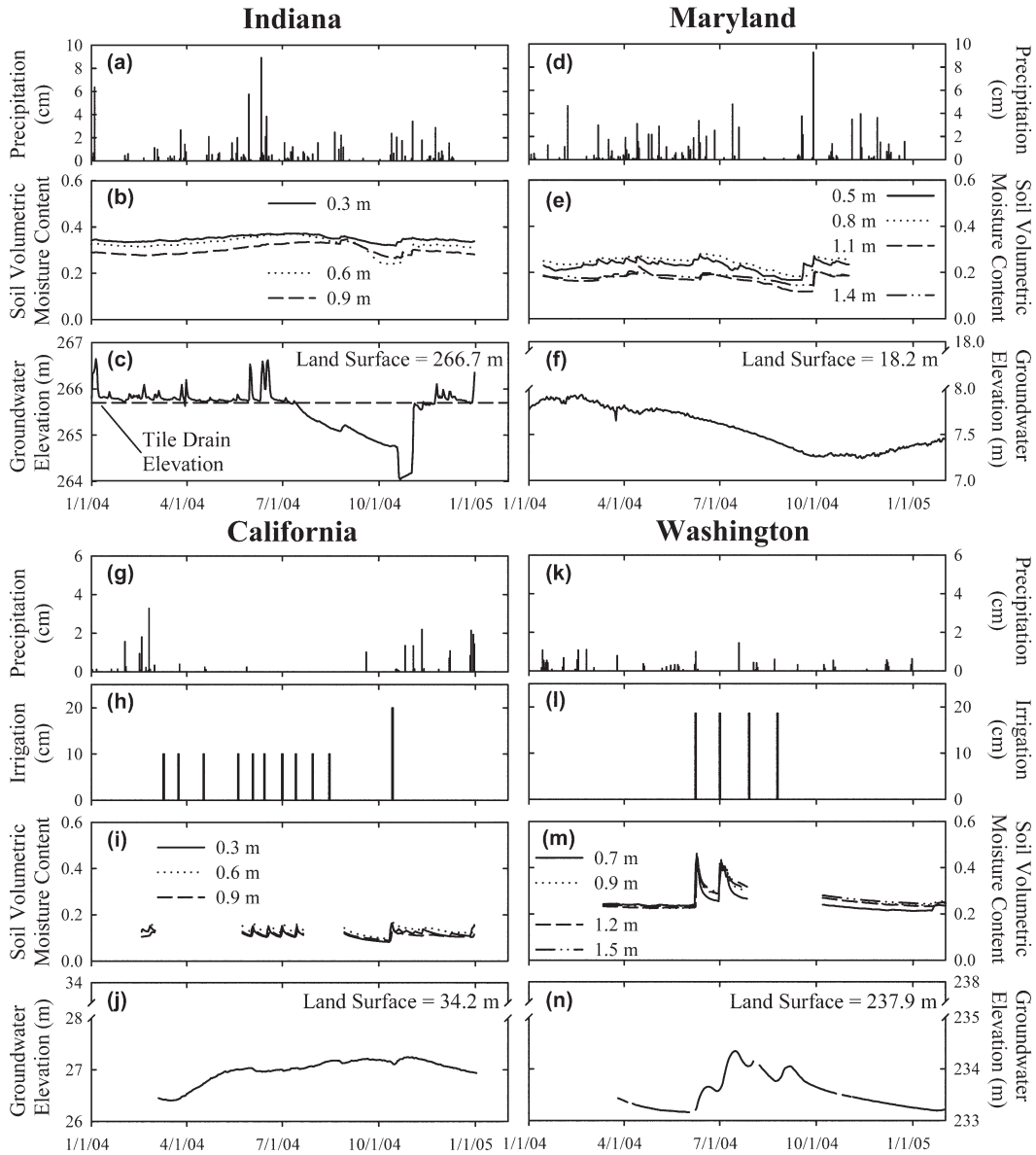

Fig. 4. Daily precipitation, irrigation, soil volumetric moisture content, and groundwater elevation for the Indiana, Maryland, California, and Washington intensive unsaturated zone study sites. Also shown are the depths below land surface for each water content reflectometer used to monitor volumetric moisture content and the elevations of the land surface above the 1988 National Geodetic Vertical Datum.

sponding to irrigation. Changes in the soil moisture content (Fig. 4M) clearly indicated the movement of wetting fronts through the shallow unsaturated zone in response to irrigation, which resulted in increases in groundwater elevation.

Soil Water Storage

Although there were short-term increases and decreases in the amount of water stored in the unsaturated zone throughout 2004, moisture contents at the end of the year were similar to those at the beginning of the year for all sites. Even though groundwater levels approached the land surface at the Indiana site after large precipitation events (Fig. 4C), the soil moisture content (Fig. 4B) varied only slightly and was close to saturation for most of the year. During a dry period in September, however, when the rate of evapotranspiration exceeded that of precipitation, there was a notable decrease (most apparent at the 0.6-m depth) in measured moisture content.

Figure 4E shows that moisture content of the shallow soil at the Maryland site tended to be greater than that of deeper soils. Moisture content here declined at all depths over the course of the growing season because crops consumed water at a rate greater than precipitation, thus reducing recharge. Groundwater levels also declined during this period (Fig. 4F). These trends at the Maryland site continued until September, at which time a heavy rainfall produced noticeable increases in soil moisture.

At the California site, moisture content data (Fig. 4I) showed rapid movement of wetting fronts through the sandy soils. This rapid movement was also reflected in the daily change in water storage (Fig. 3C), which showed quick wetting front responses to irrigation. There was good agreement between wetting front

movements as measured by reflectometers and rises in groundwater levels (Fig. 4I and 4J).

At the Washington site, the moisture content in the unsaturated zone increased markedly during irrigation and declined slowly thereafter (Fig. 4M). Soil moisture response to water input and subsequent increases in the water-table elevation were more dynamic at this site than at the other study sites, possibly because of differences in irrigation volumes (Fig. 4H and Fig. 4L), in soil textures, and in depth to groundwater (Table 1).

Travel Time and Velocity

The residence times and the velocities of water movement in the unsaturated zone that were estimated with the piston-flow model (Table 4) represent average residence times and velocities for all unsaturated zone water; some water may move more quickly, whereas other water moves more slowly. It was not possible to calculate accurate travel times and velocities from the bromide tracer data because of the limited frequency at which water samples were obtained from lysimeters. Nonetheless, bromide concentration data (Fig. 7) provided useful qualitative information.

Detection of bromide at depths as great as 1.5 m at the Indiana site within 7 d of application (Fig. 7) was surprising, given the low permeability of the glacial till. This rapid transport indicated the presence of preferential flow paths, and indeed desiccation cracks in the soil after dry periods were observed at this site. Concentrations of bromide at the 0.9- and 1.2-m depths remained steady for some time after application, supporting the idea that a small amount of water was transported initially through preferential flow paths. The remaining bromide was likely partitioned into the soil matrix, within which transport was much slower. It is conceivable that a large amount of the applied bromide was flushed out of the soil through tile drains, thus confounding the results of the tracer test. Bromide concentrations at the 0.9-m depth began to increase noticeably in late summer. This is unusual because it was a period of low precipitation, reduced soil moisture, falling groundwater levels, and high evapotranspiration rates. Perhaps bromide was concentrated in the pore water as water was extracted by plants (Kung, 1990; Zimmermann et al., 2002).

At the Maryland site, bromide was not detected below the upper 0.6 m of the unsaturated zone (Fig. 7). With the exception of one sample from the 0.6-m depth, concentrations of bromide from all suction lysimeters were equal to or less than detection limits. These results are consistent with those given in Fig. 3B, which shows most recharge occurring during the nongrowing season.

The deepest movement of bromide in the unsaturated zone occurred at the California site. Figure 7 shows that bromide concentrations peaked at the 0.9-m depth within 8 d after application, with the entire tracer mass being transported past this depth within about 2 mo. At the 4.6-m depth, the peak concentration of bromide was measured 134 d after application. At the 6.1-m depth, the peak was first detected 365 d after application (data not presented). Extrapolation of travel times of the peak concentration at the 4.6- and 6.1-m depths to the water table at a depth of 7.2 m would produce an estimated travel time similar to the 1.9 yr predicted by the piston-flow approach. This rapid transport of bromide is attributed to the high irrigation rate and the permeable sediments.

Travel times for the bromide tracer at the Washington site were nearly identical for the 1.2- and 1.8-m depths; peak con-

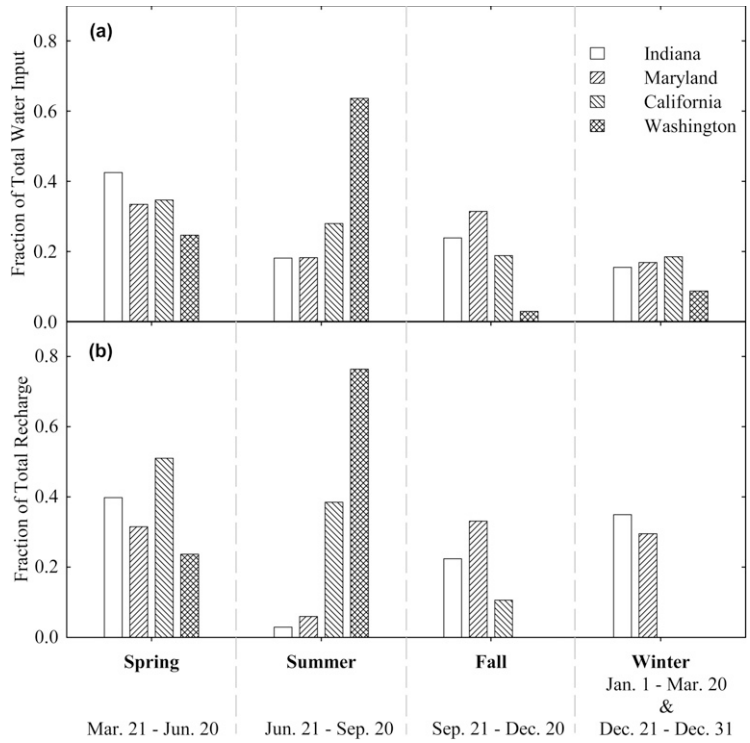

Fig. 5. Seasonal distribution of (a) total water input, and (b) total recharge for each study site.

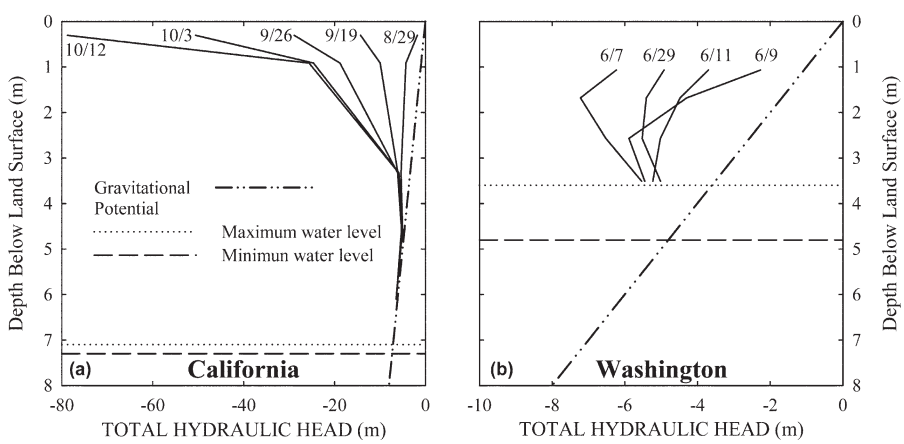

Fig. 6. Profiles of total hydraulic head with depth in the unsaturated zone for (a) the California study site during a period of no irrigation after the last growing season irrigation event in mid-August and (b) the Washington study site before irrigation (7 June 2004) and after the first irrigation event on 8 June 2004.

Table 4. Estimated residence times within the unsaturated zones of the four study sites using the piston-flow model.

Study site	Average volumetric moisture content	Average unsaturated zone residence time	Average unsaturated zone water velocity
	dimensionless	yr	cm d^{-1}
Indiana	0.34	0.8	0.4
Maryland	0.21	7.1	0.4
California	0.11	1.9	1.0
Washington	0.22	8.1	0.1

centrations were reached after 72 d. A rise in concentration at the 1.8-m depth just 1 d after application of the tracer was omitted from Fig. 7; it was assumed that this sample was contaminated in the field. The bromide concentration at the 2.7-m depth still appeared to be rising 100 d after application.

Tracking wetting fronts using moisture content reflectometry probes resulted in relatively fast velocity estimates for each study location (21.3, 22.1, 19.1, and 50.8 cm d^{-1} for the Indiana, Maryland, California, and Washington study locations, respectively); however, these estimated velocities are for depths less than 1.5 m. It is expected that velocities would decrease with depth within the unsaturated zone.

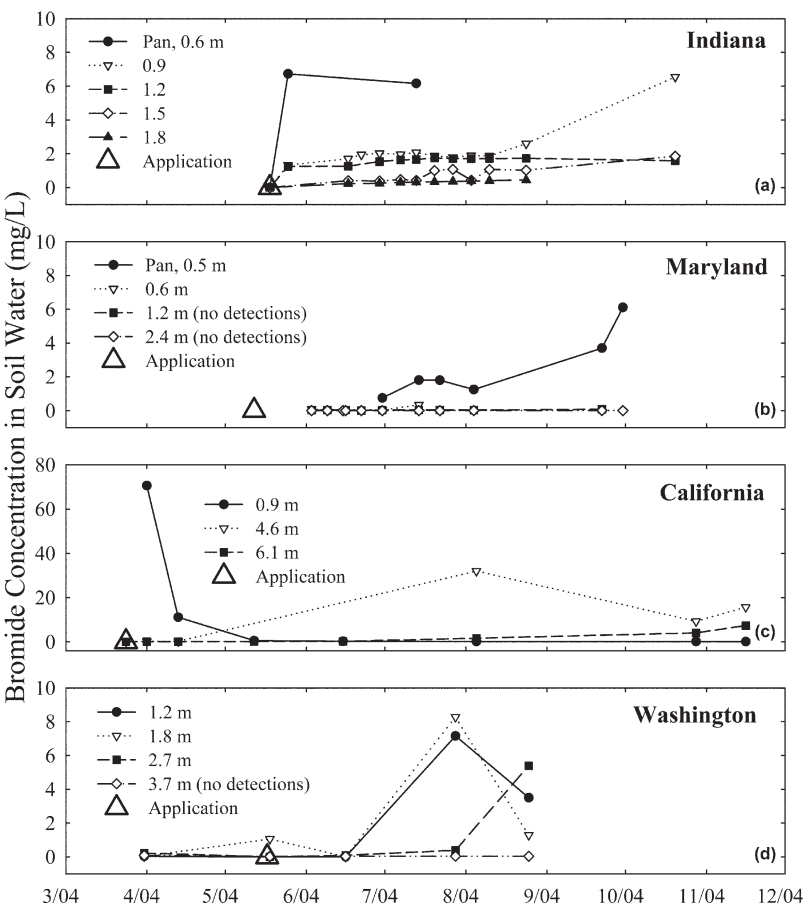

Fig. 7. Time series of the concentration of bromide at different depths in the unsaturated zone at the (a) Indiana, (b) Maryland, (c) California, and (d) Washington study sites.

Discussion

Precipitation patterns differed among study sites, but there were some similarities between the Indiana and Maryland sites and between the California and Washington sites. Annual precipitation totals (for 2004) for all sites were within 20% of long-term averages of nearby weather stations. Estimates of evapotranspiration agree well with regional estimates (Hancock and Brayton, 2006; USGS, 1990; University of California Cooperative Extension, 2005; U.S. Department of the Interior–Bureau of Reclamation, 2006). Evapotranspiration was about 65% of the water input at the Indiana and Maryland sites, 61% at the California site, and 90% at the Washington site. Recharge accounted for 51, 32, 29, and 13% of water input for Indiana, Maryland, California, and Washington sites, respectively. Recharge estimates are similar to estimates for kilometer-scale recharge areas based on groundwater age dates (Green et al., 2008). The annual change in soil-water storage at each site was negligible.

Irrigation amounts reported for the California and Washington sites were obtained from the almond grower and the local irrigation district, respectively. Those for the California site were considered relatively accurate in that the water was applied with a sprinkler, which was metered. Irrigation deliveries at the Washington site were from surface water channeled though open ditches and buried lines. The water poured over a weir box at a constant head maintained by the irrigation district. The amount of water delivered over the irrigation season was estimated from the head level at the weir box. This method of quantifying irrigation deliveries could have resulted in some error.

Residual terms (water input minus the sum of recharge and evapotranspiration and change in storage) for the water budget for 2004 are shown in Table 3. Imbedded in these residual terms is any surface runoff that may have occurred but was not measured and any precipitation that may have been intercepted by plants or plant debris that was not evaporated. Analysis of surface-water data from nearby streamgauging stations indicated that streamflow was dominated by tile drains at the Indiana site (Stone and Wilson, 2006) and by baseflow at the Maryland site (Hancock and Brayton, 2006). A small amount of runoff was seen at the bottom of the irrigated field at the Washington site. The residual terms for the Maryland site (about 5% of water input) and Washington site (about 3% of water input) are low. For the California site, the residual is less than 10% of water input. For the Indiana site, water outputs exceeded inputs by 14.2 to 17.2 cm, or 16 to 19% (depending on the evapotranspiration calculation method used). The water budget deficit likely indicates that some of the transpired water at this site originated in the saturated zone rather than in the unsaturated zone. The decrease in the water table during the growing season (Fig. 4C)

indicates that groundwater had an important role in the water budget for the Indiana agroecosystem.

Marked differences were observed between the timing of recharge at irrigated and nonirrigated sites. Water movement downward through the unsaturated zone occurred when precipitation or irrigation rates exceeded those of evapotranspiration for some period of time. For the nonirrigated study sites in the eastern USA, this period extended from the beginning of January into spring, and from late fall to the end of December. For the irrigated study sites in California and Washington, irrigation totals exceeded evapotranspiration during the 1- or 2-d periods in which irrigation occurred. These short periods, which occurred several times during the growing season, accounted for virtually the entire amount of recharge at these sites in 2004. Recharge in response to precipitation outside of the growing season was negligible at these sites. Monitoring of groundwater levels at the California and Washington sites did not begin until March of 2004. Although some recharge from precipitation could have occurred at these sites in January and February, the well hydrographs reveal a water-level minimum at the beginning of the record, indicating that no appreciable recharge had taken place before the start of water-level monitoring.

The bromide concentration data in Fig. 7 show that pore water typically travels at a wide range of velocities across a single profile and that the simplistic assumptions of the piston-flow model are not entirely valid. Percolating water does not move in discreet packets but rather mixes and exchanges with and displaces the resident unsaturated zone water. The percolating water also can move along preferential flow paths that facilitate rapid transport times. For all sites except Maryland, bromide-tracer test data based on leading edge of the pulse (Fig. 7) indicated more rapid transport than that indicated by piston-flow estimates (Table 4). This is not an inconsistency. The estimates in Table 4 assume no diffusion or mixing of unsaturated zone waters. Each piston-flow estimate represents an average velocity for all water in the soil profile at a site. Relatively quick movement indicated by early detection of bromide at several depths means that some fraction of water applied with or after the bromide tracer application traveled at a rate greater than the average rate. Likewise, the long tails behind the bromide concentration peaks at some locations (Fig. 7) indicate that some of that water traveled at slower rates.

At the Indiana site, preferential flow paths seemed to have an important role in bromide transport. Simulations made using the Root Zone Water Quality model resulted in a better fit with field data when the preferential flow path component of the model was used for that site (Randall E. Bayless, U.S. Geological Survey, written commununication, 2006). Stone and Wilson (2006) used chloride mixing analysis and hydrograph separation techniques to show that preferential flow at the Indiana site is an important transport pathway to the tile drains. Field observations of desiccation cracks also support the notion that preferential flow paths serve as an important transport mechanism at the site. Preferential flow paths were not directly observed at the other study sites; however, tracer-test data for California and Washington indicate that water moved within the unsaturated zone at velocities faster than the average piston-flow estimates for these study sites.

The Indiana site is the only one for which the data explicitly show that some bromide traveled from land surface to the water table within one growing season. At the California and Washington sites, bromide was detected within 1 to 1.5 m of the water table, so it is conceivable that some bromide may have reached the water table. The largest difference between the piston-flow estimate of residence time in the unsaturated zone (Table 4) and the results of the bromide tracer test (Fig. 7) appear at the Washington site, where the piston-flow numbers imply that water applied on land surface should move downward at a rate of about 0.1 cm d^{-1}. The bromide concentration peak moved past the 1.8-m depth in approximately 2.4 mo, which is a rate of 2.5 cm d^{-1}. These results could be explained by a large amount of immobile water in the unsaturated zone, with comparatively rapid transport through a small volume of highly conductive zones such as vertical clastic dikes. These results also could mean that the recharge rate has been underestimated.

Movement of bromide with unsaturated zone water was more rapid, and the measured pulses were more distinct, at the two irrigated sites (California and Washington) than at the nonirrigated sites (Fig. 7). This is attributed to large water inputs at the irrigated sites. Within 5 mo after application of the bromide, 100 cm of irrigation water had been applied at the California site, and 90 cm had been applied at the Washington site. In contrast to the velocities of up to 57 cm d^{-1} determined for the irrigated California study site, Green et al. (2005) found velocities of about 2 cm d^{-1} from a bromide tracer test conducted in a similar setting with no irrigation and about 30 cm of precipitation over 130 d.

It could well be asked if the results of a 1-yr study of the transport of water into and through the unsaturated zone at four agricultural sites are representative of longer-term conditions at those sites. Multiple-year studies are desirable for assessing the effects of annual climate variability on these processes. Because studies such as this are difficult and expensive to conduct, few multiple-year investigations appear in the literature. The original plan for this study called for 2 yr of continuous monitoring of water budget components. Problems with instrumentation and access to study fields resulted in 2004 being the only year in which nearly complete data sets were obtained for all sites.

Precipitation in 2004 was within 20% of historical annual totals at all sites. Evapotranspiration rates estimated for 2004 were similar to measured or estimated historical rates (within 5% for the Indiana and California sites, 10% for the Maryland site, and 20% for the Washington site). If irrigation practices and precipitation patterns are consistent from year to year at each site, then the patterns in the other water budget components observed for 2004 may also be relatively consistent over time. Irrigation practices are not likely to change substantially at the California site because the almond trees will occupy the field for several years. At the Washington site, crop types and associated agricultural management practices have undergone many changes in recent years. (In particular, many previously furrow-irrigated fields in the basin have been converted to sprinkler or drip irrigation.) Hence, the results from this site may not be as indicative of long-term trends as results from the other sites.

The soybean/corn crop rotation at the Indiana and Maryland sites is typical of agricultural practices in the eastern USA; crops and agricultural practices are not likely to change appreciably at these sites. Recharge and all other components of the water budget were much more dependent on precipitation patterns at these sites than at the California and Washington sites. Precipitation at the Maryland and Indiana sites for 2004 was less than average annual totals. As a consequence, the amount of recharge estimated for 2004 may be less than what would be expected in a year of average precipitation (although, in addition to the total amount of precipitation, the distribution, frequency, and intensity of precipitation during the year can affect recharge rates). Similar to findings of this study, two multiple-year water budget studies conducted in humid regions (Brye et al., 2000; Healy et al., 1989) found that although there was little water movement through the unsaturated zone during the growing season, heavy rainfalls in late spring could result in the movement of substantial amounts of water through the unsaturated zone. If such events occurred soon after chemicals were applied to a field, it is conceivable that those chemicals could be transported rapidly through the unsaturated zone. Brye et al. (2000) and Healy et al. (1989) also found that variability in water budget components was not substantial from year to year.

Results from this study indicate that the timing and patterns in precipitation and irrigation largely control the seasonal variability and overall rates of groundwater recharge. Other factors, such as soil properties, land-surface slope, depth to the water table, and agricultural practices have been noted as potential factors influencing recharge (Nolan et al., 2006). Indeed, the highly permeable sediments at the California site allowed irrigation water to rapidly transport the bromide tracer, and preferential flow paths and a shallow water table controlled by tile drains resulted in unexpectedly high recharge rates at the Indiana site. Yet the dominant nature of precipitation and irrigation showed that all other factors were of secondary importance in controlling recharge at these study sites in 2004.

Conclusions

Field data collected at four agricultural sites in different regions of the USA were used to calculate water budgets, estimate rates of groundwater recharge, determine times of water travel through the unsaturated zone, and identify factors that influence these phenomena.

Annual precipitation totals for the sites were within 20% of long-term averages of nearby weather stations. Evapotranspiration was about 65% of the water input at the Indiana and Maryland sites, 61% at the California site, and 90% at the Washington site, with estimated evapotranspiration rates within 20% of published estimates. Recharge accounted for 51, 32, 29, and 13% of the total water input for the Indiana, Maryland, California, and Washington sites, respectively. The annual change in soil-water storage at each site was negligible, and the overall closure of the water budget was considered to be acceptable.

Virtually all recharge at the irrigated sites (California and Washington) occurred in response to 1- or 2-d irrigation events, when the water input rate exceeded the rate of evapotranspiration. Recharge at the nonirrigated sites occurred primarily outside of the growing season. Even with the high-intensity application of irrigation water, the percentage of the total water input going to recharge is less for the irrigated sites than for the nonirrigated sites. This was because irrigation occurred during the growing season when the evapotranspiration rates were high, but a substantial fraction of the precipitation at the nonirrigated sites fell outside of the growing season when evapotranspiration was minimal.

Preferential flow paths seem to have had an important role in the movement of bromide in unsaturated zone water at the Indiana site. Evidence of preferential flow paths was not found at the other three study sites; however, bromide tracer-test data indicate that rapid transport of water through the unsaturated zone did occur at the California and Washington sites.

Average residence time of water in the unsaturated zone, calculated by use of a piston-flow model approach, ranged from less than 1 yr at the Indiana site to more than 8 yr at the Washington site. Results of bromide tracer tests indicate that at three of the four sites, a fraction of the water applied at land surface may have traveled through the unsaturated zone to the water table in less than 1 yr.

Acknowledgments

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