SWAT2009_LUC: A Tool to Activate the Land Use Change Module in SWAT 2009

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Abstract. *In watersheds where land use and land cover changes take place over the modeling period, using a single land use geospatial dataset is not a true representation of the watershed condition. This article describes development of SWAT2009_LUC, a computer-based, geospatial tool that ingests multiple land use/land cover geospatial datasets and other associated information interactively and activates the land use change (LUC) module in the latest release of the Soil and Water Assessment Tool (SWAT 2009). The geospatial tool was tested in an urbanizing watershed in northwest Arkansas by using three temporal land use geospatial data layers acquired during 1999, 2004, and 2006. The results show that the land use distribution generated by the tool was consistent with the input land use layer for each year and was updated correctly during the model run. Model simulations with and without the activation of the LUC module showed that groundwater was underpredicted by up to 15%, while surface runoff was overpredicted by up to 13% at the subwatershed scale when a single post-development land use layer was used. Overall, the results showed that activating the LUC module using the SWAT2009_LUC tool improves the spatial and temporal hydrological responses from the SWAT 2009 model.*

Keywords. *Change, Geospatial, Hydrology, Interface, Land use, Modeling, SWAT.*

Among the various causes of water quality degradation, land uses can have one of the greatest impacts. Temporal land use changes (LUCs) either due to urbanization or deforestation have been widely reported to influence the water cycle (e.g., Miller et al., 2002), sedimentation (e.g., Ouyang et al., 2010), and agrochemical losses (e.g., Ahearn et al., 2005) in watersheds. Past studies have reported an empirical relationship between land use distribution and water quality at the watershed scale (Haggard et al., 2007; Migliaccio et al., 2007) and demonstrated that certain LUC, such as urbanization, can even mask the effect of any concurrent conservation practices (Chiang et al., 2010). Understanding hydrological alterations resulting from land use changes has been identified as a major research need (DeFries and Eshleman, 2004), and its quantification has become an integral aspect of many catchment-scale water assessment studies (Calder, 1999; DeFries et al., 2004).

Physically based models are useful tools for such assessments since they provide a comprehensive yet cost-effective way to evaluate the relationship between long-term land use changes and hydrologic processes in a watershed. For instance, previous studies conducted using the Long-Term Hydrologic Impact Assessment (L-THIA) model reported that an increase in imperviousness greatly increased average annual surface runoff (Bhaduri et al., 2000; Choi et al., 2005). Similarly, Twine et al. (2004) used the Integrated Biosphere Simulator (IBIS) model for the entire Mississippi River basin to quantify the hydrological impacts of deforestation and changing grass cover to crop cover. While such modeling studies help decision-makers target regional-scale impacts, land use change may often be a local phenomenon and have disproportional subwatershed-scale impacts. Distributed models offer an advantage in such scenarios because they have the necessary spatial resolution to represent localized land use changes. Among various distributed models, the physically based Soil and Water Assessment Tool (SWAT) has found wide application in various watershed assessment studies (Borah and Bera, 2004).

Land use change assessment studies using the SWAT model have been previously reported (Fohrer et al., 2001; Lin et al., 2009; Ghaffari et al., 2010; Ouyang et al., 2010; Wang and Kalin, 2011). In these studies, researchers replaced current land uses with alternatives in the model to understand and quantify hydrological and water quality impacts. Assessment of futuristic LUC impacts have also been conducted by using projected land use geospatial datasets in calibrated SWAT models (e.g., Kalin and Hantush, 2009; Tong et al., 2009). Collectively, the knowledge gained from these studies has improved modeling algorithms and our overall understanding of LUC impacts at various spatial and temporal scales. However, use of a single land use layer in previous LUC assessments could result in stationarity of model responses. Accurate model predictions depend, in part, on how well matched the watershed responses are to the temporal resolution of land use input data. White and Chaubey (2005) observed that changing land uses could alter the hydrology and sedimentation in a watershed; however, this information is unknown to a model that is operating based on a single land use geospatial dataset. This was especially critical in their study area because the SWAT model received land use infor-

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mation from a single pre-development land use layer, thereby introducing a source of additional uncertainty.

Recognizing this limitation in SWAT, a LUC module was incorporated into the latest version, SWAT 2009, and was briefly introduced by Arnold et al. (2010). A detailed discussion of the mechanism by which the LUC module represents temporal land use is presented in the next section. In spite of this much-required enhancement to SWAT, only two studies known to us have thus far made use of this module (Chiang et al., 2010; Saraswat et al., 2010). This could be attributed, in part, to the intensive input data requirement to activate this module. The module requires fractional areas of every hydrological response unit (HRU), the finest subdivision of the SWAT model, each time the land use is updated. Considering that in medium- to large-scale watersheds, the number of HRUs can range from a few hundred to thousands, updating the fractional areas in response to multiple years of land use datasets available for a SWAT project could be a daunting task and prone to manual errors. Hence, there is a need for an automated tool that can accurately produce the necessary input data files required to activate the LUC module. Another factor that may have contributed to the lack of usage of LUC module is the fact that its applicability has not yet been evaluated. Chiang et al. (2010) used the LUC module to separate out water quality impacts resulting from land use changes and implementation of conservation practices, while Saraswat et al. (2010) used the module without comparing its efficacy. A focused study comparing model hydrological responses with and without the LUC module promises to provide valuable insight for SWAT modelers and help in evaluating if activating this module would be a worthwhile effort for their study area.

This study has two major objectives: (1) to develop a user-friendly computer-based application to assist modelers in creating input files required to activate the LUC module, and (2) demonstrate the LUC module's usefulness for watersheds where land use has changed during the modeling period. Results obtained from this study should provide the necessary tools, demonstrate applicability, and thereby increase usage of the LUC module in SWAT 2009.

LUC Module Concept

SWAT is a distributed watershed model that is capable of calculating watershed processes for all homogeneous areas within a watershed. To support this task and prepare the necessary input files, the model's algorithm is integrated with a geographical information system (GIS) using an interface called ArcSWAT (Winchell et al., 2008). ArcSWAT first divides a watershed into smaller areas called subwatersheds using either user-defined thresholds or user-defined boundaries. Using a GIS-based overlay operation, the subwatersheds are further divided into homogeneous areas called HRUs, which are assumed to have the same land use, soil, and slope (Pai et al., 2011). Because of the heterogeneity within a subwatershed, the same unique combination of land use, soil, and slope is found in multiple locations. Consequently, HRUs tend to be fragmented in nature, as demonstrated by Pai et al. (2011).

Availability of detailed land use, soil, and slope GIS geospatial datasets can result in too many unique combinations and increase the number of HRUs. For instance, a subwatershed with four land use types, ten soil types, and four slope classes will result in 160 ($4 \times 10 \times 4$) HRUs. This multiplier effect substantially increases the computational time, which in turn may adversely affect the success of modeling projects. To mitigate this situation, ArcSWAT provides an option for reducing the number of HRUs by using threshold percentages. Threshold percentages, provided separately for land use, soil, and slope, result in merging of those land uses, soils, and slope classes that occupy less than a predetermined percentage area within every subwatershed.

Subsequently, using relevant geospatial input layers, ArcSWAT parameterizes each HRU with several specific characteristics, such as its area, slope, land use, soil properties, etc. Of particular interest in this study is the area of the HRU calculated by ArcSWAT. For each HRU, the interface calculates the number of cells that have a unique combination of land use, soil, and slope and divides this by the total number of cells within a subwatershed to output the fractional area. This fractional area, also termed as HRU_FR in the model, ranges from 0 to 1, with a higher number indicating larger occupation in the subwatershed. For instance, a value of 0.1 indicates that the HRU occupies 10% of the subwatershed area. The HRU fractional area and its land use, in combination, reflect the land use distribution of the watershed at that spatial scale.

In the newer version of the SWAT model (SWAT 2009), the LUC module allows the user to update land use distribution by updating the HRU_FR variable during the model run. This process could be better understood using a simplified hypothetical scenario, as illustrated in figure 1. Consider a subwatershed with three HRUs (HRU-1, HRU-2, and HRU-3) in 1992 and 1999. In the year 1992, let us say that HRU-1, HRU-2, and HRU-3 encompassed forest, urban, and pasture areas and occupied 30%, 40%, and 30% of the subwatershed, respectively (fig. 1a). However, by 1999 due to increased urbanization, the forest, urban, and pasture areas occupied 30%, 50%, and 20% areas, respectively (fig. 1b). Notice that HRU-3 was initially a pasture HRU and is now a combination of 20% pasture and 10% urban. As a result, the HRU_FR variable for HRU-1, HRU-2, and HRU-3 is updated from 0.3, 0.4, and 0.3 to 0.3, 0.5, and 0.2, respectively. The constraint set for this redistribution is that the sum of HRU_FR for a subwatershed should be equal to 1. The LUC module in SWAT 2009 can be used to update such land cover changes multiple times during the model run depending on the availability of land use geospatial data. To activate the LUC module in this scenario, the model needs two files in the TxtInOut folder: lup.dat and a user-defined HRU fraction text file (say, file1.dat). Syntaxes for these files are available in the SWAT 2009 input/output documentation (Neitsch et al., 2009). Essentially, the lup.dat file provides the model with information about when the land use has changed, while file1.dat provides updated values of HRU_FR for each HRU for a particular year.

Understanding the geospatial processes behind the development of HRU layers by ArcSWAT was important during the development of the SWAT2009_LUC tool. Once the user uploads the land use, soil, and elevation layers, ArcSWAT performs a grid-based overlay operation to identify unique combinations of land use, soil, and slope (derived from elevation) in every subwatershed. Each unique combination is then assigned an identification number (henceforth called HRU ID). Thereafter, using the HRU ID information, a thematic raster layer is created for the entire watershed that spatially identifies all HRUs. This raster layer, which is created by de-

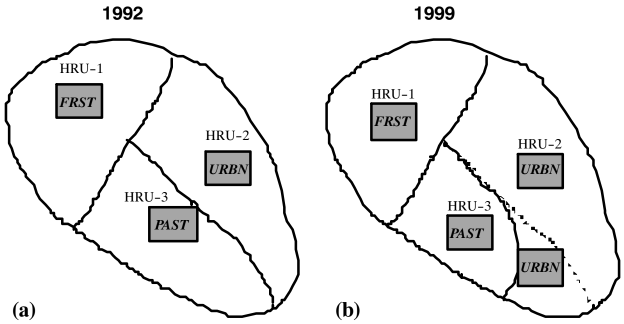

Figure 1. Illustration of forest (FRST), urban (URBN), and pasture (PAST) within a hypothetical subwatershed: (a) spatial distribution in 1992, and (b) spatial distribution in 1999 showing increase in urban land cover.

fault in all SWAT projects, is stored in the Watershed\Grid folder of the SWAT project with filename HRU1s.aux.

If thresholds are applied to the SWAT project, due to merging, then the number of HRUs in the SWAT project is reduced compared to the situation when no thresholds are applied. Therefore, the default HRU raster (i.e., HRU1s.aux) is no longer an accurate spatial representation of the HRUs. ArcSWAT also creates a shapefile, stored in the Watershed\Shapes folder with filename hru1.shp that was primarily developed for use by visualization programs such as VizSWAT, although it is not spatially accurate (R. Srinivasan, personal communication, 9 May 2009). Currently, a geospatial layer does not exist to define accurate spatial locations of HRUs in SWAT projects with HRU thresholds.

However, spatial definition of the HRUs in raster format was a critical requirement for the SWAT2009_LUC tool algorithm. Therefore, a new approach was developed to derive a post-threshold HRU raster, which is discussed later in this article.

Materials and Methods

Depending on the size of the watershed, the resolution of input layers, and the threshold percentages applied for HRU delineation, the number of HRUs in a SWAT project can range from a few hundred to thousands. Therefore, calculating the HRU fractional area for multi-year land use geospatial datasets can be laborious and potentially a source of errors, as stated earlier. The following section describes the development of an automated tool to produce the necessary input files required to activate the LUC module in SWAT 2009.

SWAT2009_LUC Tool

The LUC concept described in the previous section is adapted in a user-friendly graphical user interface called SWAT2009_LUC (fig. 2). Three major panels (SWAT Input Data, Land Use Map Input, and Process Data) guide the user in providing the necessary input information and retrieving the output from SWAT2009_LUC. The elements within these panels such as pushbuttons, dropdowns, and form fields are sequentially enabled so that users can systematically provide the required information. The input requirement starts with the user interactively identifying the SWAT2009_LUC fold-

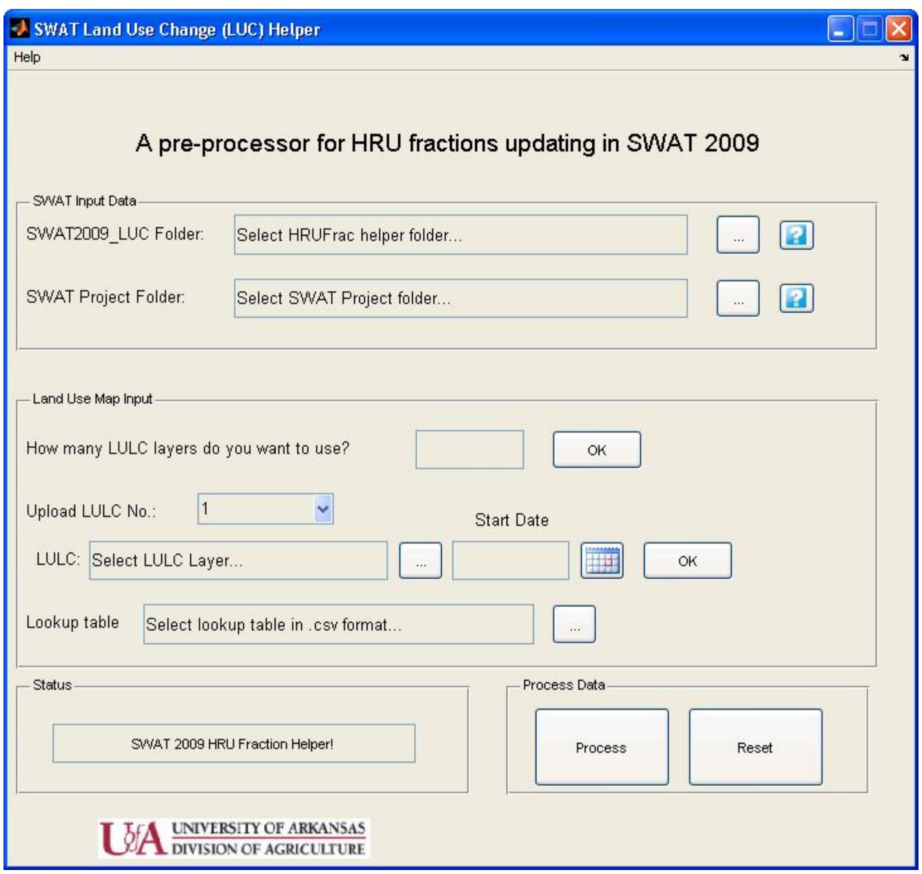

Figure 2. SWAT2009_LUC tool for developing input files to activate the land use change (LUC) module in SWAT 2009.

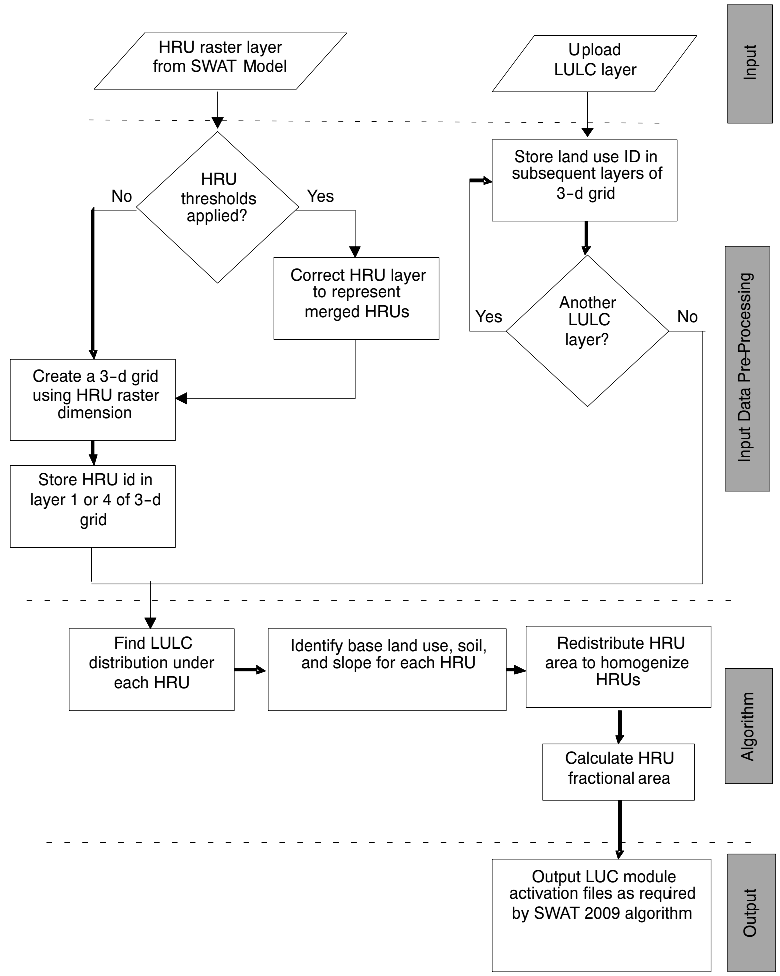

Figure 3. Flowchart of the SWAT2009_LUC tool for activating the land use change (LUC) module for dynamically updating land use/land cover (LULC) in SWAT 2009.

er. Once this folder is identified, the tool creates three other subfolders within this folder (Shape, Raster, and Output, to store vector, grid, and output files, respectively) as the user continues to interactively provide input data to this tool. The functionality of the tool after the user identifies the SWAT2009_LUC folder is explained in the following paragraphs and illustrated in figure 3.

Once the SWAT2009_LUC folder is created, the user is prompted to identify the SWAT project folder, following which, the tool automatically identifies the HRU raster created by ArcSWAT. Since ArcSWAT is integrated with ArcGIS (ESRI, Redlands, Cal.), the HRU layer is stored in a proprietary format. To maintain the stand-alone nature of this tool, the open-source geospatial abstraction data library (GDAL, 2010) was incorporated within SWAT2009_LUC, which allows conversion of the HRU raster to a geo-referenced tag image file format (GeoTiff). The GeoTiff format is widely used by a variety of commercial and open-source GIS software. The GeoTiff HRU is stored as layer 1 in a three-dimensional (3-D) grid whose extent is determined by the extent of the HRU layer. A similar grid-based data manipulation format was used by Pai et al. (2011) in the Field_SWAT tool to map the HRU outputs to user-defined field boundaries.

To support this grid-based operation in SWAT2009_LUC tool, a raster layer was required that identifies the spatial location of the HRUs. However, as mentioned earlier, in SWAT projects where HRU thresholds are applied, currently there exists no raster layer to spatially locate the HRUs. Therefore, an approach was developed to derive a post-threshold HRU raster using available information. ArcSWAT creates a post-threshold HRU shapefile, with filename hru1.shp, which informs SWAT2009_LUC if thresholds are applied. The attribute table of hru1.shp contains a list of the HRU IDs that actually passed the threshold. We call these HRUs the dominant HRUs. In other words, dominant HRUs are those HRUs that have passed the user-defined threshold for land use, soil, and slope within a subwatershed.

This information is used by the SWAT2009_LUC tool to spatially identify those cells within the HRU raster (HRUs1.aux) that are dominant (i.e., those that passed the threshold). The remaining HRUs are those whose land use, soil, and/or slope occupy an area within the subwatershed that is less than the thresholds provided by the user (henceforth called non-dominant HRUs). Information from hru1.shp thus allows SWAT2009_LUC to spatially separate out dominant and non-dominant HRUs in HRUs1.aux. Moreover, the information in the shapefile also allows SWAT2009_LUC to match the HRU IDs between those present in the default raster (HRUs1.aux) and those that are ultimately used in the SWAT project (hru1.shp).

Table 1. Illustration of HRU merging based on Euclidean allocation methodology: (a) an example of binary layer with 1 representing dominant HRUs and 0 showing non-dominant HRUs, (b) Euclidean distances to the nearest dominant HRU cell, and (c) row and column numbers of the nearest dominant HRU cell.

(a) Binary HRUs						(b) Euclidean Distance to Nearest Dominant						(c) Euclidean Distance Allocation					
0	0	0	0	1	0	2.24	1.41	1.00	1.00	0.00	1.00	(2,3)	(2,3)	(2,3)	(1,5)	(1,5)	(1,5)
0	0	1	0	0	0	1.41	1.00	0.00	1.00	1.00	1.00	(3,2)	(3,2)	(2,3)	(2,3)	(1,5)	(3,6)
0	1	0	0	0	1	1.00	0.00	1.00	1.41	1.00	0.00	3,2)	(3,2)	(2,3)	(2,3)	(3,6)	(3,6)
0	1	0	0	0	1	1.00	0.00	1.00	1.00	1.00	0.00	(4,2	(4,2)	(4,2)	(5,4)	(5,5)	(4,6)
0	0	1	1	1	1	1.41	1.00	0.00	0.00	0.00	0.00	(4,2)	(4,2)	(5,3)	(5,4)	(5,5)	(5,6)
0	0	0	1	0	0	2.24	1.41	1.00	0.00	1.00	1.00	(4,2)	(5,3)	(5,3)	(6,4)	(5,5)	(5,6)

In order to develop a thematic equivalence between the default raster (HRUs1.aux) and vector layer (hru1.shp) created in thresholded SWAT projects, non-dominant HRUs were merged with neighboring dominant HRUs using a Euclidean allocation method. In this method, first, a separate binary layer, with 1's and 0's representing dominant and non-dominant HRUs, respectively, was created and stored as layer 2 in the 3-D grid. Then, Euclidean distances were calculated from all dominant HRUs to nearby non-dominant HRU cells and stored in layer 3. Finally, the nearest-neighbor approach was used to merge dominant HRUs with non-dominant HRUs in HRUs1.aux.

This three-step procedure can be better explained using a hypothetical rectangular subwatershed containing 36 cells (6 rows and 6 columns), as shown in table 1. Table 1a shows the binary HRU layer for this subwatershed, which is stored as layer 2 in the 3-D grid. In this layer, the cells with value of 1 indicate dominant HRUs while those with a value of 0 indicate non-dominant HRUs. Dominant HRU cells have been highlighted in gray for better visualization. Table 1b indicates the minimum Euclidean distance for the subwatershed for each HRU. Euclidean distances were calculated using the following formula:

$$\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{1}$$

where (x_1, y_1) and (x_2, y_2) represent the coordinates of the non-dominant HRU and the nearest dominant HRU, respectively.

As a result, notice that the dominant HRUs are assigned a value of 0.00, while the other cells are denoted with a value of 1.00, 1.41, or 2.24 units depending on the distance to the nearest dominant HRU. Using this information, each non-dominant HRU cell is allocated to the nearest dominant HRU cell, as indicated by the row and column numbers in table 1c. This concept was applied to HRUs1.aux to derive a post-threshold HRU layer using a matrix-based operation within MATLAB.

The derived HRU layer consists of exactly the same number of HRUs used by the SWAT model; however, more importantly, it provides a spatial definition for all HRUs, which was critical for use in SWAT projects with HRU thresholds. To validate this method, the estimated areas occupied by HRUs within a subwatershed using this method were manually compared with those calculated by ArcSWAT that are printed in the "hru" table within its project database. Once the HRU layer is developed and stored in layer 4 of the 3-D grid of SWAT2009_LUC, the requirements for the SWAT Input Data panel are complete.

Subsequently, the Land Use Map Input data panel can be used to upload multiple land use geospatial datasets. The tool assumes that all GIS layers uploaded are geo-referenced and in the same projection system as the HRU layer. Checks have been incorporated into the tool to warn users of inconsistent land use geospatial datasets. Nevertheless, users are encouraged to geo-reference land use datasets and ensure that their extents match spatially with the HRU layer created by ArcSWAT. Once proper land use geospatial datasets are uploaded, the tool converts ESRI-based formats to geo-tiff formats using GDAL. This completes the input requirement of SWAT2009_LUC, after which the user can press the Process button.

The algorithm then spatially identifies the cells for each HRU and extracts the corresponding land use data for those cells. In addition, it reads all the HRU text files in the TxtInOut folder of the SWAT project to extract the base land use, soil, and slope definition of each HRU. Because of land use change, it is likely that HRUs will not remain homogenous during the model run, as demonstrated in figure 1. In other words, for instance, a pasture HRU may have several cells classified as various other land uses in the subwatershed. The algorithm searches for other similar HRUs to distribute the non-homogenous cells. For instance, if the pasture HRU mentioned earlier has few cells containing urban area, the algorithm will search for urban HRUs with similar characteristics within the same subwatershed. If an HRU with the same land use and soil is not identified, then the algorithm looks for a HRU match with the same land use. Once a suitable match is identified, the non-homogenous cells are allocated to this HRU. This logical distribution is done to maintain the homogeneity of HRUs while making sure that the fractional HRUs within a subwatershed are equal to 1. The fractional area is re-calculated for each land use layer and printed in the Output folder as per the LUC module format requirements. The tool also makes a copy of the lup.dat and land use update files (one for each land use layer) in the TxtInOut folder of the SWAT project, which activates the LUC module in SWAT 2009.

In some cases, a suitable HRU may not be found to receive non-homogenous cells. For instance, if some of the pastures were converted to urban areas in a non-urban subwatershed, then SWAT2009_LUC will not be able to find a suitable HRU match within that subwatershed. Consequently, the model will continue to simulate with the existing land use for that particular HRU. This limitation is inherent in the current SWAT model framework: the model does not allow any new land uses to be introduced after initial delineation. Overcoming this limitation will probably require SWAT code modifications to introduce new land uses (or HRUs) based on temporal land use information. SWAT code modifications were outside of the scope of this work but will be addressed in future enhancements to SWAT2009_LUC.

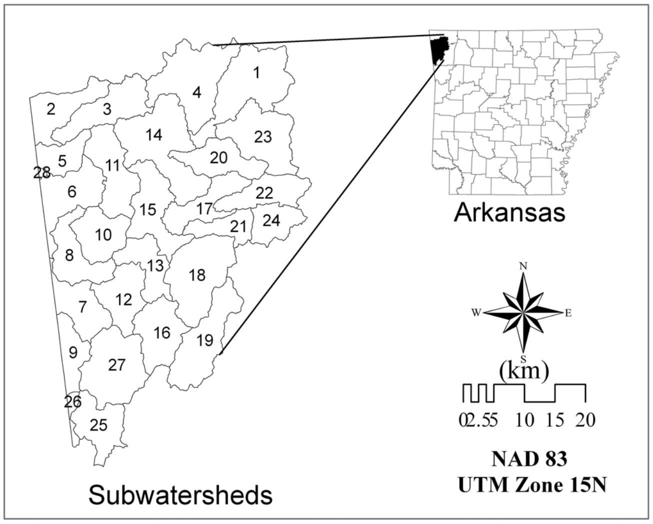

Figure 4. Location of the watershed and subwatershed boundaries of the Illinois River drainage area in Arkansas (IRDAA).

Case Study: Illinois River Drainage Area in Arkansas (IRDAA)

Although the tool is applicable to any watershed, its application is demonstrated for a SWAT model developed for an urbanizing watershed in the Illinois River drainage area in Arkansas (IRDAA; 1963 km^2; fig. 4). A detailed discussion of the study area, SWAT model setup, and input data layers has been reported previously (Saraswat et al., 2010; Saraswat and Pai, 2011). In this article, only relevant aspects of the model setup are discussed.

SWAT Model Setup

The model was set up using the ArcSWAT 2009.93.1 interface with the SWAT 2009 (version 427) algorithm. The watershed and subwatersheds were delineated using 8- and 12-digit hydrologic unit code (HUC) boundaries, respectively. Subwatershed 28 in the 12-digit HUC boundary layer has a small area (<0.1%) and hence was excluded from further analysis. Topography and soils data were introduced into the model using a 10 m digital elevation model (DEM) and soil survey geographic (SSURGO; USDA-NRCS, 2005) datasets, respectively, while the land use layer from the year 2006 was used to delineate initial HRUs in the model. This resulted in 8,051 HRUs, which were further merged using arbitrary thresholds of 5%, 10%, and 0% for land use, soil, and slope classes, respectively. Merging of HRUs resulted in 1,126 HRUs in the SWAT project. Precipitation and temperature during the study period (1997-2008) were acquired using a combination of NEXRAD and gauge station data, depending on their availability. These datasets were made compatible with the SWAT model using a post-processing geostatistical tool developed by Zhang and Srinivasan (2010). All other SWAT inputs were kept at their default values.

Land use changes in the past decade have been dynamic in the northwest Arkansas region (White and Chaubey, 2005) and in this watershed (Haggard, 2010). Hence, three land use geospatial datasets from 1999, 2004, and 2006 were used to update the initial 2006 land use distribution of HRUs using the LUC module. The land use distribution at the watershed scale generally showed increasing urban areas and decreasing pastures and forest areas from 1999 to 2006 (table 2).

Table 2. Distribution of major land uses in the Illinois River Drainage Area in Arkansas (IRDAA) watershed.

Year	Pastures (%)	Forest (%)	Urban (%)
1999	56	36	7
2004	49	37	12
2006	45	37	13

Evaluation Procedure

Due to the localized nature of economic growth, LUC is not uniform for all subwatersheds of the IRDAA. To understand the model response to such spatially variable land use changes, it was important to evaluate hydrological outputs at the subwatershed scale. The evaluation procedure for this study was two pronged. First, it was verified that the tool produced accurate input files for activating the land use change module. To ensure the accuracy of input files, first, the sum of the fractional area of all HRUs within a subwatershed was confirmed to be equal to 1. This requirement conforms to the basic definition of the HRU_FR variable, as discussed earlier. In addition, it was also confirmed separately whether the land use distribution produced by the input files was consistent with the land use layer supplied by the user. This was done manually by aggregating the HRU areas for each land use on a subwatershed basis and comparing it with the input LULC layer. To verify the functionality of the output files, a test was performed to determine if the input files produced by SWAT2009_LUC activated the LUC module. This was done by checking to see if the HRU areas were dynamically changing in the HRU output file (output.hru).

The second part of the evaluation consisted of verifying model sensitivity to this module by comparing model hydrological responses with and without the LUC module during the study period (1997-2008). The scope of this evaluation was limited to hydrologic processes in SWAT; water quality outputs was not considered at this time, but will be addressed in the future. Evapotranspiration, surface runoff, and groundwater are among the most dominant hydrological processes in the IRDAA (Green and Haggard, 2001). Model responses for these processes were evaluated with the LUC module turned on and off. The objective was to check the sensitivity of the module for these processes.

Results and Discussion

SWAT2009_LUC was developed in the MATLAB (The Mathworks Inc., Natick, Mass.) programming environment and is a stand-alone tool, which implies that it does not require any other GIS software on the computer. The tool was utilized to create LUC module input files for the IRDAA watershed consisting of 1,126 HRUs, which were delineated using the 2006 land use layer. Three land use geospatial datasets from 1999, 2004, and 2006 were input into the tool, with land use updates arbitrarily scheduled for January 1 of each year. As mentioned earlier, the tool organizes HRU and land use information into a grid format. The size of the grid used was 7,040 rows and 4,630 columns. Note that the grid size is a function of the original HRU layer created by ArcSWAT, which in turn is a function of the DEM layer that is read into the project.

The strength of MATLAB in processing large matrices was leveraged for this application. With all the necessary input layers and information fed into SWAT2009_LUC, the processing time for the three land use geospatial datasets was about 5 min on a desktop computer with 64-bit processor and 8 GB of RAM. This reflects a tremendous savings in time for a modeler, who may otherwise have to spend considerable time manually calculating the HRU fractional area for land use updates. Subsequently, the interface automatically copied the required files (lup.dat, file1.dat, file2.dat, and file3.dat) to the TxtInOut folder of the SWAT model, which activated the LUC module.

Because thresholds were used while developing the SWAT model, the original HRU raster developed by ArcSWAT does not accurately identify the new HRU locations. As such, the tool used a Euclidean distance allocation method to merge dominant HRUs in the original HRU raster with non-dominant HRUs. The fractional area of all HRUs within the subwatershed was equal to 1, which conforms to the definition of the HRU_FR variable. The areas of 1,126 HRUs in the newly developed HRU raster matched closely ($R^2 = 0.98$) to the HRU areas output by ArcSWAT (fig. 5). Efforts will be made in the future to enhance our algorithm so that this correlation can be improved. In addition, it was verified that the HRU area dynamically changed on January 1 of 1999, 2004, and 2006 upon scrutiny of the HRU output file (output.hru).

The land use redistribution produced because of changing HRU area closely matched the land use distribution in the LULC layer for all years. The results for the 1999 LULC layer are presented in figure 6. In this cluster bar plot, urban, forest, and pasture land use distribution from the 1999 LULC (solid border) are stacked for each subwatershed and compared with those estimated by the SWAT2009_LUC (dotted border). It is clear from the figure that land use distributions closely followed and reflected the land use from 1999. The minor discrepancies observed could have resulted because of the merging effect of HRUs. The actual land use distribution input to the SWAT model is always slightly different from the input land use distribution (Bosch et al., 2004). Nonetheless, the LUC module input files produced by the tool were found to be reasonably true to their input land use geospatial datasets.

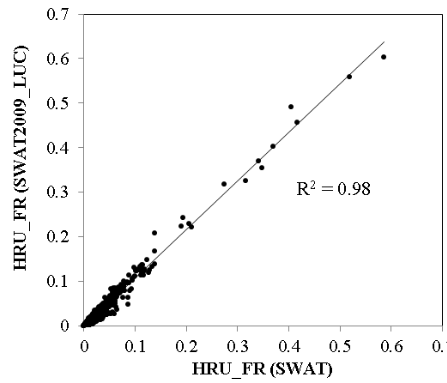

Figure 5. Relationship between HRU fractional area (HRU_FR) calculated by ArcSWAT and SWAT2009_LUC.

The next phase of evaluation was to understand the usefulness of the LUC module for simulating dominant hydrological processes in the IRDAA. The research question was: Are the model responses sensitive to the activation of the LUC module? To evaluate this, the model was run with and without the LUC module activated on a yearly time scale, and its overland output file (output.sub) was used to quantify the average annual evapotranspiration (ET), surface runoff, and groundwater flow. Note that the simulations without the LUC module were a function of the 2006 land use, which is characterized by large urban developments, especially in the eastern part of the watershed (subwatersheds 21, 22, 23, and 24). To quantify the land use change, a bar plot showing differences between 1999 and 2006 for each subwatershed and three major land uses has been placed on the same *x*-axis to understand how land use change could have a feedback effect on hydro-

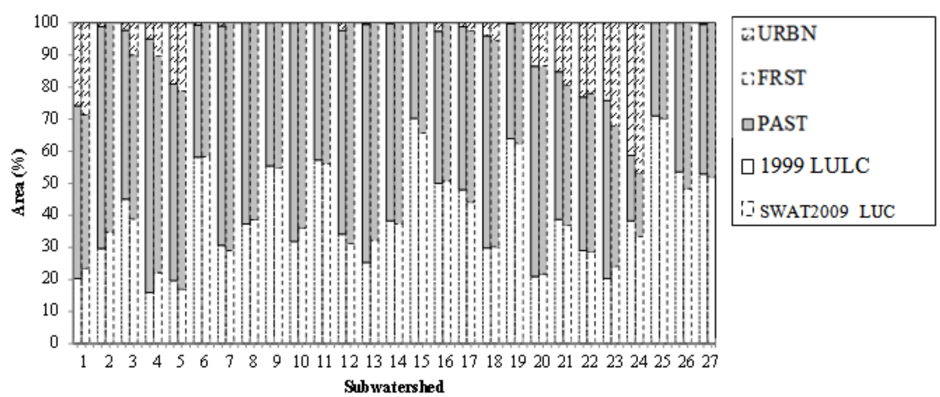

Figure 6. Pairwise subwatershed comparison of land use distribution estimated by SWAT2009_LUC tool (dotted border) against 1999 land use layer data (solid border). Left columns indicate land use distribution from 1999 land use, while right columns indicate those estimated by SWAT2009_LUC.

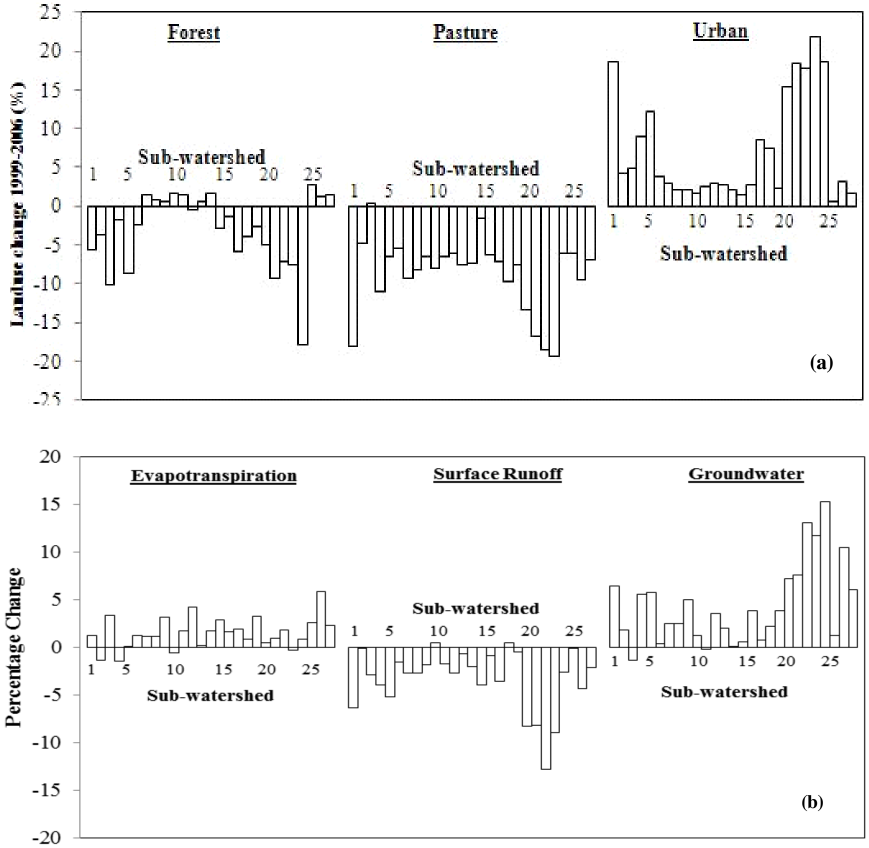

Figure 7. Effect of using single land use layer on key hydrological processes: (a) land use change (LUC) between 1999 and 2006 for each subwatershed, and (b) percentage change in evapotranspiration, surface runoff, and groundwater when the LUC module is activated.

logical processes (fig. 7a). Depending upon the subwatershed, urban areas increased from 2% to 22% between 1999 and 2006, while during the same period forest and pasture land uses mostly decreased, with a maximum of 18%.

Figure 7b shows the percentage increase or decrease in simulated annual ET, surface runoff, and groundwater flow when the LUC module was activated. Activating the LUC module resulted in a gradual changing of land use from pervious to impervious surfaces, as mentioned above. Hence, we see that once the LUC module was activated, annual average groundwater flow mainly increased, with a maximum of 15%, while surface runoff mostly decreased, with a maximum of 13%.

Higher surface runoff and lower groundwater are typically associated with impervious areas (Tong et al., 2009). With the LUC module deactivated, the model used information from a single post-development land use layer. As a result, temporal subwatershed-scale surface runoff was overpredicted. This effect was greater for subwatersheds showing the largest increases in urban areas, where correspondingly the highest groundwater increases and evapotranspiration and surface runoff decreases were exhibited. The larger groundwater flow simulated when the LUC module was activated is perhaps a better reflection of temporal variation of land uses in the IRDAA.

In contrast, ET showed smaller changes with a general increasing trend when the LUC module was activated. ET is a combination of evaporation and transpiration. As the land cover changes from plant cover to impervious areas, transpiration is likely to decrease while evaporation is likely to increase. These two sub-processes appear to have a balancing effect in the subwatersheds of the IRDAA during the study period. Ghaffari et al. (2010) have shown that these two sub-processes can be non-linear in nature, while Li et al. (2007) showed that a threshold exists for land use to change in a watershed before ET and runoff show dramatic increases or decreases.

Regardless of the actual volume of increases or decreases in the hydrological responses, it is clear that the LUC module imparts sensitivity to the model against changing land uses in the watershed. However, as seen from figure 6b, this may not be spatially uniform; subwatersheds with greater urbanization exhibited greater impacts on hydrological processes. By using the SWAT2009_LUC tool and activating the LUC module in SWAT, temporal land uses can be quickly input into the SWAT model and the impact of land use changes can be better appraised. Because the model is distributed in nature, its subwatershed outputs are important not only for calibration/validation processes but also to identify critical subwatersheds (Tripathi et al., 2003). Such inter-subwatershed comparisons benefit from accurate representation of their respective land use changes. Other studies have also documented the sensitivity of the SWAT model to land use input (Heathman et al., 2009). Hence, improved spatially distributed model responses can be expected from using the SWAT2009_LUC tool.

One of the questions that may arise from this study is: Does the predictive ability of the model improve when the LUC module is activated? From figure 7b, it is obvious that the model sensitivity to LUC module activation is not spatially uniform. The benefits of using the LUC module are dependent on the intensity and scale of land use changes. SWAT models that are calibrated at a single-gauge in a watershed with little land use change may not exhibit the benefit of such improved spatially distributed responses. Other researchers have observed that small errors in impervious land surfaces could have a substantial effect on the uncertainty of runoff modeling results (Stuede and Johnson, 1990; Endreny et al., 2003; White and Chaubey, 2005). The findings from this study showed that in subwatersheds with greater land use changes (such as in subwatersheds 22, 23, and 24), an average of 13% higher groundwater and 8% lower surface runoff contribution was simulated when the LUC module was activated. This is likely to improve the temporal predictive ability of the model since it is a function of land use changes. However, we did not have a long-term measured dataset from either of these urbanizing subwatersheds to verify if the activation of the LUC module resulted in better predictions. Overall, based on the land use change pattern, we speculate that model responses better reflect land use changes when the LUC module is activated. Nevertheless, availability of a measured long-term dataset from an urbanizing area is expected to further improve our understanding of the LUC module in SWAT.

Summary

The results from this article advance SWAT model applications in two ways. First, they provide SWAT modelers with a novel computer-based geospatial tool, SWAT2009_LUC, to prepare input files required to activate the LUC module in SWAT 2009. Results from application to the IRDAA SWAT model showed that the tool was able to produce LUC module input files that successfully and accurately changed the land use three times during the model run period. Once the tool ingests the necessary input datasets and information, the time required for development of these files was only about 5 min. Because the LUC module input is data intensive, this tool can encourage modelers to quickly verify if incorporating land use changes enhances their models' predictive abilities.

Secondly, the results provide theoretically underpinning and demonstrate advantages of the new LUC module in SWAT 2009. Model responses were studied with and without the LUC module activated for the urbanizing IRDAA watershed. Depending on the subwatershed, the urban areas increased by 2% to 22% during the study period, which resulted in overprediction of groundwater by up to 15% when the LUC model was not activated. In addition, a single post-development LULC layer overpredicted the surface runoff for most subwatersheds. In summary, activation of the LUC module is expected to result in improved temporal and spatial hydrological responses at the subwatershed scale.

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