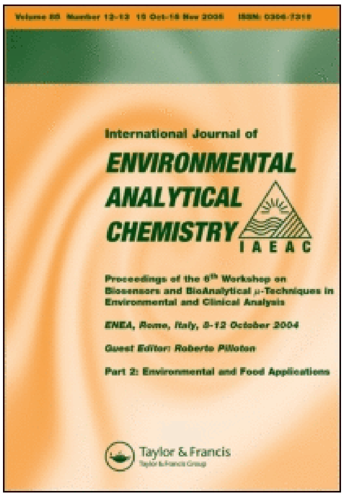

International Journal of Environmental Analytical Chemistry
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713640455

Use of a watershed model to characterize the fate and transport of fluometuron, a soil-applied cotton herbicide, in surface water

Richard H. Coupe[a]
[a] US Geological Survey, Jackson, MS 39208, USA

Online publication date: 18 November 2010

To cite this Article Coupe, Richard H.(2007) 'Use of a watershed model to characterize the fate and transport of fluometuron, a soil-applied cotton herbicide, in surface water', International Journal of Environmental Analytical Chemistry, 87: 13, 883 — 896

To link to this Article: DOI: 10.1080/03067310701627819

URL: http://dx.doi.org/10.1080/03067310701627819

Intern. J. Environ. Anal. Chem.
Vol. 87, Nos. 13–14, 15 November–10 December 2007, 883–896

Taylor & Francis
Taylor & Francis Group

Use of a watershed model to characterize the fate and transport of fluometuron, a soil-applied cotton herbicide, in surface water

RICHARD H. COUPE*

US Geological Survey, 308 South Airport RoadJackson, MS 39208, USA

(*Received 12 January 2007; in final form 5 August 2007*)

The Soil and Water Assessment Tool (SWAT) was used to characterize the fate and transport of fluometuron (a herbicide used on cotton) in the Bogue Phalia Basin in northwestern Mississippi, USA. SWAT is a basin-scale watershed model, able to simulate hydrological, chemical, and sediment transport processes. After adjustments to a few parameters (specifically the SURLAG variable, the runoff curve number, Manning's *N* for overland flow, soil available water capacity, and the base-flow alpha factor) the SWAT model fit the observed streamflow well (the Coefficient of Efficiency and R^2 were greater than 60). The results from comparing observed fluometuron concentrations with simulated concentrations were reasonable. The simulated concentrations (which were daily averages) followed the pattern of observed concentrations (instantaneous values) closely, but could be off in magnitude at times. Further calibration might have improved the fit, but given the uncertainties in the input data, it was not clear that any improvement would be due to a better understanding of the input variables.

Keywords: SWAT; Bogue Phalia; Fluometuron; Mississippi; Cotton

1. Introduction

Agriculture has been identified as one of the major contributors to the degradation of surface waters in the United States [1]. However, it is clear that the production of food and fibre must continue and that methods and procedures must be identified and implemented to ameliorate the effects of agriculture on water quality. Additionally, agriculture must remain economically viable for the continued health and safety of our Nation's citizens and, ultimately, the world community at large.

Modern agriculture is a complex business that is constantly changing due to economic pressures, changing technology, and market forces. There is an axiom in economics called the 'Law of Unintended Consequences', [2] which is defined as 'situations where an action results in an outcome that is not (or not only) what is intended. The unintended results may be foreseen or unforeseen, but they should be the logical or likely results of the action'. The same axiom can be applied to agriculture.

*Fax: +1-601-933-2901. Email: rhcoupe@usgs.gov

International Journal of Environmental and Analytical Chemistry
ISSN 0306-7319 print/ISSN 1029-0397 online
DOI: 10.1080/03067310701627819

For example, producers in the Midwest USA were encouraged to add subsurface drainage to improve yields in fields with high water tables because, without subsurface drainage, they could develop nitrogen deficiencies due to denitrification [3]. Installing subsurface drainage did improve yields, reduce runoff, peak outflow rates, and sediment losses; however, while decreasing losses of some agricultural chemicals, it increased the losses of others [4]. The unintended consequence was that nitrate was routed directly into the streams without having the opportunity to be denitrified [5] in the soil. The large amount of nitrate being discharged from the Mississippi River has been linked to expanding areas of low dissolved-oxygen in the Gulf of Mexico [6]. Another example is the use of conservation tillage as a mechanism to reduce sediment erosion. The unintended consequence here was that although conservation tillage decreased sediment erosion, the large amount of organic matter left on fields in conservation tillage intercepted a significant amount of applied herbicides. Hence, the herbicide application rate had to be increased; in some cases, this has led to increased herbicide movement offsite into surface waters [7].

The ability to predict the effects of management changes to agriculture on the water quality of a watershed is imperative to balance the economic needs of the producer with environmental concerns. Although extensive research has been done to describe the effect of changing management practices on plot- and field-scale areas, less is known about how land-use changes are reflected at the watershed scale. Watershed models are valuable tools for examining the effect of land use on hydrology and water quality. However, for a model to be of practical use, it needs to be robust, be easy to use, and have readily available input datasets.

One model developed for the purpose of evaluating the effects of land-use practices on water quality at the watershed scale is called the Soil and Water Assessment Tool (SWAT). SWAT has been used successfully by many investigators throughout the world to simulate streamflow, sediment, and nutrient loadings [8, 9]; a more complete list is available online at http://www.brc.tamus.edu/swat/index.html. However, there has been little work to assess the ability of SWAT to simulate the movement of pesticides and no assessment conducted in the hot and humid southeastern United States. The authors of SWAT [10] concluded that SWAT could realistically predict the movement and transport of pesticides in a midwestern basin. Isoxaflutole, a soil-applied corn herbicide, and a degradate of isoxaflutole were successfully compared with observed concentration data in four midwestern reservoirs [11].

One of the greatest impediments to the evaluation of SWAT's ability to simulate pesticide movement is probably the lack of data collected frequently enough to define the pesticide concentrations. The US Geological Survey (USGS) National Water Quality Assessment Program (NAWQA) has done so at a few locations across the county. The authors of SWAT used NAWQA data from Indiana to evaluate SWAT's ability to predict offsite pesticide movement [10]. The NAWQA Program, collected weekly to biweekly water samples from the gauging station at the outlet of the Bogue Phalia in 1996 and 1997. These samples were analysed for nutrients, suspended sediment, and selected pesticides [12].

There are four herbicides that were possible candidates for modelling from these data: atrazine, cyanazine, fluometuron, and metolachlor. Each had greater than 75% of their values above the detection level and were used extensively throughout the Bogue Phalia Basin during this time period. Fluometuron was chosen as the herbicide to model, as it is the only herbicide used exclusively on one crop. Fluometuron was used on almost all acres of cotton grown in the Bogue Phalia Basin as a pre-emergent application and then again 3–4 weeks later as a post-emergent application [13]. Fluometuron has a water solubility of $110\,mg\,L^{-1}$, a K_{ow} of 242 at 25°C, and a field half-life of 85 days [14].

The objective of this research was to (1) evaluate the effectiveness of SWAT for simulating the hydrology of a $1270\,km^2$ basin located in the Bogue Phalia Basin in northwestern Mississippi, USA, using, wherever possible, default parameters and data sets that are readily available through the national database incorporated within BASINS; and (2) evaluate the ability of SWAT to predict concentrations of fluometuron in the Bogue Phalia Basin in Mississippi.

2. Experimental

2.1 *Model description*

The US Environmental Protection Agency (US EPA) has developed the software system Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) as a tool for the assessment of watersheds [8, 15]. BASINS operates in a Geographic Information System (GIS) platform and supplies default databases, software to automatically delineate a watershed, and efficiently imports, classifies, and overlays land-use and soil maps; it then chooses the optimal combination of the Hydrologic Response Units (HRUs) classes for each sub-watershed. BASINS interfaces data directly with several watershed-scale models including SWAT.

SWAT was developed by the US Department of Agriculture, Agriculture Research Service, in the early 1990s to move beyond field-sized models to large river basins [16]. SWAT is an operational or conceptual model that was developed to assist water-resource managers in assessing water supplies and in measuring the effect of non-point source pollution on large river basins. The primary considerations in model development were to stress (1) climate and management impacts; (2) water-quality loadings and fate; (3) flexibility in basin discretization; and (4) continuous time simulation. SWAT has been packaged with the USEPA BASINS model that includes inputs (soil, land-use, weather, etc.) that are readily available over large areas so the model can be used in routine planning and decision-making. SWAT simulates the major hydrological components and their interactions as simply, and yet as realistically, as possible [16]. SWAT2000 is the version of SWAT used in this study [17, 18]. It is a continuous-time model that operates on a daily time step. The objective of SWAT is to be able to predict the effects of management on water, sediment, and agricultural chemical yields in large, ungauged basins. To satisfy the objective, the model (a) is physically based (calibration is not possible on ungauged basins), (b) uses readily available inputs, (c) is computationally efficient to operate on large basins in a reasonable time, and (d) is continuous in time and capable of simulating long periods for computing the effects of management changes. SWAT uses a command structure for routing runoff and chemicals through a watershed. Commands are included for routing flows through streams and reservoirs, adding flows, and inputting measured data from wastewater treatment plants. The sub-basin/sub-watershed components of SWAT can be placed into eight major components: hydrology, weather, erosion/sedimentation, soil temperature, plant growth, nutrients, pesticides, and land management.

The algorithms within SWAT used to model pesticide movement and fate can be divided into three components: pesticide processes in land areas, transport of pesticides from land areas to the stream network, and in-stream pesticide processes. SWAT uses algorithms from three models to simulate each of these processes: (1) Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model [19], (2) Erosion Productivity Impact Calculator (EPIC) [20], and (3) a simple mass balance developed by Chapra [21]. The fate and transport of the pesticides in this study are controlled by key properties of the pesticide: half-life, water solubility, and K_{oc} (organic partitioning coefficient). These parameters are supplied by the program but can be modified by the user. There is another scalable value called 'application efficiency', which can be used for calibration.

2.2 *Watershed description*

The Bogue Phalia Basin is located in northwestern Mississippi and flows in a north–south direction from its headwaters near the Mississippi River levee in Bolivar County to its confluence with the Big Sunflower River in Washington County (figure 1). The basin is located in the low, relatively flat alluvial plain of the Mississippi River, a slightly undulating area of little topographic relief with an average southward slope of about 0.25 m km^{-1}. The USGS operates a gauging station near the town of Leland, MS. The drainage basin upstream from the gauging station is approximately 1270 km^2 and is located mostly in Bolivar County. Land use in the Bogue Phalia Basin above the gauging station site is 80% agricultural. The next largest land-use category is forested wetlands with 10.5%. Agriculture in the basin is dominated by soybean production, with lesser amounts of cotton and rice, and even less corn. In Bolivar County in 1996, there were about 88,000 ha of soybean, 25,000 ha of cotton, 5800 ha of corn, and 27,000 ha of rice planted. In Washington County in 1996, there were 48,000 ha of soybean, 39,000 ha of cotton, 12,200 ha of corn, and 11,200 ha of rice planted [22]. The channel slope is approximately 0.4 m km^{-1}, and the channel length upstream from the gauging station is approximately 93.7 km.

Most of the soils in the Bogue Phalia Basin are heavy clay 'gumbo' type soils, ideal for rice agriculture (figure 1, table 1). Cotton and corn are grown on the ridges and slightly more permeable areas along the margins of the basin. The interior of the basin is dedicated to rice and soybean agriculture. The Bogue Phalia Basin is a surface-water-driven system with most of the water moving off site via streams and rivers and little movement into the underlying aquifer [23].

2.3 *Watershed delineation*

Within BASINS, there are two methods of watershed delineation; manual and automatic [24]. Given the objectives of this study, the automatic watershed delineation was chosen. One of the key inputs during the delineation is the minimum critical source area. This defines the minimum drainage area required to form the beginning of a stream; the values suggested by the BASINS software were used.

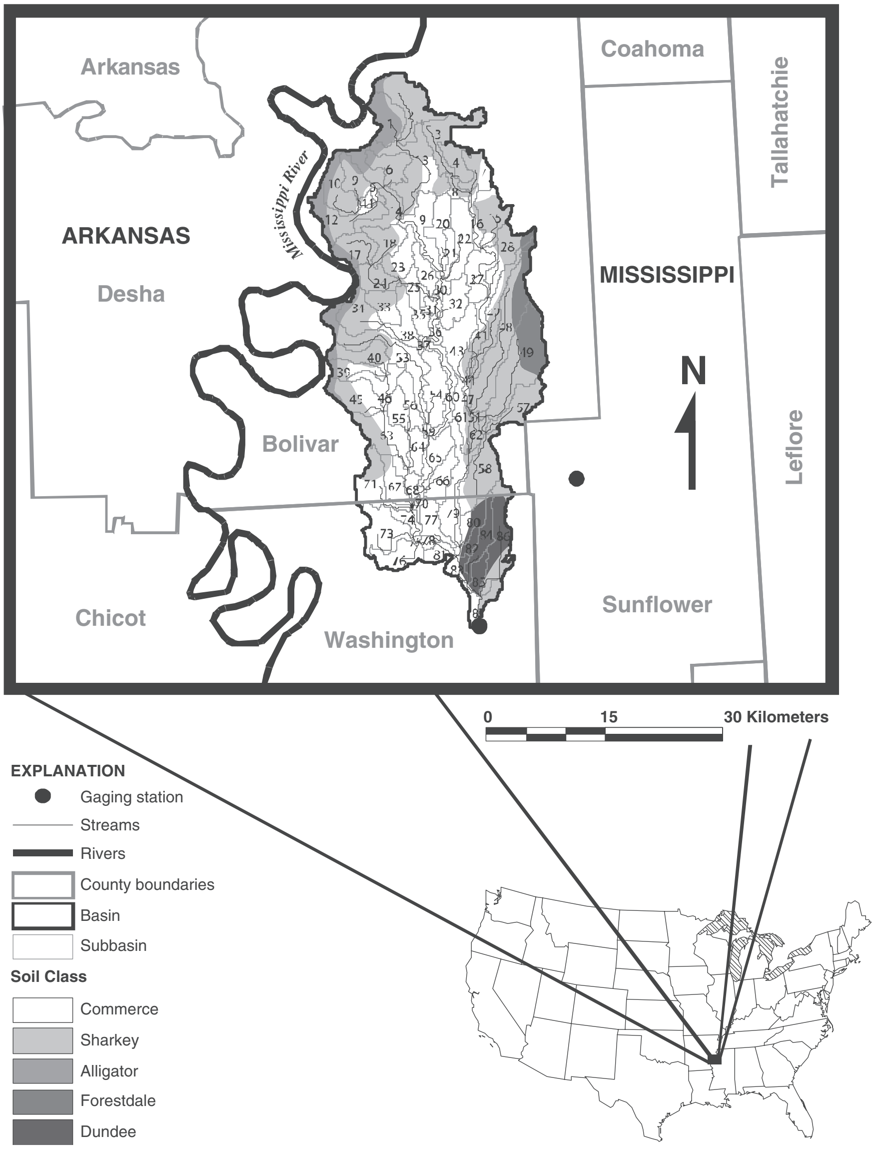

Figure 1. Map showing the location of the Bogue Phalia Basin, gauging station, soil classes, within the basin, and sub-basins.

Table 1. Characteristics of soils within the Bogue Phalia Basin, northwestern Mississippi, USA.

			Texture		
Soil name	Percentage of basin	Soil hydrological group	Clay (%)	Silt (%)	Sand (%)
Sharkey	46.5	D	50.00	27.77	22.23
Forestdale	41.2	C	31.50	48.50	20.00
Commerce	5.3	C	20.50	68.14	11.36
Alligator	4.0	D	50.00	27.72	22.23
Dundee	3.1	C	20.00	68.57	11.43

It has been shown that runoff volume is relatively invariant to the size and number of sub-basins [25–28], but that there is an optimal number of sub-basins needed to adequately simulate fine sediment [26], best management practices [28], and sediment, nitrate, and inorganic phosphorus [25]. The general consensus derived from these studies is that the optimal sub-basin size should be between 2 and 5% of the total basin size, and that any smaller sub-basin sizes are unnecessary. Using the default values, the BASINS program delineated the Bogue Phalia Basin into 87 sub-basins.

Each sub-basin will have one or more HRUs, which are unique for that sub-basin, according to the combinations of land use and soils. The BASINS software allows the user to designate the minimum percentage below which land use or soil is considered too small to be uniquely identified. For land use, the percentage used was 5%, and for soils it was 10%. HRUs within a sub-basin are not spatially linked, but their non-point source contributions are summed to calculate sub-basin loads that are subsequently routed through the watershed. The BASINS software created 160 HRUs within the Bogue Phalia Basin.

2.4 *Input data*

2.4.1 Land cover, elevation, and soils. SWAT2000 automatically derives landscape parameters from digital topographic, land cover, and soil data using an ArcGis 3.3 interface. Digital topographic data are from the USGS National Elevation Dataset, a seamless mosaic of best-available elevation data derived from 7.5-min, 30-m-resolution elevation data. Digital land cover is from the USGS National Land Cover Dataset and is derived from the early to mid-1990s Landsat Thematic Mapper satellite data classified into 21 possible land covers based on a modified Anderson Land Cover Classification. The spatial resolution of the data is also 30 m. Digital soil data use the State Soil Geographic (STATSGO) database, a digital general soil association map developed by the National Cooperative Soil Survey that consists of a broad-based inventory of soil and non-soil areas that can be mapped.

2.4.2 Climate. Daily precipitation and daily minimum and maximum temperatures were obtained from the National Climatic Data Center http://cdo.ncdc.noaa.gov/CDO/cdo for three sites in and around the study area (table 2). These were the only sites available with data for this location and for 1996–1998.

Table 2. Names and locations of weather stations in or near the study area which provided data used in the SWAT model.

Weather station identification number	Name	State	County	Latitude	Longitude
30,240	Arkansas Post	Arkansas	Arkansas	34°02′ N	−91°21′ W
221,743	Cleveland	Mississippi	Bolivar	33°48′ N	−90°43′ W
223,605	Greenville	Mississippi	Washington	33°23′ N	−91°04′ W

2.4.3 Management. To assign crops and management practices to specific HRUs, the following assumptions were made:

1. Because most of the basin is in Bolivar County and much of the county is included in the basin, Bolivar County crop statistics (http://www.nass.usda.gov/ms/) were used to determine crop acreage. The 1996–1997 crop acreage for corn, cotton, rice, and soybean was 3.8, 16.6, 19, 60.6%, respectively.
2. All of Commerce and Dundee soils were planted in cotton; the balance of the cotton acreage were randomly assigned to Forestdale soils, and all of the corn was randomly assigned to Forestdale soils.
3. If an HRU was planted to cotton or corn, it was unchanged throughout the entire simulation.
4. All rice acreage was assumed to be on a 1-year soybean/rice rotation.

Management scenarios (planting dates, irrigation, tillage, fertilizer, and pesticide application dates and rates, etc.) were created from the Planning Budgets written by the Mississippi Agricultural & Forestry Experiment Station and the Mississippi Cooperative Extension Service [13].

2.5 *Model evaluation*

Three statistics are used to evaluate the model's simulated streamflow *versus* observed streamflow; (1) the Nash and Sutcliffe Coefficient of Efficiency (COE) equation one [29], (2) the coefficient of determination or R^2 [30], and (3) the root mean square error (RMSE) [30]. The value for the COE can range from negative infinity to 1.0, with higher values indicating a better overall fit and 1.0 indicating a perfect fit. A negative COE indicates that the simulated streamflows are less reliable than using the average of the observed data. The COE is calculated as

$$\mathrm{COE} = 1 - \left(\frac{\sum_{i=i}^{n} (Q_i - S_i)^2}{\sum_{i=1}^{n} \left(Q_i - Q_{\mathrm{avg}}\right)^2} \right), \quad (1)$$

where Q_i is the observed daily discharge; S_i is the simulated daily discharge; and Q_{avg} i the average daily discharge.

Based on Motovilov *et al.* [31], the simulated streamflows are considered 'good' for values of COE > 0.75, whereas for values between 0.36 and 0.75, the simulated streamflows are considered 'satisfactory.' The R^2 value indicates the fraction of the variance explained by regression; therefore, values closer to 1.0 indicate less variance and a better fit. Minimizing the RMSE minimizes the variance and the bias.

The fluometuron and sediment concentrations simulated by SWAT are daily average concentrations, and those from the USGS are instantaneous observed concentrations. Any type of direct comparison is problematic, as pesticide and sediment concentrations can change several orders of magnitude in a short time (minutes to hours) during a runoff event. Therefore, the simulated daily average concentrations were visually compared with the instantaneous observed concentrations.

Simulated streamflow data from SWAT were compared with streamflow data collected at the USGS gauging station located on the Bogue Phalia near Leland, MS (07288650) and to fluometuron and sediment concentrations in water-quality samples collected at the same site. The USGS NAWQA Program collected 61 depth- and width-integrated and flow-weighted water samples from the Bogue Phalia near Leland from February 1996 through December 1997. These water samples were analysed for sediment and, on filtered samples, fluometuron concentrations. Because the fluometuron concentrations are determined on filtered samples, they are compared with the dissolved fraction from the simulated data. Because of its water solubility, most of the fluometuron would be expected to be in the dissolved phase, except at extremely high sediment concentrations. Details on the collection, analysis, quality-control, and quality-assurance procedures can be found in Coupe [12]. Water-quality data and the discharge data are available online at http://waterdata.usgs.gov/nwis.

2.6 *Calibration and validation*

The primary transport mechanism of many environmental contaminants is through water flow [8]. Because of this, accurate simulation of the hydrological component of the system is a prerequisite for accurate contaminant transport modelling.

It is important to understand that SWAT is not a 'parametric model' with a formal optimization procedure to fit data. Instead, a few important variables that are not well defined physically, such as runoff curve number and Universal Soil Loss Equation's cover and management factor, may be adjusted to provide a better fit [32].

Calibration of the model followed the Neitsch *et al.* [10] guidelines. Hydrological calibration and validation of the model on a daily basis focused on the USGS gauging station located on the Bogue Phalia near Leland. Measured daily streamflow data from this site were used for the calibration and validation of the model. The model was calibrated using the 1996 and 1997 calendar year data and validated using 1998 calendar year data. The gauge was in operation before 1996, but as a stage-only station; the discharge record did not begin until October 1995. The simulation was begun in 1992 to allow the model to 'warm up'. Criteria for acceptable hydrological calibration were artificially set at $R^2 > 0.6$, COE > 0.6, and a generally good match between simulated *versus* observed hydrographs.

3. Results and discussion

Figure 2 shows the results from the first 'cold run' of the SWAT model. That is, only the default parameters supplied or calculated by SWAT were used. The results indicate that, for the most part, the peaks and valleys of the hydrograph are followed relatively closely, albeit the estimated discharge has higher peaks and higher low flows than observed discharge.

In this study, the variable SURLAG (surface runoff lag coefficient) was the most important parameter used to improve the fit between simulated and observed discharge (table 3). Lenhart *et al.* [33] observed that the SURLAG could be a sensitive parameter with respect to its effect on the model output under some circumstances.

The SURLAG parameter is a coefficient used to calculate the amount of surface runoff released to the main channel on a daily basis. As the SURLAG value is decreased, more water is held in storage, and the subsequent effect is to smooth the

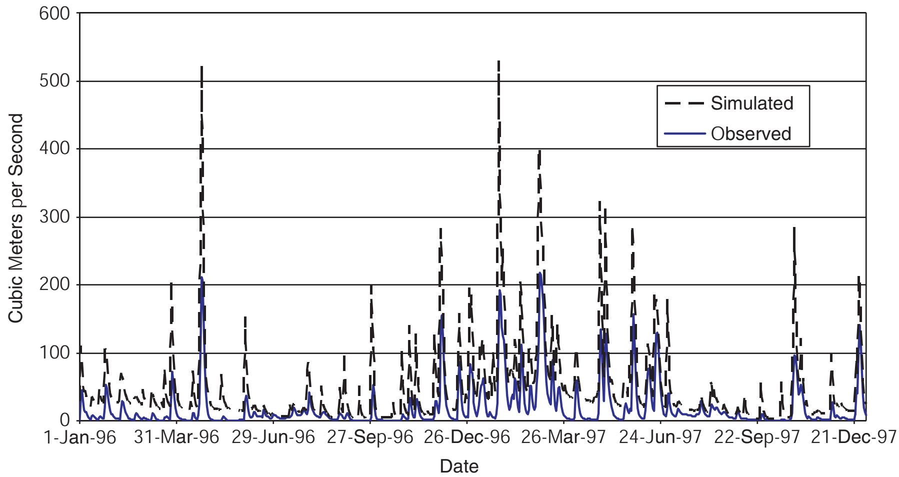

Figure 2. Simulated *vs*. observed discharge for 1996 and 1997 for the Bogue Phalia near Leland, Mississippi, 'Cold Run', using default parameters before calibration.

Table 3. Results for of SWAT calibration for discharge for 1996–1997[a].

Metric	Initial results (cold run)	Changes to SWAT input values (under generic management) CN reduced by 10% SURLAG = 1.5 Ov_n = 0.35 Sol_AWC + 0.08 ALPHA_BF = 0	Specific management
COE	0.02	0.64 (0.66)	0.64 (0.66)
R^2	0.39	0.68 (0.69)	0.69 (0.71)
RMSE	2.24	1.35 (1.18)	1.36 (1.2)

[a]SURLAG: surface-runoff lag coefficient; CN: curve number; Ov_n: Manning's *N* for overland flow; Sol_AWC: soil available water capacity; ALPHA_BF: base-flow alpha factor; values in parentheses are from verification year 1998.

streamflow hydrograph. The model was improved by changing the SURLAG parameter from its default value of four to 1.5. This makes physical sense given the extremely low topographical relief of the basin. Because water is moved by gravity, it follows that in areas with low relief, the water probably moves slower than it does in areas with more relief. Changes to the runoff curve number, Manning's *N* for overland flow, and the soil available water capacity all were related to the movement of water. The recession constant (ALPHA_BF) characterizes the groundwater recession curve or return flow, with values ranging between zero and 1.0, with larger numbers indicating a flatter recession. Setting ALPHA_BF to zero from its initial value of 0.048 virtually eliminates the contribution of return flow to stream runoff [34]. This may not be as unreasonable as it first seems as the contribution of return flow to streamflow decreases as the runoff potential increases. The Mississippi Alluvial Plain has a relatively high runoff, despite its relative flatness, due to climatic factors, agricultural practices, and soil conditions [35].

For the most part, the results comparing the observed runoff with the simulated runoff are quite good; the Nash–Sutcliff COE and the R^2 are both near 0.7 (figure 3, table 3). However, there are consistent differences between the simulated runoff and the

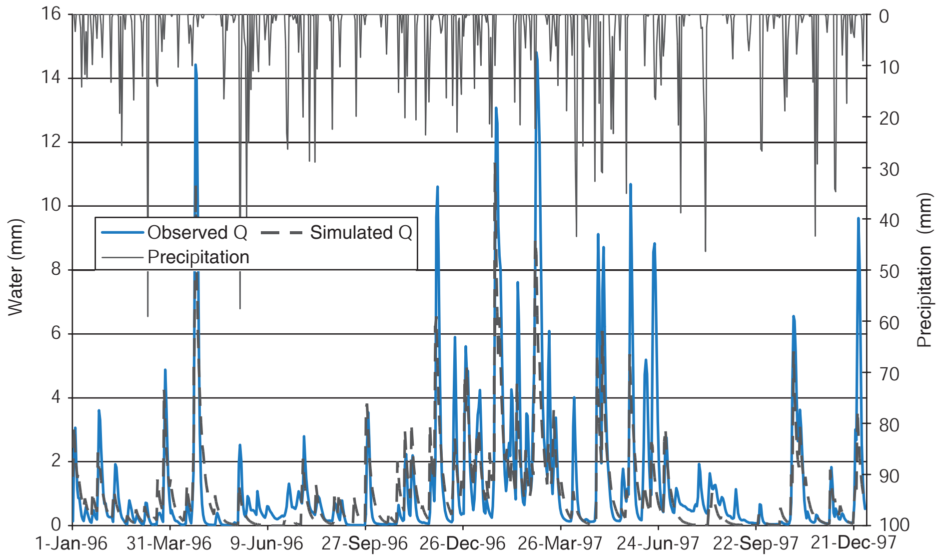

Figure 3. Simulated discharge, after calibration, from the SWAT model *vs.* observed discharge from the Bogue Phalia near Leland, Mississippi, gauging station for 1996 and 1997.

observed runoff. Note that the model does not accurately fit the falling limb of the hydrograph and tends to attenuate the streamflow more compared with observed values (see 4/30/96). Also, the model indicates that the Bogue Phalia has zero flow (see 6/29/96) sometimes during the summer, which was not recorded by the gauge, and in late summer, the model sometimes simulates a small runoff event following precipitation (see 10/96 and 10/97), whereas the observed data show no corresponding event.

One difference concerning hydrology in the Bogue Phalia Basin, which is somewhat unusual with respect to the basins where SWAT was developed, is rice agriculture. Conventional rice flooding in the Bogue Phalia Basin uses approximately 80 cm of water per year, and as much as 60% of that amount is lost from the fields as runoff [36]. SWAT2000 does not have a straightforward mechanism for handling a rice flood, and in fact, under the management scenarios, the model will not allow irrigation in excess of field capacity. With almost 23,000 ha of rice in the Bogue Phalia Basin, there could be a substantial amount of unaccounted-for water being released during the 3 months of June, July, and August. This may explain why the model simulates zero flow during these months, while the gauge on the Bogue Phalia always indicated flow.

Although no attempt was made to calibrate the model for sediment, it is instructive to examine how the model compares with observed data, as this would be an indicator of whether the model was accurately simulating processes in the watershed. The observed data are instantaneous concentrations derived from samples collected over a short (1 h or less) time span, whereas the concentration from the SWAT model is a daily average. The sediment concentration in a stream can change several orders of magnitude over the duration of a storm event; therefore, direct comparisons between the average daily concentrations and the instantaneous concentrations need to be evaluated with this in mind. The simulated concentrations generally are within an order of magnitude of the observed concentrations, except for those time periods when the model simulates zero flow (figure 4). A 1 : 1 comparison of observed *versus* simulated sediment concentrations

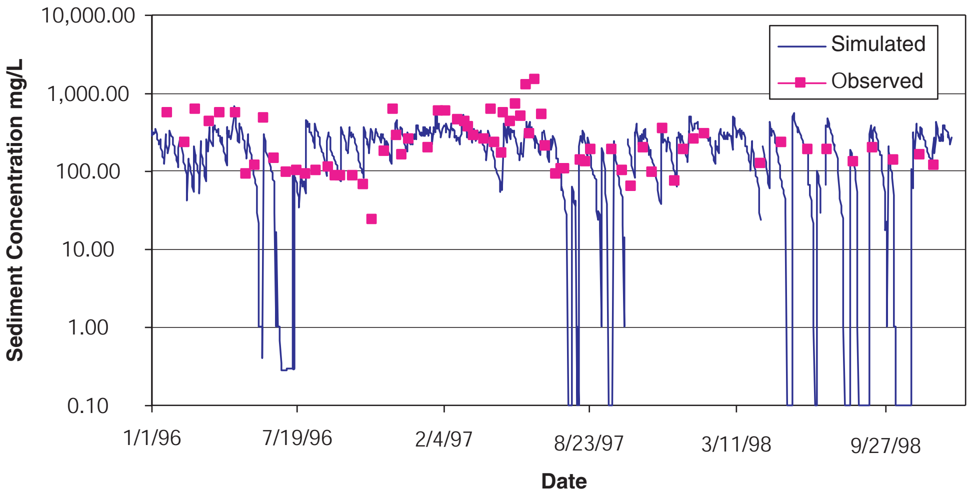

Figure 4. Simulated mean daily sediment concentrations and observed instantaneous concentrations from the Bogue Phalia near Leland, Mississippi, 1996–1998.

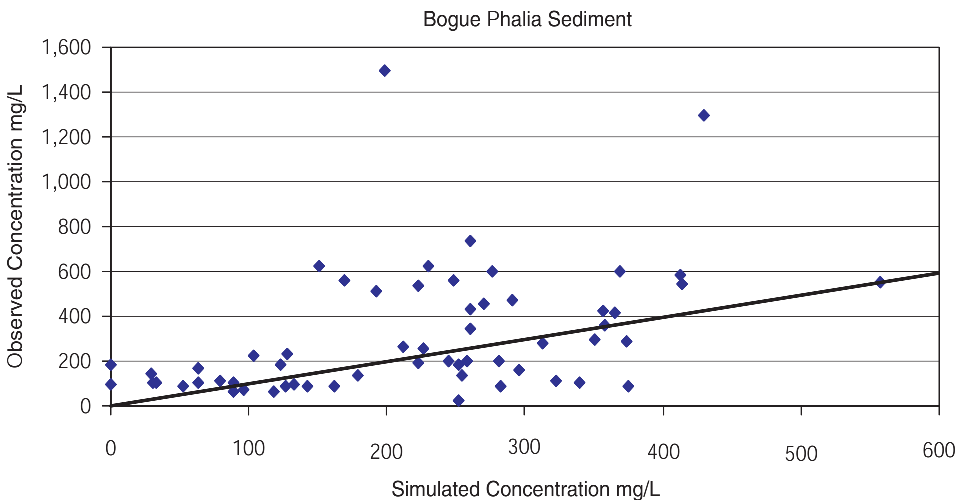

Figure 5. Simulated mean daily sediment concentrations *vs.* observed instantaneous concentrations shown with the 1 : 1 line from the Bogue Phalia near Leland, Mississippi, 1996–1998.

indicates a slight bias in that the observed concentrations tend to be higher than the simulated concentrations (figure 5).

Because field-specific information as to when applications of fluometuron occurred was not available, an average date and rate were used. For the first simulation, fluometuron applications to all cotton fields occurred on May 15, and a second application occurred on 1 June at 0.84 kg ha^{-1} and 0.73 kg ha^{-1} application rates, respectively. It is unreasonable to expect that all 20,100 ha of cotton in the basin received applications at the same time; in fact, in both 1996 and 1997, the dates of applications were either during or preceding a large storm event. This accounts for the very high simulated concentrations in the Bogue Phalia following application (figure 6). It is clear from figure 6 that there are two separate applications of fluometuron applied during the spring and early summer, but it appears that instead of two nearly instantaneous applications, fluometuron is applied over a period of several weeks.

In the next simulation, the application of fluometuron began on 27 April and was evenly distributed over the next month, with the second application occurring 3 weeks after the first application. The results are reasonable with the simulated and observed data following each other much more closely and are usually within an order of magnitude (figure 7). The simulated concentrations are still higher than the observed

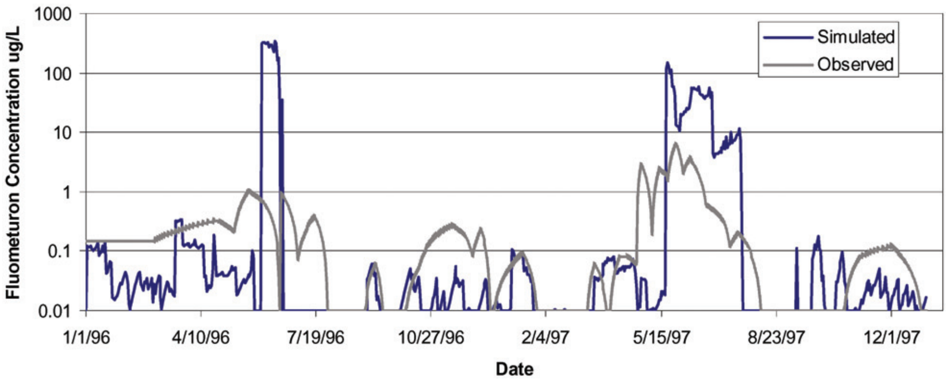

Figure 6. Results from the SWAT model for fluometuron for two applications of fluometuron to all 20,100 ha of cotton occurring on 15 May and 1 June at 0.84 kg ha^{-1} and 0.73 kg ha^{-1} application rates, respectively. The observed data are interpolated by a straight line between samples and observed values below the detection limit were set to 0.01 μg L^{-1} and for comparison simulated values below 0.01 μg L^{-1} were set to 0.001 μg L^{-1}.

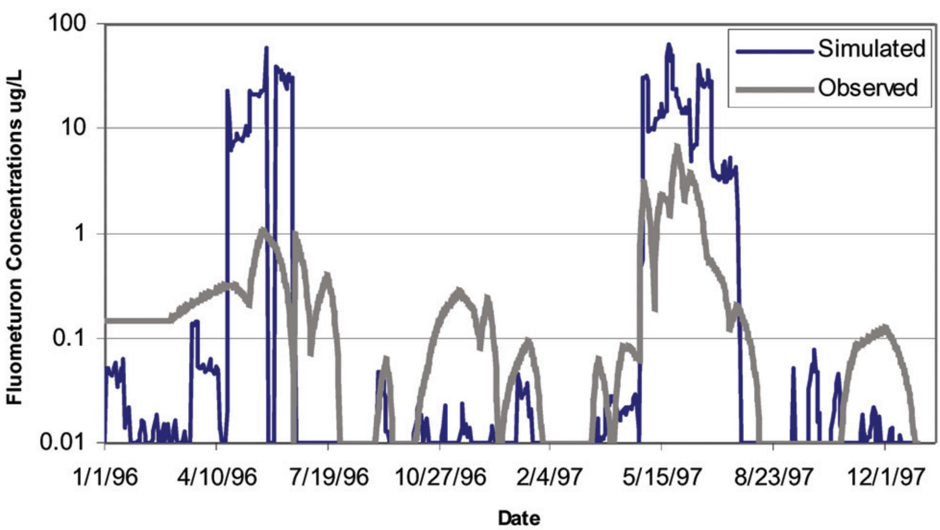

Figure 7. Simulated and observed fluometuron concentrations from management scenario with distributed fluometuron applications beginning 27 April and ending on 21 June.

immediately following application. There could be a couple of reasons for this discrepancy: (1) the model does not capture the processes that control runoff well or (2) the simulated application timing and/or amounts are inaccurate. Without exact information on the specific application of fluometuron, it is difficult to discern between the two. The model could be adjusted and the simulated concentration brought closer to the observed by changing the timing or amounts of fluometuron applied, changing the properties of the herbicide (i.e half-life), or changing model parameters that control runoff. Although the fit would be better, it is unclear whether the model would better represent reality, as it is unknown which process or processes are not currently represented well.

4. Conclusions

At the scale of the Bogue Phalia (too large for specific information to be available and too small for averaging to eliminate the need for site specific data), there are considerable uncertainties associated with input data. These, together with the simplifying assumptions within the model, indicate that SWAT probably should not be used to predict the exact date, time, and concentration of a pesticide in a stream. However, the model does offer the potential to assess the likelihood of contamination of surface waters by a given compound in a given situation and, as such, could prove to be a useful tool for planning, management, and regulatory purposes. The SWAT model appears to be a robust basin-scale watershed model, one that is able, without the need for unwieldy amounts of data, to give reasonable results and could be a useful tool for agriculture and society in the continuing quest to successfully manage our natural resources.

References

[1] US Environmental Protection Agency. *National Water Quality Inventory—2000 Report*, EPA-841-R-01-001, p. 207 (2002).
[2] R.K. Merton. *Am. Sociol. Rev.*, **1**, 6 (1936).
[3] F.R. Troeh, J.A. Hobbs, R.L. Donahue. *Soil and Water Conservation*, 2nd Edn, Prentice-Hall, Englewood Cliffs, NJ (1991).
[4] R.W. Skaggs, M.A. Breve, J.W. Gilliam. *Crit. Rev. Environ. Sci. Tech.*, **24**, 1 (1994).
[5] J.M. Fenelon, R.C. Moore. *J. Environ. Qual.*, **27** (1998).
[6] N.N. Rabalais, R.E. Turner. In *Coastal Hypoxia: Consequences for Living Resources and Ecosystems*, N.N. Rabalais, R.E. Turner (Eds), American Geophysical Union, Washington, DC (2001).
[7] W. Intarapapong, D. Hite, L. Reinschmiedt. *J. AWRA*, **38**, 2 (2002).
[8] D.D. Bosch, J.M. Sheridan, H.L. Batten, J.G. Arnold. *Trans. ASAE*, **47**, 5 (2004).
[9] K. Wu, Y.J. Xu. *J. AWRA*, **42**, 5 (2006).
[10] S.L. Neitsch, J.G. Arnold, R. Srinivasan. *Pesticides Fate and Transport Predicated by Soil and Water Assessment Tool (SWAT)*, p. 96, US Department of Agriculture, Publication 2002–2003, College Station, TX (2002).
[11] T. Ramanarayanan, B. Narasimhan, R. Srinivasan. *J. Agric. Food Chem.*, **53**, 8848 (2005).
[12] R.H.Coupe. *Occurrence of Pesticides in Five Rivers of the Mississippi Embayment Study Unit, 1996–98*, p. 55, US Geological Survey WRIR 99-4159 (2000).
[13] Anonymous. *Delta 1997 Planning Budget, Agricultural Economics Report 81*, Mississippi State University (1997).
[14] Ahrens. *Herbicide Handbook*, 7th Edn, p. 352, Weed Science Society of America (1994).

[15] M. Di Luzio, R. Srinivasan, J.G. Arnold. *J. AWRA*, **38**, 4 (2002).
[16] J.G. Arnold, N. Fohrer. *Hydrol. Processes*, **19**, 563 (2005).
[17] S.L. Neitsch, J.G. Arnold, J.R., Kiniry, R. Srinivasan, J.R. Williams. *Soil and Water Assessment Tool Theoretical Documentation: Version 2000, TWRI Report TR-191*, Temple, TX (2002a).
[18] S.L Neitsch, J.G. Arnold, J.R., Kiniry, R. Srinivasan, J.R. Williams. *Soil and Water Assessment Tool User's Manual: Version 2000, TWRI Report TR-192*, Temple, TX (2002b).
[19] R.A. Leonard, W.G. Knisel, D.A. Still. *Trans. ASAE*, **30**, 1403 (1987).
[20] J.R. Williams, P.T. Dyke, W.W. Fuchs, V.W. Benson, O.W. Rice, E.D. Taylor. *EPIC—Erosion/Productivity Impact Calculator: 2. User Manual*, A.N. Sharpley and J.R. Williams (Ed.), US Department of Agriculture Technical Bulletin No. **1768**, p. 127 (1990).
[21] S.C. Chapra. *Surface Water-Quality Modeling*, p. 844, McGraw-Hill, Boston, MA (1997).
[22] T.L. Gregory. *Mississippi Agricultural Statistics, 1988–1997*, Mississippi Agricultural Statistics Service (1998).
[23] J.K. Arthur. *Hydrogeology, Model Description, and Flow Analysis of the Mississippi River Alluvial Aquifer in Northwestern Mississippi*, US Geological Survey WRIR 01-4035 (2001).
[24] US Environmental Protection Agency. *Better Assessment Science Integrating Point and Nonpoint Sources BASINS 3.0 User's Manual*. Available online at: http://www.epa.gov/ost/basins (accessed May 2005).
[25] M. Jha, P.W. Gassman, S. Secchi, R. Gu, J. Arnold. *J. AWRA*, **40**, 3 (2004).
[26] R.C. Binger, J. Garbrecht, J.G. Arnold, R. Srinivasan. *Trans. ASAE*, **40**, 5 (1997).
[27] T.W. Fitzhugh, D.S. Mackay. *J. Hydrol.*, **236** (2000).
[28] M. Arabi, R.S. Govindaraju, M.M. Hantush, B.A. Engel. *J. AWRA*, **42**, 2 (2006).
[29] J.E. Nash, J.E. Sutcliffe. *J. Hydrol.*, **10**, 182 (1970).
[30] D.R. Helsel, R.M. Hirsch. *Statistical Methods in Water Resources*, p. 522, Elsevier, Amsterdam, Netherlands (1992).
[31] Y.G. Motovilov, L. Gottschalk, K. England, A. Rodhe. *Agric. Forest Meteorol.*, **98–99**, 257 (1999).
[32] J.G. Santhi, C. Arnold, J.R. Williams, W.A. Dugas, R. Srinivasan, L.M. Hauck. *J. AWRA*, **35**, 5 (2001).
[33] T. Lenhart, K. Eckhardt, N. Fohrer, H.G. Frede. *Phys. Chem. Earth*, **27**, 1149 (2002).
[34] H. Manguerra, B. Engle. *J. AWRA*, **34**, 1149 (1998).
[35] C. J. Schmitt, P. V. Winger. *Factors Controlling the Fate of Pesticides in Rural Watersheds of the Lower Mississippi River Alluvial Valley*, Transactions of the 45th North American Wildlife and Natural Resources Conference, pp. 354–375 (1980).
[36] Mississippi Rice Promotion Board. *Water-Saving Irrigation for Mississippi Rice Production,* Mississippi State University, Mississippi State, MS, pp. 15–17 (2005).