National, Holistic, Watershed-Scale Approach to Understand the Sources, Transport, and Fate of Agricultural Chemicals

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This paper is an introduction to the following series of papers that report on in-depth investigations that have been conducted at five agricultural study areas across the United States in order to gain insights into how environmental processes and agricultural practices interact to determine the transport and fate of agricultural chemicals in the environment. These are the first study areas in an ongoing national study. The study areas were selected, based on the combination of cropping patterns and hydrologic setting, as representative of nationally important agricultural settings to form a basis for extrapolation to unstudied areas. The holistic, watershed-scale study design that involves multiple environmental compartments and that employs both field observations and simulation modeling is presented. This paper introduces the overall study design and presents an overview of the hydrology of the five study areas.

Agricultural activities have resulted in widespread degradation of the quality of surface and ground waters. Crop production areas, pastures, rangeland, feedlots, and animal feeding operations have been listed as sources of contamination for 70% of the impaired river miles surveyed in the United States (USEPA, 2000). Of particular concern to human health and ecosystem function are elevated concentrations of nutrients (nitrogen and phosphorus) and pesticides and their degradates in surface and ground waters. Additional research is needed to evaluate the processes controlling the transport and fate of agricultural chemicals to determine the effects of agricultural practices on the quality of the nation's water resources.

The sources, transport, and fate of an agricultural chemical are controlled by the combination of agricultural activities, environmental setting, biological conditions, and chemical properties. The spatial scales relevant to the transport of these chemicals span many orders of magnitude, ranging from field plots to regional hydrologic systems. While considerable research has been conducted at the field scale, the understanding of processes at larger scales, that encompass multiple environmental compartments, is generally lacking.

A series of papers in this issue of *Journal of Environmental Quality* report the findings from a national effort that has adopted a holistic, mass-budget approach to studying the sources, transport, and fate of water and selected agricultural chemicals (Alvarez et al., 2008; Bayless et al., 2008; Domagalski et al., 2008; Duff et al., 2008; Essaid et al., 2008; Fisher and Healy, 2008; Green et al., 2008a, 2008b; Hancock et al., 2008; Puckett et al., 2008; Steele et al., 2008; Vogel et al., 2008; Webb et al., 2008). These papers focus on comparing and contrasting the environmental processes that control the behavior of water and agricultural chemicals within and between the various environmental compartments, such as the atmosphere, surface water, ground water, and the unsaturated zone.

This study made environmental observations and applied mathematical models at a range of scales from the field (<1 km^2) to large watersheds and aquifer systems (>10,000 km^2). Particular attention has been given to the small watershed scale (about 3–15 km^2) to collect the data necessary to calculate mass budgets. It is recognized that precise mass budgets for agricultural chemicals are probably not possible at this scale, but the approach provided a useful paradigm for the study's field and modeling designs. Results gained by using this approach can add to the knowledge of

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environmental transport and fate processes, and to the ability to extrapolate findings to unstudied areas and to different scales.

The overarching questions this study addresses are: (i) How do environmental processes and agricultural practices interact to affect the transport and fate of agricultural chemicals in the hydrologic systems of nationally important agricultural settings? and (ii) What are the effects on water quality and implications for management of water resources?

This study is part of the U.S. Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program, which assesses the quality of streams, ground water, and aquatic ecosystems in major river basins and aquifer systems across the nation (USGS, 2006). During its first decade (1991–2001), NAWQA scientists completed assessments in 51 study areas. This work provided baseline data and information on the occurrence of pesticides, nutrients, volatile organic compounds, trace elements, and radon in water, as well as on the condition of aquatic habitat and fish, insect, and algal communities. Each assessment followed a nationally consistent study design and methodology, thereby providing information about local water-quality conditions, as well as insight on where and when water quality varied regionally and nationally. During its second decade (2002–2012), NAWQA is reassessing 42 of the 51 study areas. These assessments will fill critical gaps in the characterization of water-quality conditions, determine temporal trends at many of the monitoring sites, and build on earlier assessments that link water-quality conditions and trends to natural and human factors, including the sources, transport, and fate of agricultural chemicals.

Selection of Study Locations

The design of this study integrates the collection and analysis of field data and the numerical modeling needed to evaluate the sources, transport, and fate of water and selected agricultural chemicals in a variety of nationally important agricultural settings. Agricultural settings are the superposition of hydrologic settings and agricultural systems, defined by crops and their associated agricultural management practices (such as chemical use, water management, soil manipulation, and harvesting). The hydrologic setting is the combination of surface and subsurface hydrologic systems, characterized by specific topography, geology, soils, and meteorology. The agricultural systems were defined by the classification of cropland devised by Gilliom and Thelin (1997) that suggests that regional agricultural patterns can be characterized by the distribution of crops. This classification scheme combined the general land-use information (USGS Land Use Land Cover data; Anderson et al., 1976) with county-level crop information from agricultural census data (U.S. Department of Commerce, 1995). Two classification schemes were developed, one for row crops and the other for orchards, vineyards, and nurseries. The classifications were based on combinations of one to three crops that accounted for >50% of the harvested area in each county. The classification schemes include 67 groupings for row crops and 45 groupings for orchards, vineyards, and nurseries.

The hydrologic settings were identified on the basis of the hydrologic landscapes concept (Winter, 2001). Wolock (2003) and Wolock et al. (2004) applied this concept to the lands of the United States through the use of geographical information system (GIS) tools and principal components and cluster analysis. The landscapes were grouped into 20 noncontiguous regions on the basis of similarities in land-surface form, topography, surface and subsurface texture, and climate characteristics.

Classification based on the superposition of the agricultural systems and hydrologic settings resulted in 655 unique agricultural settings. Of these settings, 131 had an area >1000 km^2 within the NAWQA study areas (USGS, 2006). Nationally, these 131 agricultural settings account for 81% of the agricultural land area, 81% of pesticide use, 74% of insecticide use, 87% of herbicide use, 79% of nitrogen use, and 80% of phosphorus use. The locations for the studies reported here were chosen from among the 131 agricultural settings with the intent that findings from these detailed studies will provide insight and a means to extrapolate to other areas with similar agricultural settings. Additional agricultural settings are currently being studied.

Description of the Study

Study Design

In this whole-system approach, five environmental compartments and the interfaces and pathways that connect these compartments (Fig. 1) were addressed by a combination of field observations and model simulations to provide information on the sources, transport, and fate of water and agricultural chemicals. These data were coupled with field-scale information on agricultural activities (crops, irrigation, drainage, management practices, and chemical use) and larger spatial information available from national data bases (soils, weather, chemical use, and cropping patterns) to provide information across the variety of scales addressed in this study.

After the general locations of the study areas were chosen as described above, study sites were selected across a range of scales. From a surface-water perspective, there are three scales of interest. The large watersheds integrate a variety of land uses (NAWQA integrator watersheds, on the order of 10^5 km^2). The intermediate-sized agricultural watersheds are nested within the integrator watershed and are characteristic of the agriculture of the region (NAWQA indicator watersheds, on the order of 10^4 km^2). The small watersheds are in turn nested within the intermediate-sized watersheds and are almost entirely in agriculture (on the order of 10^1 km^2). The multiple scales are necessary to help understand how the natural hydrologic setting and the superimposed agricultural system interact to affect the fate and transport of agricultural chemicals within the watersheds. NAWQA indicator watersheds were chosen because long-term records of flow and water quality already exist for these sites.

The studies in each of the areas included the same set of environmental compartments, but the study at each location was adapted to address the unique characteristics of the local setting (Table 1). The study design centered around nested surface-water subbasins, as described above. The selection of the small watershed for the most intensive study was based on a dominant land use, simplicity of the hydrologic system, cooperation of the growers/

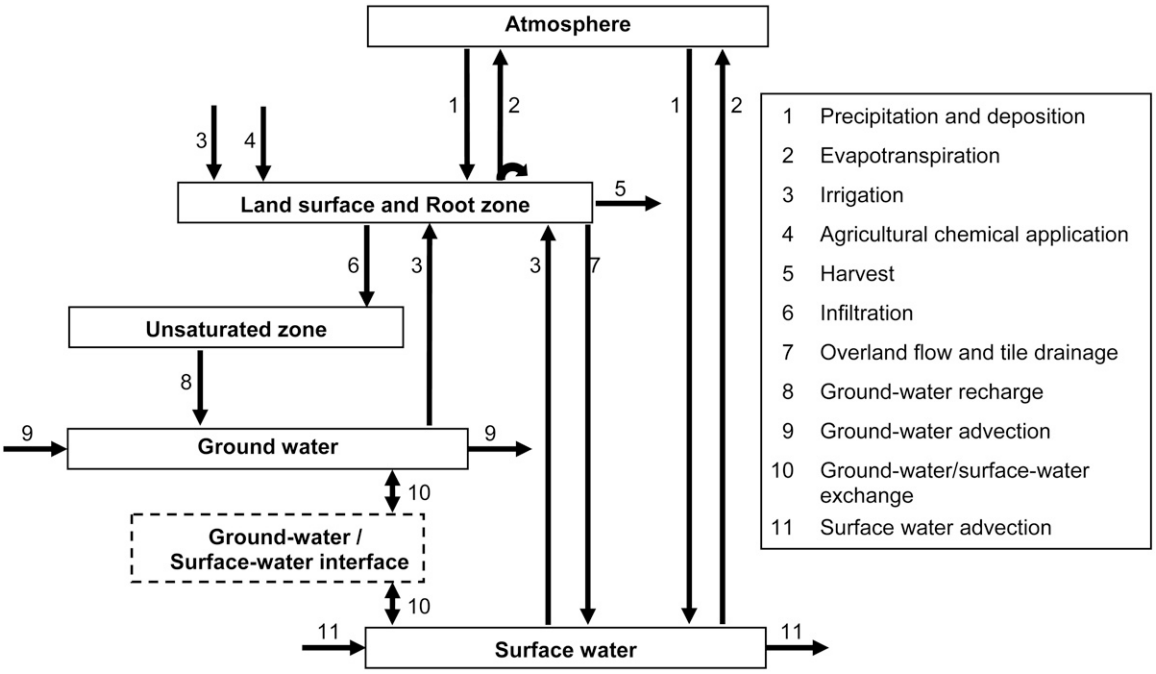


Fig. 1. Conceptual model of the environmental compartments and inter-compartmental pathways relevant to water and chemical transport.

landowners, and accessibility for field activities. Surface-water chemistry and discharge were monitored at the outlet from each of these nested subbasins. Within the small subbasin, one or more fields were chosen for intensive studies of the unsaturated zone, overland flow, and/or subsurface (tile) drain processes, if these compartments were locally important. In each study area, at least one of the unsaturated zone sites was instrumented with soil moisture instruments, a rain gage, and a weather station to calculate crop-specific evapotranspiration. Over a distance of 0.5 to 2.5 km, a series of well nests was installed along an approximate flow path in the shallow ground-water system and monitored for water level and water quality. Age-tracer data indicated that the water residence times within these flow systems were on the order of decades, and this information provided insights into water and chemical inputs to ground water over time. At least one well nest was co-located with an unsaturated zone site, and the most downgradient nest was located in the stream riparian zone. Near the most downgradient nest, a three-dimensional array of piezometers within the riparian zone and streambed was installed to monitor ground-water level, surface-water stage, and water chemistry to quantify interactions between ground water and surface water. Shallow wells located throughout each study area were monitored for ground-water level and water quality to provide a context for the more detailed ground-water and ground-water/surface-water interaction studies. Figure 2 shows this study design for one of the locations. Similar figures are shown for the other study locations in the supplemental material section of this paper (Capel et al., 2008).

Environmental Observations

Both discrete and continuous measurements were made within each of the environmental compartments, depending on data needs and available technologies. Discrete observa-

Table 1. Environmental compartments included at each location.

Compartment	Maryland	Indiana	Nebraska	California	Washington
Atmosphere					
Weather	weather station	weather station	weather station	weather station	weather station
Chemicals	rain sampler	rain sampler	rain sampler	rain sampler	air sampler§
Surface water					
Large scale	–‡	White River	Elkhorn River	San Joaquin River	Yakima River
Intermediate scale	–	Sugar Creek	Maple Creek	Merced River	Granger Drain
Small scale	Morgan Creek	Leary Weber Ditch	Unnamed tributary	Mustang Creek	DR2
Overland flow site	No	Yes	No	No	Yes
Tile drain site	No	Yes	No	No	No
Unsaturated zone sites	Yes	Yes	Yes	Yes	Yes
GW areal wells†	Yes	Yes	Yes	Yes	Yes
GW flow system	Yes	No	Yes	Yes	Yes

† GW: Ground water.

‡ –: Not applicable.

§ Since rain is infrequent during the growing season, the rain was not collected for chemical analysis.

tions included obtaining samples and performing chemical or physical analyses of water, soil, sediment, aquifer material, and suspended solids. Continuous observations included water-quality parameters (pH, dissolved oxygen, temperature, specific conductance), hydrologic parameters (surface-water discharge, ground-water level, and soil moisture and matric potential), and standard meteorological parameters. The details of both the discrete and continuous measurements are presented in the supplemental material section of this paper (Capel et al., 2008).

The discrete samples were analyzed for a wide variety of constituents that served as indicators of agricultural contamination and, more importantly, as tracers of environmental and hydrologic processes. Comparing and contrasting the spatial and temporal variability in concentration and fluxes, both within and between the various study areas, was beneficial in illuminating these processes and putting their relative importance in a broad context. The same general suite of constituents was quantified in every sample. Field parameters (pH, dissolved oxygen, specific conductance,

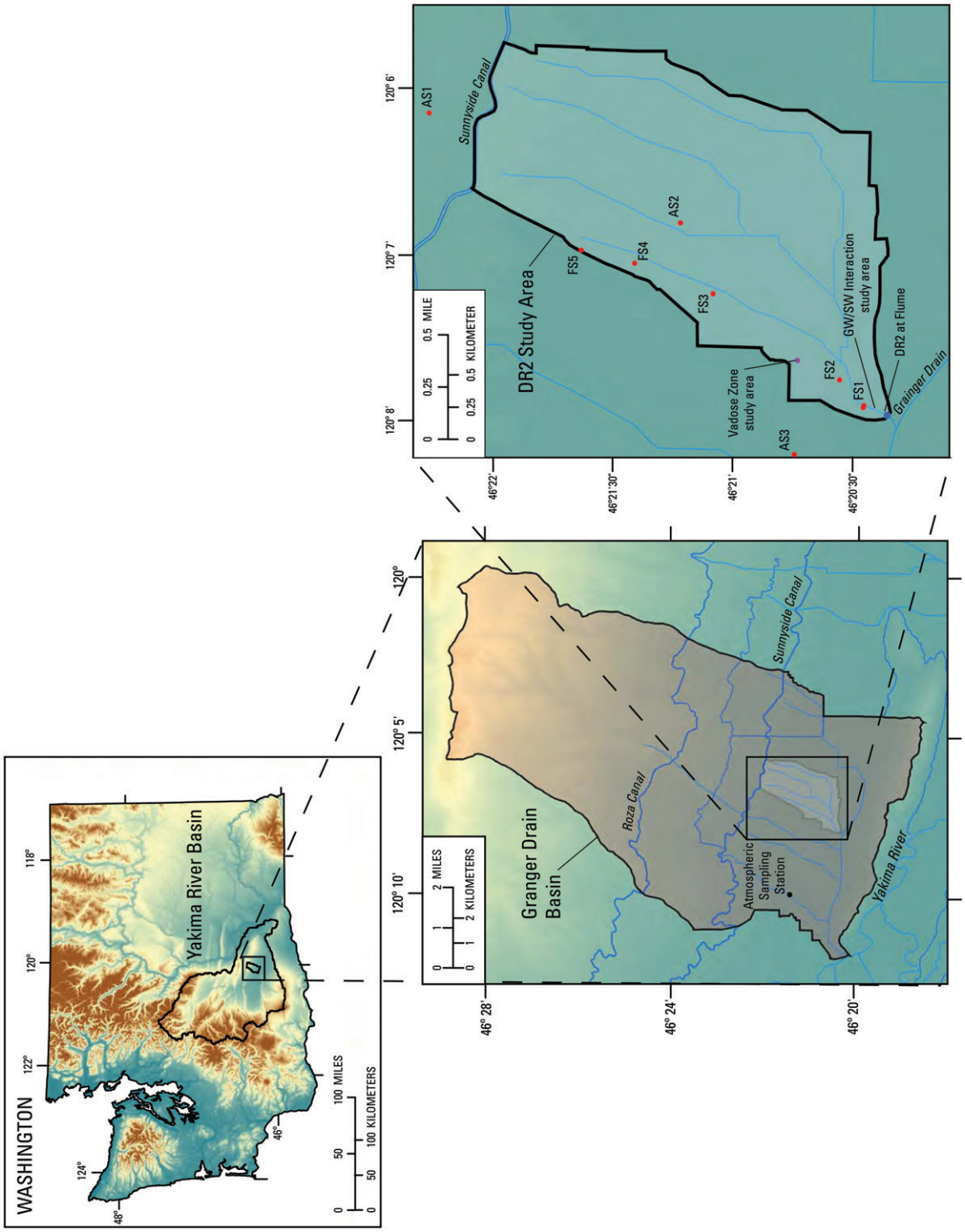


Fig. 2. Study design applied to the Washington location. The Yakima River, Granger Drain, and DR2 are the nested watersheds at three scales. The red circles show the location of each well nest. Those designated as "FS" are part of the flow system study. This flow system terminates at the GW/SW interaction study area near the DR2 surface-water gage. The wells designated as "AS" are part of the well network to characterize the local ground water. The unsaturated zone study area includes lysimeters and soil moisture instruments at various depths, a weather station, and a water-table well. There were no tile drain or rain sampling components to this study, since neither of these are important factors in this environment.

temperature, and alkalinity) were measured as each sample was being collected, and the samples were later analyzed for major ions, nutrients (nitrogen and phosphorous species), selected pesticides and degradates (mostly triazine and acetanilide herbicides and organophosphorous insecticides), and dissolved organic carbon. In addition, the surface-water and overland flow samples were analyzed for suspended sediment, and particulate carbon and nitrogen. Subsurface water samples (ground water and hyporheic zone) were analyzed for chemical markers (tritium, chlorofluorocarbons, sulfur hexafluoride, or a combination of the three) that were then used to estimate the age of the water (time since the water entered the subsurface). Solid samples (sediment and soil) were analyzed for particle size distribution, organic matter (loss on ignition), and bulk density. Unsaturated zone sediment samples were also analyzed for water content, nitrate, and chloride. Samples, representative of the important subsurface layers, were analyzed for mineralogy, redox-sensitive minerals, selected pesticides and degradates, and organic carbon and nitrogen. In a few cases, water or solids were analyzed for isotopes of sulfur, nitrogen, oxygen, hydrogen, or a combination of the four, to better understand the system. The same sample collection and processing protocols and analytical laboratories were used for all five study areas to allow for direct comparisons. The details of sample collection and processing and lists of the target analyses are presented in the supplemental material section of this paper (Capel et al., 2008).

Modeled Observations

Although environmental observations provide the foundation for understanding the behavior of water and agricultural chemicals in these studies, there are practical spatial and temporal limitations to the extent of field observations. Mathematical simulation models were used to supplement and extend field observations in cases where it was not feasible to make direct field observations. These models were used to aid interpretation and extrapolation of the field observations and to make predictions for unstudied areas. For these studies, the goals of modeling were to (i) provide information for the mass budgets, (ii) examine processes that could be responsible for agricultural chemical transport, (iii) examine how geographic location, climate, hydrogeology, and farming practices affect the flow of water through a watershed, (iv) predict the fate of agricultural chemicals that are not well characterized or measured at the study sites, and (v) evaluate the performance of other models.

Two watershed models were selected to simulate the hydrologic and chemical processes occurring in each watershed. The U.S. Department of Agriculture (USDA) Soil and Water Assessment Tool (SWAT, version SWAT2000; Neitsch et al., 2002) was chosen because of its widespread use in the agricultural research community. The Water, Energy, and Biogeochemical MODel (WEBMOD, based on theory found in TOPMODEL; Webb et al., 2006) was selected because it is based on hydrologic processes.

For ground-water simulations, the USGS model, MODFLOW (McDonald and Harbaugh, 1988), was chosen. MODFLOW models were applied with the MODPATH program to estimate ground-water sources and flow paths (Pollack, 1994).

Two unsaturated zone models were chosen for different purposes. The USDA Root Zone Water Quality Model (RZWQM; Ahuja et al., 2000) was selected for process-based modeling at the intensively studied unsaturated zone sites. RZWQM contains particular features desirable to this study, such as fully integrated macropore flow and extensive farming-simulation modules. For watershed-wide simulations of water and chemical transport through the unsaturated zone, the Leaching Estimation and Chemistry Model/CALculation Flow (LEACHM/CALF; Wagenet and Hutson, 1986; Hutson and Wagenet, 1992) model was selected. These models were chosen following side-by-side comparisons with other transport codes (Nolan et al., 2005).

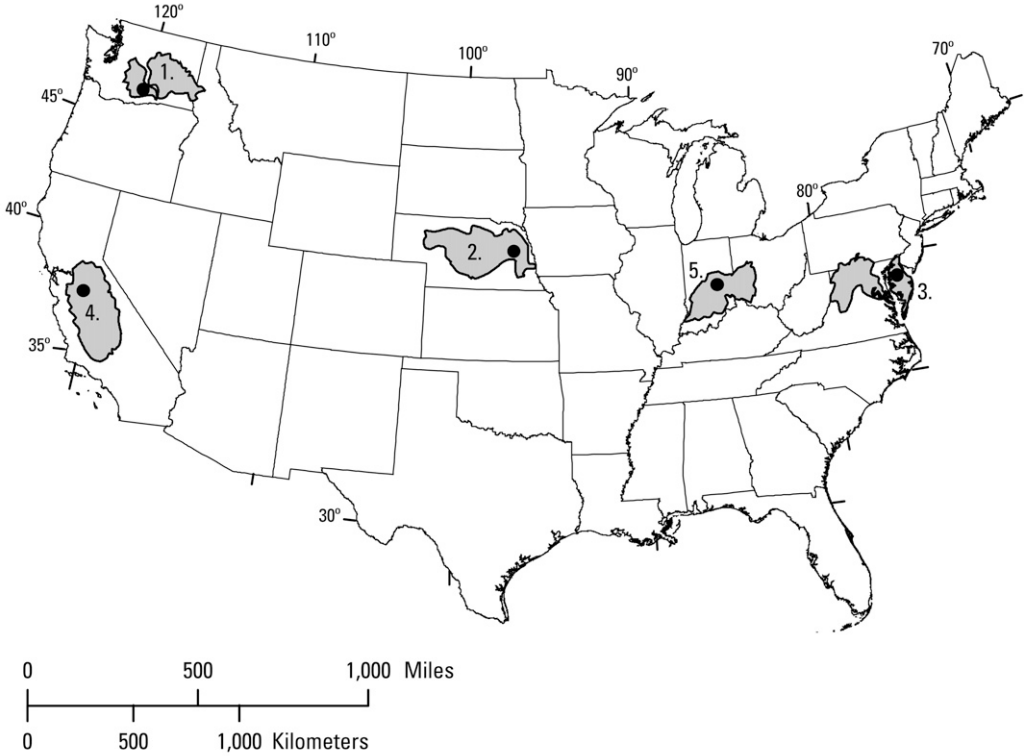
The flux of water between ground water and streams was estimated by modeling one-dimensional vertical flow of water and heat through the streambed (Constantz and Stonestrom, 2003). Evapotranspiration was estimated using the Penman–Monteith method (Allen et al., 1998), the Priestly-Taylor method (Priestly and Taylor, 1972), the Kimberly-Penman method (Wright, 1982), the Hargreaves method (Hargreaves and Samani, 1982), or a combination of the Penman–Monteith method and a modified version of the Penman method (Pruitt and Doorenbos, 1977) depending on the location and data availability. Annual loads carried by surface water were estimated from measured constituent concentrations and stream discharge data by either (i) a rating-curve method that regresses seasonal stream discharge against measured constituent concentrations (LOADEST2, Cohn et al., 1989; Crawford, 1991), (ii) summing loads calculated for individual storms, or (iii) interpolation of the concentrations on days in which samples were not obtained. Finally, end-member mixing analysis was used to help determine the sources of water and chemicals in different environmental compartments.

Study Locations

Site Descriptions

Five locations, representing five different agricultural settings, are reported in this issue of the *Journal of Environmental Quality* (Fig. 3). These five locations form two natural groups to compare and contrast. Farms in the three easternmost locations (Maryland, Indiana, and Nebraska) grow mostly corn and soybeans, and natural rainfall is the principal source of water to the watersheds (Table 2). In the two western locations (California and Washington), a mixture of orchards, vineyards, and row crops is grown with water that comes almost entirely from irrigation.

In any environmental setting, a number of land-surface, subsurface, and climatic characteristics influence the behavior and transport of water and chemicals. For agricultural areas, these characteristics include watershed area, soil properties, crop types, irrigation practices, drainage enhancements, streamflow characteristics, and whether the local subsurface flow system exchanges water with the deeper, regional ground-water system. These characteristics vary considerably among the five study areas, which provided an opportunity to compare and contrast these diverse settings. More detailed summaries of these five areas can be found in the supplemental material section of this paper (Capel et al., 2008). Full descriptions of the environmental and agricultural settings can be found in



EXPLANATION

- Study basin location

1. Central Columbia Plateau (CCYK) - Granger Drain Study Basin
2. Central Nebraska Basins (CNBR) - Maple Creek Study Basin
3. Potomac River Basin and Delmarva Peninsula (PODL) - Morgan Creek Study Basin
4. San Joaquin-Tulare Basins (SANJ) - Merced River Study Basin
5. White, Great and Little Miami River Basins (WHMI) - Sugar Creek Study Basin

Fig. 3. Study area locations.

papers by Payne et al. (2006 for WA), Gronberg and Kratzer (2006 for CA), Fredrick et al. (2006 for NE), Lathrop (2006 for IN), and Hancock and Brayton (2006 for MD).

Comparison of the Hydrology and Water Budgets of the Five Small Watersheds

Comparison of the 2004 water budgets for each of the five small watersheds (Table 3) illustrates the substantial differences in hydrology that characterize these basins. The most straightforward component of the hydrologic budgets (Table 3) for each small watershed was annual streamflow, which was calculated from data collected at USGS gaging stations at the subbasin outlet over the course of the current study (Fig. 4). The data necessary to quantify the other components of the water budgets, compiled from a variety of sources, differed by study area and are summarized below. As can be seen from Table 3, the relative importance of each water-budget component varies substantially among the five small-scale watersheds.

Washington

The DR2 subbasin is heavily irrigated with surface water delivered via canals from outside the drainage area. The volume of this imported irrigation water is considerably greater than natural precipitation within the subbasin, and is an important part of the water budget. Another important part of the overall water budget for this subbasin is ground-water inflow. The considerable net inflow of ground water results from the fact that the areal boundaries of the underlying ground-water flow system do not coincide with those of the surface-water flow system on which the water budget is based. This discrepancy in boundaries is a result of the engineered irrigation-delivery system, which does not necessarily follow natural topography and has thus altered the surface basin

Table 2. Environmental and agricultural characteristics of the five study areas.

	Maryland	Indiana	Nebraska	California	Washington
Intermediate stream	—	Sugar Creek	Maple Creek	Lower Merced River	Granger Drain
Subbasin area (km^2)		240	955	831	160
Mean annual discharge (m^3/s)		2.9	2.27	19.4	34.4
Percent agriculture (%)		75	95	55	52
Small stream	Morgan Creek	Leary-Weber Ditch	Un-named	Mustang Creek	DR2
Subbasin area (km^2)	31	7.2	1.5	17.5	5.5
Mean annual discharge (m^3/s)	0.31, Continuous	0.9, Intermittent	~0.001, Intermittent	~0.01, Intermittent	4.93, Continuous
Percent agricultural (%)	74	97	97	90	89
Primary crops†	Corn, soybeans, small grain (60%) Pasture, hay (13%) Nursery, orchard (1.5%) Animal operations (0.3%)	Corn (50%) Soybeans (50%)	Corn (50%) Soybeans (50%)	Almonds (45%) Vineyards (12%) Corn, grain (16%)	Corn, grain (42%) Grapes, juice (17%) Pasture (11%)
Average annual precipitation (cm)	112	100	72.3	33	17.6
Irrigation source	Intrabasin ground water	None	Deep ground water	Deep ground water and interbasin canal	Interbasin canal
Irrigated agriculture (%)	10	0	30	>95	>95
irrigation method	Center pivot	None	Center pivot	Sprinkler, drip	Rill, sprinkler, drip
Soil permeability	Moderate	Moderate to low	Low	High to moderate	Moderate to low
Artificially enhanced soil drainage?	No	Yes	No	No	Yes
Local ground-water system connection to regional ground-water system	Intermediate:— Small: Yes	Intermediate: In some locations Small: Yes	Intermediate: Yes Small: No	Intermediate: Yes Small: No	Intermediate: Yes Small: Yes

† Percentages are based on total agricultural land in the intermediate subbasin, except for Maryland.

boundaries. Shallow subsurface flow in this area has been modified by an extensive system of buried drains. This drainage system has a strong influence on the shallow ground-water system and its contribution to surface water. However, much of the system has been in place for many decades and its location, extent, and design are not well known. Crops in the subbasin are diverse. In most of the area, crops and agricultural management practices differ both from field to field and from year to year. While agricultural systems in general cannot be assumed to be at steady state with respect to water and chemical transport, this is especially true for areas of diverse crop types and management practices that change from year to year. To complete the hydrological mass balance, precipitation data and daily crop-specific evapotranspiration data were obtained from a weather station at Harrah, WA, approximately 35 km from the small watershed (Bureau of Reclamation, 2006). These evapotranspiration data were coupled with field-scale crop data obtained from land-use surveys to estimate total subbasin evapotranspiration. The quantities of ground water flowing into and out of the subbasin were estimated from MODFLOW simulations. Irrigation and canal-leakage data were obtained from the local irrigation district (Sunnyside Valley Irrigation District, Sunnyside, WA, unpublished data, 2004).

California

This study area is irrigated with ground water delivered via sprinklers or micro sprinklers. The minimum volume of this irrigation water needed for crops is used and soils are coarsely textured, so there is little surface runoff to Mustang Creek. A layer of hardpan approximately 1 m below the land surface extends through much of the Upper Mustang Creek subbasin, impeding the vertical movement of water and profoundly affecting the water cycle. The water table is greater than 50 m below land surface and is disconnected from the surface system, except for irrigation pumpage. Mustang Creek flows only in response to large rainfall events that typically occur during the winter. Data from a weather station at Denair, CA, approximately 13 km from the small watershed, were used to calculate annual precipitation (California Department of Water Resources, 2006). Information on the quantity of irrigation applied was obtained directly from land managers. Ground-water flow was simulated using MODFLOW. Evapotranspiration was estimated with SWAT using the Hargreaves method.

Nebraska

In the Nebraska small watershed, a relatively impermeable layer in the shallow subsurface effectively separates the local subsurface ground water from deeper, regional ground water. Precipitation that infiltrates the surface soil flows laterally to the stream in a shallow, transient flow system. Overland flow resulting from precipitation has a quick and strong influence on streamflow resulting in flashy discharge and providing a direct,

Table 3. Annual contributions in centimeters of water per year for the six major components of the water budget for the five small study basins for water year 2004.

Components (cm of water)	Maryland	Indiana	Nebraska	California	Washington
Basin inputs					
Precipitation	116	87	73	17	14
Ground water flow†	–2	1	–	–	48
Interbasin irrigation	–	–	3	115	93
Canal leakage	–	–	–	–	8
Basin outputs					
Evapotranspiration	78	54	72	128	86
Stream discharge	36	34	4	4	76

† Total water entering the basin as ground water minus total water leaving the basin as ground water.

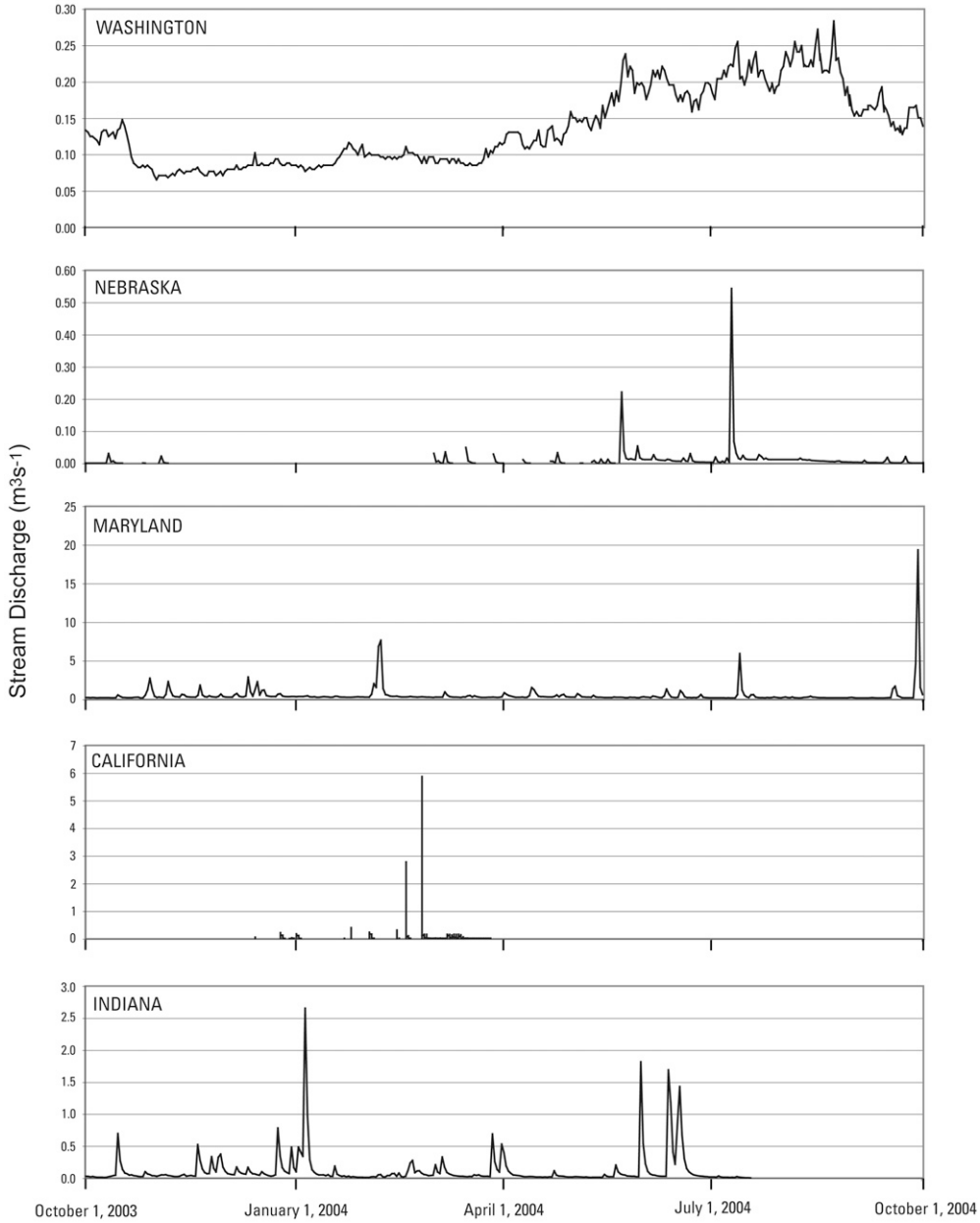


Fig. 4. Annual hydrology of the outlets of the five focus subbasins.

relatively rapid transport pathway for chemicals. Precipitation data were obtained from a weather station at Columbus, NE, approximately 15 km from the small watershed (National Climatic Data Center, 2006). Net ground-water flow to the subbasin was estimated with the SWAT watershed model. The amount of interbasin irrigation water applied was estimated on the basis of land-manager surveys. Evapotranspiration was estimated with SWAT, using the Penman–Monteith method. Output from SWAT simulations also were used to fill data gaps in the streamflow record resulting from equipment malfunction.

Indiana

Leary Weber Ditch is underlain by an extensive system of subsurface (tile) drains, which efficiently transports water to the stream. This routing bypasses much of the natural subsurface flow system. As a result, the artificial drainage system has a large influence on the magnitude and timing of flow in the receiving stream (Stone and Wilson, 2006). By altering residence time in the subsurface, these drains also affect the quality of water entering the stream. The surficial glacial deposits in this area create substantial heterogeneity in shallow subsurface flow conditions. Heterogeneity imposed by clay stringers embedded in the glacial till greatly influences ground-water flow at the subbasin scale, but this could not be adequately characterized with this level of data collection. The scale of the heterogeneity is such that it is most apparent at the intermediate scale (on the order of 10^4 km^2) of ground-water flow. Annual precipitation was calculated from data collected at an onsite weather station. Evapotranspiration was estimated with the Priestly-Taylor equation, using air tem-

perature and radiation data collected at the weather station. The contribution of ground water to the annual budget was estimated as the difference between subbasin inflow (precipitation) and outflows (streamflow and evapotranspiration).

Maryland

Grassed waterways that direct overland runoff, and small sediment retention ponds are common on many farms in the Morgan Creek study area. These ponds have a large influence on hydrology and chemical transport by altering evaporation, attenuating streamflow response to precipitation, and promoting focused ground-water recharge. The shallow aquifer under the Morgan Creek subbasin exchanges water with the deeper regional system, but below the Morgan Creek streambed a 2-m-thick layer of low-hydraulic-conductivity sediment impedes direct flow between the stream and the aquifer. Instead, ground water discharges to seeps along the margins of the floodplain, and this water flows overland to the stream. Consequently, the seepage faces contribute significant quantities of water and dissolved chemicals to the stream. Annual precipitation in the small watershed was estimated from the mean annual precipitation for the period 1975 to 2004 measured at a weather station at Chestertown, MD, approximately 8 km from the small watershed (National Climatic Data Center, 2006). Ground-water flow was simulated using MODFLOW. Evapotranspiration was estimated by subtracting subbasin outflows (surface water and ground water) from precipitation.

Similarities and Differences among the Watersheds

The general differences in the five small watersheds are illustrated by comparing and contrasting an annual water budget (Table 3). Precipitation is the major source of water for the Nebraska, Maryland, and Indiana study areas, whereas irrigation water imported from outside the subbasin is the most important source of water for the Washington and California study areas. The Washington study area is the only one of the five for which a net ground-water contribution (total water entering the basin as ground water minus total water leaving the basin as ground water) to the budget is significant. As is typical for agricultural settings, evapotranspiration is an important outflow component in all five subbasins. In contrast, the importance of stream discharge to the overall water budget varies considerably among the study areas. Because of the large volume of imported irrigation water and the substantial year-round contribution of ground water to the water budget, the Washington subbasin has the greatest annual streamflow yield. Conversely, stream yield in the Nebraska and California subbasins, which are effectively disconnected from the regional ground-water system, is a considerably smaller component of the overall water budget.

Hydrographs of subbasin outflow (Fig. 4) provide further insights into the hydrologic similarities and differences of the five small subbasins. These hydrographs show that physical subbasin characteristics and climate result in considerable differences in the magnitude of peak flows, the relative differences between base flow and peak flow, and the annual distribution of stream discharge. Peak flows range from <0.5 m^3s^{-1} at the Washington site to nearly 20 m^3s^{-1} at the Maryland site. The relative difference between stream discharge during typical base-flow conditions and during peak-flow events provides insight and corroborates information gained from the annual water budget. At the Maryland site, base flow and peak flow differed by more than two orders of magnitude. In contrast, base flow and peak flow differed by only a factor of about three at the Washington site, reflecting the significant contribution of ground water, flowing in from beyond the surface-water subbasin boundary, to the annual water budget. Stream flow at the Nebraska and California small stream sites periodically ceases altogether, reflecting the ability of relatively impermeable layers in the shallow subsurface to effectively disconnect these subbasins from deeper ground water. To account for these differences in the hydrograph, all stream sampling at the Washington subbasin was conducted at regular, predetermined intervals, whereas at the other four subbasins, stream sampling consisted of a mix of regular interval sampling and event-driven sampling aimed at capturing water-quality characteristics during abrupt changes in the hydrograph.

Challenges and Insights for the Whole-System Approach

The whole-system approach described herein and in the following series of papers poses unique challenges due to the dissimilar scales of space and time that are relevant in the various environmental compartments. For example, transport of water through a stream reach generally occurs within hours, whereas the transport of ground water over the same distance may take decades. Similarly, significant chemical gradients may occur over a distance of centimeters in the unsaturated zone and at the ground-water/surface-water interface, but span tens of meters or more in ground water. The challenges posed by the scales of space and time relevant to different environmental compartments were considered carefully during the study design. The papers in this series demonstrate how these challenges were addressed to provide both an understanding of the individual compartments, as well as the environmental system as a whole.

In addition to the general challenge posed by the broad range of relevant space and time scales, these multiple-compartment studies in agricultural settings were faced with logistical challenges such as physical access limitations in cropped areas and land-owner concerns. At times, such logistical issues precluded data collection at some key locations and study designs had to be adjusted accordingly.

Although regional- or subregional-scale ground-water flow models had been developed for several of the study areas in previous investigations, the scale of the small watersheds (on the order of 10^1 km^2) posed unique challenges. For example, a high degree of uncertainty in conditions within the top few meters of the ground-water flow system is typical for regional-scale modeling, but is generally not a concern at that scale. In contrast, accurate characterization of flow in the topmost layer of the ground-water system was critical to understanding flow and transport at these smaller scales, where connectivity with the surface-water flow system is key. Adequate characterization of the ground-water flow system at the small watershed scale

required both areally distributed data to characterize the overall subbasin flow system, as well as fine-scale horizontal and vertical data to characterize the connectivity of ground water to the unsaturated zone and to the surface-water system.

A better understanding of the environmental processes that govern the sources, transport, and fate of water and agricultural chemicals provides important tools to overcome the temporal and spatial limitations inherent in field studies. These advances in understanding such processes also have the potential for improving mathematical simulations of the environment. The following series of papers report the improved understanding of the processes that were identified as important for each of the agricultural settings.

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