Defining Soil and Water Assessment Tool (SWAT) hydrologic response units (HRUs) by field boundaries

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Abstract: The Soil and Water Assessment Tool (SWAT) is widely used to relate farm management practices to their impacts on surface waters at the watershed scale, yet its smallest spatial unit is not generally defined by physically meaningful boundaries. The hydrologic response unit (HRU) is the smallest spatial unit of the model, and the standard HRU definition approach lumps all similar land uses, soils, and slopes within a subbasin based upon user-defined thresholds. This standard method provides an efficient way to discretize large watersheds where simulation at the field scale may not be computationally feasible. In relatively smaller watersheds, however, defining HRUs to specific spatial locations bounded by property lines or field borders would often be advantageous, yet this is not currently possible within the ArcSWAT interface. In this study, a simple approach is demonstrated that defines HRUs by field boundaries through addition of uniquely named soils to the SWAT user soil database and creation of a field boundary layer with majority land use and soil attributes. Predictions of nitrogen, phosphorus, and sediment losses were compared in a case study watershed where SWAT was set up using both the standard HRU definition and field boundary approach. Watershed-scale results were reasonable and similar for both methods, but aggregating fields by majority soil type masked extremely high soil erosion predicted for a few soils. Results from field-based HRU delineation may be quite different from the standard approach due to choosing a majority soil type in each farm field. This approach is flexible such that any land use and soil data prepared for SWAT can be used and any shapefile boundary can divide HRUs.

Keywords: watershed, modeling, Soil and Water Assessment Tool (SWAT), hydrologic response units, field boundaries, common land units, landuse management

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1 Introduction

The Soil and Water Assessment Tool (SWAT)[1] is a hydrologic model widely used internationally and in the United States for water quality and natural resource management. The SWAT model is flexible, capable of simulating the response of catchments ranging from small watersheds to large river basins as a function of land use, management and cropping systems, landform characteristics, and climate forcing. It can utilize detailed agricultural management, making it particularly well suited for simulating the response of agricultural watersheds. In addition, its open source programming makes it especially useful for research purposes and flexible for adaptations and continued model development[2].

A SWAT configuration is set up using elevation and optional stream data to delineate subbasins within a

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watershed of interest. Subbasins are spatially distributed, and streamflow and associated contaminants are routed from one subbasin to another. The smallest spatial units, hydrologic response units (HRUs), are not distributed, may not be continuous, and there is no routing among them. Much of the SWAT simulation occurs at the HRU level, including impacts of agricultural management and conservation practices on crop production, hydrology, and water quality.

The HRUs are normally defined by lumping similar land use, soil type, and optionally slope characteristics within a given subbasin based on user-defined thresholds for each category. In this standard method, the user can control the number of HRUs by applying a threshold on land area permitted for a given land use or soil type within a subbasin. Fewer HRUs may be desirable for achieving computational efficiency. At the small watershed to field scale, however, individual field management may become an important consideration, and field-based outputs and potentially inputs may be necessary depending upon simulation objectives. In particular, if SWAT model results are to be communicated to stakeholders such as farmers, landowners, or land managers, outputs should match socially meaningful area units such as parcels, fields, or even counties.

Some researchers have addressed the need for field-based outputs from the SWAT model by post-processing. Gitau et al.[3] overlaid HRUs with field boundaries to map HRUs to a small farm. An existing tool called Field_SWAT[4] converts model outputs from the HRU scale to fields using a field boundary layer. Field_SWAT takes SWAT outputs, the SWAT-created HRU raster, and a field boundary shapefile, uses MATLAB's[5] inpolygon function to determine which HRUs cells have their center within each farm field, and uses a statistical process, such as an area-weighted average of all HRU cells within a field, to aggregate HRU outputs to field boundaries. Still others have created similar tools using ArcGIS[6].

However, there are applications where field boundaries need to be taken into account in the SWAT model setup, rather than only in post-processing. For example, most conservation practices in SWAT are represented at the HRU scale, and yet it may not be possible to enter known practices on particular fields into the model if HRUs are discontinuous and lumped together lands representing many different owners. Similarly, if farm management practices such as fertilizer application and tillage are known for particular crop fields, the standard HRU definition would provide no means for altering them in the HRU management files. In these situations, field boundaries would be the appropriate basis for defining HRUs during the model setup stage. Others have recognized this limitation and sought to control HRU delineation in their work: Teshager et al.[7] conducted a process quite similar to the one we outline in this study, and Veith et al.[8,9] and Ghebremichael et al.[10,11] modified model inputs to define HRUs by field boundaries in farm-sized watersheds—but they have not provided details on the process or how it impacted model results.

The goal of this work is to further extend the SWAT model's usefulness by presenting an approach for HRU definition by a farm field boundary layer. The specific objectives of this work were (1) to create a spatial dataset of farm field boundaries for a case watershed, (2) to set up SWAT using field boundaries to define HRUs, and (3) to compare the field boundary approach to a standard method of HRU definition based on hydrology, water quality, and other quantitative and qualitative measures of model performance.

2 Methodology

2.1 Brief description of the Soil and Water Assessment Tool (SWAT)

SWAT[1] is a watershed model commonly used to estimate the water quantity and quality impacts of land use and land management on surface waters. The model takes data inputs such as land management and land use, soils, elevation, and daily climate, and routes flow and nutrients in the land and within the reach and simulates crop growth. A model is configured by providing this input data for a watershed of interest and using one of the available model interfaces—ArcSWAT, AVSWAT, or MWSWAT—to define subbasins and HRUs. The

SWAT tools used in this study were SWAT 2012, Release 622, and ArcSWAT 2009.10.1.

The SWAT model is in continuous development and updated revisions are frequently available on the model website. One of SWAT's subroutines that is particularly important for hydrologic/water quality simulation in the U.S. Midwestern Corn Belt is subsurface tile drainage. In this study we used the recently added tile drainage routine based on the Hooghoudt and Kirkham tile drain equations[12], which predict tile flow as a function of tile drain depth, spacing, and size.

2.2 Study area

Little Pine Creek watershed, located in Tippecanoe County of west-central Indiana, served as a case study watershed for testing the HRU definition by field boundary approach (Figure 1).

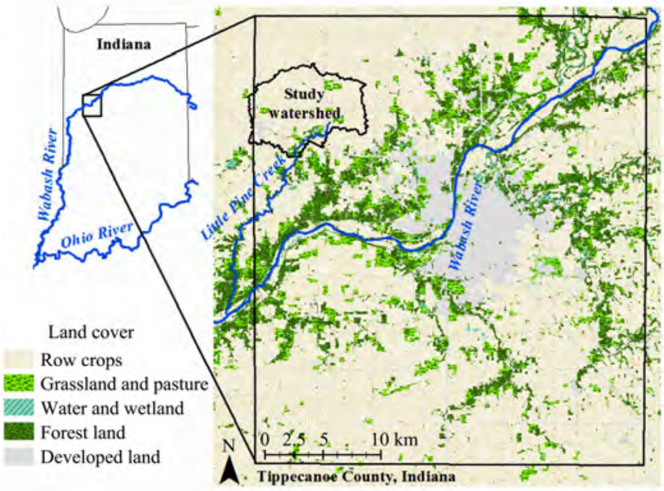

Figure 1 Little Pine Creek watershed in Tippecanoe County, west-central Indiana. Land cover data is from the National Land Cover Database for 2006[13]

The watershed is 56 km^2 in size and primarily agricultural in land use, as corn and soybean production occurs on 80% of its land. The remainder of the watershed is in grassland (10%), hay (6%), and forestland (4%). Fairly flat, the watershed has an average slope of only 1.2% and is characterized by poor soil drainage. Over half of the watershed is composed of poorly, very poorly, or somewhat poorly drained soils, and dominant soil types are Sloan, Drummer, Chalmers, Toronto, and Raub. Common well drained soils are Throckmorton, Strawn, and Sparta. West-central Indiana has a humid continental climate, with one-meter average precipitation and an average annual temperature of 11°C[14]. Poor natural soil drainage combined with heavy precipitation averaging nearly 300 mm in the March–May time period, during which farmers prepare fields for planting, make these fertile lands difficult to farm without artificial drainage. Subsurface tile drains are pipes installed approximately 1 m below the soil surface. They can be applied randomly, or in a systematic fashion with parallel placement and regular spacing. Subsurface tile drainage has become increasingly common and we estimated that it is present in 67% of Little Pine's croplands.

2.3 Approach to hydrologic response unit (HRU) definition by field boundaries

The field boundary layer used in this work was the Common Land Unit (CLU) layer for agricultural land from the United States Department of Agriculture (USDA) Farm Service Agency (FSA). The USDA CLUs are defined as "the smallest unit of land that has a permanent, contiguous boundary, a common land cover and land management, a common owner and a common producer in agricultural land associated with USDA farm programs"[15]. A current CLU dataset with its attributes is only accessible by the FSA and its partnerships, but a version of the data stripped of all attributes distributed prior to the 2008 Farm Bill can be purchased by the public. The CLU layer was purchased from GISDataDepot[16]. Non-field areas of the watershed include roads, wooded areas, and houses, which were assigned field boundaries or allocated to nearby crop fields (Figure 2).

In order to define one HRU as one field, each field needed to have one land use, one soil type, and one slope. Slope was not considered because a single slope was used for each HRU definition to ensure HRUs were not fragmented within original field boundaries, but multiple slopes could be used if desired. Land use data in this study was obtained from the USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL)[16], which was implemented as a raster grid with land cover type attribute code. Soil map and soil layer attributed data were obtained from the USDA Soil Survey Geographic Database (SSURGO)[17]. Other soil and land use data sources may be used, provided their information exists or is added to the appropriate SWAT databases. Within each field boundary, the land use and soil type with the greatest number of cells was assigned to the entire field.

Figure 2 The CLU layer (semi-transparent white with black outlines) has non-field areas, slivers between fields, and small HRUs due to roads and other non-farm land uses

The key to ensuring HRUs are defined by field boundaries is to assign a unique soil (or, alternatively, land use) name to every field in the study area. Majority land use and soil type are necessary, but not sufficient, for a one-to-one mapping of one field to one HRU, as fields with the same soil and land use in a given subbasin would still be automatically lumped into the same HRU. Therefore, field boundaries were kept separate by creating soils with unique names for every field. An alternate approach could have used uniquely named land uses instead, but there is currently an upper limit of a few hundred land uses in an ArcSWAT setup. Assigning unique soil names required addition of new soils to the SWAT database usersoil table. Lookup tables were created to map unique soil names for each field boundary to a SSURGO soil map unit key (Mukey), which is a unique identifier for each soil in the database. Each new soil name was added as an entry in the usersoil table with all attributes identical to the matching soil Mukey except for the soil name ('SNAM'). When HRUs are defined in the SWAT setup, the model sees each field as having a unique soil type. ArcMap 10.0[18] and MATLAB[5] were used for the majority of the methodology. The methods were not tested in the AVSWAT or MWSWAT interfaces. Additional details of this process are provided in Box 1.

2.4 Model setup

Watershed models for the Little Pine watershed were set up for HRU definition by both the standard method and by field boundaries. For both HRU definition approaches, 10-meter elevation data[20] and burned in streams from the National Hydrography Dataset[21] were used to delineate the watershed. A stream threshold of 200 hm^2 was used, which resulted in a stream density similar to the National Hydrography dataset in the region of the case study watershed. An outlet point at the location of the gage station was added and selected as the watershed outlet. Definition of land use, soils, and slope was the only aspect that differed between the two approaches. In the standard approach, original NASS land use and SSURGO soils data were used to define the HRUs, while the HRU by field boundary approach used the pre-processed field boundary layer with majority land use and soil. Only one slope class (0–2%) was used in both approaches to define the slopes. In all subsequent steps, including the 0%/0%/0% threshold for HRU definition, the two approaches were treated the same.

Model inputs of precipitation and temperature were obtained from the National Climate Data Center[22]. Other required daily climate data (solar radiation, wind speed, and relative humidity) were generated internally in SWAT. Other model decisions included using the Penman-Monteith method (IPET = 1) for estimating evapotranspiration, using the SCS curve number approach (IEVENT = 0) as a function of soil moisture (ICN = 0) for computing surface runoff, and turning off in-stream water quality processes (IWQ = 0).

Several management and parameter changes were made to corn and soybean HRUs based on local knowledge of agriculture in this region. Corn and soybeans lands were considered to be in a two-year rotation.

Box 1 Detailed methodology for defining HRUs based on field boundaries using CLUs as field boundaries, NASS for land use and SSURGO soils data. The method could be adjusted for other data sources.

Phase 1: Preparing the field boundary layer in ArcMap

1) *Clip* field boundary layer to a mask of the watershed to reduce processing time.
2) Remove boundary layer "slivers" using the ArcToolbox *Integrate* tool (10 m tolerance).
3) Fill in non-farm parcels (missing from field boundary layer) using the *Union* tool on the field boundary layer and the mask.
4) Separate non-continuous features formed by the union tool using the *Feature to Polygon* tool.
5) Select small polygons in the new boundary layer using the *Select by Attributes* tool for features smaller than 1 ha.
Remove these small polygons using the *Eliminate* tool, merging them with larger polygons that share the longest boundary.

Phase 2: Selecting the majority land use and soils in ArcMap

7) Assign the majority soil and land use to each field:
a. Use the *Zonal Statistics as Table* tool with the new field boundary layer as the zone-defining layer, the feature ID (FID) as the field defining each zone, and NASS land use as the raster that contains values for which to calculate a statistic. The attribute field containing the predominant land use within each field boundary is called "Majority".
b. Use *Join Field* to join the new table to the field boundary layer (input dataset) by FID (input join field) with output join field VALUE and "Majority" as field to join.
8) Repeat 7) using SSURGO soils instead of NASS, double checking the attribute table to confirm "Majority" (NASS land use) and "Majority_1" (SSURGO Mukey) fields were joined.
9) Use *Add Field* to create a field called "Lookup" with type "long" populated with FID values for use in HRU definition.
10) Export the attribute table and save all records in a field boundaries textfile.

Phase 3: Creating soils and land use lookup tables

11) Create land use and soil lookup tables:
a. Create a field boundary lookup table (.csv) by adding the field boundaries textfile and editing in Excel to remove all columns except Lookup, Majority, and Majority_1.
b. Create a land use lookup table (.csv) by mapping each land use attribute code to the SWAT name for a given land use in the crop database (e.g., CORN for corn). The process is simplified if NASS land uses are already represented in the SWAT crop database.
c. Create a soil lookup table (.csv) by mapping soil Mukey to soil name in SWAT's usersoil table in the SWAT2012.mbd database. Here we used the SSURGO Processing Tool[19] for ArcSWAT to create a soil lookup table and populate SWAT's usersoil database with SSURGO, but this step is no longer required as SWAT now includes SSURGO soils in its SWAT_US_SSURGO_ Soils.mdb database.

Phase 4: Updating SWAT database using MATLAB

12) We created a simple MATLAB script to add unique soil types for each field boundary to the SWAT usersoil table. The script reads the lookup tables and usersoil database, adds a row to the usersoil database for each farm field, gives it a unique name based on the field's Lookup number, and copies the rest of the soil information from the correct soil type in the usersoil table. (Note that soil names must begin with a letter rather than a number.)
13) Updated usersoil and lookup tables are output as Excel spreadsheets. Use Microsoft Access to append the usersoil spreadsheet to the usersoil table in SWAT2012.mdb.

Phase 5: Setting up SWAT by field boundaries

14) Start a new project in ArcSWAT, referencing the updated SWAT2012.mdb in the project setup.
15) In *Land Use/Soils/Slope Definition*, enter the final field boundaries shapefile, select the field lookup and the crop and soil lookup tables for Land Use and Soils, respectively. Check the box to create a shapefile of all HRUs for visualization purposes.
16) In *HRU definition*, use a 0%/0%/0% threshold for lumping land uses, soils, and slopes, since the dataset is preprocessed to the field scale.
17) All remaining steps are unchanged in the HRU definition by field boundaries approach.

Soybeans were no-till planted on May 24 and harvested on October 7. After soybean harvest, a broadcast phosphorus application and chisel plowing prepared the land for corn planting in the spring. Prior to planting of corn on May 6, disk plow tillage was performed on April 15 and nitrogen fertilizer was injected on April 22. Corn was harvested on October 14. Nitrogen and phosphorus fertilizer application rates were estimated from land-grant university recommendations[23] to obtain corn and soybean yields equivalent to the average crop yields for the county containing the watersheds, Tippecanoe County, for the period 2007-2012[24].

All corn and soybean HRUs with soil drainage class of 'somewhat poorly drained,' 'poorly drained,' or 'very poorly drained,' were assumed to have tile drainage. Depth to the drains (DDRAIN) was assumed to be 1 m, as is common in Indiana, and the tile drainage lag time (GDRAIN) was set to 24 hours. The depth to impermeable layer (DEP_IMP) was changed from the default of 6 m to 1.2 m. To simulate tile drainage using the latest tile drainage routine in SWAT 622, the drainage flag (ITDRN) in the basins.bsn file was set to 1, and parameters in the new.sdr files were set as follows: effective drain radius (RE_BSN) of 20 mm, distance between tiles (SDRAIN_BSN) of 20 000 mm, drainage coefficient (DRAIN_CO_BSN) of 20 mm/d, pump capacity (PC_BSN) of 0 mm/h, and multiplication factor between SWAT saturated hydraulic conductivity and lateral conductivity (LATKSATF_BSN) of 4. Curve number was reduced by 20% in tile-drained lands to simulate increased infiltration. In additional, the surface lag runoff coefficient (SURLAG) was set to 0.5 d, because of the small size of the watershed, and Manning's n for overland flow (OVN) was set to 0.3 for both watersheds.

2.5 Model comparison

The two methods for HRU definition were compared to one another and to measured data in several ways for a three year time period of 2009-2012[25–27], for which measured data was available at the watershed outlet. Percentage of poorly drained soils and land uses were quantified, and also compared visually, to determine the impact of assigning one soil type and land use to each farm field. Water balance at the watershed outlet was compared using standard statistics for daily and monthly simulated and observed hydrograph goodness-of-fit: the correlation coefficient (R^2) and Nash-Sutcliffe coefficient (E_{NS})[28,29], as well as annual depth of stream flow and tile drainage over the watershed. Nutrient and sediment concentrations and loads were compared against measured data using monthly R^2 and E_{NS} values, as well as standard summary statistics of daily means, standard deviations, and the range of extreme values. Simulated loads of nitrate, total phosphorus, and sediment were taken from the output.rch file. Corresponding observed daily nitrate, total phosphorus, and sediment loads were calculated from weekly measured concentrations using observed flows for days the samples were taken. Monthly observed loads were estimated using average daily flows over the month and average weekly nutrient and sediment concentrations. Simulated annual HRU-level total nitrogen, phosphorus, and sediment loading was obtained from the HRU output file, added to ArcGIS as a table, and joined to the original HRU shapefiles. These were displayed in ArcMap for visual comparison of the two approaches.

3 Results and discussion

3.1 SWAT model setup by two HRU definition approaches

The number of subbasins was 15 under both approaches. The standard method of HRU definition produced 960 HRUs, while the HRU definition by field boundaries produced 418. Most of the additional HRUs in the standard method represented non-cropped lands, as row-crop (corn and soybean) HRUs from the two approaches totaled 356 in the standard method and 320 in the field boundary method. Figure 3 shows the HRUs defined by each approach.

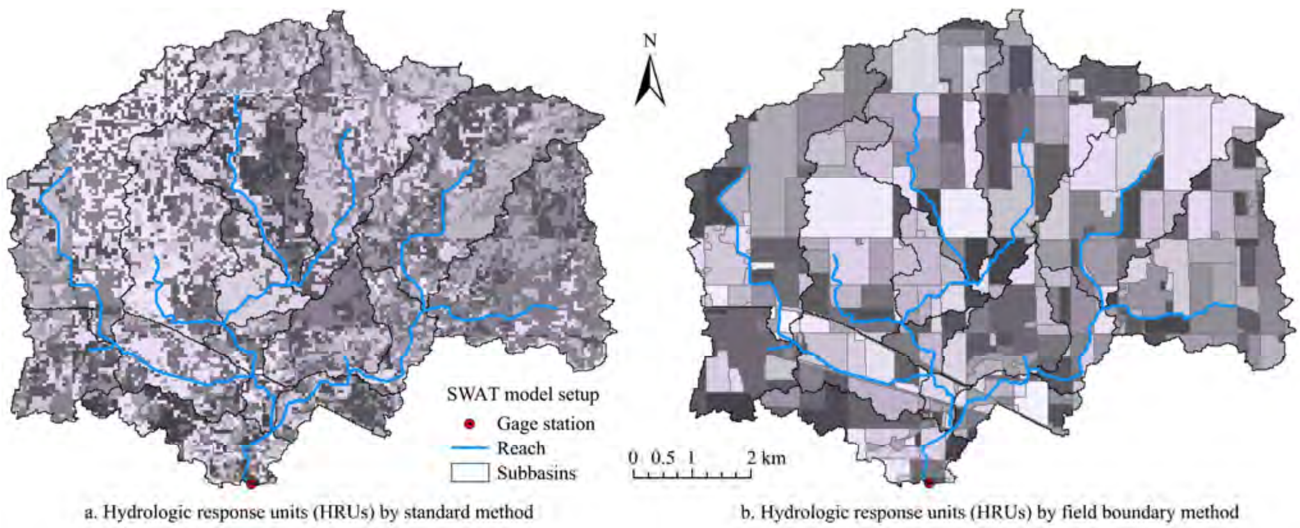

Figure 3 HRUs in the Little Pine Creek watershed using the standard method (960 HRUs) (a) and the field-based method (418 HRUs) (b). Each shade of gray represents one HRU.

3.2 Influence of HRU definition method on soil type and land use

The percent of land in corn and soybean land uses was higher under the field-based approach, because non-field areas classified as grasslands were integrated into adjacent farm fields (Table 1, Figure 4). Soil type locations were altered more than that for land use (Figure 5), for two main reasons: 1) the field boundary layer already took into account most land use changes in a heavily agricultural watershed, and 2) soil polygons are smaller, more heterogeneous, and shaped with greater irregularity than land use polygons. Assigning each field its majority soil resulted in large areas of the same soil type. A vertical line separating soil types near the western edge of the watershed is located at a county border, where presumably two different surveyors made an assessment. The prevalence of poorly drained soils is nearly identical in the two approaches (Table 1), yet patterns of soil drainage class (Figure 6) and tile-drained croplands (Figure 7) are quite different. Especially notable is the distinction between excessively drained soils in the western part of the watershed and the primarily poorly drained soils elsewhere. The field boundary approach heightens that disparity such that a large, continuous portion of the watershed is excessively drained. Overall, it appears that the land use is fairly well preserved in the field boundary approach, and soil prevalence is similar, yet spatial heterogeneity of soils is vastly altered. From these alone it may be expected that the watershed-scale outputs of the two methods would be quite similar, while field-based outputs would show greater divergence.

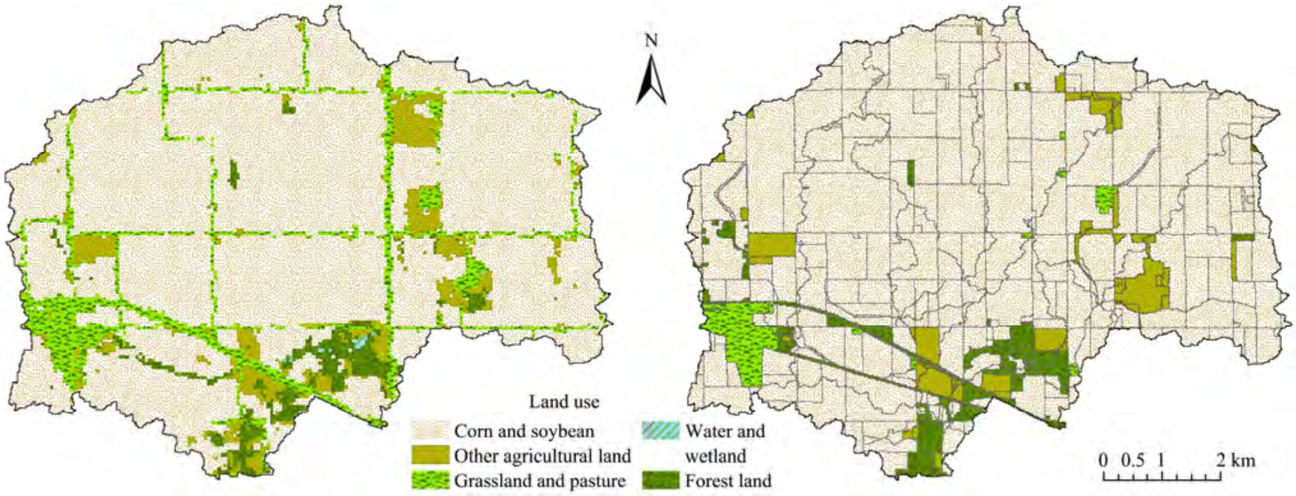

Figure 4 HRU land use by the standard HRU method (left) and field boundary method (right).
Many small non-cropland patches were eliminated in the field-based HRU method, especially grass alongside roadways.

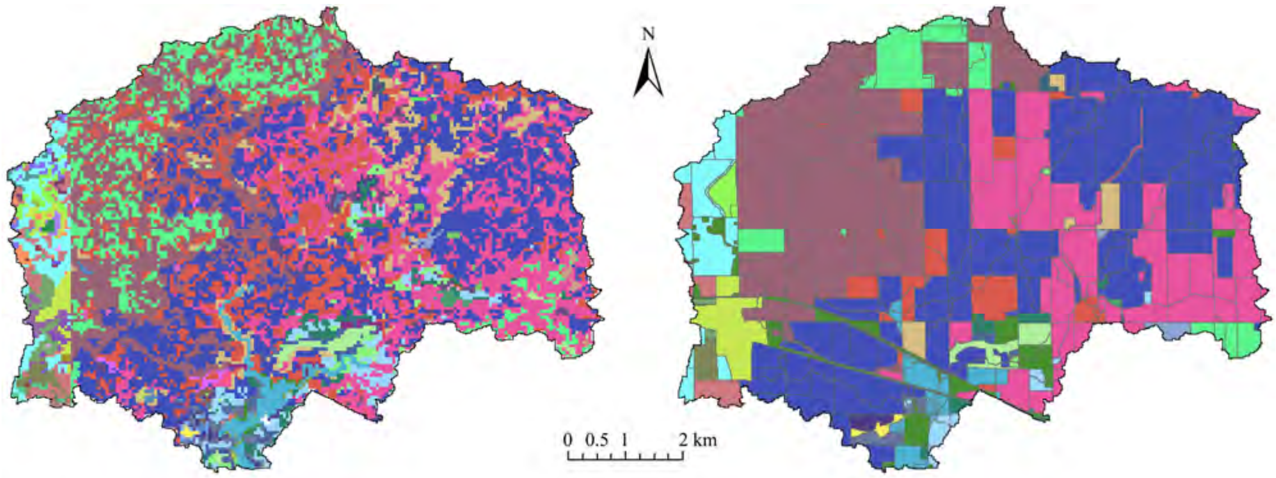

Figure 5 HRU soil type by the standard HRU method (left) and field boundary method (right).
The same color map is used for the two maps, showing the elimination of fine detail of spatially heterogeneous soil types.

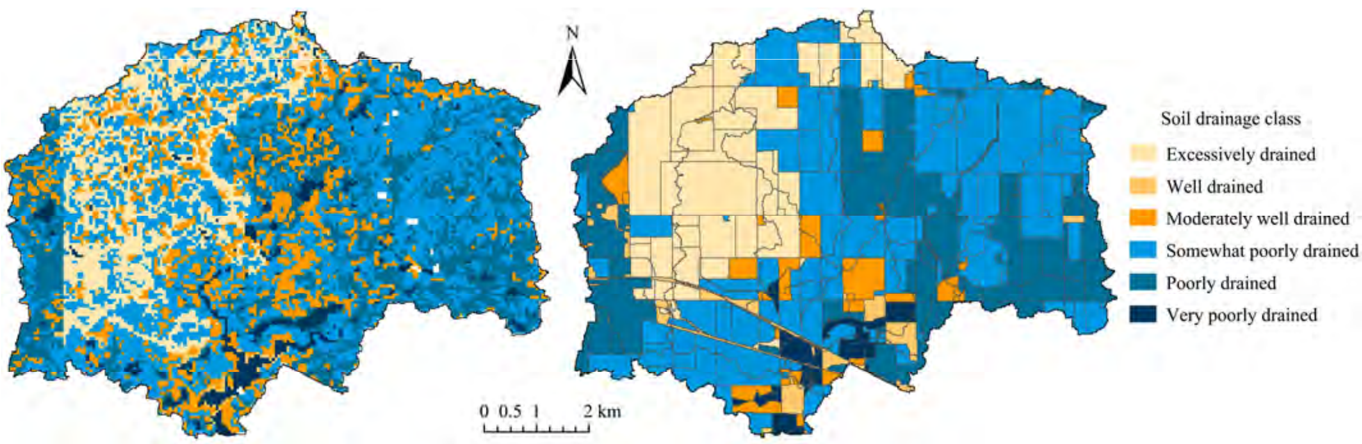

Figure 6 Soil drainage class for HRUs defined by the standard method (left) and field boundary method (right). Excessively drained soils were the majority drainage class for only the western part of the watershed, while most of the watershed had somewhat poorly drained soils.

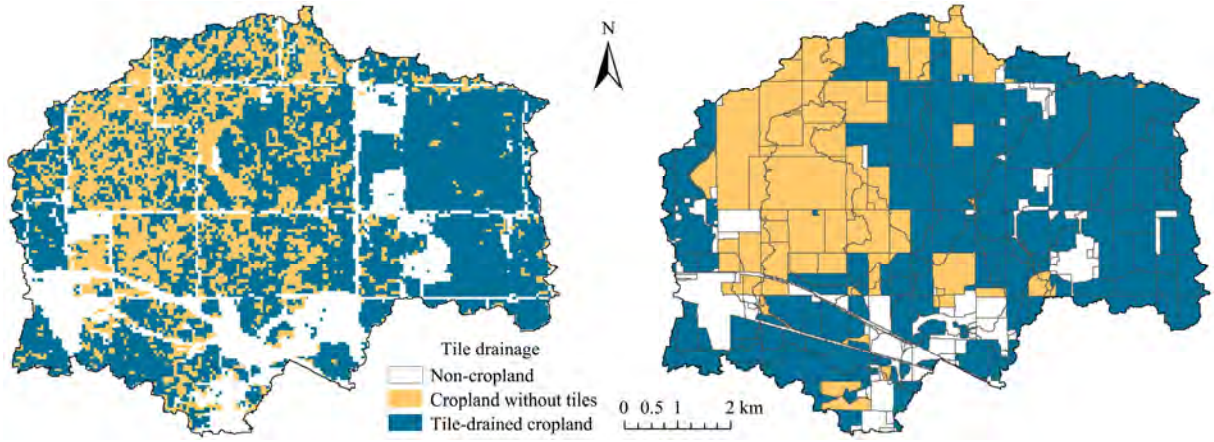

Figure 7 Estimate of tile-drained lands for HRUs defined by the standard method (left) and field boundary method (right).

Table 1 Land uses and soils in Little Pine Creek watershed based on the two HRU definition methods

	Standard method	Field boundary method
Percent of land use in watershed/%		
Corn	47	51
Soybean	33	37
Hay	6	5
Grass	10	2
Forest	4	5
Other	1	0
Percent of soils in watershed/%		
Somewhat poorly drained	41	41
Poorly drained	21	24
Very poorly drained	4	3
Total poorly drained	67	68
Tile-drained (% of watershed area)	53	59
Tile-drained (% of cropland area)	67	68

The 10-year average simulated corn yields were somewhat similar in the two approaches: 9.9 t/hm^2 for the standard approach versus 10.4 t/hm^2 for the field boundary approach. These SWAT estimated corn yields were close to the 10.1 t/hm^2 average corn yield based on USDA NASS estimates for Tippecanoe County during 2007-2012[24]. The simulated soybean yields were 2.8 t/hm^2 for both approaches, lower than the corresponding USDA NASS based average soybean yield of 3.3 t/hm^2 in 2007-2012.

3.3 Accuracy of simulated hydrology

Water balance and hydrology were quite reasonable for both approaches, despite using an uncalibrated model (Table 2). Daily or monthly R^2 above 0.6 and E_{NS} above 0.5 are generally considered a satisfactory fit for streamflow simulations[28,29]. Total depth of flow traveling through the watershed outlet of 0.42 m/yr corresponds fairly well to the measured value of 0.39 m/yr. Overall, both approaches yielded good estimation of water balance and hydrology at the daily and annual time scale.

Table 2 Water balance and goodness-of-fit for simulated stream flow against measured gage data

	Statistic	Standard method	Field boundary method
Flow at watershed outlet			
Goodness-of-fit	R^2 daily	0.67	0.63
	E_{NS} daily	0.67	0.63
	R^2 monthly	0.79	0.78
	E_{NS} monthly	0.79	0.78
Total flow depth in m/yr	Annual average	0.42	0.42
Tile flow in m/yr	Annual average	0.15	0.17

Notes: Measured flow depth was 0.39 m/yr for the three-year period in 2009-2012. Precipitation averaged 1.05 m/yr during that period. The SWAT model was not calibrated in either method.

Tile drainage accounted for 35%-41% of the total streamflow, which may be somewhat low for these heavily tile-drained lands. It is likely that some of the fields considered well drained (Figure 6) have some level of tile drainage installed; if so, the estimate of tile drains would be somewhat low. In addition, the tile drainage parameters used in this work are reasonable guesses, but there has been only limited analysis of model sensitivity to these parameters as the drainage routine is fairly new in the SWAT model[12,30]. Moriasi et al.[30] presented a case study of the new tile drainage approach, and the parameters we used here were largely similar to those they used: our drain depth (DDRAN) was 0.2 m closer to the surface, reflecting known differences between geographic regions; they spaced drains (SDRAIN) a little further apart at 27 m; and they calibrated the multiplication factor for lateral conductivity

(LATKSATF) to 3.8, while we chose to use a value of 4. One notable difference in our method was the maximum depth that can be drained in 24 hours, or drainage coefficient (DRAIN_CO), which they calibrated to 51 mm/d. We set DRAIN_CO to 20 mm/d, because tile drainage systems in the area are typically designed to drain 10-20 mm/d. We found, however, that daily flow was quite sensitive to DRAIN_CO, and daily hydrograph peaks could not be reached unless DRAIN_CO was set to a high value. It may be pertinent for future model development to determine a suitable infiltration approach for tile drained lands, which would allow for greater surface runoff during peak events.

3.4 Accuracy of simulated nutrients and sediment

Nitrogen, phosphorus, and sediment daily concentrations and loads at the watershed outlet were generally similar in the two approaches at the watershed scale (Table 3). Summary statistics for all days for three years did not differ considerably from summary statistics generated for (1) only those days with measured data or (2) monthly averages (not shown). The influence of turning off in-stream water quality modeling was insignificant as well, possibly due to the small size of the watershed and corresponding reach (not shown).

Predicted nitrate-N concentrations were somewhat lower, with greater temporal variability than the measured data. Measured nitrate-N concentrations had fairly smoothed fluctuations, while simulated results for the daily timescale showed spikes and drops according to precipitation (not shown). Figure 8 shows the spatial distribution of total nitrogen losses from all HRUs by the two HRU definition methods. The magnitude of total nitrogen losses clearly followed the soil drainage class and presence of tile drainage.

Table 3 Nutrient and sediment balance summary statistics from output.rch comparing two HRU definition methods against measured data at the watershed outlet for 2009-2012

Variable	Statistic	Standard method	Field boundary method	Observed values (2009-2012)
Nitrate-N concentration, /(mg·L^{-1})	Mean	3.5	3.2	6.6
	Standard deviation	5.0	5.1	4.0
	Minimum	0.0	0.0	0.03
	Maximum	46	44	23
Nitrate-N loading, /(kg·d^{-1})	Mean	470	520	560
	Standard deviation	1 500	1 800	995
	Minimum	0.00	0.00	0.01
	Maximum	22 000	23 000	6 400
Total phosphorus concentration, /(mg·L^{-1})	Mean	0.28	0.20	0.14
	Standard deviation	0.12	0.11	0.13
	Minimum	0.02	0.01	0.00
	Maximum	0.77	0.54	0.89
Total phosphorus loading/(kg·d^{-1})	Mean	16	11	13
	Standard deviation	23	16	44
	Minimum	0.1	0.0	0.00
	Maximum	210	130	370
Sediment concentration, /(mg·L^{-1})	Mean	65	37	22
	Standard deviation	48	29	33
	Minimum	3.1	2.9	1.2
	Maximum	400	230	260
Sediment loading, /(kg·d^{-1})	Mean	4 700	2 700	4 200
	Standard deviation	9 800	5 400	22 000
	Minimum	10	10	1.1
	Maximum	130 000	58 000	220 000

Note: All statistics were calculated from daily loads and concentrations reaching the watershed outlet over the model evaluation period.

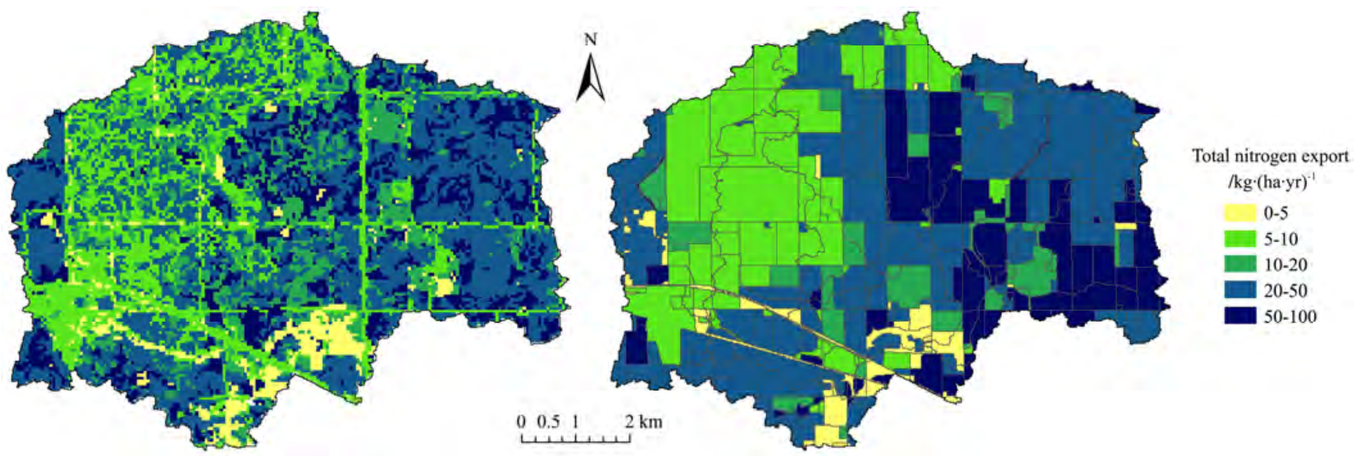

Figure 8 Annual average total nitrogen exported from HRUs defined by the standard method (top) and field boundary method (bottom). Total nitrogen losses were the greatest from tile-drained lands, and much lower from excessively drained soils.

Simulated phosphorus loads and concentrations at the watershed outlet were somewhat greater by the standard HRU definition approach compared to the field boundary approach and measured data. The disparity in sediment concentration was even greater, although total sediment loading from the standard method was fairly comparable to measured data. Sediment and phosphorus export was highly skewed, with a few highly erodible lands having very high predicted losses, which is masked in the field-based HRU method. Figures 9 and 10 clearly depict sediment and phosphorus export having more highly skewed distributions than nitrogen, as evidenced by the predominance of pollutant export in the lowest two or three categories on the five point scale (note that the scales are already built for skewed distributions, and they are similar for all pollutants, with the middle category aimed near the sample mean). The field boundary approach shows fewer extremes of high phosphorus and sediment transport than the standard approach, presumably because the average slope for the entire field was used.

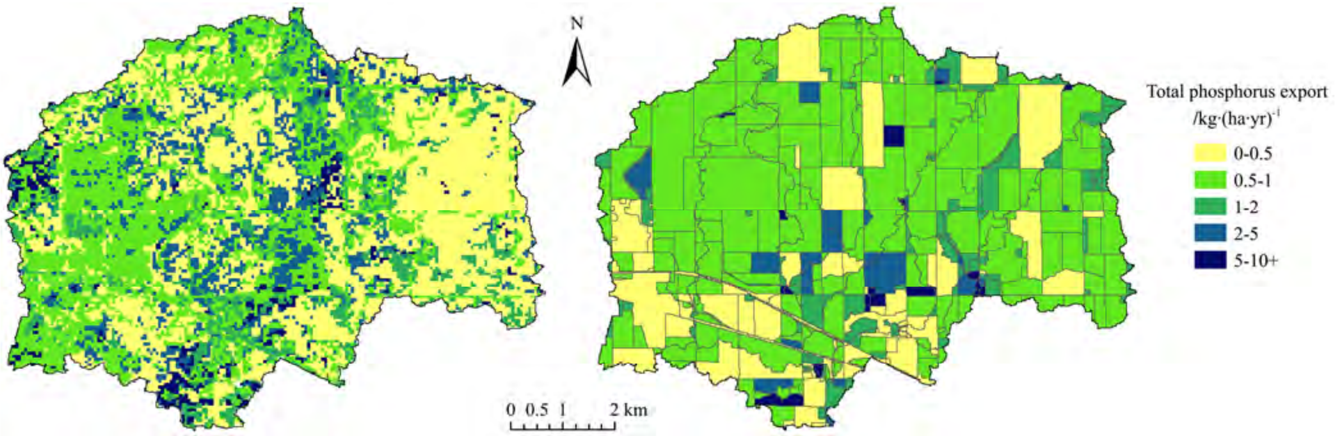

Figure 9 Annual average total phosphorus exported from HRUs defined by the standard method (left) and field boundary method (right). Phosphorus had a highly skewed distribution. The field boundary method masked the most extreme phosphorus losses, including outliers from the standard HRU method that exceeded 25 kg/(hm^2·yr).

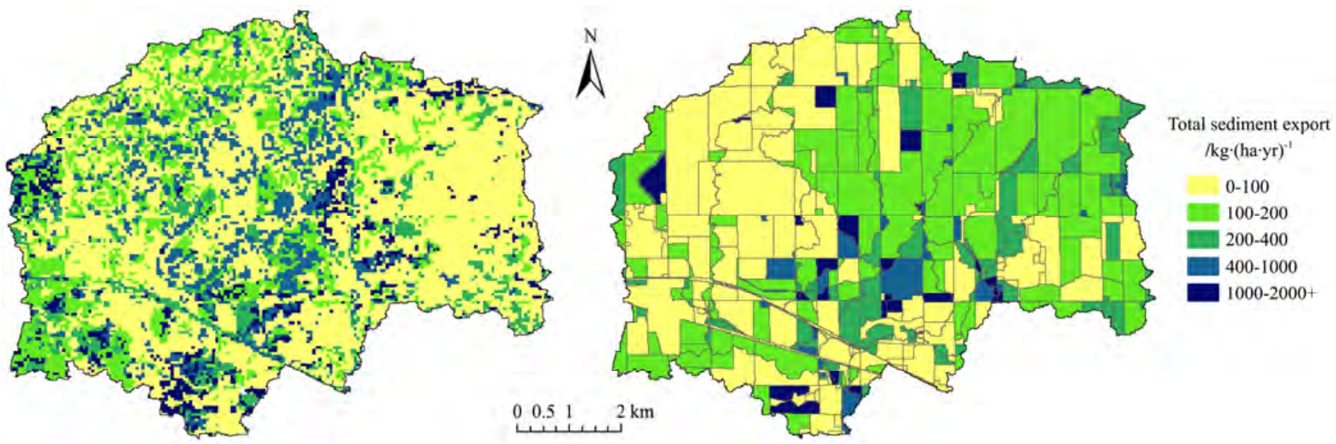

Figure 10 Annual average sediment exported from HRUs defined by the standard method (left) and field boundary method (right). Outliers in the highest category exceeded 50 t/(hm^2·yr) in the standard HRU method.

The simulated nutrient and sediment losses had somewhat acceptable performance according to measures of R^2 and E_{NS}. Monthly average loads yielded R^2 of 0.4-0.6 for nutrients and sediment, and E_{NS} of 0.46 for nitrate. Unfortunately, E_{NS} for monthly average sediment and phosphorus loading was below zero for both approaches. Model calibration could improve the timing of nutrient loading to some extent, but a peculiar phosphorus pattern in the measured data that may be due to application of manures on a University Farm is unlikely to be reproduced with current assumptions about farm management. Perhaps it is sufficient that daily loads and concentrations are near the measured range for nutrients and sediments.

4 Conclusions

A simple approach was developed for defining HRUs in the SWAT by field boundaries. The HRUs were defined by field boundaries through the addition of uniquely named soils to SWAT's usersoil database and the assignment of one majority soil to each field. If the upper limit on the number of land use categories allowed in an ArcSWAT database was raised in the future, land use could be used instead, which more closely matches the field boundary layer, and which would allow for subdivision of HRUs based on soils. This case study demonstrates just one possible approach to defining SWAT's HRUs by crop field boundaries. It is a flexible approach wherein a user can separate HRUs by any boundary layer. While basin-level water and nutrient balance were reasonable by this approach, field-level outputs by this method may differ more from the standard method based on the size of field boundaries used due to selecting a majority soil in each crop field.

Defining HRUs by field boundaries increases the usability of the SWAT model for a number of small watershed and field scale applications, such as targeting conservation practices to farm fields, as well as incorporating more detailed spatially explicit management and conservation practice information into the SWAT model. The approach resulted in reasonable water, nitrogen, phosphorus, and sediment balance at the watershed scale, and performed in many ways similar to the standard model set up. This may extend the usability of SWAT to a broader range of applications, particularly for communication with stakeholders who desire to see model inputs and outputs correspond meaningfully to fields. Field-based results match the scale of management changes and most conservation practices, and may be more readily comprehended by farmers.

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