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HYDROLOGIC EVALUATION OF THE LOWER MEKONG RIVER BASIN WITH THE SOIL AND WATER ASSESSMENT TOOL MODEL

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ABSTRACT

The Mekong River Commission (MRC) was established in 1957, to facilitate the joint planning and management of the Mekong River Basin. In 1995, an agreement was signed by Laos, Thailand, Vietnam, and Cambodia regarding how to share and protect the Mekong River's resources. This study documents the ability of the Soil and Water Assessment Tool (SWAT) to simulate the hydrology of a 629,520 km^2 basin which is comprised of the area south of China including the Midstream and Delta catchment areas. The SWAT model, version 2003, has been applied to generate the runoff for the Mekong River Basin which has been divided into eight subareas covering the areas upstream of Kratie, around Tonle Sap (the Great Lake) and some parts of Vietnam. First, the SWAT model parameters for the gauged streamflows along the tributaries of the Mekong River were calibrated and validated for periods of 1985-1992 and 1993-2000, respectively. The statistical evaluation results for model calibration and validation show that the Nash-Sutcliffe efficiency (N_{SE}) monthly and daily values generally range between 0.8 and 1.0 for all of the mainstream monitoring stations. The Mekong River Basin is one of the largest drainage areas that the SWAT model has been successfully applied to and aids in the establishment of a hydrologic baseline for this region. The LMRB simulation demonstrates that the model can potentially be used as an effective water quantity tool within this basin. The dominant challenge in modeling this watershed was the time and computer resources required.

Keywords: *Mekong river commission, water quantity, SWAT, hydrological model, Mekong river basin.*

1. INTRODUCTION

The Mekong River is the longest major river in southeastern Asia with a drainage area that covers portions of six countries. The river originates in China and flows through or borders Myanmar, Laos, Thailand, Cambodia and Vietnam. The Mekong River Basin (MRB) is the land area that includes the streams and rivers that run into the Mekong River. The headwaters commence on the Tibetan Plateau and continue through regions with varying elevation, topography and vegetation. Only the Amazon River Basin has more water and biodiversity than the MRB. The Lower Mekong River Basin (LMRB; Cambodia, Lao PDR, Thailand and Viet Nam) is populated with approximately 60 million people and is considered to be one of the most culturally diverse regions of the world. Agriculture, fishing and forestry provide employment for approximately 85% of the basin's residents (MRC, 2009). The Mekong Delta is highly productive and its inhabitants are dependent on its food and fishery production. Due to reliance on the aquatic resources within this region, it is essential to their survival that pollution is minimized to maintain the fish population and reduce soil salinization. Interest in the hydrology of the MRB continues to grow due to the water shortages, floods, and salt water intrusion it endures and for economic development purposes.

The MRB can potentially feed up to 300 million people a year based on its rice production. Some farmers are trying to produce more rice using multiple irrigation techniques. This water usage reduces the

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quantity and quality of downstream water that reaches the Mekong Delta. Environmental degradation is a primary concern for the areas sharing the MRB's resources. Preservation of the waterways and the quantity and quality of the river will benefit the environment as well as future generations. With the current rate of population growth, the economy is expected to grow based on manufacturing and services rather than agriculture adding to the demands already being placed on the basin's natural resources such as overfishing, deforestation, overharvesting due to a lack of regulation.

Each country in the Indo-China Peninsula has different priorities regarding natural resource management. Their respective populations and level of development vary which impact their decisions and order of priorities. The capitol cities of Lao PDR (Laos) and Cambodia, Vientiane and Phnom Penh, are both located near the Mekong River. This results in increased interest on the part of both countries regarding decisions affecting the LMRB. Lao PDR (Laos) has five million people and water resources that have the potential to be developed. Cambodia has 10 million people and relies on the Tonle Sap (the Great Lake) (Fig. 1) for the majority of its freshwater fish in Southeast Asia. Any degraded water quality from the Mekong River can impact this lake and those whom depend on its resources. Northeast Thailand has over 20 million people; due to excessive vegetation removal, soil erosion, and salinization of arable lands, water quality is declining in nearby water bodies that stress the quality of the water resources. The final portion of the LMRB has about 20 million Vietnamese whom depend heavily on rice paddy production in the Mekong Delta. The rice production occurs on about 2.5 million hectares and is some of the most highly productive agricultural land in the world. During the dry season, production occurs at a fraction of the total possible in order to limit salt water intrusion. If water quality (salt water intrusion) and quantity decline in the dry season, the Mekong Delta could be irreversibly impacted since it is already heavily impacted by the tide which can vary by four meters during the dry season.

In an effort to facilitate cooperation with managing the MRB water usage, the Mekong River Commission (MRC) was established in 1957. The MRC represents The Kingdom of Cambodia (Cambodia), The Lao People's Democratic Republic (Laos), The Kingdom of Thailand (Thailand), and The Socialist Republic of Viet Nam (Vietnam) whose countries are directly impacted by the Mekong River. These countries signed an agreement in 1995 (MRCS, 2005) regarding the sharing and protection of the Mekong River's resources under the guidance of the MRC, with a primary focus on the LMRB. The Upper MRB (UMRB) is located in portions of China and Myanmar (Burma); they participate only as dialogue partners because the Mekong River is not as critical a resource for those two countries.

This study focuses on the usage of the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Arnold and Forher, 2005; Gassman et al., 2007) to assess if the model can effectively simulate the hydrologic balance of the large region that encompasses the LMRB. The objectives of this study were: 1) to evaluate the accuracy in simulating the hydrologic balance of the LMRB, and 2) to test the model's hydrologic viability at several gauges throughout the LMRB. This study provides the opportunity to use extensive gauge data to determine how well the SWAT model can simulate a large region.

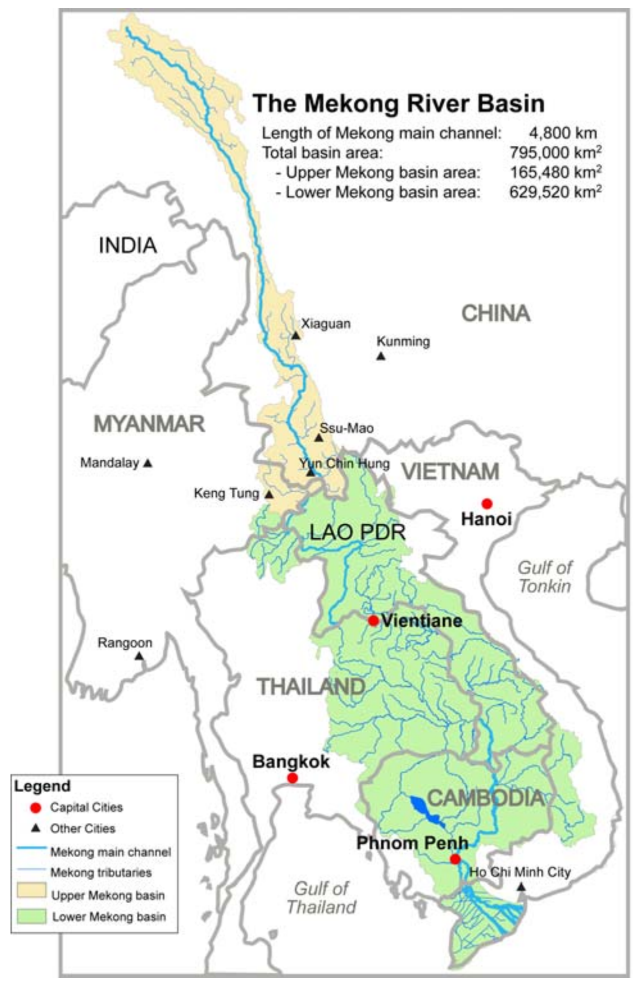

Fig. 1: The Mekong River Basin and its characteristics (MRC, 2009)

2. THE MEKONG RIVER BASIN

The total catchment area of the MRB is 795,000 km^2 and produces approximately 475,000 million m^3 of runoff during the rainy season (MRC, 1997). The entire length of the Mekong River is 4,800 km long (Figure 1) and is the tenth largest river in the world on the basis of mean annual flow at the river mouth (MRC, 2005). The LMRB has a total basin area of 629,520 km^2 with a river length of 4,200 km. Figure 1 illustrates the shape of the MRB and the longitudinal profile of the Mekong River from the headwater to the river's mouth. The source of the Mekong River is located in China's Qinghai Province (Figure 1); from there it flows across the Chinese Province of Yunnan, then forms the border between Myanmar (Burma) and Lao PDR (Laos), and continues on forming most of the border between Lao PDR and Thailand. Once the Mekong exits Thailand, it flows next across Cambodia, passes through a delta in southern Vietnam, and ultimately empties into the South China Sea. Approximately 78% of it comprises the Lower Mekong River Basin (LMRB) that includes the four downstream riparian countries of Lao PDR (Laos), Thailand, Cambodia and Vietnam. Table 1 describes the MRC participants by country and the respective areas that are located within the boundaries of the MRB. Acrisols are the dominant soil order, which are tropical soils that have a high clay accumulation in a horizon and are extremely weathered and leached. Their characteristics include low fertility and high susceptibility to erosion if used for arable cultivation (FAO, 2000). Due to the dominance of the Acrisol soils, rice is the main crop grown. The rest of the areas are mixtures of deciduous and evergreen covers as well as woodland and shrubland with some undisturbed forest land.

3. SWAT BACKGROUND AND INPUT DATA

3.1 The Soil and Water Assessment Tool

The SWAT model has undergone continuous development by U.S. Department of Agriculture since 1990 (Williams et al., 2008; Gassman et al., 2007). SWAT is a continuous time model that operates on a daily time step. The model is physically based, uses readily available inputs, is computationally efficient for use in large watersheds, and is capable of simulating long-term yields for determining the impact of land management practices (Arnold and Allen, 1996). Components of SWAT include: hydrology, weather, sedimentation/erosion, soil temperature, plant growth, nutrients, pesticides, and agricultural management (Neitsch et al., 2002a; 2002b).

SWAT contains several hydrologic components (surface runoff, ET, recharge, stream flow, snow cover and snow melt, interception storage, infiltration, pond and reservoir water balance, and shallow and deep aquifers) that have been developed and validated at smaller scales within the EPIC (Williams et al., 1984), GLEAMS (Leonard et al., 1987), and SWRRB (Williams et al., 1985; Arnold et al., 1990) models. Interactions between surface flow and subsurface flow in SWAT are based on a linked surface-subsurface flow model developed by Arnold et al. (1993). Characteristics of this flow model include non-empirical recharge estimates, accounting of percolation, and applicability to basin-wide management assessments with a multi-component basin water budget. The surface runoff hydrologic component uses Manning's formula to determine the watershed time of concentration and considers both overland and channel flow. Lateral subsurface flow

Table 1: Mekong River Basin countries including area and portion of country in the MRB

Nations	Area (km^2)	Mekong River Basin portion in nation (km^2)
The People's Republic of China	9,597,000	165,000
The Union of Myanmar (Burma)	678,030	24,000
The Lao Peoples Democratic Republic (Laos)	236,725	202,000
The Kingdom of Thailand	513,115	184,000
Cambodia	181,100	155,000
Social Republic of Viet Nam	331,700	65,000

can occur in the soil profile from 0 to 2 m, and groundwater flow contribution to total streamflow is generated by simulating shallow aquifer storage (Arnold et al., 1993).

Current SWAT reach and reservoir routing routines are based on the ROTO (a continuous water and sediment routing model) approach (Arnold et al., 1995), which was developed to estimate flow and sediment yields in large basins using subarea inputs from SWRRB. Configuration of routing schemes in SWAT is based on the approach given by Arnold et al. (1994). Water can be transferred from any reach to another reach within the basin. The model simulates a basin by dividing it into subwatersheds that account for differences in soils and land use. The subbasins are further divided into hydrologic response units (HRUs). These HRUs are the product of overlaying soils and land use.

3.2 Previous SWAT Model Simulations for Large River Basins

The SWAT model has been applied to national- and watershed-scale projects within the United States, the European Union (Barlund et al., 2007), China (Hao et al., 2004), India (Kaur et al., 2004), Australia (Sun and Cornish, 2006) and Africa (Schuol and Abbaspour, 2006). Gassman et al. (2007) summarizes streamflow calibration and validation results for several watersheds throughout the world. The contiguous United States was divided into 18 Major Water Resource Regions (MWWR) for the Hydrologic Unit Model of the United States (HUMUS). The SWAT model was successfully applied within these regions which contributed to the U.S. Resources Conservation Act Assessment of 1997. The HUMUS project used approximately 2,100 8-digit hydrologic unit areas that were delineated by the USGS. Average annual simulated runoff results were compared to long-term USGS stream gauge records. Results indicated that over 45 percent of the modeled U.S. was within 50 mm the measured data while 18 percent was within 10 mm. The model underpredicted runoff in mountainous areas that may have been a reflection of the lack of climate stations present at high elevations. Considering the spatial resolution of the databases and assumptions needed in order to simulate large-scale hydrologic conditions, the SWAT model was able to realistically simulate the water balance.

The SWAT model has also been used to simulate other large river basin systems including the Lushi hydrological station which is part of the Yellow River's monitoring system (Hao et al., 2004). The Lushi watershed area is 4623 km^2 and is characterized by a mountainous landscape. The hydrologic component of the model was calibrated for five years and validated with nearly two years of data. The observed and simulated monthly flows showed agreement of Nash-Sutcliffe efficiency values ($N_{SE;}$ Nash and Sutcliffe, 1970) values greater than 0.8 for the calibration and validation periods.

3.3 Input Data

The SWAT hydrologic model requires soil parameter input for bulk density, available water capacity, texture, organic matter, saturated conductivity, land use (crop and rotation), management (tillage, irrigation, nutrient and pesticide applications), weather (daily precipitation, temperature, solar radiation, wind speed), channels (slope, length, bankfull width and depth), and the shallow aquifer (specific yield, recession constant, and revap coefficient) (Neitsch et al., 2002a; 2002b).

The ArcView SWAT (AVSWAT) interface (Di Luzio et al., 2004) was applied to process and manage Geographic Information Systems (GIS) digital elevation data (90 m), a single land use map (1x satellite images) and a soil map classified according to the Food and Agriculture Organization (FAO) 1988 system, which have been developed in coordination with the MRC. Using the SWAT interface, the LMRB upstream of Kratie in Cambodia (Figure 2) was disaggregated into eight subareas with a total of 510 subbasins (Figure 2). The six subareas (Figure 2) that have hydrologic gauges along the mainstem and tributaries of the Mekong River were calibrated and validated for periods of 1985-1992 and 1993-2000, respectively. Subareas 1 through 6 are directly linked to the Mekong River while the seventh and eighth subareas are linked to the Mekong River mainstream via tributaries (Figures 1 and 2). One of the eight subareas simulated includes the first subarea which contains the first outlet (103) even though it had negligible flow. The outlet from subbarea 1 (103) is the inlet for subbarea 2 (Figure 2).

The dominant Hydrologic Response Unit (HRU), which comprises a land use type and a soil class, has been assigned to each subbasin totaling 1,567 HRUs. The physical and hydraulic properties of soils have been obtained from the Global Soil Database (GBS) supplemented by local soil pedon data provided by the the Mekong River Commission Secretariat (MRCS, 2005).

Soil data was provided per participating country and was compiled by the MRC. The model was also set up with a single land use map. Threshold values

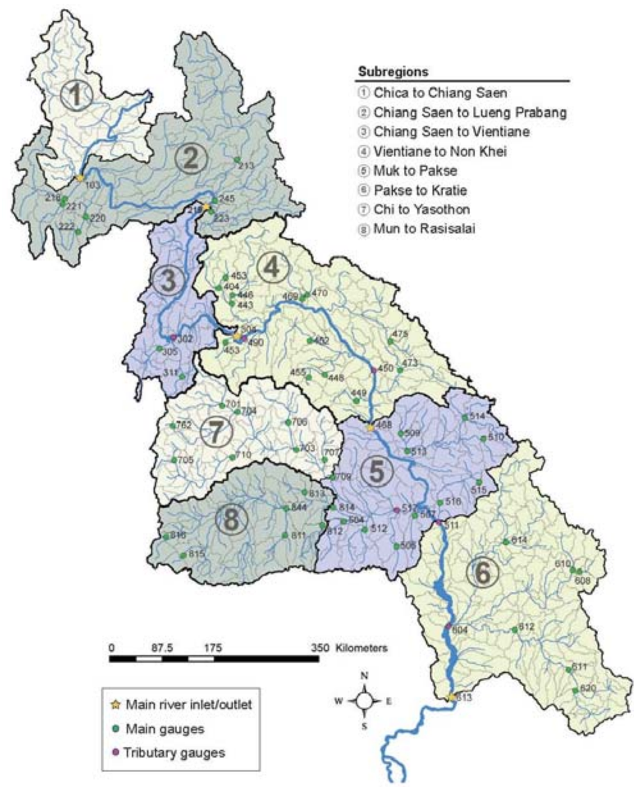

Fig. 2: Identification of the Lower Mekong River Basin subareas and gauges

between 15-19% and 16-18% were for the land use and soils, respectively, for each of the subareas simulated, which covers the LMRB from the China-Lao border to Kratie in Cambodia. The dominant land use map was data classified from the MRCS Forest Cover Monitoring Project and the entire dominant (landuse ≥ 15%) land uses are included.

Daily precipitation totals were obtained from the FAO and the World Meteorological Organization. Solar radiation, wind speed, and humidity values from observed daily values from their respective countries were used (MRC, 2001). When gaps were present in the record, the nearest climate station to the area was used; no climate interpolation occurred. The Penman-Monteith potential evapotranspiration option was used for all model simulations. Rainfall data used in the model were averaged using a multi-quadratic function approach, which relied on rainfall data from a gauging network, which were sparse in some areas.

4. MODEL CALIBRATION APPROACH

4.1 Statistical Evaluation Method

Grayson et al. (1992) provided guidelines for analyzing any model. In accordance with these authors' guidelines for testing the usefulness of a model, measured data were tested against SWAT2003 simulated data. The performance of the SWAT model, version 2003, was evaluated using a statistical analysis to determine the quality and reliability of the predictions when compared to observed values. The goodness-of-fit measure is the Nash-Sutcliffe efficiency (N_{SE}) value.

$$N_{SE} = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum\left(O_i - \overline{O}\right)^2}$$

Where n is the number of observations during the simulated period, O_i and P_i are the observed and predicted values at each comparison point i, and $\overline{O}$ and $\overline{P}$ are the arithmetic means of the observed and predicted values. The N_{SE} value was used to compare predicted values to the mean of the average monthly, and daily gauged discharge for the watershed, where a value of 1 indicates a perfect fit. For this study, the statistical value ratings for N_{SE} from Moriasi et al. (2007) are used (Table 2).

In addition to testing the usefulness of the model, it is important that the model is calibrated using representative precipitation events that include high and low streamflows (Green et al., 2006). Di Luzio and Arnold (2004) used representative storm events to successfully test the hourly streamflow component of SWAT. Although findings can be reported for short

Table 2: General reported performance ratings for N_{SE} (adapted from Moriasi et al., 2007)

Criteria	Value	Rating	Modeling Phase	Reference
N_{SE}	> 0.65	very good	calibration and validation	Saleh et al. (2000)
N_{SE}	0.54 - 0.65	adequate	calibration and validation	Saleh et al. (2000)
N_{SE}	≥ 0.50	satisfactory	calibration and validation	Santhi et al. (2001); adopted by Bracmort et al. (2005)

time periods, longer time spans are desired because they are expected to encompass the range of environmental variability that exists. A longer period of record implies that more of the variability will be captured; however, it is the highs and lows of the rainfall events that must be included in the calibration periods in order to obtain adequate validation results.

4.2 Model Calibration Methods

Initially, a parameter sensitivity analysis was performed per gauged subarea (1-6). Only the most sensitive parameters were adjusted in order to minimize calibration variances between the subareas for this large watershed. Table 3 lists the ranges of adjusted parameters suggested by Neitsch et al. (2002a) and the calibrated values of the adjusted parameters used for discharge calibration of the SWAT2003 model for the Mekong River basin. The soil evaporation compensation factor (ESCO), the initial soil water storage expressed as a fraction of field capacity water content (FFCB), the surface runoff lag coefficient and initial SCS runoff curve number to moisture condition II (CN2) values are generally high due to the tropical climate in which these simulations occur. The CN2 values are valid based on SCS (1972) tropical soil values and reflect the characteristics of the LRMB soils (i.e., high surface clay levels and extremely weathered and leached conditions); these were adjusted to represent the dominant land use classes. All other parameters were kept at the SWAT default values.

The calibrated SWAT model parameter values were determined from tributary and mainstream gauged measured data from 1985-1992 and then were validated with stream data from 1993-2000. An automated base flow separation technique was used to fractionate surface runoff from base flow (Arnold et al., 1995). Flow from the aquifer to the stream is lagged via a recession constant derived from daily streamflow records (Arnold and Allen, 1996).

The SWAT model simulations for each catchment (subareas 1-6) upstream of Kratie are calibrated against the observed natural flows. The first gauge was established on the China-Mynamar border where the flow from the border gauge was used as inflow for Mynamar. Additionally, there are three gauges which have seven upstream subbasins. The portion of the MRB in China is ungauged; therefore, the uppermost stream gauge in the LMRB was used as the starting calibration point (Figure 2; outlet/inlet 103).

5. RESULTS AND DISCUSSION

5.1 Water Balance

The Mekong River flows at 5,000 m elevation on the Tibetan plateau and eventually reaches the South China Sea. Due to the variation in topography, soil and land use the amount of precipitation received per subarea ranges greatly (Table 4), i.e. 0.1 to 564.1 mm month^{-1}, because of the contribution of the tributaries and orographic effects. The SWAT predicted hydrologic values presented in Table 4 average the monsoonal low (April or May) and high (September or October) flows. Total water yield is greatest for the areas that have the highest precipitation.

Table 3: Calibrated values of adjusted parameters for discharge calibration of the SWAT2003 model for the Lower Mekong River Basin for all eight simulated areas

Parameter	Description	Range	Calibrated Value
ESCO	Soil evaporation compensation factor	0.1 to 1.0	0.950-0.997
FFCB	Initial soil water storage expressed as a fraction of field capacity water content	0 to 1.0	0.990-0.995
Surlag	Surface runoff lag coefficient (days)	0 to 4	0.263-4.00
CN2	Initial SCS runoff curve number to moisture condition II	30 to 100	44-83

Table 4: Lower Mekong River Basin water balance

Gauge Subarea*	Gauge Name	Average Precipitation	Precipitation Range	Average Surface Runoff	Ground Water Flow	Total Water Yield	PET	ET
		---------- mm month^{-1} ----------						
2	Chiang Saen to Luang Prabang	120.0	0.1 - 329.3	6.4	13.3	29.3	101.6	62.7
3 , 4	Vientiane to Mukdahan	172.3	6.0 - 564.1	25.4	60.9	98.3	121.0	71.2
5, 7	Chi up to Yasothon	91.0	8.0 - 266.3	10.6	5.9	16.5	117.0	76.2
8	Mun up to Raisisalai	92.1	10.0 - 326.3	1.2	7.5	8.4	120.8	76.2

*Subarea numbers refer to their location on Figure 2.

Table 5. Calibration and validation results for mainstream gauges for SWAT subbasins upstream of Kratie in the subareas 1-6 (subbasin numbers 103-613)

Mainstream Gauge Subbasin Outlet	Mainstream Gauge Name	Catchment area (km^2)	Calibration Period	Monthly N_{SE}	Daily N_{SE}	Validation Period	Monthly N_{SE}	Daily N_{SE}
103	Mekong at Chiang Saen	189000	1/1/1985-12/31/1992	0.99	0.97	1/1/1993-12/31/2000	0.99	0.97
245	Mekong at Luang Prabang	268000	1/1/1985-12/31/1992	0.97	0.95	1/1/1993-12/31/2000	0.98	0.94
302	Mekong at Chiang Khan	292000	1/1/1985-12/31/1992	0.99	0.97	1/1/1993-12/31/2000	0.99	0.97
304	Mekong at Vientiane	299000	1/1/1985-12/31/1992	0.99	0.94	1/1/1993-12/31/2000	0.99	0.94
450	Mekong at Nakhon Phanom	373000	1/1/1985-12/31/1992	0.97	0.96	1/1/1993-12/31/2000	0.97	0.96
468	Mekong at Mukdahan	391000	1/1/1985-12/31/1992	0.98	0.96	1/1/1993-12/31/2000	0.98	0.97
490	Mekong at Nong Khai	302000	1/1/1985-12/31/1992	1.00	0.99	1/1/1993-12/31/2000	0.99	0.99
511	Mekong at Pakse	545000	1/1/1985-12/31/1992	0.99	0.98	1/1/1993-12/31/2000	0.99	0.98
604	Mekong at Stung Treng	635000	1/1/1985-12/31/1992	0.97	0.93	1/1/1993-12/31/2000	0.98	0.94
613	Mekong at Kratie	646000	1/1/1985-12/31/1992	0.97	0.92	1/1/1993-12/31/2000	0.98	0.94

The results for the 10 mainstream gauges (Figure 2) and tributary gauges for SWAT subbasins upstream of Kratie are presented in Table 5 and 6, respectively. The mainstream gauge calibration and validation monthly and daily N_{SE} values range from 0.92 to 1.00 and 0.94 to 0.99, respectively. Figure 2 illustrates the main inlet/outlets along the Mekong River and the ability of SWAT to simulate runoff in the LMRB as compared to observed data are presented in Table 4. The observed and simulated daily data for gauges 450 and 813 are presented in Figures 3 and 4, respectively. The seasonal fluctuations in rainfall presented in Table 4 are illustrated in both Figures 3 and 4. In general, the areas with more gauge data from which the calibrated parameter values were determined resulted in higher N_{SE} values for the respective subarea (i.e. subarea 4; Tables 5 and 6)). The key monitoring stations which provided gauged data resulted in simulated output with N_{SE} values ≥ 0.8 (Table 5). The sites along the Mekong's tributaries had monthly and daily N_{SE} values ranging from -0.01 to 0.95 and 0.37 to 0.90, respectively (Table 6). Subareas seven and eight had poor results based on the lack of data from which to calibrate its parameters. The entire LMRB indicates the importance of establishing gauge sites and the impact of the amount of data available for model parameter value determination.

In accordance with Grayson et al. (1992), SWAT2003's runoff simulation data were tested against measured runoff data. The monthly and daily averaged simulated stream discharge results (Table 5) were judged to be very good, based on the criteria suggested by Moriasi et al. (2007). The errors in gauging stations vary across the flow range but are more pronounced at the extreme low and high flows. The low flows were generally affected by recording errors while the higher flows were affected by rating errors. This can be corrected by improved instrumentation and improved rating estimates. Reasonable results were obtained for the areas with flat gradients of rainfall coverage. For all mainstream gauges, the model predicted the flow volumes within 1% error for year-round and high flow periods and 3% for low flow periods. The N_{SE} values for both monthly and daily flows for all of the gauging stations were higher than 0.9.

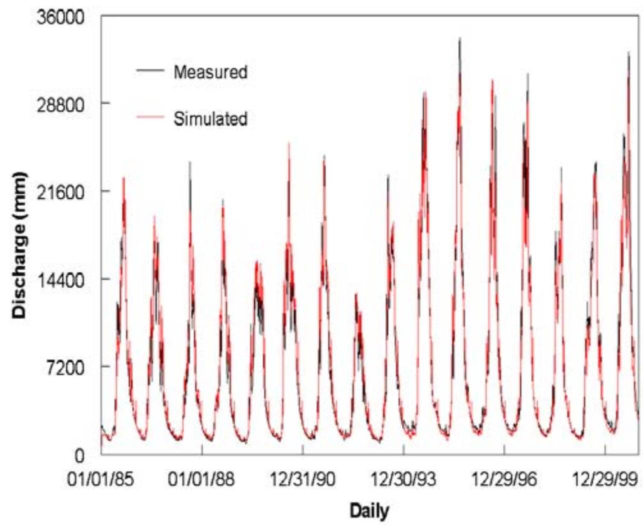

Fig. 3: Measured and simulated daily discharge for the MRB at the mainstream Gauge 450 from January 1985 through December 2000

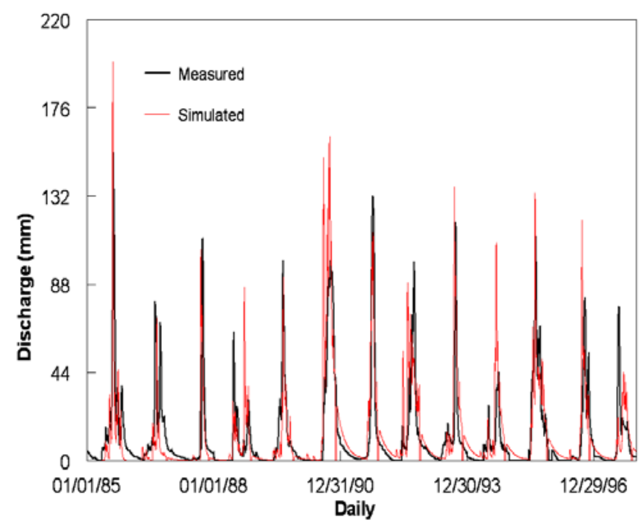

Fig. 4: Measured and simulated daily discharge for the MRB at Gauge 813, from January 1985 through December 1997, which is not directly linked to the Mekong River

Table 6: Calibration and validation results for tributary gauges

Tributary Gauge Subbasin Outlet	Tributary Gauge Name	Catchment area (km^2)	Calibration Period	Monthly N_{SE}	Daily N_{SE}	Validation Period	Monthly N_{SE}	Daily N_{SE}
213	Nam Ou at Muonag Ngoy	19700	1985-1992	0.72	0.55	1993-1999	0.75	0.55
218	Mekok at Chiang Rai	6060	1985-1992	0.71	0.66	1993-1999	0.79	0.65
219	Nam Suoung at Ban Sibounhom	5800	1985-1992	0.51	0.36	1993-1999	0.84	0.63
220	Nam Mae Ing at Thoeng	5700	1985-1992	0.74	0.49	1993-1999	0.85	0.77
221	Nam Mae Lao at Ban Tha Sai	3080	1985-1992	0.58	0.47	1993-1999	0.77	0.65
222	Nam Mae Ing at Khao Ing Rod	3450	1985-1992	0.65	0.52	1993-1999	0.73	0.63
223	Nam Khan at Ban Mout	6100	1985-1992	0.46	0.30	1993-1999	0.53	0.41
305	Nam Heuang at Ban Pak Huai	4090	1985-1992	0.69	0.43	1993-1999	0.79	0.65
311	Nam Loei at Ban Wang Saphung	1240	1985-1992	0.59	0.38	1993-1999	0.57	0.42
403+404	Nam Leak at Ban Hin Heup	5115	1985-1992	0.62	0.45	1993-2000	0.89	0.78
443+456	Nam Ngum at Ban Pak Khanoung	14300	1985-1992	0.78	0.64	1993-1999	0.90	0.84
446	Nam Ngum at Dam site	14200	1985-1992	0.69	0.50	1993-1999	0.82	0.66
448	Nam Oon at Ban Pok Yai	2140	1985-1992	0.83	0.76	1993-1999	0.58	0.52
449	Nam Kam at Na Kae	2360	1985-1992	0.80	0.73	1993-1999	0.85	0.77
451	Huai Mong at Ban Kruat	2370	1985-1992	0.70	0.55	1993-1996	0.76	0.67
452	Nam Songkhram at Ban Tha kok Daeng	4650	1985-1992	0.95	0.91	1993-1999	0.89	0.86
469	Nam Ngiep at Muong Mai	4270	1987-1992	0.82	0.65	1993-2000	0.74	0.63
470	Nam Sane at Muong Borikhan	2230	1987-1992	0.76	0.54	1993-2000	0.87	0.71
473	Se Bang Fai at Mahaxai	4520	1985-1992	0.72	0.56	1993-2000	0.76	0.62
475	Nam Theun at Ban Signo	3370	1986-1992	0.71	0.50	1993-2000	0.73	0.52
504	Huai Sam Ran at Ban Tha Rua	2890	1985-1992	0.62	0.46	1993-1999	0.42	0.30
506	Lam Dom Yai at BanFang Phe	1410	1985-1992	0.76	0.48	1993-1999	0.77	0.37

Table 6. Continued.

Tributary Gauge Subbasin Outlet	Tributary Gauge Name	Catchment area (km^2)	Calibration Period	Monthly N_{SE}	Daily N_{SE}	Validation Period	Monthly N_{SE}	Daily N_{SE}
507	Lam Dom Noi at SirindhornDam site		1985-1992	0.82	n/a	1993-1999	0.73	n/a
509	Se Chomphone at Ban Kengkok	2640	1985-1992	0.81	0.55	1993-1999	0.79	0.55
510	Se Lanong at Muong Nong		1985-1992	0.68	0.44	1993-1999	0.61	0.38
512	Huai Khayung at Saphan Huai Khayung	2900	1985-1992	0.67	0.42	1993-1999	0.43	-0.10
513	Se Bang Hieng at Ban Keng Done	19400	1985-1992	0.85	0.73	1993-1999	0.89	0.75
514	Se Bang Hieng at Tchepon	3990	1985-1992	0.67	0.39	1993-1999	0.62	0.44
515	Se Done at Saravanne	1172	1985-1992	0.71	0.44	1993-1999	0.81	0.67
516	Se Done at Souvannakhili	5760	1985-1992	0.73	0.57	1993-1999	0.93	0.67
517	Nam Mun at Ubon	n/a*	1985-1992	0.97	0.94	1993-1999	0.95	0.91
608	Se San (Dac Bla) at Kontum	3060	1985-1992	0.65	0.47	1993-2000	0.60	0.20
610	Krong Ko Po at Trung Nghai	n/a	1985-1992	0.84	0.51	1993-1999	0.75	0.32
612	Sre Pok at Lomphat	n/a	1985-1992	0.50	-0.33	1993-1999	0.46	-0.40
614	Se Kong at Attapeu	10500	1988-1992	0.68	0.42	1993-2000	0.65	0.40
620	Sre Pok (Ea Krong) at Cau 14	8650	1985-1992	0.75	0.14	1993-2000	0.72	0.41
701	Nam Pong at Ban Chom Thong	2570	1985-1992	0.68	0.52	1993-2000	0.74	0.50
703	Lam Pao at Kamalasai	5680	1985-1992	0.85	0.79	1993-1999	0.80	0.72
704	Nam Pong at Ubol Ratana Dam site	n/a	1985-1992	0.90	n/a	1993-2000	0.72	n/a
705	Huai Rai at Ban NonKiang	1370	1985-1992	0.88	0.69	1993-2000	0.81	0.58
706	Lam Pao at Lam Pao Dam site	n/a	1985-1992	0.83	n/a	1993-2000	0.80	n/a
707	Nam Yang at Ban Na Thom	3240	1985-1992	0.81	0.65	1993-1999	0.46	0.37
709	Nam Chi at Yasothon	43100	1985-1992	0.89	0.79	1993-1999	0.74	0.70
710	Nam Chi at Ban Chot	10200	1985-1992	0.71	0.54	1993-2000	0.79	0.72

Table 6. Continued.

Tributary Gauge Subbasin Outlet	Tributary Gauge Name	Catchment area (km^2)	Calibration Period	Monthly N_{SE}	Daily N_{SE}	Validation Period	Monthly N_{SE}	Daily N_{SE}
762	Nam Phrom at Chulabhorn Dam site	n/a	1985-1992	0.53	n/a	1993-2000	0.42	n/a
812	Huai Thap Than at Ban Huai Thap Than	n/a	1985-1992	0.79	0.69	1993-1998	0.82	0.70
813	Lam Sieo Yai at Ban Ku Phra Ko Na	n/a	1985-1992	0.74	0.61	1993-1997	0.71	0.55
814	Nam Mun at Rasi Salai	44600	1985-1992	0.81	0.72	1993-2000	0.77	0.60
815	Lam Pra Plerng at Lam Pra Plerng Dam site	n/a	1985-1992	0.62	n/a	1993-2000	0.46	n/a
816	Lam Ta Kong at Lam Ta Kong Dam site	n/a	1985-1992	-0.01	n/a	1993-2000	0.07	n/a
844	Nam Mun at Satuk	26800	1985-1992	0.59	0.38	1993-1996	0.77	0.63

*n/a = indicates data was not available.

6. CONCLUSIONS

Once a successful and realistic hydrologic simulation has been established for a large watershed, SWAT can then be utilized for simulating multiple scenarios over long periods of time to assist in the best management and policy decisions being made. Because both nonpoint and point source pollutant concentrations depend on flow, ensuring that the hydrologic balance can be predicted accurately allows another resource for countries to use to protect their quality and quantity of water on which they rely.

This study confirmed that SWAT2003 was able to simulate the hydrology of the Lower Mekong River Basin and that it can be used as a water management tool for this large system. The evaluation results for model calibration and validation indicate that the Nash-Sutcliffe efficiency monthly and daily efficiency values generally ranged between 0.8 and 1.0 at all of the mainstream monitoring stations. The results also showed that the SWAT model was able to address the water inlets and outlets present in the basin. The work completed in this study complies with the 1995 agreement with Laos, Thailand, Cambodia and Vietnam and is in collaboration with the Mekong River Commission whose role is to facilitate joint planning and management of the Mekong River Basin.

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REFERENCES

1. Arnold, J.G. and P.M. Allen. 1996. Estimating hydrologic budgets for three Illinois watersheds. J. Hydrol. 176:57-77.
2. Arnold, J.G., P.M. Allen, and G. Bernhardt. 1993. A comprehensive surface-groundwater flow model. J. Hydrol. 142:47-69.
3. Arnold, J.G., P.M. Allen, R.S. Muttiah, and G. Bernhardt. 1995. Automated base flow separation and recession analysis techniques. Groundwater 33:1010-1018.
4. Arnold, J.G. and N. Fohrer. 2005. SWAT2000: current capabilities and research opportunities in applied watershed modeling. Hydro. Process. 19(3):563-572.
5. Arnold, J.G., R. Srinivasan, and R.S. Muttiah. 1994. Large-scale hydrologic modeling and assessment. In: Effects of Human-Induced Changes on Hydrologic Systems. AWRA Annual Summer Symp., Jackson Hole, WY. American

Water Resources Association Tech. Pub. Ser. TPS-94-3, AWRA, Bethesda, MD, pp. 1-16.
6. Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. J. Amer. Wat. Res. Assoc. 34:73-89.
7. Arnold, J.G., J.R. Williams, A.D. Nicks, and N.B. Sammons. 1990. SWRRB: A Basin scale simulation model for soil and water resources management. Texas A&M Univ. Press, College Station.
8. Bärlund, I., T. Kirkkala, O. Malve, and J. Kämäri. 2007. Assesing the SWAT model performance in the evaluation of management actions for the implementation of the Water Framework Directive in a Finnish catchment. Environ. Model. Soft. 22(5):719-724.
9. Di Luzio, M. and J.G. Arnold. 2004. Development of models and conservation practices for water quality management and resource assessments. J. Hydrol. 298:136-154.
10. Di Luzio, M., J.G. Arnold, and R. Srinivasan 2004. Integration of SSURGO maps and soil parameters within a geographic information system and nonpoint source pollution model system. J. Soil Water Conserv. 59:123-133.
11. FAO. 1988. Soil Map of the World. Revised Legend. Reprinted with corrections. World Soil Resources Report 60. FAO, Rome.
12. FAO. 2000. FAO Land and Plant Nutrition Management Service: ProSoil – Problem Soils Database. Food and Agriculture Organization of the United Nations, Rome, Italy. Available at: http://www.fao.org/ag/agl/agll/prosoil/acri.htm.
13. Gassman, P.W., M.R. Reyes, C.H. Green, and J.G. Arnold. 2007. The Soil and Water Assessment Tool: historical development, applications, and future research directions. Trans. ASABE. 50(4):1211-1250.
14. Grayson, R.B., J.D. Moore, and T.A. McMahon. 1992. Physically based hydrologic modeling. 2. Is the concept realistic? Water Resour. Res. 26:2659-2666.
15. Green, C.H., M.D. Tomer, M. Di Luzio, and J.G. Arnold. 2006. Hydrologic Evaluation of the Soil and Water Assessment Tool for a Large Tile-Drained Watershed in Iowa. Trans. ASABE. 49(2):413-422.
16. Hao, F., X. Zhang, and Z. Yang. 2004. A distributed non-point source pollution model: calibration and validation in the Yellow River Basin. J. Environ. Sci. 16(4):646-650.
17. Jirayoot, K. and Trung, L. D.2005. Decision Support Framework – The Transboundary Analysis Tool Developed by Mekong River Commission. Proceedings of the International Symposium on Role of Water Sciences in Transboundary River Basin Management, 10-12 March 2005, Ubon Ratchathani, Thailand, Herath, S., Dutta, D., Weesakul, U., and Das Gupta, A. (eds), United Nations University.
18. Kaur, R., R. Srivastava, R. Betne, K. Mishra, and D. Dutta. 2004. Integration of linear programming and a watershed-scale hydrologic model for proposing an optimized land-use plan and assessing its impact on soil conservation—A case study of the Nagwan watershed in the Hazaribagh district of Jharkhand, India. Int. J. Geogr. Inf. Sci. 18(1):73-98.
19. Leonard, R. A., W. G. Knisel, and D. A. Still. 1987. GLEAMS: Groundwater Loading Effects of Agricultural Management Systems. Trans. ASAE. 30:1403-1418.
20. MRC. 1997. Mekong River Basin diagnostic study—Final report. Report No. MKG/R. 97010. Mekong River Commission, Bangkok, Thailand.
21. MRC. 2001. Annual Report 2000. Phnom Penh: Mekong River Commission.
22. MRC. 2005. Overview of the Hydrology of the Mekong Basin.
23. MRC. 2009. Mekong River Commission for Sustainable Development: About the Mekong, water at work. Mekong River Commission, Vientiane, Lao PDR. Available at: http://www.mrcmekong.org/about_mekong/water_work.htm
24. MRCS. 2005. Mekong River Commission for Sustainable Development: About the MRC. Mekong River Commission, Vientiane, Lao PDR. Available at: http://www.mrcmekong.org/about_mrc.htm#MRCs
25. Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel, and T.L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE (in press).
26. Nash, J.E. and J.E. Sutcliffe. 1970. River flow forecasting through conceptual models. Part I –A discussion of principles. J. Hydrol. (Amsterdam) 10:282-290.
27. Neitsch, S.L., J.G. Arnold, J.R. Kiniry, J.R. Wiliams, and K.W. King. 2002a. Soil and Water Assessment Tool Theoretical Documentation Version 2000. GSWRL Report 02-01, BRC Report 02-05, TR-191. College Station, Texas: Texas Water Resources Institute.
28. Neitsch, S.L., J.G. Arnold, J.R. Kiniry, R. Srinivasan, and J.R. Wiliams. 2002b. Soil and

Water Assessment Tool User's Manual Version 2000. GSWRL Report 02-02, BRC Report 02-06, TR-192. College Station, Texas: Texas Water Resources Institute.

29. Saleh, A, J.G. Arnold, P.W. Gassman, L.M. Hauk, W.D. Rosenthal, J.R. Williams, and A.M.S. MacFarland. 2000. Application of SWAT for the Upper North Bosque River watershed. Trans. ASAE 43(5):1077-1087.
30. Santhi, C., J.G. Arnold, J.R. Williams, W.A. Dugas, R. Srinivasan, and L.M. Hauck. 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources. J. Amer. Water Resour. Assoc. 37(5):1169-1188.
31. Schuol, J. and K.C. Abbaspour. 2006. Calibration and uncertainty issues of a hydrological model (SWAT) applied to West Africa. Adv. Geosci. 9:137-143.
32. Sun, H. and P.S. Cornish. 2006. A catchment-based approach to recharge estimation in the Liverpool Plains, NSW, Australia. Aust. J. Agric. Res. 57:309-320.
33. United States Department of Agriculture, Soil Conservation Service. 1972. SCS National Engineering Handbook, Section 4: Hydrology. U.S. Department of Agriculture, Washington, D.C.
34. Williams, J.R., J.G. Arnold, J.R. Kiniry, P.W. Gassman, and C.H.Green. 2008. History of model development at Temple, Texas. *Hydrological Sciences Journal*. 53(5): 948-960.
35. Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27:129–144.
36. Williams, J.R., A.D. Nicks, and J.G. Arnold. 1985. Simulator for water resources in rural basins. J. Hydraulic Eng., ASCE, 111(6):970-986.
37. World Meteorological Organization, 2000. Climate Data and Monitoring. Available at: http://www.wmo.int/pages/themes/climate/index_en.php

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PREDICTING THE EFFECTS OF LAND USE CHANGE ON RUNOFF AND SEDIMENT YIELD IN MANUPALI RIVER SUBWATERSHEDS USING THE SWAT MODEL

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ABSTRACT

The quantitative prediction of environmental impacts of land use changes in watersheds could serve as a basis for developing sound watershed management schemes, especially for Philippine watersheds with agroforestry systems. The Soil and Water Assessment Tool (SWAT) model was parameterized and calibrated using data from two Manupali River subwatersheds with an aggregate area of 200 ha, to simulate the effect of land use change on runoff volumes, sediment yield and streamflows.

Model simulation results demonstrated that SWAT can predict runoff volumes and sediment yield with Nash-Sutcliffe Efficiency (NSE) ranging from 0.77 to 0.83 and 0.55 to 0.80, respectively. Simulation of land use change scenarios using the SWAT model indicated that runoff volume and sediment yield increased by 3% to 14% and 200% to 273%, respectively, when 50% of the pasture area and grasslands is converted to cultivated agricultural lands. Consequently, this results in a decrease of baseflow of 2.8% to 3.3%, with the higher value indicating a condition of the watershed without soil conservation intervention. Moreover, an increase of 15% to 32% in runoff volume occurs when the whole subwatershed is converted to agricultural land. This accounts for 39% to 45% of the annual rainfall to be lost as surface runoff. While simulation results are subject to further validation, this study has demonstrated that the Soil and Water Assessment Tool (SWAT) model can be a useful tool for modeling the impact of land use changes in Philippine watersheds.

Keywords**:** *Land use change, runoff, sediment yield, SWAT, modeling, Philippines.*

1. INTRODUCTION

Conversion of native forest to agricultural lands is prevalent in the Philippines. This is driven by the growing population and increasing demand for food as well as the short-term benefit derived from this land conversion. The Manupali River watershed is a typical example of the many watersheds in the country today that have undergone land conversion and continuously experiencing environmental degradation and causing off-site pollution and heavy sedimentation of rivers, reservoir and hydropower dams.

The Manupali is an important watershed in the Philippines as it provides water to irrigate around 15,000 ha of ricelands (Daño and Midmore, 2002). It is rich in natural resources and has attracted many migrants because of the opportunity to pursue profitable economic activities in agriculture. Agricultural expansion has led to the extensive conversion of forest lands and grasslands into corn and other cropped land. Recently, expansion of sugarcane, banana, and corn cultivation at low altitudes, and of vegetable and corn at higher altitudes has occurred substantially at the expense of perennial crops (Lapong et al., 2008). With the favorable

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climate and promise of high net return from growing cash crops in these areas, it is expected that upland farming will further increase and land conversion will eventually spread to higher elevations and more steeply sloping lands.

Intensive cultivation of annual crops, aggravated by steep slopes, heavy rainfall, and poor soil conservation practices, leads to serious soil erosion problems. This process consequently results in soil nutrient depletion or the continuous detachment and transport of nutrient-rich particles from the top soil (Ella, 2005). The eroded sediment may also adsorb and transport agricultural contaminants such as pesticides, phosphate and heavy metals posing threats to aquatic life (Ella, 2005) and may create health problems for farm families and those living downstream. Moreover, soil erosion may result in significant off-site effects including river and reservoir sedimentation affecting hydroelectric power generation and irrigation efficiencies (NWRB, 2004). Thus, unless conservation-oriented land management practices are employed, patterns of land use typically found in watersheds, such as the Manupali River watershed, will generate substantial soil erosion and over time could worsen the poverty of upland farmers as well as generate downstream costs (Paningbatan, 2005).

Developing a quantitative prediction model for assessing the impacts of land use changes on runoff and sediment yield in watersheds is therefore of paramount importance. A model can provide the basis for developing policy interventions and for developing sound watershed management schemes that ensure environmental and economic sustainability. Among the most widely used computer simulation modeling tools for predicting runoff and sediment yield is the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Gassman et al., 2007). To date, no applications of SWAT in the Philippines have been reported in the peer-reviewed literature. A few studies have reported land use change effects on soil erosion in the Philippines based on applications of other simulation models, such as the Water Erosion Prediction Project (WEPP) model (Ella, 2005), the Erosion-Productivity Impact Calculator (EPIC) model (Poudel et al., 2000) and the Agricultural Production Systems Simulator (APSIM) model (Nelson et al., 1998). However, predictions of land use change effects on soil erosion using SWAT have yet to be performed for Philippine watershed conditions.

Thus, this study was conducted to determine the effects of various land use patterns on runoff and sediment yield in selected subwatersheds of the Manupali River using the SWAT model. Specifically, the objectives are to parameterize, calibrate and use the SWAT model in simulating the effects of land use change on runoff and sediment yields.

2. METHODOLOGY

2.1 Description of Study Area

The Kiluya and Kalaignon are two subwatersheds within the 600 km^2 Manupali River watershed in Lantapan, Bukidnon, Philippines (Fig. 1). These subwatersheds have a total area of about 200 ha with intensive cultivation of corn and vegetables crops. The existing land cover is comprised of 16.8% dense forest, 29.5% agricultural crops (predominantly corn and vegetables), 53.0% grasslands, shrubs and small trees, and 0.7% footpath. The topography is rolling to hilly, and ranges in elevation from 900 m above mean sea level at the outlet of the two subwatersheds to

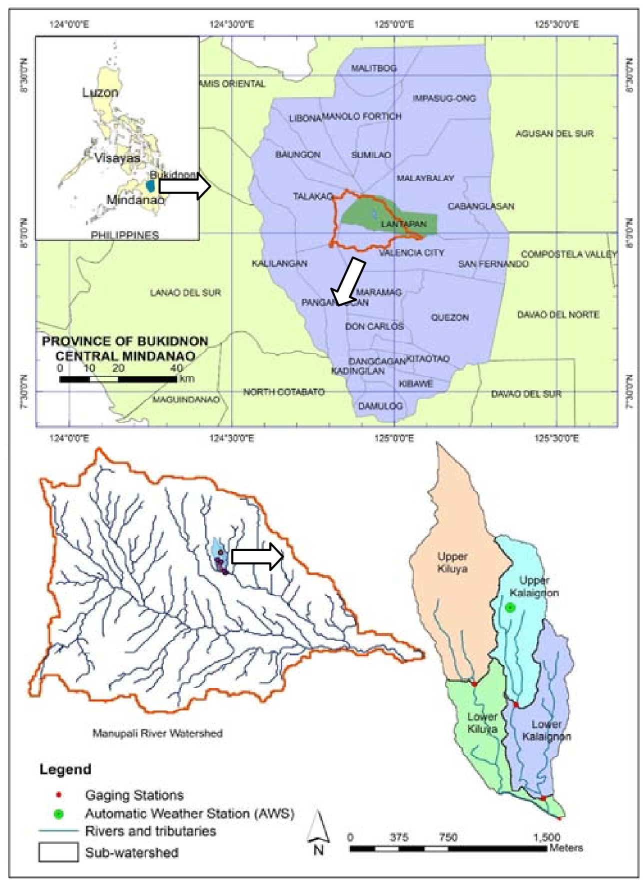

Fig. 1: The Manupali River watershed and test subwatersheds showing the locations of gaging stations and automatic weather station (AWS) and their location in the province of Bukidnon, Philippines

about 2,000 m at their upstream peak. Soils in these subwatersheds are predominantly clayey due to the extent of fine-grained volcanic rocks, various sedimentary derivatives and pyroclastics (BSWM, 1985). Rainfall is distributed throughout the year with an average annual rainfall of 2,347 mm with rainfall peaks from June to October. Mean temperature ranges from 17 ^{o}C to 28 ^{o}C. Relative humidity ranges from 86 to 98 percent.

2.2 SWAT Model Description

SWAT is a physically-based, river basin-scale, continuous event hydrologic model developed to quantify the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions (Arnold et al., 1998). Major model components describe processes associated with water movement, sediment movement, soils, temperature, weather, plant growth, nutrients, pesticides and land management. A watershed is subdivided into subwatersheds and hydrologic response units (HRUs), a subwatershed unit having unique soil and land use characteristics. The water balance of each HRU in the watershed is represented by several storage volumes. Surface runoff from daily rainfall is estimated using a modified SCS curve number method, and sediment yield is calculated with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977). Selected conservation and water management practices can also be simulated in SWAT. Conservation practices that can be accounted for include terraces, strip cropping, contouring, grassed waterways, filter strips, and conservation tillage (Gassman et al., 2007). Filter strips are areas of grass that add a buffer to land masses that may be subject to sediment production. The edge-of-field strips may be defined for an HRU in current versions of SWAT by indicating a filter strip width. The filter strip can lessen or prevent the loss of soil including nutrients and bacteria in surface runoff as it passes through the filter strip (Neitsch et al., 2005) and can be used to simulate the presence of grasses and/or trees that act as border strip between fields. An improved method of simulating filter strips will be available in future versions of SWAT (White and Arnold, 2009).

2.3 Preparation of the SWAT Model Inputs

Spatial data required by the model include a digital elevation model (DEM), land use map and soil map. In this study, the DEM map was prepared by digitizing a 1:50,000 scale topographic map with contour intervals of 20 m in ArcGIS 9.2 software. This was converted into a raster DEM map with pixel size of 10 m x 10 m using the topographic tool of ENVI 4.5. The DEM map was used to delineate the subwatersheds and generate the slope map of the test watershed for the SWAT simulations.

The land use map was generated from the Ikonos images taken in May 2007. The acquired Ikonos images came with two resolutions, namely 1 m x 1 m panchromatic and 4 m x 4 m multispectral images. Prior to land use classification, the multispectral image was fused to the panchromatic image to increase its resolution to 1 m x 1 m. The resulting image was then used to classify the various land uses present in the area. Four land uses were identified and classified as previously stated.

The soil map of the study area was extracted from the soil map of the Philippines prepared by the Bureau of Agricultural Research. Specific soil properties such as texture, organic matter content, soil erodibility, infiltration rate among others were compiled from various literatures (e.g., Lapong et al., 2008; Paningbatan, 2005; BSWM, 1985).

Time series of meteorological data such as rainfall, temperature, solar radiation, relative humidity, and wind speed were compiled into proper format required by SWAT from previous weather data obtained from the automatic weather station of SANREM-CRSP installed at the study site. Time series of runoff volume and sediment yield measured in 2004 by Lapong et al. (2008) were used to calibrate the model.

2.4 SWAT Model Development

The SWAT2005 model (Neitsch et al., 2005) and the ArcSWAT version 2.1.2a interface (Olivera et al. 2006) were used in this study. Using the generated DEM map and locations of four known gaging stations, the study area was delineated and subdivided into four subwatersheds namely, lower and upper Kiluya and lower and upper Kalaignon. Each subwatershed was further subdivided into hydrologic response units (HRU) by overlaying the slope map, generated from the DEM, with the soils and land use maps.

More specific land uses were used to better represent the spatial variation of vegetation in the watershed (Table 1). This was done by subdividing the major land uses into their specific land uses by percentages which were estimated based on field observations. For instance, it was estimated that corn areas occupy about 60% while cabbage and potato occupy about 20% each of the total agricultural area in the study area. The slope map was also subdivided into four classes. Table 2 shows the different land uses present at the different slope classes.

Using the SWAT default parameters, the watershed conditions were simulated from 1994 through 2004 using daily historical weather information. The simulated runoff and sediment yield in 2004 were compared to the runoff and sediment yield measured by Lapong et al. (2008) in the same year at the same gaging stations. Considering that SWAT is not a 'parametric model' with a formal optimization procedure to fit any data and that it uses physically-based inputs, original parameters were adjusted to provide a better fit. The curve number (CN2) were adjusted within 10 percent from the tabulated curve numbers to reflect conservation tillage practices and soil residue cover conditions of the watershed. Also, the linear factor (SPCON) and exponential factor (SPEXP) for channel sediment routing and filter width parameter (FILTERW) were adjusted to provide a better fit to observed sediment yield in the area. The sequence of adjusting the model parameters were based on the procedures outlined by Santhi et al. (2006). Table 3 shows a summary of the optimized model parameters.

Table 1: Land use classification at the study area

LAND USE	AREA (ha)	PERCENT OF TOTAL
Agricultural		
Corn	35.3	17.7
Cabbage	11.8	5.9
Potato	11.8	5.9
Pasture/Grassland		
Ranged grasslands	74.2	37.1
Pasture with brushes	31.8	15.9
Forest		
Mixed forest	23.5	11.8
Deciduous trees	10.1	5.0
Foot path	1.4	0.7
TOTAL	199.9	100.0

Table 2: Land use area (ha) at various slopes at the study site

LAND USE	SLOPE (%)				TOTAL
	0-8	8-18	18-30	Above 30	
Agricultural	12.4	3.0	14.7	28.7	58.9
Pasture or Grasslands	22.6	6.4	28.6	48.4	106
Forest	7.4	2.1	10.3	13.7	33.6
Footpath	0.2	0.1	0.3	0.8	1.4
TOTAL	42.7	11.6	54.0	91.7	199.9

2.5 Evaluation of Land Use Change Effect on Runoff and Sediment Yield

In order to develop sound management schemes for protecting the watershed and to determine the impact of land use changes specifically on runoff volume, baseflow, and sediment yield, the calibrated model was run to simulate eight land use change scenarios (Table 4).

For each scenario, certain percentages of the existing land use were converted into agricultural lands using the generic SWAT agricultural land use. The key processes and related model parameters such as crops grown, P-factor of USLE, infiltration rate, runoff curve number, and filter width were also modified in the appropriate SWAT input files. P-factor values of 0.6 and 1.0 were used in simulations to reflect the condition of the watershed with and without soil conservation intervention, respectively. A P-factor of 0.6 represents a generic soil conservation practice such as contouring or terracing that could be applied in the area to reduce soil erosion. A filter width of 10 m was provided in all simulation scenarios to partly reflect the vegetable agroforestry (VAF) system being investigated under the Sustainable Agriculture and Natural Resources Management (SANREM) project (Reyes, 2008). That is, the effect of trees that are integrated in vegetable farms in the study area to reduce soil erosion and sediment transport is accounted by the filter width. The simulated runoff volumes and sediment yields at the various scenarios were used as basis in developing recommendations for the sustainable management of the watershed.

2.6 Data Analysis

The predicted and measured runoff volumes and sediment yield in 2004 were summarized and plotted weekly to compare their temporal distribution. The goodness of fit between the simulated and measured runoff volumes and sediment yields in the four subwatersheds was evaluated using the coefficient of determination (R^2). Model performance was also evaluated using the model efficiency developed by Nash and Sutcliffe (1970) given as:

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(X_{mi} - X_{pi}\right)^2}{\sum_{i=i}^{n}\left(X_{mi} - \overline{X}_m\right)^2}$$

where NSE is the efficiency of the model, X_{mi} and X_{pi} are the measured and predicted values, respectively and $\overline{X}_m$ is the average of measured values. A value of NSE=1.0 indicates a perfect prediction while a negative value indicates that the prediction is less reliable than using the sample mean. In addition, the root mean square error (RMSE) was used to evaluate how much the model prediction overestimates or underestimates the measured values. In each scenario, the mean runoff volume, stream flow and sediment yield over a five-year simulation excluding a six-year initialization period were calculated by the model and used to assess the impact of the land use change.

3. RESULTS AND DISCUSSION

3.1 Prediction of Runoff Volume

The daily simulated runoff volumes in each of the four subwatersheds were lumped into weekly totals and compared with the measured runoff volumes at the subwatershed outlets in 2004. Figure 2 shows that the simulated runoff volumes matched well with the

Table 3: The SWAT model parameters adjusted during calibration

PARAMETER NAME	DEFAULT VALUE	CALIBRATED VALUE
Curve number, CN2	– *	±10%
Baseflow alpha factor, ALPHA_BF	0	0.05
Manning's n for the main channel, CH_N2	0.014	0.075
Linear factor, SPCON	0.001	0.01
Exponential Factor, SPEXP	1.5	2.0
Filter width, FILTERW	0	10

* varies by landuse

Table 4: Land use change scenarios simulated in the study

SCENARIO	LAND USE CHANGE	SOIL CONSERVATION*
1	50% of grasslands converted to agricultural lands	With soil conservation
2	50% of grasslands converted to agricultural lands	Without soil conservation
3	100% of grasslands converted to agricultural lands	With soil conservation
4	100% of grasslands converted to agricultural lands	Without soil conservation
5	100% of grasslands and 50% forest lands converted to agricultural lands	With soil conservation
6	100% of grasslands and 50% forest lands converted to agricultural lands	Without soil conservation
7	100% of grasslands and 100% forest lands converted to agricultural lands	With soil conservation
8	100% of grasslands and 100% forest lands converted to agricultural lands	Without soil conservation

* 'With soil conservation' assumes a practice such as contour farming was used (P_{usle} = 0.60); 'without soil conservation' assumes that there was no support practice effect (P_{usle} = 1.0)

measured values at each of the four subwatersheds. Agreement between measured and simulated runoff volumes at the four subwatersheds was further indicated by a relatively high coefficient of determination, R^2, ranging from 0.87 to 0.90 (Table 5). The adequacy of the SWAT model to simulate the runoff volumes was also indicated by a relatively high *NSE* values ranging from 0.77 to 0.83. Morever, the adequacy of the model was further demonstrated by its clear response to extreme rainfall events resulting in high runoff volumes (Fig. 2). These results indicate that important hydrologic processes such as runoff in tropical watersheds can be modeled realistically using the SWAT model.

3.2 Prediction of Sediment Yield

Temporal variations of observed and simulated sediment yield at the outlet of each of the four subwatersheds in 2004 are shown in Figure 3. The time to peak of sediment yield was adequately captured by the model. Except for overprediction of sediment yield in the case of Upper Kiluya, the simulated values generally agreed with measured sediment yield with R^2 ranging from 0.58 to 0.82 and a Nash Sutcliffe model efficiency (NSE) ranging from 0.55 to 0.80 (Table 6).

A closer examination of the results indicates that in some events the SWAT model overestimated the sediment yield by as much as 306% in the upper subwatersheds particularly in Upper Kiluya and underestimated the peak sediment yields in the lower subwatersheds by as much as 36%. This behavior of the simulated sediment yields indicates high deposition of sediments as they travel along the channel. This was partly addressed during the calibration by adjusting the linear factor (SPCON) and exponential factor (SPEXP) for channel sediment routing to their maximum values of 0.01 and 2, respectively. The discrepancy between the simulated and observed sediment yield values may be attributed to channel erosion, especially during high flows, and other factors which the model could not adequately capture such as channel scouring and erosion and the presence of temporary channel embankment, which is used by the farmers to retard channel flow velocity. Nevertheless, the overall adequacy of the model to simulate sediment yields in the watershed indicates its usefulness as a management tool to predict the effects of land use changes in relatively small watersheds. It should be noted that most of the previous applications of SWAT dealt with large watersheds. This study has therefore provided additional evidence that the SWAT model can also generate reasonable hydrologic simulations even for relatively small watersheds. The SWAT model performance in this study, as indicated by R^2 and NSE, is also comparable with the other SWAT model applications in equally small watersheds as reported by Gassman et al. (2007).

Table 5: Comparison between the simulated and observed runoff volumes at the test subwatersheds

WATERSHED	WEEKLY MEAN RUNOFF VOLUME (m^3)		RMSE	R^2	NSE
	Observed	Simulated			
Lower Kiluya	3809	4098	3014	0.88	0.82
Upper Kiluya	2610	2820	1977	0.88	0.83
Lower Kalaignon	2992	2848	2368	0.90	0.80
Upper Kalaignon	1470	1449	1323	0.87	0.77

Table 6: Comparison between the simulated and observed sediment yield at the test subwatersheds

WATERSHED	WEEKLY MEAN SEDIMENT YIELD (tons)		RMSE	R^2	NSE
	Observed	Simulated			
Lower Kiluya	1.95	2.09	1.84	0.82	0.80
Upper Kiluya	0.84	3.39	4.17	0.70	-5.16
Lower Kalaignon	3.96	2.53	5.83	0.80	0.55
Upper Kalaignon	1.03	1.12	1.45	0.58	0.58

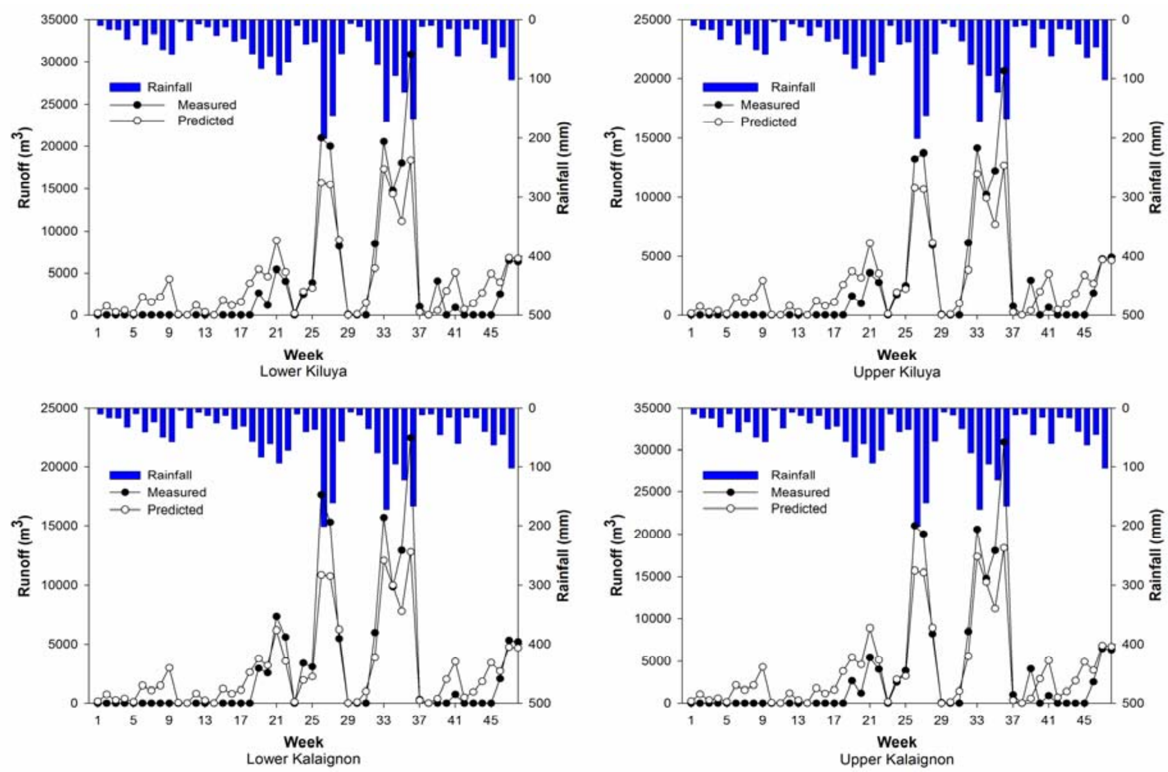

Fig. 2: Observed and simulated runoff volumes superimposed with the weekly rainfall at the test subwatersheds

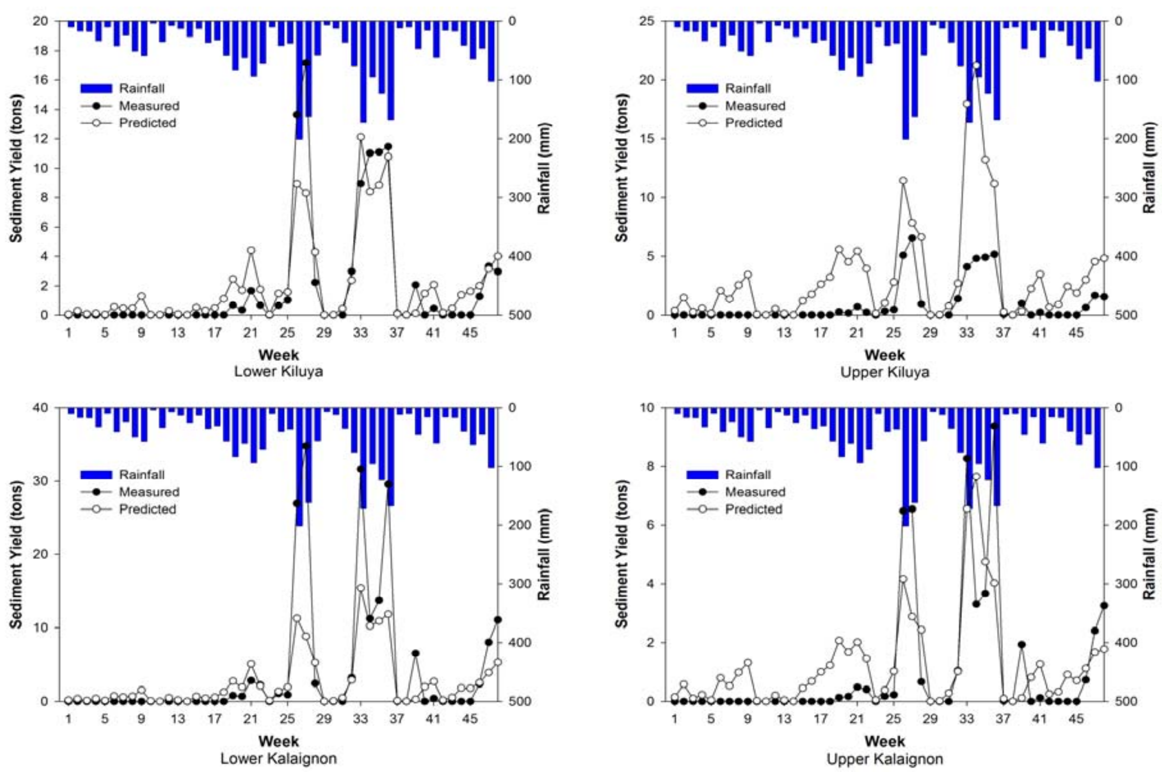

Fig. 3: Observed and simulated sediment yield superimposed with weekly rainfall at the four subwatersheds

3.3 Simulation of Hydrologic Impacts of Land Use Change

To assess the effects of land conversion in the study area, the calibrated model was run to simulate various scenarios of land use changes on runoff volumes, sediment yields and baseflows. Results of the simulations indicate that runoff volume increases when pasture/grassland and forest areas are converted to agricultural lands (Fig. 4a). An increase of about 3% to 14% in runoff volume occurs when 50% of the pasture and grasslands are converted to agriculture lands. On the other hand, an increase of 15% to 32% in runoff volume occurs when the entire subwatershed is converted to agricultural land. The higher value indicates a condition of the watershed without soil conservation intervention. At a glance, this percentage increase may seem insignificant; however, considering that the mean annual runoff volume is 791 mm yr^{-1}, which represents 34% of the mean annual rainfall in the area, an increase of 11% to 24% when all pasture and grasslands are converted to agricultural land means that 37% to 42% of the annual rainfall is likely to be lost as surface runoff. Alternatively, when the whole watershed is converted to agricultural land, 39% to 45% of the mean annual rainfall is likely to be lost as surface runoff. Such conditions will cause significant soil erosion, depleting soil nutrients, sedimentation of reservoirs, and flooding of low lying areas at the downstream. The eroded sediment may also adsorb and transport agricultural contaminants such as pesticides, phosphate and heavy metals posing serious threat to aquatic life (Ella, 2005) and may create health problems for farm families and those living downstream. These results can impact the wildlife and fish in the streams and also the water supply of the watershed especially during dry periods.

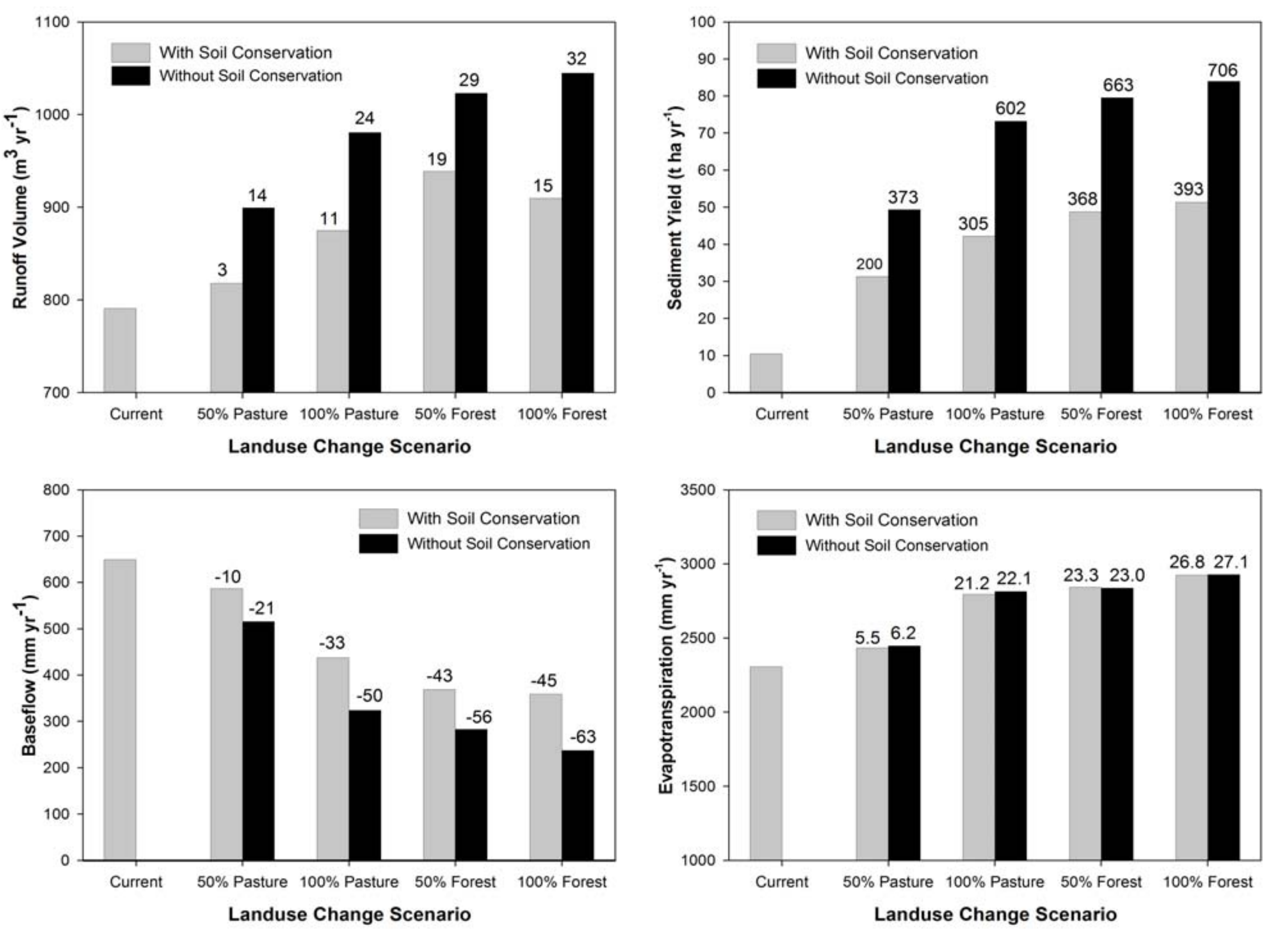

Fig. 4: Simulated runoff volume (mm yr^{-1}), sediment yield (t ha^{-1} yr^{-1}), baseflow (mm yr^{-1}), evapotranspiration (mm yr^{-1}) for various land use scenarios in the study area. (The numbers on top of the bars indicate the percentage change from its current value. The 50% pasture, 100% pasture, 50% forest, and 100% forest indicates the percentage area of these land uses converted to agricultural land)

A dramatic increase in sediment yield is predicted as pasture, grassland and forest areas are converted to agricultural lands, even with the intervention of soil conservation practices such as contouring (Fig. 4b). Converting 50% of the pasture and grasslands to agricultural crops is likely to increase the current sediment yields of 10.4 t ha^{-1} yr^{-1} to about 31 t ha^{-1} yr^{-1} and up to 49 t ha^{-1} yr^{-1} when no soil conservation intervention is employed (Fig. 4b). Likewise, converting the whole watershed to agricultural lands is likely to increase the sediment yield to 51 t ha^{-1} yr^{-1} and up to 84 t ha^{-1} yr^{-1} (Fig. 4b). Simulation results show that the mean annual sediment yield in fallow areas is about 296 t ha^{-1} compared to areas planted to corn, cabbage, and potato having sediment yields of 40 t ha^{-1}, 34 t ha^{-1}, and 59 t ha^{-1}, respectively. The current sediment yield of the watershed of 10.43 t ha^{-1} yr^{-1} is in fact near the upper limit of tolerable soil loss of 11.2 t ha^{-1} yr^{-1} (Hudson, 1995). Thus, rather than expanding the current agricultural areas to increase crop production, efforts should be exerted to improve present crop cultural management practices of farmers and train them to employ soil conservation practices to reduce soil erosion rate, thereby rehabilitating and sustaining the whole watershed.

Finally, the simulation results indicate that conversion of pasture, grasslands and forest to agricultural land use will result in a decrease in baseflow (defined as stream water yield less surface runoff) by as much as 63% (Fig. 4c). This decrease in water yield may be attributed to increased surface runoff and decreased infiltration as a result of conversion of forest to agricultural land use. Forest vegetation dissipates raindrop energy; retards surface runoff velocity, increases evapotranspiration rates, and increases the soil organic matter, all of which lead to greater infiltration and lower surface runoff (Schwab et al., 1992). According to Paningbatan (2005), forest areas in the study area have an infiltration rate of about 100 mm hr^{-1} while agricultural land planted with corn and vegetables with and without soil conservation intervention have an infiltration rate of 60 mm hr^{-1} and 17 mm hr^{-1}, respectively.

Considering that the test watershed is a part of the Manupali river basin, an increase in surface runoff and sediment yield and decrease in baseflow will have serious environmental effects not only to the communities living in the study area but also those living downstream. Efforts should therefore be exerted to address forest conversion to agricultural crops. Policies addressing this problem should be done both at the local and national level. Likewise, an intensive information and education campaign on the consequences of forest conversion and ways of rehabilitating the watershed should be done. Finally, this study recommends that alternative livelihood opportunities for upland farmers be considered in policy implementation.

4. SUMMRAY AND CONCLUSIONS

The SWAT model was parameterized and calibrated in selected Manupali River subwatersheds in the Philippines with an aggregate area of 200 ha to simulate the effects of land use on runoff volumes, sediment yield and baseflow. Results indicated that SWAT adequately predicted the runoff volumes of the test watershed with Nash-Sutcliffe Efficiencies (NSE) ranging from 0.77 to 0.83. Runoff volumes and their temporal variation were adequately captured by the SWAT model. Likewise, with the exception of the Upper Kiluya subwatershed, the model adequately predicted the sediment yield of the test watersheds with NSE ranging from 0.55 to 0.80. While these simulation results are subject to further validation, this study showed that the Soil and Water Assessment Tool (SWAT) model can be used as a management tool for modeling the impact of land use change in Philippine watersheds.

In order to develop sound management schemes for protecting the watershed and to determine the impact of land use changes on runoff volume, baseflow and sediment yield, the calibrated model was used to simulate eight different land use scenarios. The results indicated that converting pasture, grasslands and forest to agricultural crops will result in increased runoff volumes, increased sediment yields, and decreased baseflow. Converting 50% of the pasture and grassland to agricultural crops increases predicted runoff volumes and sediment yields by 3% to 14% and 200% to 273%, respectively, with the higher value indicating a condition of the watershed when no soil conservation intervention is applied. Consequently, this will decrease baseflow by about 45% to 63%. An increase of 15% to 32% in runoff volume is likely to occur when the whole subwatershed is converted to agricultural land. This accounts for 39% to 45% of the annual rainfall to be lost as surface runoff. These changes will cause significant soil erosion, depleting soil nutrients, hasten sedimentation of reservoirs, and increase flooding of low-lying areas at the downstream.

The adverse effects of pasture and forest conversion to agricultural crops as demonstrated by SWAT model simulations clearly indicate an alarming situation and may be experienced in other watersheds in the Philippines having the same land use pattern as the test watersheds in this study. Efforts should therefore be exerted to address forest conversion to agricultural crops. We therefore recommend that policies addressing this problem should be formulated both at the local and national level. Parallel to this, an intensive information and education campaign on the consequences of forest conversion and ways of rehabilitating the watershed should likewise be initiated. Finally, alternative livelihood opportunities for the upland farmers should be considered in policy implementation.

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REFERENCES

1. Arnold, J. G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. J. Amer. Water Res. Assoc. 34(1): 73-89.
2. BSWM. 1985. Land resources evaluation report for Bukidnon province: the physical land resources volume 1. Bureau of Soils and Water Management, Department of Agriculture, BSWM-DA, Manila, Philippines.
3. Daño, A.M., and D.J. Midmore. 2002. Analyses of soil and water conservation technologies in vegetable based upland production system of Manupali Watershed. 12th ISO Conference, Beijing.
4. Ella, V.B. 2005. Simulating soil erosion and sediment yield in small upland watersheds using the WEPP model. In: I. Coxhead and G.E. Shively, eds., Land use change in tropical watersheds: Evidence, causes and remedies. CABI publishing. Wallingford, Oxfordshire, UK. pp 109-125.
5. Gassman, P.W., M.R. Reyes, C.H. Green, and J.G. Arnold. 2007. The Soil and Water Assessment Tool: historical development, applications, and future research directions. Trans. ASABE. 50(4): 1211-1250.
6. Hudson, N. 1995. Soil conservation. BT Batsford Limited, London. 391 pp.
7. Lapong, E. R., V.B. Ella, M.G. Villano and P.M. Bato. 2008. Effects of Climatic Factors and Land Use on Runoff, Sediment Load, and Pesticide Loading in Upland Microcatchments in Bukidnon, Philippines. Philippine J. Agric. Biosyst. Engr. 6: 49-56
8. National Water Resources Board (NWRB). 2004. Water for food: Aiming for self-sufficiency and rural development. In: Ella, V.B. 2005. Simulating soil erosion and sediment yield in small upland watersheds using the WEPP model. In: I. Coxhead and G.E. Shively, eds., Land use change in tropical watersheds: Evidence, causes and remedies. CABI publishing. Wallingford, Oxfordshire, UK. pp 109-125.
9. Nash, J.E., and J.E. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I. A discussion of principles. J. Hydrol. 10: 282-200.
10. Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2005. Soil and Water Assessment Tool Theoretical Documentation, version 2005. Temple, Tex.: USDA-ARS Grassland, Soil and Water Research Laboratory. Available at: www.brc.tamus.edu/swat/doc.html.
11. Nelson, R.A., J.P. Dimes, D.M. Silburn, E.P. Paningbatan, and R.A. Cramb. 1998. Erosion/Productivity Modelling of Maize Farming in the Philippine Uplands Part II: Simulation of Alternative Farming Methods. Agric. Syst. 58(2): 147-163.
12. Olivera, F., M. Valenzuela, R. Srinivasan, J. Choi, H. Cho, S. Koka, and A. Agrawal. 2006. ArcGIS-SWAT: A geodata model and GIS interface for SWAT. J. Amer. Water Res. Assoc. 42(2): 295-309.
13. Paningbatan, Jr. E.P. 2005. Identifying soil erosion hotspots in the Manupali River watershed. In: I. Coxhead and G.E. Shively, eds., Land use change in tropical watersheds: Evidence, causes and remedies. CABI publishing. Wallingford, Oxfordshire, UK. pp 126-132.
14. Poudel, D.D., D.J. Midmore, and L.T. West. 2000. Farmer participatory research to minimize soil

erosion on steepland vegetable systems in the Philippines. Agric. Ecosyst. and Environ. 79: 113-127.
15. Reyes, M.R. 2008. SANREM Agroforestry and sustainable vegetable production in Southeast Asian watersheds. Annual Report, SANREM - CRSP. Greensboro, N.C.: North Carolina A&T State University. Annual Report.
16. Santhi, C., R. Srinivasan, J.G. Arnold, and J.R. Williams. 2006. A modeling approach to evaluate the impacts of water quality management plans implemented in Texas. Environ. Model. Soft. 21: 1141-1157.
17. Schwab, G.O., D.D. Fangmeier, W.J. Elliot and R.K. Frevert. 1992. Soil and Water Conservation Engineering. John Wiley & Sons, Inc. New York, New York.
18. White, M. and J. Arnold. 2008. Development of a simplistic vegetative filter strip model for sediment and nutrient retention at the field scale. *Hydrol. Process.* 23(11): 1602-1616.
19. Williams, J.R., and H.D. Berndt. 1977. Sediment yield prediction based on watershed hydrology. Trans. ASAE 20(6): 1100-1104.

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SENSITIVITY ANALYSES OF HYDROLOGIC AND SUSPENDED SEDIMENT DISCHARGE IN THE ABASHIRI RIVER BASIN, HOKKAIDO REGION, JAPAN

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ABSTRACT

The Soil and Water Assessment Tool (SWAT) was applied to the Abashiri River basin from 2001 to 2007 using a daily time step. After confirming the reproducibility of the model, hydrological sensitivity analyses against monthly river discharge, evapotranspiration (ET), snow water equivalent (SWE), and suspended sediment (SS) load were conducted under various climate change scenarios. The results of calibration and validation indicated that the model provided satisfactory representation of the flow and SS load discharge. In addition, the hydrological sensitivity analyses revealed that the influence of climate change in the basin will be stronger during winter than summer, especially from January to March. Variation analyses revealed that discharge increased drastically under every scenario from January to March, with the exception of a combination of a 20% decrease in precipitation and a 1ºC increase in temperature in January. Furthermore, the ET increased greatly in March due to a multiplier effect of natural conditions and temperature increase scenarios. Moreover, although the SWE decreased in almost all cases, it increased in some cases in December, January, and February. Increasing snow melt in response to an early thawing season and/or precipitation during winter resulted in an increase in SS load discharge, especially during February. On an annual basis, the mean SS load decreased in every scenario except for those in which precipitation increased.

Keywords: *Cold climate region, GIS, global climate change, soil and water assessment tool.*

1. INTRODUCTION

It is very important that integrated management of river systems be conducted with consideration of future climate change and anticipated cultural development to ensure that natural resources are used in a sustainable manner. It is predicted that the average annual temperature in northern Japan will increase by nearly 4ºC under the IPCC global warming SRES-A2 scenario (JMA, 2005). In addition, the results of this scenario suggest that the warmer climate will lead to changes in the precipitation amounts and patterns, which has the potential to influence watershed hydrology. Such changes will also likely affect agricultural activities, species diversity and the local economy in and around the Abashiri River basin. Thus accurate impact assessment is very important.

Many studies have been conducted to evaluate the influence of climate change on river discharge patterns in cold climate regions. For example, Xu (2000) used a conceptual monthly water balance model to estimate the effects of a significant increase in winter flow and a decrease in spring and summer runoff as a result of climate change scenarios in central Sweden. Singh and Kumar (1997) found that annual snowmelt runoff, glacier melt runoff and total stream flow in the Himalayan Basin increased linearly as temperature increased. In addition, studies have been conducted to evaluate the effects of climate change on suspended sediment (SS) transport. For instance, Nearing et al. (2005) investigated the response of seven soil erosion models to climate change and found that changes in rainfall and cover were likely to have a greater effect on soil erosion than runoff, but that all of these factors would likely have a significant impact. Moreover, Thodsen et al. (2008) predicted that climate change would have a direct effect on the transport of suspended sediment in rivers through erosion processes and increased river discharges, while it would have an indirect effect through changes in land use and land cover, using the University of British Columbia (UBC) Watershed Model (Quick and Pipes, 1977). Specifically, they

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estimated that the mean annual suspended sediment transport will increase in response to the climate becoming warmer and wetter. Extensive applications of the Soil and Water Assessment Tool (SWAT) watershed-scale water quality model (Arnold and Forher, 2005) have also been reported for climate change impacts on watershed hydrology and/or pollutant movement by Gassman et al. (2007).

This study was conducted by using the SWAT model to estimate how scenarios of potential increases in temperature and increases or decreases in precipitation would affect simulated hydrologic discharge, evapotranspiration (ET), and the snow water equivalent (SWE). In addition, the effects of climate scenarios on the simulated SS load from the basin were also evaluated.

1.1 Study Area

The Abashiri River basin is located in the northeastern part of Hokkaido Region, Japan (Figure 1). The basin covers an area of approximately 1,100 km^2. The length of the river from its source to the Hongo River discharge observation station (43° 54' 36.0 N 144° 08' 19.0 E), where the outlet of the entire basin is located, is approximately 120 km. About 80% of the land in the basin is forest, while 19% is agricultural land that is primarily used to cultivate upland crops such as wheat, sugar beets and Irish potatoes. Lake Abashiri is located downstream of the Abashiri River system and has an area of 33 km^2 and an average depth of 6.1 m, which makes it the eighth largest brackish (salty) water lake in Japan.

The Abashiri River basin contributes approximately 80% of the total watershed area to the lake; thus, changes in the pattern and quantity of water discharged from the Abashiri River will directly impact the aquatic environment in the lake. For instance, it is possible that climate change could lead to increased water temperature and decreased salinity (in the case of increasing precipitation) in the lake. Such changes would lead to changes in the habitat of aquatic animals in the lake. In a study conducted to evaluate the Hii River system in Shimane Prefecture, Somura et al. (2009) found that future generations of a brackish water clam called *Corbicula japonica* Prime in Lake Shinji may be negatively impacted by a reduction in reproduction in response to an increase in the inflow of water discharged from the Hii River under various climate change scenarios. The same variety of brackish water clam is found in Lake Abashiri, where the annual catch of the clam is approximately 800 tons (Abashiri City, 2008). This catch accounts for 7.4% of national total and is the largest in the Hokkaido Region.

This area experiences four distinct seasons and has a climate of a typical coastal region characterized by a relatively long sunshine duration throughout the year and a comparatively small amount of snow cover within the Hokkaido Region. The average total annual precipitation at the Tsubetsu weather gauge, which is located at the center of the basin, is approximately 800 mm. Additionally, the average daily wind speed at the Tsubetsu weather gauge and the daily humidity at the Abashiri weather gauge are 1.8 m/s and 74%, respectively. During winter, especially from December to February, the average daily minimum temperature is less than -10ºC and the daily maximum temperature is often less than 0°C (Figure 2). As a result, the surfaces of the river and the lake freeze during winter.

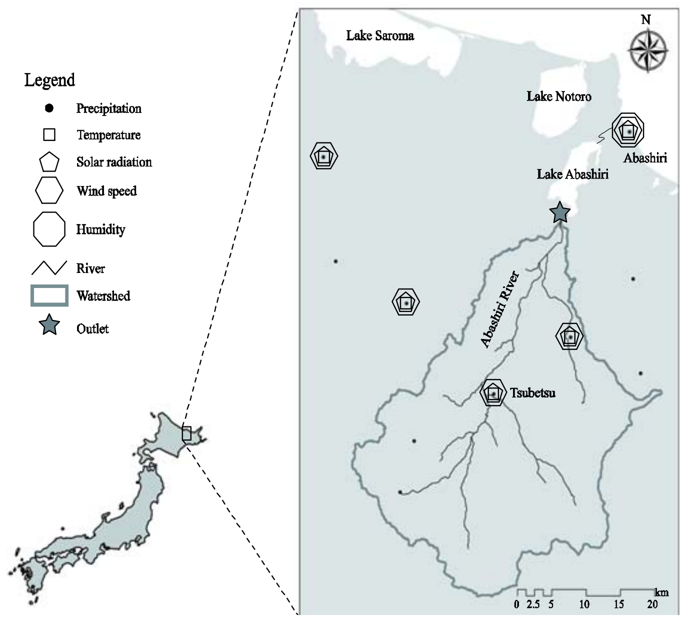

Fig. 1: Location of the Abashiri River basin, Hokkaido Region, Japan

2. METHODOLOGY

2.1 Brief Description of the SWAT Model

The SWAT model is a physically-based continuous time hydrologic model with an ArcView GIS interface that was developed by the Blackland Research and Extension Center and the USDA-ARS (Di Luzio et al., 2004) to predict the impact of land management practices on water, sediment, and

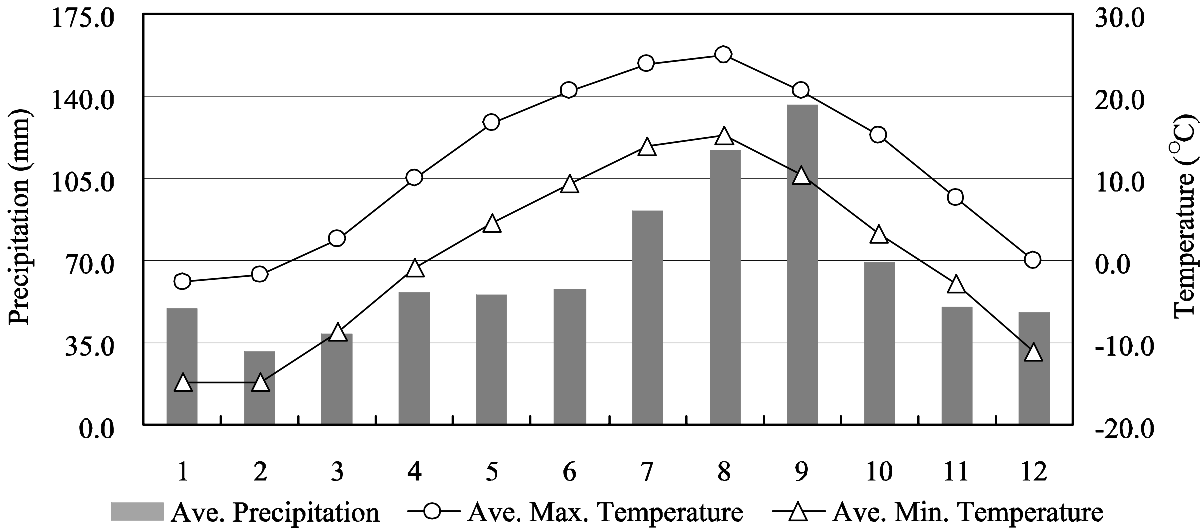

Fig. 2: Changes in the average monthly precipitation and the average daily maximum and minimum temperature from 1989 to 2007 at the Tsubetsu weather gauge

agricultural chemical yields in large complex basins with varying soil types, land uses and management conditions over long periods of time. The main driving force behind the SWAT model is its hydrological component. In the model, the hydrological processes are divided into two phases, the land phase, which controls the amount of water, sediment, and nutrient loading in the receiving waters, and the water routing phase, which simulates movement through the channel network. The SWAT model considers both natural sources (e.g. mineralization of organic matter and N-fixation) and anthropogenic contributions (fertilizers, manure and point sources) as nutrient inputs. The SWAT model delineates watersheds into sub-basins that are interconnected by a stream network. Each sub basin is further divided into hydrologic response units (HRUs) based on unique soil / land class characteristics without any specified location in the sub basin. The flow, sediment, and nutrient loading from each HRU in each sub basin are then summed, after which the resulting loads are routed through channels, ponds, and reservoirs to the watershed outlet (Arnold et al, 2001). A single growth model in the SWAT model is used to simulate all crops based on simplification of the EPIC crop model (Williams et al., 1984). Phenological development of the crop is based on daily heat unit accumulation. The model also uses the WXGEN weather generator model (Sharpley and Williams, 1990) to generate climate data or fill in gaps in the measured records.

2.2 Simulation Approaches

The SWAT model was applied to the Abashiri River basin from 1998 to 2007 using a daily time step. After SWAT was set up, sensitivity analysis was performed using a Latin Hypercube and a one-at-a-time method (van Griensven et al., 2006). Eighteen sensitive parameters were selected from the results of this analysis based on their effects on the flow and SS discharges (Table 1). Next, an auto-calibration process was conducted using the shuffled complex evolution (SCE) algorithm (Duan et al., 1992). The model was calibrated against river and SS load discharges simultaneously. The years from 1998 to 2000 were treated as the warm up period of the SWAT model during the simulation. The parameter values were calibrated using both the flow and SS discharges from 2001 to 2004 (4 years) and validated from 2005 to 2007 (3 years). Scenario analyses were then executed after ensuring the model was reproducible using the river and SS load discharges at the Hongo Outlet. In the scenario analyses, the precipitation and temperature varied uniformly across all months during the simulation period. Based on information provided by the Japan Meteorological Agency (JMA), changes in precipitation were set to P ± 0%, P ± 10%, and P ± 20%. In addition, changes in temperature were set to T + 1ºC, T + 2ºC, T + 3ºC, and T + 4ºC. All combinations of precipitation and temperature change were simulated. Although the model simulation was executed using a daily time step and the SS discharge was simulated in the model continuously, the observed SS data were not measured every day. Thus, the observed SS data and simulated SS values were compared for the same day, to evaluate the reproducibility of the SWAT model.

Table 1: SWAT parameters used for auto-calibration and the determined optimal values

No.		Parameter name	Lower bound	Upper bound	Optimal value	imet
CLIMATE						
1	SMTMP	Snow melt base temperature (°C)	-3.0	5.0	4.2	1
2	TIMP	Snow pack temperature lag factor	0.01	1.0	0.2	1
HYDROLOGICAL CYCLE						
3	ALPHA_BF	Baseflow alpha factor (days)	0.001	1.0	1.0	1
4	CANMX	Maximum canopy storage (mmH_2O)	0.0	10.0	3.5	1
5	CH_N	Manning's "n" value for the tributary channels	0.01	0.5	0.4	1
6	CN2	Initial SCS runoff curve number for moisture condition II	-10.0	10.0	-7.7	2
7	ESCO	Soil evaporation compensation factor	0.001	1.0	1.0	1
8	GW_REVAP	Groundwater "revap" coefficient	0.01	0.4	0.09	1
9	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mmH_2O)	0.0	5000.0	350.8	1
10	RCHRG_DP	Deep aquifer percolation fraction	0.0	1.0	0.0	1
11	SLOPE	Average slope steepness (m/m)	0.0	0.6	0.15	1
12	SOL_AWC	Available water capacity of the soil layer (mmH_2O/mm soil)	0.05	1.0	0.38	1
13	SOL_Z	Depth from soil surface to bottom of layer (mm)	-25.0	25.0	19.4	3
14	SURLAG	Surface runoff lag coefficient	0.4	10.0	0.96	1
SEDIMENT						
15	CH_COV	Channel cover factor	0.0	1.0	0.17	1
16	CH_EROD	Channel erodibility factor	0.0	0.6	0.04	1
17	SPCON	Coefficient of the sediment transport equation	0.001	0.1	0.06	1
18	USLE_P	USLE equation support practice factor	-50.0	50.0	-5.5	3

Note: imet means variation methods available in auto calibration (1: Replacement of initial parameter by value, 2: Adding value to initial parameter, 3: Multiplying initial parameter by value)

2.3 Input Data Descriptions

The SWAT model requires meteorological data such as daily precipitation, maximum and minimum air temperature, wind speed, relative humidity and solar radiation data. In addition, spatial data sets such as digital elevation model (DEM), land cover, and soil maps are required. Meteorological data were obtained from the JMA (2008), which maintains gauges to measure precipitation, air temperature and wind speed in and around the basin. However, because there were no gauges to monitor the relative humidity data in the basin, the relative humidity data from the city of Abashiri was used instead. Additionally, the solar radiation data were calculated by the Angstrom formula (FAO, 1998) using the actual sunshine duration in the basin that were recorded by the JMA.

Daily discharge data were obtained at the Hongo Outlet and formatted for use with the SWAT model. The data were provided by the Hokkaido Regional Development Bureau, a division of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). In addition, the SS concentration was monitored at the Hongo Outlet once a month by the Hokkaido Regional Development Bureau. Furthermore, SS discharge during periods of snow melt and rainfall events during summer were monitored on an irregular basis by the Abashiri city office. Both sets of data were used in this analysis. Additionally, because this study paid attention to SS load discharge, the SS loads were calculated using the observed SS concentration and river discharge data sets.

DEM data were prepared using a digital map with a 50-m grid elevation created from a 1:25,000 topographic map published by the Geographical Survey Institute (GSI, 2001). Land-use GIS data based on digital national information that identified categories such as paddy fields, upland fields, orchards, denuded land, forests, densely populated areas and water were used in this study. The data were obtained from the MLIT (1988). All types of land-use except orchards were found to be present in the basin (Figure 3).

GIS-referenced soil data were clipped from a 1:500,000 soil map Fundamental Land Classification Survey prepared by the MLIT (1969). The following nine soil types were observed in the study region: Fluvisols, Gleysols, Haplic Andosols, Histosols, Humic Cambisols, Lithosols, Ochric Cambisols, Podozols, and Rhegosols. With the exception of Fluvisols and Rhegosols, all of the aforementioned soil types were present in the study basin (Figure 3).

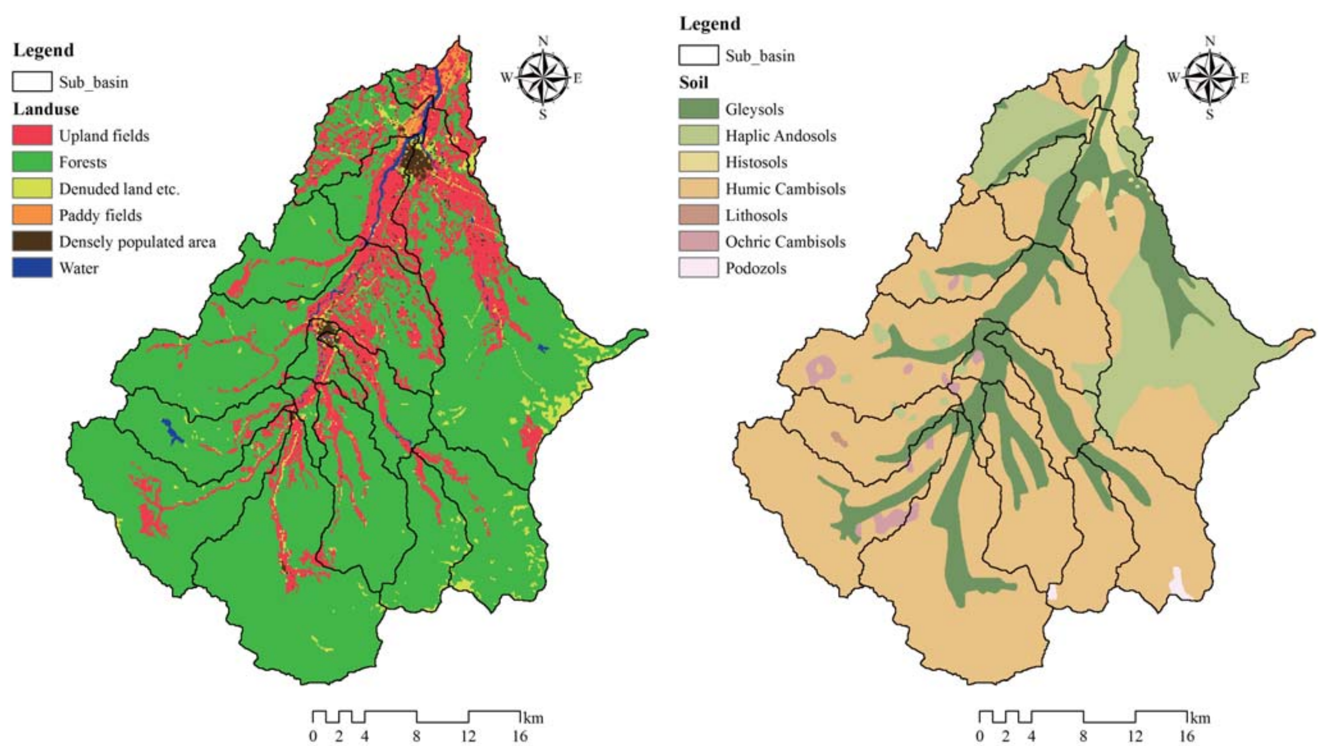

Fig. 3: Land use and soil classification GIS data maps

2.4 Model Performance Evaluation

The SWAT model was calibrated and validated using observed data based on daily evaluations of the river and SS discharges that were determined almost monthly. Initial assessment of the results are performed using graphical techniques, which provide a visual comparison of simulated and observed constituent data and a first overview of the model performance (ASCE, 1993). The coefficient of determination (R^2), Nash-Sutcliffe efficiency (*NSE*), root mean square error (*RMSE*) – observations standard deviation ratio (*RSR*), and percent bias (*PBIAS*) were then used to statistically evaluate the model performance.

The R^2 value is an indicator of the strength of the relationship between the observed and simulated values. R^2 ranges from zero to one, with a value of zero indicating no correlation and a value of one indicating that the predicted dispersion equals the measured dispersion (Krause et al., 2005). Gassman et al. (2007) reported that daily R^2 statistics have been used in many previously conducted SWAT studies. The *NSE* value (Nash and Sutcliffe, 1970) indicates how well the plot of the observed values versus the simulated values fits the 1:1 line. The *NSE* values range from – ∞ to one, with values less than or very close to zero indicating unacceptable or poor model performance and values equal to one indicating perfect performance. The *NSE* value is calculated using the following equation:

$$NSE = 1.0 - \left(\sum_{i=1}^{n} (Y_{obs,i} - Y_{cal,i})^2 \Big/ \sum_{i=1}^{n} (Y_{obs,i} - Y_{obs\_mean})^2 \right) \quad (1)$$

where n is the number of registered data, $Y_{obs,i}$ is the observed data at time i, $Y_{cal,i}$ is the simulated data, and Y_{obs_mean} is the mean value of the observed data.

The *RSR* value is calculated as the ratio of the *RMSE* and the standard deviation of the measured data (Moriasi et al., 2007). The *RSR* value incorporates the benefits of error index statistics and includes a scaling/ normalization factor. The value varies from the optimal value of zero, which indicates zero *RMSE* or residual variation, to a large positive value (Moriasi et al., 2007). The *RSR* value is calculated using the following equation:

$$RSR = RMSE / STDEV_{obs} = \left(\sqrt{\sum_{i=1}^{n} (Y_{obs,i} - Y_{cal,i})^2} \right) \Big/ \left(\sqrt{\sum_{i=1}^{n} (Y_{obs,i} - Y_{obs\_mean})^2} \right) \quad (2)$$

where n is the number of registered data, $Y_{obs,i}$ is the observed data at time i, $Y_{cal,i}$ is the simulated data, and Y_{obs_mean} is the mean value of the observed data.

The *PBIAS* is used to determine if the average tendency of the simulated data is larger or smaller than their observed counterparts (Gupta et al., 1999). The optimal value of *PBIAS* is zero, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, while negative values indicate model overestimation bias (Gupta et al., 1999). The *PBIAS* is calculated using the following equation:

$$PBIAS = \left(\sum_{i=1}^{n} (Y_{obs,i} - Y_{cal,i}) \times 100 \Big/ \sum_{i=1}^{n} (Y_{obs,i}) \right) \quad (3)$$

where, n is the number of registered data, $Y_{obs,i}$ is the observed data at time i, and $Y_{cal,i}$ is the simulated data.

Moriasi et al. (2007) developed the model evaluation guidelines for the systematic quantification of accuracy in watershed simulations and found that the model simulation could be judged as “satisfactory” if $NSE > 0.5$, $RSR \leq 0.70$, and the *PBIAS* is ± 25% for stream flow, and if $NSE > 0.5$, $RSR \leq 0.70$, and the *PBIAS* is ± 55% for sediment for the monthly time step. In this study, the daily river discharge and SS load data collected on an almost monthly basis were used for evaluating the simulation results. Typically, model simulations are poorer for shorter time steps (daily) than for longer time steps (monthly or yearly) as discussed by Engel et al. (2007); thus, the guidelines for the monthly time step were used to judge the model performance.

3. RESULTS AND DISCUSSION

3.1 Reproducibility of Daily Flow Discharge

The simulated and observed daily river discharge is shown in Figure 4. A visual comparison revealed that the results of calibration and validation at the Hongo Outlet represented the fluctuations in discharge relatively well, though some daily peaks were underestimated. The R^2 values were around 0.7 during both calibration and validation periods. Compared with the daily R^2 values of reported SWAT hydrologic studies summarized by Gassman et al. (2007), the values of calibration and validation showed relatively high reproducibility. In addition, the statistical values of *NSE*, *RSR*, and *PBIAS* complied with the criteria values summarized by Moriasi et al. (2007), indicating that the model performance for the daily river discharge was satisfactory. However, the reproducibility during winter, particularly from January to March, was low. As shown in Table 2, the difference between the simulated and observed monthly discharge from January to March was larger than during other months, especially for March (26 mm). It is likely that the precision of the observed daily discharge data during that period was lower than during other periods due to freezing of the river. Specifically, the simulated annual discharge was 513mm, while the observed discharge was 571mm during the simulated period. The difference between the simulated and observed annual flow discharge was smallest in 2003 (2.7 mm), while it was largest in 2004 (165.4 mm).

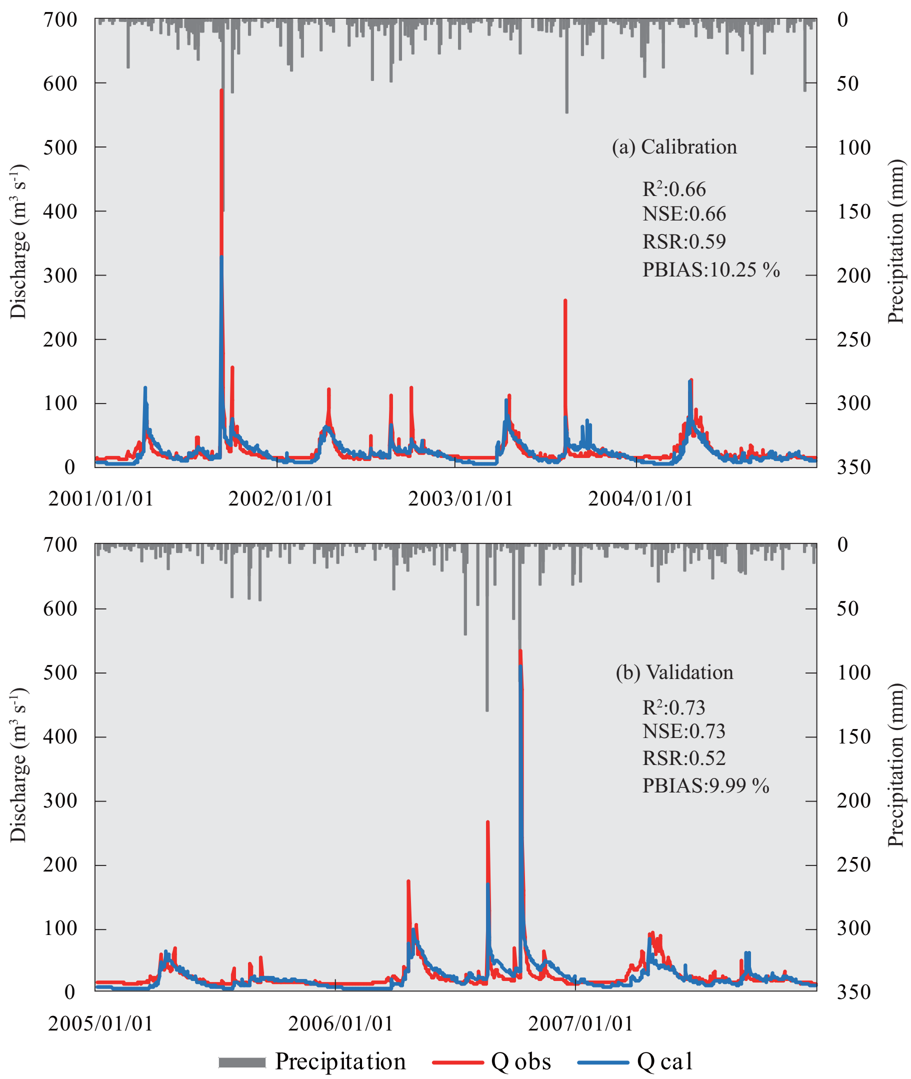

Fig. 4: Reproducibility of river discharge (a) calibration period (2001-2004), (b) validation period (2005-2007)

Table 2: Monthly observed and simulated river discharges and the difference during each month (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Obs.	24.9	22.5	39.2	109.3	74.2	32.1	31.8	48.6	57.4	68.3	35.9	26.6	570.8
Cal.	11.9	5.3	13.3	96.9	75.9	32.9	25.2	45.2	62.9	70.1	46.3	27.1	512.9
Difference	13.1	17.2	26.0	12.4	-1.7	-0.8	6.6	3.5	-5.5	-1.8	-10.4	-0.5	57.9

3.2 Reproducibility of SS Load Discharge

The statistical analyses indicated that the predicted SS load during calibration and validation was satisfactory during the target period, even though only limited observed data were available (Figure 5). The monthly load was largest in April (32.2 tons km^{-2}), followed by October and September, during which time simulated loads of 17.6 and 16.7 tons km^{-2}, respectively, were obtained (Table 3). In the study area, agricultural activities such as land cultivation and planting intensify in April after the snow melts. In addition, the river discharge increases during this period in response to the influx of melt water. These factors were likely responsible for the increased SS loads that occurred during April. Similarly, the high

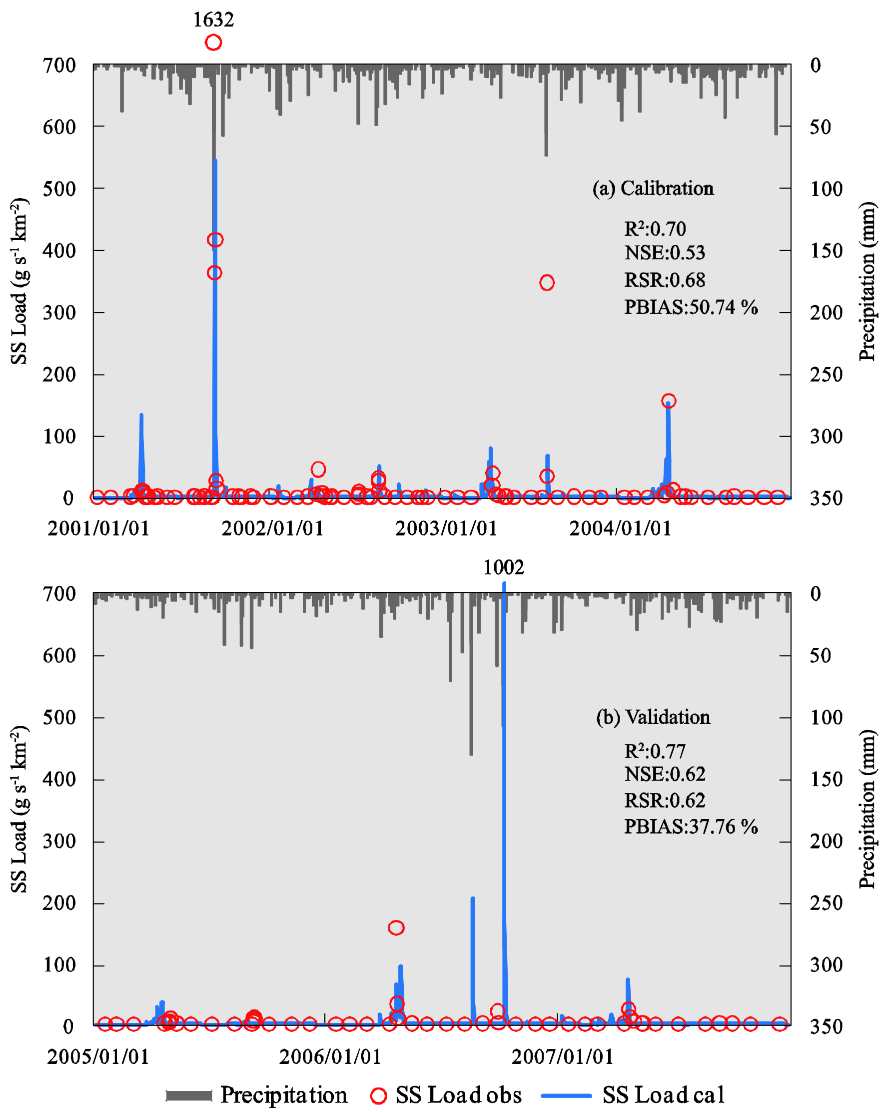

Fig. 5: Reproducibility of SS loads; (a) calibration period (2001-2004) and (b) validation period (2005-2007)

Table 3: Simulated monthly SS load discharge (tons km^{-2}) from 2001 to 2007

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
SS Load	1.2	0.3	4.5	32.2	1.6	0.7	0.7	6.8	16.7	17.6	1.6	0.7	84.4

SS loads observed in September likely occurred because the monthly precipitation is largest during that month, which leads to increased runoff and tractive force against SS. Moreover, harvest of crops and land cultivation for winter wheat primarily occur from the end of September to October, which also likely affects the SS loads. The simulated annual SS loads ranged from 30.4 tons km^{-2} (2005) to 191.7 tons km^{-2} (2006), and the average value during these periods was 84.4 tons km^{-2}. The variation in SS load during these years was influenced by the amount of annual precipitation. During the simulation period, the percentage at the Tsubetsu weather gauge was lowest in 2005 (651mm) and highest in 2006 (1184mm).

3.3 Hydrological Sensitivities of Monthly Discharge, Evapotranspiration and Snow Water Equivalent in the Basin

As shown in Figure 6, runoff in the basin was found to be somewhat more sensitive to changes in temperature than to changes in precipitation, which is similar to the results of a study conducted by Singh et al. (2006). The results of the present study revealed that discharge decreased from April to November in every precipitation decrease and temperature increase scenario. In addition, the greatest effect was observed from May to July, during which time 40% to 80% decreases in discharge were estimated. Similarly, discharge also decreased from April to October for scenarios in which only the temperature increased, but no change was observed when the temperature increase was less than 1ºC in April and October. Moreover, discharge in November did not increase or decrease when only the temperature increased. Furthermore, a scenario in which there was only a 4 ºC increase in temperature was found to lead to a 60% decrease in discharge in May and June and a 50% decrease in April and July.

Surprisingly, discharge decreased by a maximum of 60% in May in response to a 10% increase in precipitation scenario and by a maximum of 50% for a 20% precipitation increase scenario when these changes were coupled with a 4ºC increase in temperature. Conversely, during winter, especially from January to March, discharge increased significantly for every scenario, with the exception of a 20% decrease in precipitation and a 1ºC increase in temperature in January. During winter, the ratio of discharge increased in accordance with increasing temperatures when compared with the base case. This trend was found even in precipitation decrease scenarios. The maximum estimated increase in discharge was found to be 420%, and this occurred in March in response to a 20% increase in precipitation and a 4ºC increase in temperature.

This simulation showed that ET either did not change or decreased in every scenario. These findings indicate that the soil water content tends to decrease in response to global warming. Additionally, a distinctive trend in which ET began increasing during winter, especially from January to March, was observed, which was similar to the estimated discharges for winter. In addition, ET increased remarkably in March. Indeed, in every scenario involving a 4ºC increase in temperature, ET increased by approximately 100-fold during March. Currently, the ET from January to March is almost zero (smaller than 0.1 mm), but increases by approximately 10 mm in March for the scenario condition involving a 4ºC increase in temperature. This occurred because the air temperature in January and February is very cold, even after an increase of 4ºC. However, the air temperature begins to increase in March; therefore, ET increased in response to a multiplier effect of the temperature increase scenario and the natural conditions. Incidentally, it was estimated that ET varied from 10 to 30% in May, and from 0 to 20% from June to October, even though the relative variations in ET were not recognized during that period in Figure 6.

The SWE decreased remarkably through the winter from October to May. This decrease was particularly strong in November and April. In addition, the ratio of the SWE decreased in accordance with the increase in precipitation. Because this basin is located in the northeastern portion of the Hokkaido Region, the SWE did not disappear, even in response to an increase in temperature of 4ºC. Surprisingly, in a scenario involving a 20% increase in precipitation and a 1ºC increase in temperature in January, the SWE increased by 18%. Furthermore, in the case of a 20% increase in precipitation and a 2ºC increase in temperature in January and a 1ºC increase in February, the SWE also increased by 15%. Moreover, an increase in SWE was observed in December, January and February under several precipitation and temperature increase scenarios. Incidentally, the SWE in the base case was naturally almost zero in May (0.08 mm) and October (0.05 mm). As a result, the SWE decreased to zero in response to scenarios in which the temperature increased by more than 1ºC.

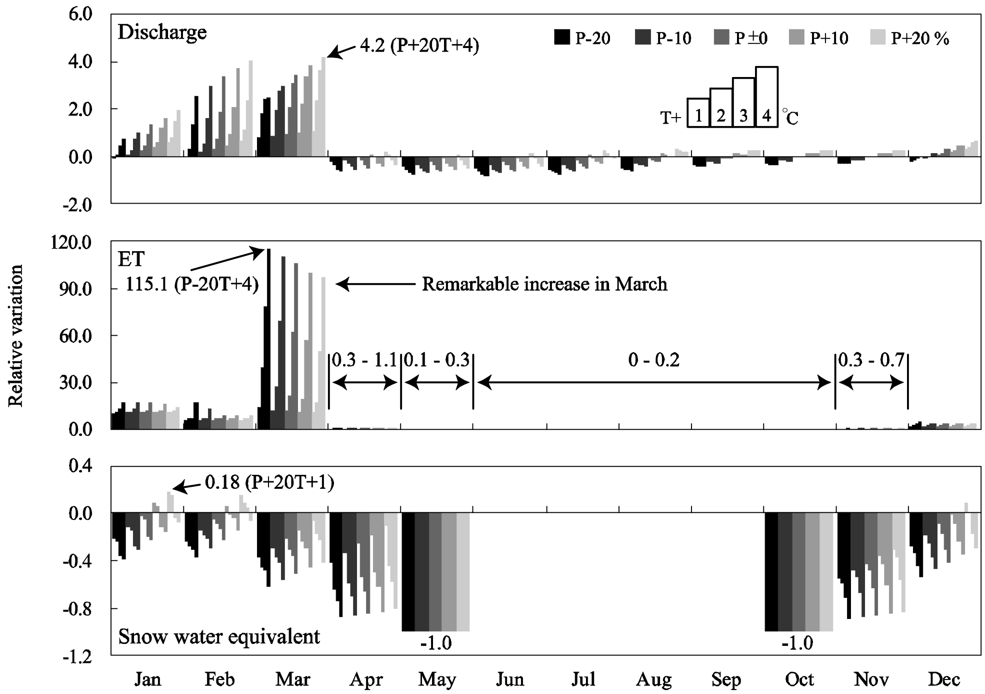

Fig. 6: Relative variations in discharge, ET, and snow water equivalent between the climate change scenarios and the base scenario

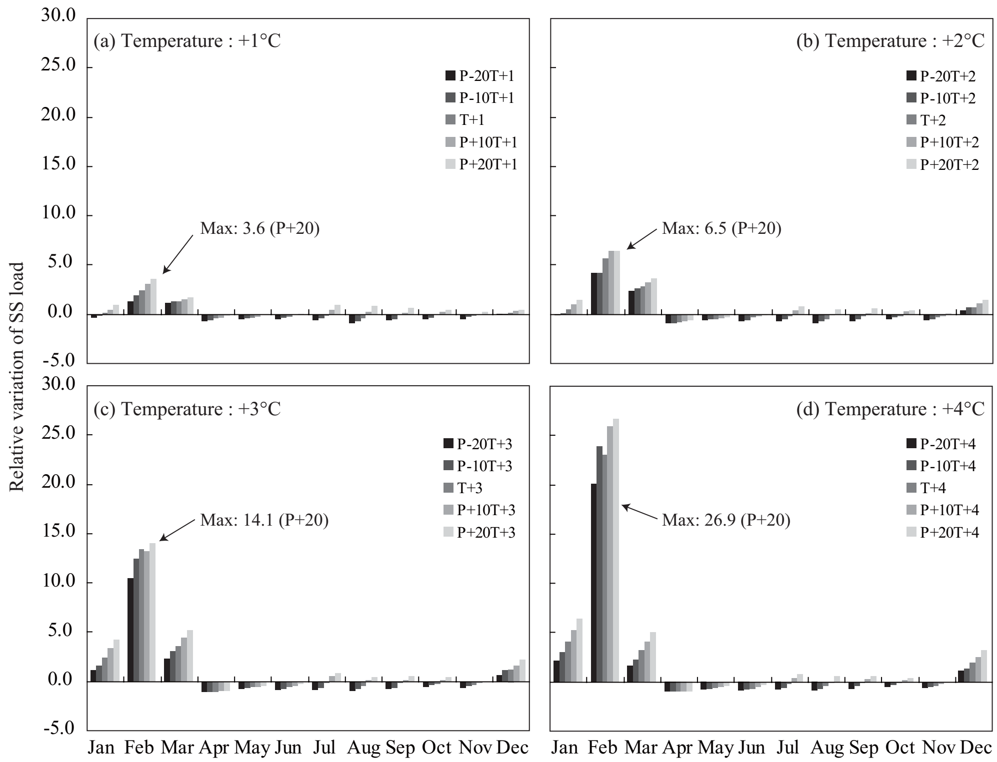

Fig. 7: Relative variations in the predicted SS loads between the climate change scenarios and the base case; combinations of all precipitation scenarios and (a) temperature + 1ºC, (b) temperature + 2ºC, (c) temperature + 3ºC, and (d) temperature + 4ºC

3.4 Sensitivity of Monthly SS Load Discharge from the Basin

The results of the sensitivity analyses showed that the greatest increase in SS loads occurred during February, followed by January and March (Figure 7). The maximum increase in SS loads was observed in February for scenarios in which there was a 20% increase in precipitation. The SS load was also predicted to be approximately 27 times greater than the base case in response to scenarios involving a 4ºC increase in temperature. Moreover, the magnitude of the temperature increase had a strong effect on the monthly SS load. This trend appeared in both precipitation decrease and increase scenarios and was especially strong in scenarios involving changes in temperature of greater than 3ºC. In the base case, the SS load in February was smallest due to the low discharge of stream flow and precipitation. Furthermore, the SS load at the Hongo Outlet was lower during winter than in spring and fall. Moreover, the results indicated that a temperature increase from 2ºC to 3ºC represents a threshold for SS loads during this period. In a previous study, Rekolainen (1989) reported that SS concentrations were higher and correlated with discharge during the later phase of snow melt, as well as with rainfall during the frost thawing period. In the simulation of the Abashiri River basin, these phenomena were considered to occur early during winter. Specifically, the simulations of the Abashiri River basin that involved temperature increases assumed that the surface of the river did not freeze often and that the river discharge and SS loads increased considerably in response to snow melt water and increasing precipitation. Conversely, the SS load tended to decrease from 3% (T+1 in September) to 98% (P-20T+4 in April) from April to November in every scenario combination, except precipitation increase scenarios. This occurred due to the decreased discharge and increased temperature that occurs during that period. Indeed, the SS loads decreased from April to June for most of the precipitation increase scenarios, after which the load began to increase gradually in accordance with the increase in discharge. Although it is difficult to determine how much of an increase occurred in other months from the figure due to the relatively large increases in the SS load that occurred from December to March, an increase in SS load of approximately 2 times that predicted in the base model was observed in July in response to a 20% increase in precipitation and a 1ºC increase in temperature.

When the annual load was considered, the mean SS load decreased in every scenario except for the precipitation increase scenarios. Specifically, the SS load increased by approximately 34% (about 113 tons km^{-2}) in response to a 20% increase in precipitation and a 4ºC increase in temperature, whereas the load decreased by 57% (about 36 tons km^{-2}) in response to a scenario that included a 20% decrease in precipitation and a 2ºC increase in temperature.

4. CONCLUSIONS

The SWAT model was applied to the Abashiri River basin in northern Japan to evaluate and predict hydrological responses in river discharge, SS loads, ET, and SWE in the basin under various climate change scenarios. The SWAT model was capable of satisfactory reproduction of measured river discharge and SS loads. However, the precision of the observed daily discharge data during winter may affect the model performance when hydrological studies are conducted in northern Japan and other cold regions worldwide. In the Abashiri River basin the minimum air temperature during winter is less than -10ºC; therefore, the river water surface may freeze in some places and at various times. In addition, accumulation of snow inside the river channel may affect the water level due to the narrow river channel width. Moreover, the river discharges were measured only once a day (at twelve noon) from December to March, but were measured hourly from April to November. Overall, these factors input uncertainty into the model and led to poor model performance during winter.

This simulation predicted that all target elements will be strongly affected by increases in temperature, and that these effects will be especially strong during winter. It is believed that a warmer climate will extend the growing season of crops due to decreasing amounts of snow. Because agriculture in the study area is restricted by a short summer and cold weather during winter, agricultural productivity may increase in response to a warmer climate, but the varieties of crops grown will likely change. In addition, the availability of water resources will change because the patterns and amount of precipitation will also change. These changes will lead to variations in the SS and nutrient runoff patterns and levels from upland fields. Moreover, the warmer climate may also damage the tourist industry in the region, which is primarily based on activities such as winter sports and surf smelt fishing. Accordingly, it is very important to consider the impact of climate change against economic and human activities when developing strategies to manage and use the resources in this region.

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REFERENCES

1. Abashiri City. 2008. Fishery statistics of Abashiri City 2007. Available at: http://www.city.abashiri.hokkaido.jp/ (in Japanese).
2. Arnold, J.G. and N. Fohrer. 2005. SWAT2000: current capabilities and research opportunities in applied watershed modeling. *Hydrological Processes* 19(3): 563-572. DOI: 10.1002/hyp.5611.
3. Arnold, J.G., P.M. Allen, and D.S. Morgan. 2001. Hydrologic model for design and constructed wetlands. *Wetlands* 21 (2): 167-178. DOI: 10.1672/0277-5212(2001)021[0167:HMFDAC]2.0.CO;2.
4. ASCE. 1993. Criteria for evaluation of watershed models. *Journal of Irrigation and Drainage Engineering* 119(3): 429-442. DOI: 10.1061/(ASCE)0733-9437(1993)119:3(429).
5. Di Luzio, M., R. Srinivasan, and J.G. Arnold. 2004. A GIS-Hydrological Model System for the Watershed Control of Agricultural Nonpoint and Point Sources of Pollution. *Transactions in GIS* 8 (1): 113-136. DOI: 10.1111/j.1467-9671.2004.00170.x.
6. Duan, Q., S. Sorooshian, and V. Gupta. 1992. Effective and Efficient Global Optimization for Conceptual Rainfall-Runoff Models. *Water Resources Research* 28 (4): 1015-1031.
7. Engel B., D. Storm, M. White, J.G. Arnold, and M. Arabi.2007. A hydrologic/water quality model application protocol. *Journal of the American Water Resources Association* 43 (5): 1223-1236. DOI: 10.1111/j.1752-1688.2007.00105.x.
8. FAO. 1998. Irrigation and Drainage Paper No.56 Crop evapotranspiration (guidelines for computing crop water requirements) by Richard G. Allen, Luis S. Pereira, Dirk Raes, Martin Smith, pp.290, ISBN 92-5-104219-5.
9. Gassman, P.W., M.R. Reyes, C.H. Green, and J.G. Arnold. 2007. The soil and water assessment tool: historical development, applications, and future research directions. *Transactions of the ASABE* 50 (4): 1211-1250.
10. GSI. 2001. Digital map 50m grid (Elevation) Nippon-I, Sixth edition (CD). Geographical Survey Institute, Tsukuba, Japan.Gupta, H.V., S. Sorooshian, and P.O. Yapo. 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering* 4 (2): 135-143. DOI: 10.1061/ (ASCE) 1084-0699 (1999) 4:2(135).
11. JMA. 2005. Summary of extreme weather report 2005. Japan Meteorological Agency, Tokyo, Japan. Available at: http://www.jma.go.jp/jma/index.html (in Japanese).
12. JMA. 2008. Climate statistics. Japan Meteorological Agency, Tokyo, Japan. Available at: http://www.jma.go.jp/jma/index.html (in Japanese).
13. Krause, P., D.P. Boyle, and F. Bäse. 2005. Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences* 5: 89-97.
14. MLIT. 1988. Digital national land information. Ministry of Land, Infrastructure, Transport and Tourism, National Land Information Office, Tokyo, Japan. Available at http://nlftp.mlit.go.jp/ (in Japanese).
15. MLIT. 1969. A 1:500,000 fundamental land classification survey GIS data (soil map). Ministry of Land, Infrastructure, Transport and Tourism, National Land Survey Division, Tokyo, Japan. Available at: http://tochi.mlit.go.jp/tockok/index.htm (in Japanese).
16. Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Binger, R.D. Harmel, and T.L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* 50 (3): 885-900.
17. Nash, J.E., and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models. Part I - A

discussion of principles -. *Journal of Hydrology* 10 (3): 282-290.

18. Nearing, M.A., V. Jetten, C. Baffaut, O. Cerdan, A. Couturier, M, Hernandez, Y. Le Bissonnais, M.H. Nichols, J.P. Nunes, C.S. Renschler, V. Souchère, and van K. Oost. 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. *Catena* 61: 131-154. DOI:10.1016/j.catena.2005.03.007.
19. Quick, M.C. and A. Pipes. 1977. U.B.C. Watershed model. *Hydrol. Sci. Bull.* 22(1): 153-161. Available at: http://www.iahs.info/hsj/220/hysj_22_01_0153.pdf
20. Rekolainen, S. 1989. Effect of snow and soil frost melting on the concentrations of suspended solids and phosphorus in two rural watershed in Western Finland. *Aquatic Sciences* 51 (3): 211-223. DOI: 10.1007/BF00877743.
21. Sharpley, A.N., and J.R. Williams (eds.). 1990. EPIC-Erosion Productivity Impact Calculator, 1. model documentation. U.S. Department of Agriculture, Agricultural Research Service, Tech. Bull. 1968.
22. Singh, P., and N. Kumar. 1997. Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river. *Journal of Hydrology* 193: 316-350. DOI: 10.1016/S0022-1694 (96) 03142-3.
23. Singh, P., M. Arora, and N.K. Goel. 2006. Effect of climate change on runoff of a glacierized Himalayan basin. *Hydrological Processes* 20 (9): 1979-1992. DOI: 10.1002/hyp.5991.
24. Somura, H., J.G. Arnold, D. Hoffman, I. Takeda, Y. Mori, and M. Di Luzio. 2009. Impact of climate change on the Hii River basin and salinity in Lake Shinji: a case study using the SWAT model and a regression curve, *Hydrological Processes* 23 (13): 1887-1900. DOI: 10.1002/hyp.7321.
25. Thodsen, H., B. Hasholt, and J.H. Kjærsgaard. 2008. The influence of climate change on suspended sediment transport in Danish rivers, *Hydrological Processes* 22 (6): 764-774. DOI: 10.1002/hyp.6652.
26. van Griensven A., T. Meixner, S. Grunwald, T. Bishop, M. Diluzio, and R. Srinivasan. 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. *Journal of Hydrology* 324: 10-23. DOI: 10.1016/j.jhydrol.2005.09.008.
27. Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Transactions of the ASAE* 21: 129-144.
28. Xu, C.Y. 2000. Modelling the effects of climate change on water resources in Central Sweden. *Water Resources Management* 14: 177-189. DOI: 10.1023/A: 1026502114663.

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OPTIMAL PLACEMENT OF CONSERVATION PRACTICES USING GENETIC ALGORITHM WITH SWAT

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ABSTRACT

The effectiveness of conservation practices depends on their placement on the fields within the watershed. Cost effective placement of these practices for maximum water quality benefits on each field requires comparing a very large number of possible land use scenarios. To address this problem, we interface a multiobjective optimization algorithm (MOA) with the Soil and Water Assessment Tool (SWAT) model and cost data to develop a tradeoff frontier of least cost of achieving nutrient reductions and the corresponding locations of conservation practices. This approach was applied to the Raccoon River Watershed, which drains about 9,400 km^2 of an intensive agriculture region in west-central Iowa. Strong calibration and validation (R^2) and Nash-Sutcliffe's coefficient (E) statistics were found for SWAT annual and monthly streamflow and nutrient predictions, most of which exceeded 0.7. Applying the MOA with the calibrated SWAT model resulted in a wide range of optimal solutions for achieving nutrient reductions in relation to the total cost of placing these practices. For example, a 30% reduction in nitrate (and a corresponding 53% reduction in total P) at the watershed outlet can be achieved with a cost of 80 $million per year. This solution frontier allows policymakers and stakeholders to explicitly evaluate the tradeoffs between cost and nutrient reductions.

Keywords: *Raccoon river watershed, SWAT, multiobjective optimization algorithm, nutrient calibration.*

1. INTRODUCTION

Conservation practices such as reduced tillage, contour farming, grassed waterways, land retirement and others have been widely used and have proven to be effective measures for reducing water quality pollutants. However, the effectiveness of these practices at the watershed level significantly depends on their placement due to the unique nature of the biophysical relationship between conservation practices and resulting water quality impacts. In addition, there are potentially large numbers of conservation practices that can be implemented on each field. This means that solving for the optimal solution (or a set of optimal solutions; i.e., equifinality (Beven, 1993)) requires comparing a very large number of possible land use scenarios. Specifically, if there are "N" conservation practices possible for adoption on each field and there are "F" fields, this implies a total to NF possible configurations to compare. In a watershed with hundreds of fields and more than a couple of conservation practices, this comparison quickly becomes unwieldy. Added to this complexity, some conservation practices are cost-effective for one nutrient and may have little or no beneficial effect on the other nutrient (even deleterious effects are possible). This implies that the optimal choice of conservation practices will depend on the degree to which control of each separate nutrient is desired.

Recent development of genetic algorithms (GAs) provides a solution strategy for this sort of problem. GAs mimic the process of evolution, which, in effect, is a method of searching for solutions among an enormous amount of possibilities. These algorithms work with populations of candidate solutions iteratively applying stochastic operations of selection, recombination, and mutation in the hope of finding improvements with respect to the optimization objectives. In general, these belong to a class of stochastic optimization method and are well suited for approximating solutions to complex combinatorial problems (e.g., Deb, 2001; Forrest, 1993). To date, limited GA applications have been performed within

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integrated watershed modeling systems. Some examples of GA interfaces with the Soil and Water Assessment Tool (SWAT) watersheds-scale water quality model (Arnold and Fohrer, 2005; Gassman et al., 2007) include Srivastava et al. (2002), Veith et al. (2003), Bekele and Nicklow (2005), and Arabi et al. (2006), which were performed at a relatively small scale. Maringanti et al. (2009) applied a multiobjective optimization algorithm (MOA) to examine the tradeoff between two objective functions for sediment, phosphorus (P) and nitrogen (N) reduction.

This study builds upon previous research performed by Jha et al. (2009), which describes a SWAT modeling framework developed for the Raccoon River Watershed in west-central Iowa and several scenarios that support possible implementation strategies to meet Total Maximum Daily Load (TMDL) criteria established for the watershed (Schilling et al., 2008). In this study, we interface an MOA with SWAT to examine optimal placement of selected conservation practices for the Raccoon River watershed, using objective functions which were built to cost-effectively reduce loadings of nitrate (NO_3) and total P at the watershed outlet. The specific objectives of this research are: (1) briefly describe the modeling system, (2) provide an overview of the model calibration and validation results, and (3) to identify least cost combinations and placement of conservation practices in the region to achieve N and P reductions for the Raccoon River Watershed.

Conservation practices chosen include reduced fertilization of row crops, three reduced tillage options, contour farming, installation of grassed waterways, and land retirement. The development of a full frontier will allow policy makers and stakeholders to explicitly see the tradeoffs between cost and nutrient reductions as well as the potential tradeoffs between the two nutrients.

2. RACCOON RIVER WATERSHED

The Raccoon River Watershed is a typical Midwest agricultural basin. It drains a region of about 9,400 km^2 in west-central Iowa (Figure 1). Current land use is predominantly agricultural with corn and soybean row crops comprising 76% of the watershed. Agricultural grasslands (alfalfa, brome, pasture and land retirement) comprise 17% of the watershed, whereas forest (4%), urban areas (2%) and water (1%) comprise the remaining land area. The river is impacted by sediment, P, and N pollution, which originate primarily from nonpoint sources (Jha et al., 2007; 2009; Schilling et al., 2008), as well as bacteria pollution from point and nonpoint sources (Schilling et al., 2008). The nutrient input sources include widespread use of fertilizers, livestock manure applications, legume fixation, and mineralization of soil N. NO_3 pollution is a particularly acute problem and is transported primarily through groundwater discharge via baseflow and tile drainage (Schilling and Zhang, 2004). The watershed's high concentrations of NO_3 have exceeded the federal maximum contamination level (MCL) standard of 10 mg/L with enough frequency since the late 1980s to warrant the Des Moines Waterworks' installation and operation of the world's largest NO_3 removal facility (White, 1996). Sections of the Raccoon River have also been listed in Iowa's Federal Clean Water Act 303(d) list of impaired waters, due to either elevated NO_3 or bacteria levels, resulting in the need for TMDLs to be developed (Schilling et al., 2008).

Fig. 1: Location of the Raccoon River Watershed and delineated subwatersheds

3. SWAT DESCRIPTION, SIMULATION FRAMEWORK, AND CALIBRATION/ VALIDATION

The SWAT model is a watershed based hydrologic and water quality model which is capable of modeling the impact of different land use and management practices on hydrology and water quality of the watershed (Arnold and Fohrer, 2005; Gassman et al., 2007). SWAT is a long-term continuous simulation model that operates on a daily time step. Major model components are hydrology, weather, soil temperature, crop growth, nutrients, bacteria, and land management. Watersheds are subdivided into subwatersheds, which are further delineated by hydrologic response units (HRUs) that consist of homogeneous soil, land use and management characteristics. The HRUs represent percentages of a subwatershed area and thus are not spatially defined in the model. Routing of water and pollutants are simulated in the model from the HRUs to the subwatershed level, and then through the stream network to the watershed outlet. Neitsch et al. (2005) provide detailed documentation of the current SWAT2005 model which was used in this study. SWAT validation and scenario applications have been reported worldwide for a wide variety of watershed scales and environmental conditions (Gassman et al., 2007).

The watershed was divided into a total of 112 subwatersheds that were generally consistent with standard 12-digit hydrologic units used by U.S. federal agencies, and more than 3,000 HRUs. Key soil, topographic, land cover, point source, and confined animal feeding operation (CAFO) data was obtained from IDNR (2009). Precipitation and temperature data required for the SWAT simulations was provided by the Iowa Environmental Mesonet (ISU, 2009). Distribution of tile drainage across the watershed was estimated using algorithms developed by Miller (2007) and Jaynes (2007). Additional details regarding these data layers, as well as key management data and other aspects of the simulation framework, are described in Jha et al. (2009).

The SWAT calibration process was performed by adjusting key hydrologic and nutrient related parameters within accepted ranges at the Van Meter gauge site (Figure 1) near the watershed outlet. An initial overall annual water balance was performed for the time period 1986 to 2004, including an assessment of partitioning between surface runoff and subsurface flow contributions to overall streamflow. SWAT-predicted annual, monthly, and daily streamflows were then calibrated for the period 1986 to 1995, followed by streamflow validation based on comparisons with streamflows measured during 1996 to 2004. Additional monthly validation was also performed for three upstream sites using the same calibrated parameters determined during the 1986 to 1995 calibration process. Nutrient calibration and validation were also performed for the same time periods based on the calibrated streamflows and additional calibrated parameters. The nutrient comparisons were performed on the basis of loads; the “measured loads” were converted from original measured concentrations with the U.S. Geological Survey (USGS) Load Estimator (LOADEST) regression model (Runkel et al., 2004). The evaluation of some of the nutrient constituents (e.g., organic N and total P) was limited to only a shorter calibration phase (2001-2004) due to insufficient data being available for validation. Statistical evaluation of the simulated results was assessed using two performance criteria: coefficient of determination (R^2) and Nash-Sutcliffe’s coefficient (E) (Nash and Sutcliffe, 1970). The accuracy of the statistics was judged based on criteria suggested by Moriasi et al. (2007). Further description of the calibration and validation process is given in Jha et al. (2009).

4. CONSERVATION OPTIONS AND COSTS

A wide array of conservation practices exist that can be used to reduce N and/or P loadings from cropland. The assessment here was limited to conservation tillage (much, ridge, and no till), contour farming, grassed waterways, terraces, cropland retirement (replaced with grass perennial cover), and a 20% reduction of fertilizer application for corn in relevant corn-soybean rotations. Conservation tillage, grassed waterways, terraces were accounted for by adjusting SWAT model parameters similar to the approaches described by Gassman et al. (2006) and Secchi et al. (2007). These conservation practices were simulated in tandem with the existing cropping systems, except for the cropland retirement option. In total, 33 different combinations of conservation practices were available for application to each cropland HRU, including the option of cropland retirement.

Conservation practice cost data was obtained from several different sources. Terraces, no-till, grassed waterways, and contouring costs were based on either U.S. Department of Agriculture (USDA) and/or Iowa Department of Agriculture and Land Stewardship (IDALS) cost share data as described in more detail by Feng et al. (2007) and Kling et al. (2007). The costs of land retirement were proxied by the cash rental rates as discussed by Feng et al. (2007) and Kling et al. (2007). The costs resulting from reduced N reductions were estimated as a function of yield curves obtained from an N-rate Calculator for corn-soybean crop sequences in the geographic zone containing the Raccoon River watershed (ISU, 2009). The cost reduction estimate was calculated on the basis of multiplying the reduced profits, determined from the yield reductions, by the price of corn.

5. MULTIOBJECTIVE OPTIMIZATION ALGORITHM

SPEA2 (Zitzler et al., 2002), the MOA used in this study, was interfaced with GALib, publicly available C++ library of genetic algorithms originally developed by Wall (2006), and SWAT which was executed within the i_SWAT Windows-based database control system (CARD, 2009), to form the complete integrated modeling system. The fundamental multiobjective optimization logic needed for this was provided by SPEA2 while the GALib provides the ability to execute the required evolutionary search algorithm. The watershed-level water quality impacts of the conservation practices are simulated within the SWAT/i_SWAT framework. Together, the integrated system provides the capacity to evaluate a wide range of conservation practice alternatives across the different landscapes in the watershed. The optimization algorithm was initialized with a population of 50 individuals (scenarios). These individuals were created in a way that was only partially random, in order to take advantage of previously known information about the study domain. This was performed by seeding the initial population with two key individuals: one that represented the baseline allocation of conservation practices and a second that represented all cropland being retired to permanent grass cover. These individuals represent the two extreme boundary points on the tradeoff frontier, where the baseline individual results in the lowest cost and highest nutrient loadings while the retired cropland individual results in the highest cost and lowest nutrient loadings. An additional 32 individuals, which represented uniform application of each of the conservation practices combinations across the entire cropped area of the watershed, were also included in the initial population to make sure a more complete coverage of the search space occurred. This seeding approach ensures that a good coverage of the objective space is obtained and that conservation practices which are determined to be the most efficient are used to help direct the stochastic search and improve the overall efficiency of the algorithm. A random approach was used for the remainder of the initial population, in which one of the 33 conservation practice options was randomly assigned to each cropland HRU in the watershed.

The calibrated SWAT model was run separately with each of 50 initial individuals. Non-dominated individuals were then selected based on the evolutionary algorithm’s multiobjective optimization function of minimizing 1) the cost of nonpoint source pollution control, 2) the mean annual NO_3 loadings at the watershed outlet, and 3) the mean annual total P loadings at the watershed outlet. Those selected individuals were used to create the next population of 50 individuals. A set of nondominated individuals surviving after several hundred generations (iterations of the evolutionary algorithm) provides an approximation to the true frontier.

6. RESULTS AND DISCUSSION

6.1 Calibration and Validation Results

Both the graphical (Figures 2 and 3) and statistical results (Table 1) show that SWAT strongly replicated most of the streamflow and NO_3 levels that were measured across the entire 23-year testing period. The majority of the R^2 and E statistics exceeded 0.8 for the predicted annual and monthly streamflows and NO_3 loads. Weaker statistics were calculated for the NO_3 calibration period due in part to less accurate estimates of some of the peak monthly NO_3 loads (Figure 3). The calibrated organic N and total P load results (Table 1 and Figures 4 and 5) were mixed for the shorter 2001 to 2004 calibration period, with weaker statistics found for organic N versus very strong R^2 and E values for total P. Virtually all of the statistics meet the criteria suggested by Moriasi et al. (2007) for successful simulation results, with the exception of the monthly NO_3 E value and the annual organic N value. Additional streamflow and nitrate calibration and validation results are discussed by Jha et al. (2009).

6.2 The Tradeoff Frontier and the Cost of Nutrient Reduction

Figure 6 shows two-dimensional projections of the tradeoff frontier of possible solutions, which consists of a large number of nondominated individuals surviving after each of the 1,174 generations. Each point on the frontier corresponds to a unique individual watershed configuration; i.e., a SWAT simulation representing a prescription for the application of conservation practices across the entire watershed. Each individual in the frontier is encoded with a unique identification number. This figure provides interesting insight on the interactions between the conservation practices considered and the two nutrients. For a given set of practices considered, once NO_3 loadings are reduced by 30% (blue individual (#638) shown in Figure 6 cost versus NO_3 graph), an automatic reduction of about 53% in total P loadings (corresponding blue individual in Figure 6 cost versus total P graph) follows. Greater reductions in NO_3 lead to simultaneous reductions in total P, suggesting complementarities in the set of practices used to achieve greater NO_3 reductions. Alternatively, the least cost watershed configuration to reduce total P by 30% (red individual (#1252) in Figure 6 cost versus Total P graph) only reduces 4% of NO_3 loading (corresponding red individual in Figure 6 cost versus NO_3 graph).

Further examination of the conservation practices chosen in these two individuals (watershed configurations) shed light on this finding. With a control cost of over $80 million/year, individual # 638 achieved a 30% reduction in NO_3 and 53 % reduction in toal P (Table 2). This is significantly more expensive than individual #1252 whose cost runs at about $4 million/year and achieves a 30% total P reduction, but only about 4% NO_3 reduction (Table 2). The detailed allocation of conservation practices for these two watershed configurations reveals that algorithm favors “grassed waterways” for total P reduction whereas “fertilizer reduction” was favored for small reduction in NO_3 and “land retirement” for medium to large reduction in NO_3 loadings. The cost of NO_3 reduction increases dramatically once land retirement has to be utilized. Table 2 also lists results for individual #1146 which achieved a 15% reduction in NO_3 with a least cost of about $23 million year[1] (substantially lower than the cost of 30% reduction) and as a by-product achieves a total P reduction of 54%.

Table 1: Calibration and/or validation for SWAT streamflow and nutrient predictions near the watershed outlet of the Raccoon River watershed

Indicator	Calibration or validation	Time Period	Annual		Monthly	
			R^2	E	R^2	E
Streamflow	calibration	1986-1995	.94	.93	.86	.86
	validation	1996-2004	.80	.76	.88	.87
NO_3	calibration	1986-1995	.56	.52	.85	.82
	validation	1996-2004	.62	.47	.74	.71
Organic N	calibration	2001-2004	.57	.39	.67	.64
Total P	calibration	2001-2004	.97	.93	.86	.84

Table 2: Example tradeoff relationship between the cost the pollutant reductions

Frontier Individual ID (#)	NO_3	Total P	Cost of achieving reductions, ($million/year)
	% reduction from baseline		
638	30.5	53.2	80.1
1252	3.9	30.2	3.6
1146	15.4	54.6	22.9

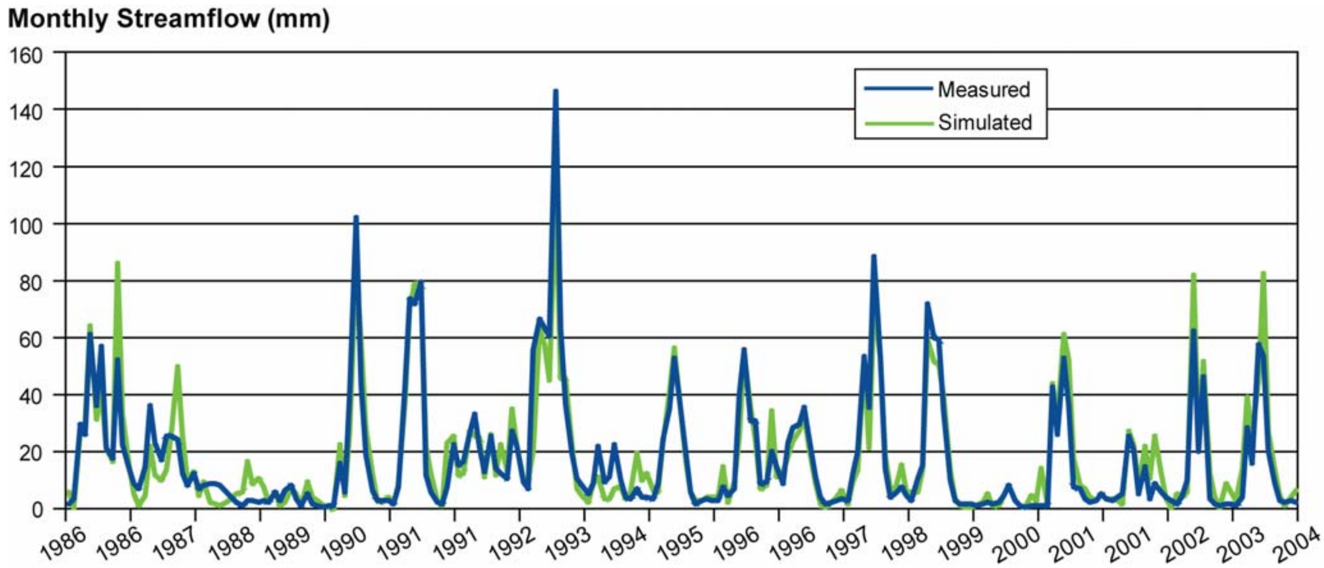

Fig. 2: Time-series comparison between the SWAT simulated and measured streamflows near the Raccoon River watershed outlet (at Van Meter gauge site)

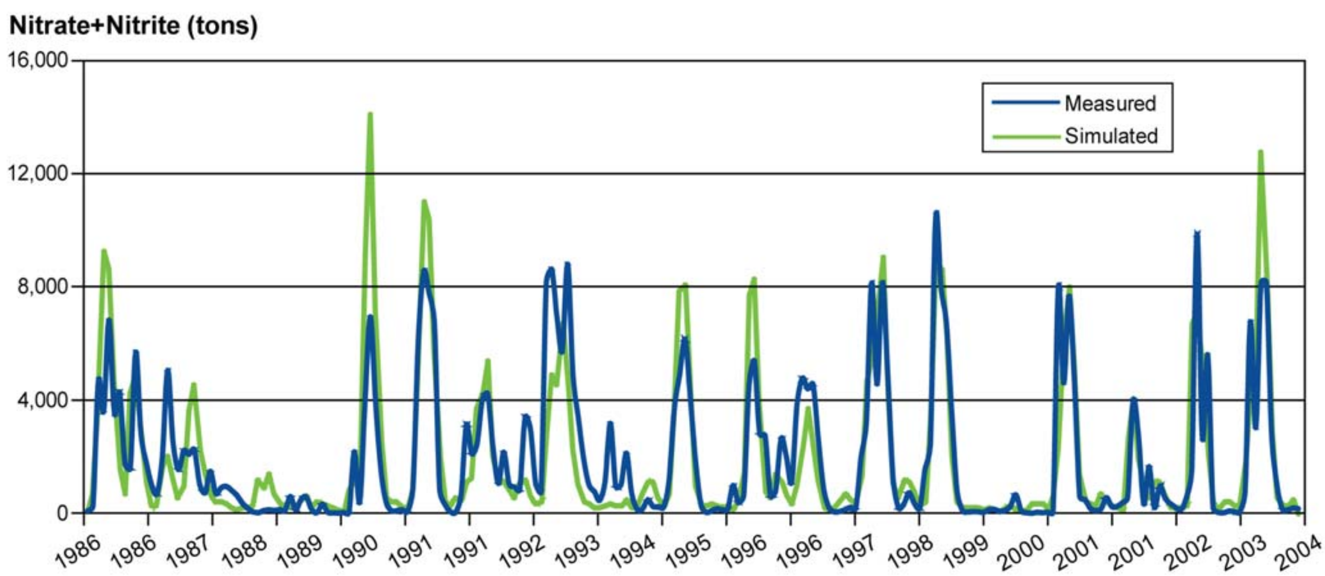

Fig. 3: Time-series comparison between the SWAT simulated and measured nitrate+nitrite (NO_3+NO_2) loads near the Raccoon River watershed outlet (at Van Meter gauge site)

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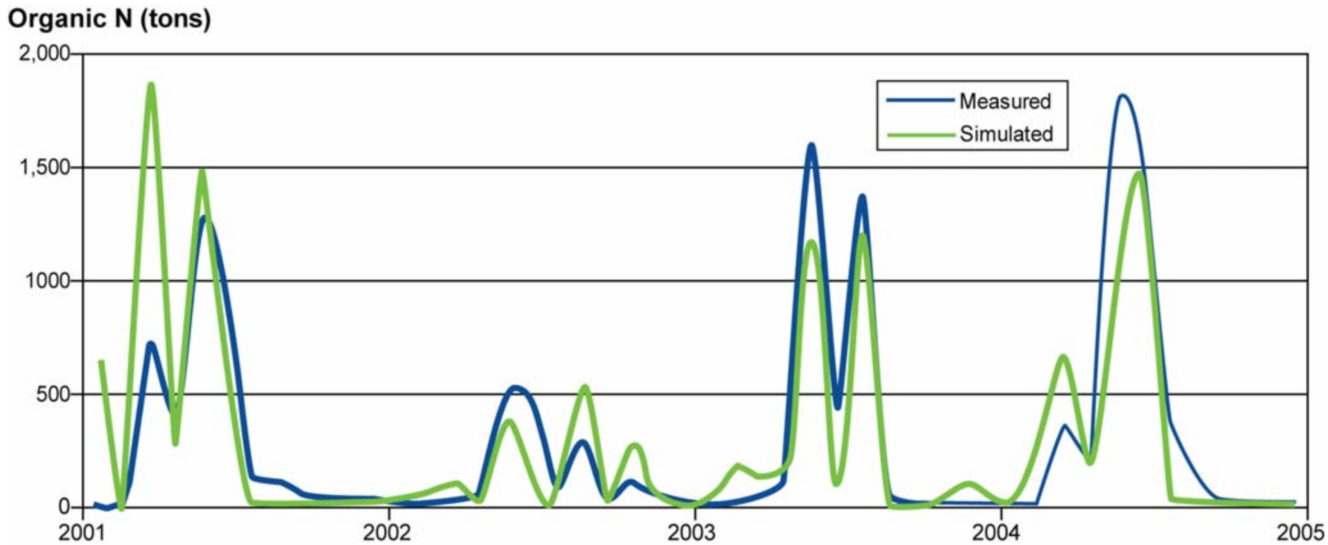

Fig. 4: Time-series comparison between the SWAT simulated and measured organic N loads near the Raccoon River watershed outlet (at Van Meter gauge site)

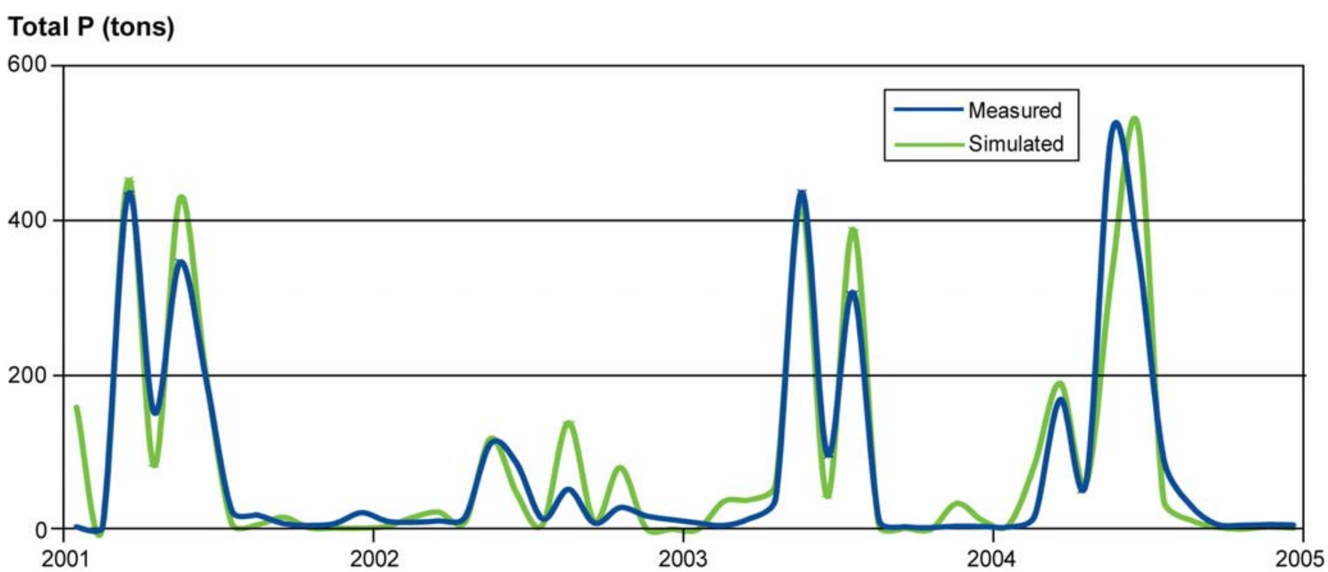

Fig 5: Time-series comparison between the SWAT simulated and measured total P loads near the Raccoon River watershed outlet (at Van Meter gauge site)

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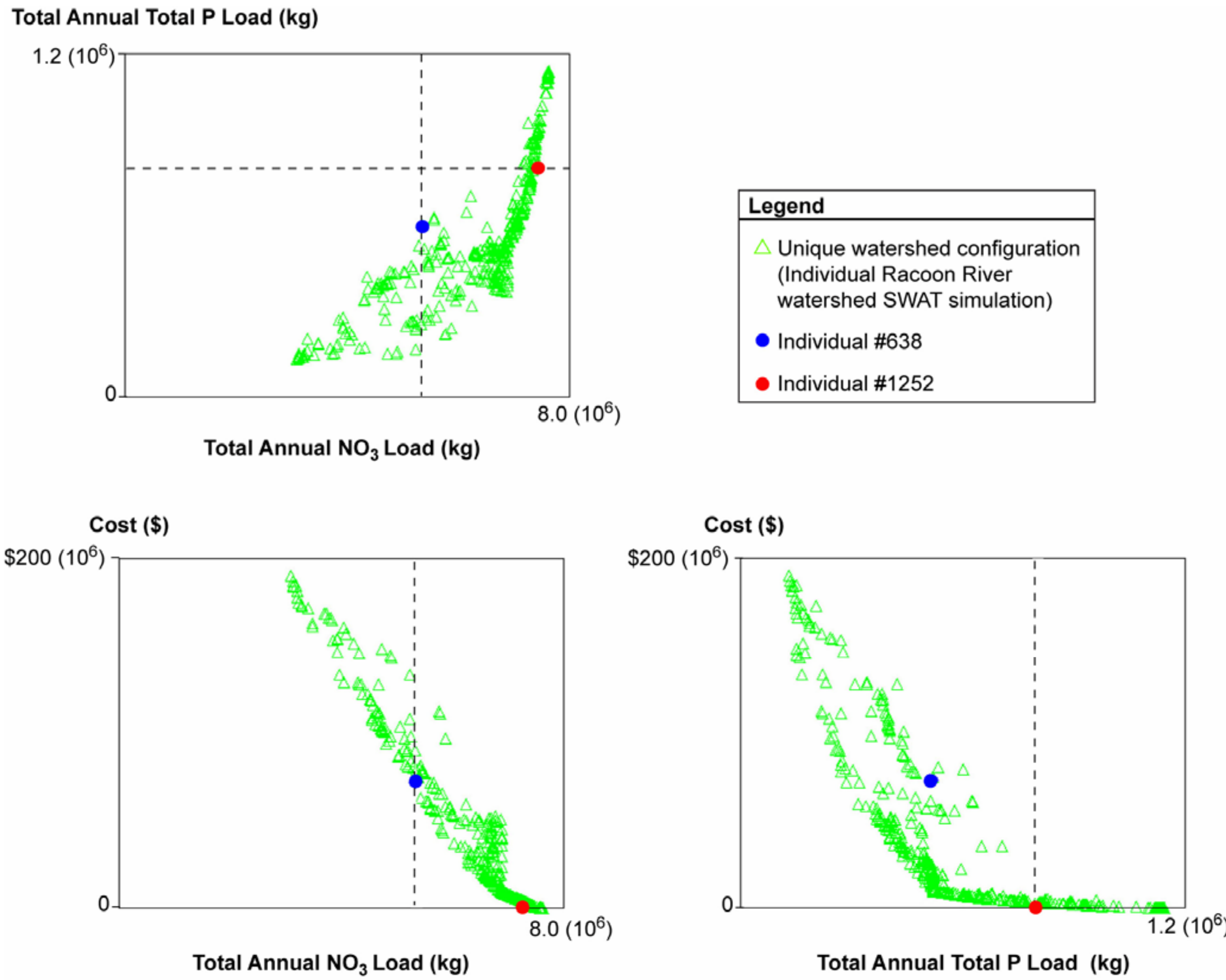

Fig. 6: Two dimensional projections of tradeoff frontiers showing tradeoffs between NO_3 and Total P, cost and NO_3, and cost and total P (for generation 1,174)

7. CONCLUSIONS

Due to the unique nature of the biophysical relationship between conservation practices and resulting water quality levels, the effectiveness of a given conservation practice on a given field depends on the placement of conservation practices and cropping systems in the watershed. Additionally, there is large number of conservation practices that could be implemented on each field. In this study, we combine the tools of evolutionary algorithms with the calibrated SWAT model and cost data to develop a frontier of least cost combinations and locations of conservation practices to achieve various NO_3 and total P reductions. This frontier provides the tradeoff relationship between nutrient reduction and the corresponding cost of placing selected set of conservation practices. For example, a total cost of $23 million/year (due to the adoption of selected conservation practices) is predicted to achieve 15 % reduction in NO_3 and corresponding 45 % in total P at the watershed outlet.

While computationally intensive, this integrated modeling approach can produce very detailed information on least cost approaches for the implementation of conservation practices, even with a large number of locations and options. However, there may be several significant limitations to this approach including enormity of the search space for the most efficient solution, limited set of conservation practices considered and the assumption in their cost estimates, SWAT model's ability to replicate the impacts of conservation practices on water quality, and so on. This study is limited to a certain set of practices and inclusion of other possibly relevant practices may alter the results. Both wetlands and buffer strips are important options but are not included in the set because current SWAT versions are not yet capable of reliably simulating these practices. Nonetheless, many more options are considered here and at a much finer spatial scale than previous analyses. Finally, this tool could be very helpful for policymakers and stakeholders to explicitly see the tradeoffs between costs and nutrient reductions.

REFERENCES

1. Arabi, M., R.S. Govindraju, M.M. Hantush. 2006. Cost-effective allocation of watershed management practices using a genetic algorithm. Water Resources Research 42, W10429, doi:10.1029/2006WR004931.
2. Arnold, J.G. and N. Fohrer. 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modeling. Hydrological Processes 19(3): 563-572.
3. Bekele, E.G. and J.W. Nicklow. 2005. Multiobjective management of ecosystem services by integrative watershed modeling and evolutionary algorithms. Water Resources Research 41, W10406, doi:10.1029/2005WR004090.
4. Beven, K.J. 1993. Prophecy, reality and uncertainty in distributed hydrological modeling. Advanced Water Resources Research 16: 41-51.
5. CARD. 2009. CARD interactive software programs. Center for Agricultural and Rural Development, Department of Economics, Iowa State University, Ames, IA. Available at: http://www.card.iastate.edu/environment/interactive_programs.aspx.
6. Deb, K. 2001. Multi-Objective Optimization using Evolutionary Algorithm. John Wiley & Sons, Inc. New York, NY.
7. Feng, H., M. Jha, P.W. Gassman, and J. Parcel. 2007. A Recent Trend in Ecological Research: Quantifying the Benefits and Costs of Ecosystem Services with Coupled Economic and Biophysical Models. In: Ecological Economics Research Trends (Ed. C.C. Pertsova). Nova Science Publishers, Hauppauge, NY.
8. Forrest, S. 1993. Genetic algorithms: principles of natural selection applied to computation. Science 261: 872-878.
9. Gassman, P.W., M.R. Reyes, C.H. Green, and J.G. Arnold. The soil and water assessment tool: historical development, applications, and future research directions. Transactions of the ASABE 50(4): 1211-12850.
10. Gassman, P.W., E. Osei, A. Saleh, J. Rodecap, S. Norvell, and J.R. Williams. 2006. Alternative practices for sediment and nutrient loss control on livestock farms. Agriculture, Ecosystems and Environment 117(2-3): 135-144.
11. IDNR. 2009. Natural resources geographic information systems library. Iowa Department of Natural Resources, Geological and Water Survey, Iowa City, Iowa. Available at: http://www.igsb.uiowa.edu/nrgislibx/.
12. ISU. 2007. Iowa Environmental Mesonet: NWS Coop. Ames, Iowa: Iowa State University, Department of Agronomy. Available at: http://mesonet.agron.iastate.edu/COOP/.
13. Jaynes, D. 2007. Personal communication. Ames, Iowa: U.S. Department of Agriculture, Agricultural Research Service, National Soil Tilth Laboratory.
14. Jha, M., P.W. Gassman, and J.G. Arnold. 2007. Water quality modeling for the Raccoon River Watershed using SWAT. Trans. ASABE 50(2): 479-493.
15. Jha, M., C.F. Wolter, P.W. Gassman, and K.E. Schilling. 2009. Assessment of TMDL implementation strategies for nitrate impairment of the Raccoon River, Iowa. Journal of Environmental Quality (revised and submitted).
16. Kling, C., S. Rabotyagov, M. Jha, H. Feng, J. Parcel, P. Gassman, and T. Campbell. 2007. Conservation practices in Iowa: Historical investments, water quality, and gaps. A Report to the Farm Bureau, Iowa Corn Growers Association, Iowa Soybean Association, and Leopold Center for Sustainable Agriculture. CARD, Iowa State Univ., Ames, IA. Available at: http://www.card.iastate.edu/environment/items/IFB_project_report_wappendices.pdf.
17. Maringanti, C., I. Chaubey, and J. Popp. 2009. Development of a multiobjective optimization tool for the selection and placement of beset management practices for nonpoint source pollution control. Water Resources Research 45, W06406, doi: 10.1029/2008WR007094.

18. Miller, G. 2007. Personal communication. Ames, Iowa: Iowa State University, College of Agriculture, Agricultural Experiment Station.
19. Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R.L. Binger, R.D. Hermel, and T. Veith. 2007. Model evaluating guidelines for systematic quantification of accuracy in water simulations. Transactions of the ASABE 50(3): 885-900.
20. Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2005. Soil and Water Assessment Tool Theoretical Documentation, version 2005. Temple, Tex.: USDA-ARS Grassland, Soil and Water Research Laboratory. Available at: http://www.brc.tamus.edu/swat/doc.html.
21. Runkel, R.L., C.G. Crawford, and T.A. Cohn. 2004. Load Estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers. USGS Techniques and Methods Book 4, Chapter A5. U.S. Geological Survey, Reston, Virginia.
22. Schilling, K.E., C.F. Wolter, D.E. Christiansen, D.J. Schnoebelen, and M. Jha. 2008. Water quality improvement plan for Raccoon River, Iowa. TMDL Report. Watershed Improvement Section, Iowa Department of Natural Resources, 202 p.
23. Schilling, K.E. and Y.K. Zhang, 2004. Baseflow contribution to nitrate-nitrogen export from a large agricultural watershed, USA. Journal of Hydrology 295: 305-316.
24. Secchi, S., P.W. Gassman, M. Jha, L. Kurkalova, H.H. Feng, T. Campbell, and C.L. Kling. 2007. The cost of cleaner water: Assessing agricultural pollution reduction at the watershed scale. Journal of Soil and Water Conservation 62(1): 10-21.
25. Srivastava, P., J.M. Hamlett, P.D. Robillard, and R.L. Day. 2002. Watershed optimization of best management practices using AnnAGNPS and a genetic algorithm. Water Resources Research 38(3): 1-14.
26. Veith, T.L., M.L. Wolfe, and C.D. Headwole. 2003. Optimization procedure for cost-effective BMP placement at a watershed scale. Journal of American Water Resources Association. 39(6): 1331-1343.
27. Wall, M. 2006. GAlib: A C++ library of genetic algorithm components, ver. 2.4.6. Available at: http://lancet.mit.edu/ga.
28. White, V. 1996. Agriculture and drinking water supplies: Removing nitrates from drinking water in Des Moines, Iowa. Journal of Soil and Water Conservation 51(6): 454-455.
29. Zitzler, E., M. Laumanns, and L. Thiele. 2002. SPEA2: Improving the Strength Pareto Evolutionary Algorithm for multiobjective optimization. P. 95-100. In: Evolutionary Methods for Design, Optimization and Control (Ed. K. Giannakoglou et al.). CIMNE, Barcelona, Spain.

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ALMANAC: A POTENTIAL TOOL FOR SIMULATING AGROFORESTRY YIELDS AND IMPROVING SWAT SIMULATIONS OF AGROFORESTRY WATERSHEDS

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ABSTRACT

The Soil and Water Assessment Tool (SWAT), a robust watershed scale hydrological model, would benefit from the improvement of its plant model subroutine. To be applicable to agroforestry, the process-oriented plant model needs to be capable of simulating interspecies light competition, as well the water balance and nutrient balance of interacting crops, grasses, and woody species. It must also be able to consider short and long term effects of various management and climate scenarios. Here we describe the usefulness of the general plant competition model Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) in this capacity. Further, we discuss a version of the model ($ALMANAC_{BF}$) that realistically simulates complex successional changes in mixed coniferous and deciduous boreal forest ecosystems. For application to agroforestry in a tropical context ($ALAMANC_{TF}$), plant physiological parameters need to be developed for relevant species and algorithms derived to describe particularities of management systems. Simulation scenarios could then be conducted and compared to forest inventory data to determine the accuracy of $ALMANAC_{TF}$ in tropical systems. Current incorporation of ALMANAC into SWAT, including $ALMANAC_{BF}$ capabilities, will improve the accuracy of watershed scale simulation of plant competition and agroforestry systems, and provide a basis for developing improved tropical systems routines. Accurate simulations will enable agroforesters and policy makers to adopt the most economically and ecologically sound management strategies at the farm and watershed scale.

1. INTRODUCTION TO ALMANAC AND SWAT

The Soil and Water Assessment Tool (SWAT) is a process-based hydrological and water resources assessment model that was developed to determine the effects of various management scenarios on water resources at the watershed scale (Arnold et al., 1998; Arnold and Forher, 2005; Gassman et al., 2007). The plant growth model currently embedded in SWAT assumes a uniform, monotypic plant stand (Krysanova and Arnold, 2008). Agroforestry simulations by SWAT would be improved by the incorporation of a plant growth model capable of simulating competition and dynamic vegetation changes over time (Arnold and Forher, 2005). Agroforestry plant communities are complex systems composed of taller woody species competing with shorter grass or crop species for light, water, and nutrients. Realistic watershed scale simulations of hydrological processes in these systems require a comprehensive, realistic process-based model capable of simulating competition for light, water, and nutrients on species growth and development, and effective at partitioning biomass among and within trees, crops, and grasses. Herein we describe just such a robust model, the Agricultural Land Management Alternatives with Numerical Assessment Criteria Model (ALMANAC; Kiniry et al., 1992).

ALMANAC has been successfully applied to a large number of crop, grass, and tree species, as well as diverse managed and unmanaged communities. Part of the reason for the wide use of ALMANAC is the ease with which parameters may be derived from existing parameters for other, similar species, or developed with straightforward field work. With species-appropriate physiologically based parameters, ALMANAC's simulations of biomass production and seed yields have been validated at various locations across North America under a variety of climatic

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conditions (Kiniry et al., 1992; Kiniry and Bockholt, 1998; Yun et al., 2001). Further, parameters for range grasses and both native and improved pasture grasses were developed and validated at diverse sites across North America (Kiniry et al., 1996; Kiniry et al., 1999; Kiniry et al., 2002; Kiniry et al., 2007; McLaughlin et al., 2006).

In agroforestry systems the tree component often plays a dominant role in determining the light, nutrient, and water resources available to other species in the system (Rao et al., 1998). ALMANAC has demonstrated capacity to simulate woody species and forest re-growth. Parameters for the woody evergreen eastern red cedar (*Juniperus virginiana* L.) and leguminous mesquite (*Prosopis glandulosa* Torr. var. *glandulosa*) were developed more than ten years ago, demonstrating the utility of ALMANAC for simulating woody species (Kiniry, 1998). Recently, ALMANAC was altered and parameterized to more effectively simulate forestry applications in boreal forests (MacDonald et al., 2008), resulting in a new version of model, $ALMANAC_{BF}$, which can predict tree, grass, shrub, and forb interactions under a variety of conditions. This is a desirable development for land managers, who need to be able to quantitatively predict agroforestry tradeoffs between various cropping methods with various species of trees and crops across a wide variety of soils and climates (Huth et al., 2003).

The use of ALMANAC and $ALAMANC_{BF}$ to simulate tree growth in the North American context suggests that ALMANAC could be successfully modified to create a tropical forest version ($ALMANAC_{TF}$) capable of simulating tropical systems, such as the tropical agroforestry systems found in southeast Asia. Agroforestry cropping systems must manage both environmental and sylvicultural effects on crops, which make maximizing production by all species in the system impossible. The ability to model species specific effects on the spatial distribution of light, nutrients, and water will greatly assist in planning and executing tree-crop systems (Everson et al., 2009). With appropriate modifications, $ALMANAC_{TF}$ will be able to simultaneously simulate tree growth and canopy development in parallel with the growth of shrubs grasses and forbs in a tropical setting. A working version of SWAT that includes $ALMANAC_{BF}$'s light competition algorithms and tree growth algorithms is currently being further validated and modified appropriately. The hypothetical $ALMANAC_{TF}$ model could be developed directly in SWAT based on these algorithms. As a component in SWAT, the model could help better model impacts and yields in large area simulations of dynamic, tropical agroforestry systems. Herein we present the argument for the development of $ALMANAC_{TF}$.

2. $ALMANAC_{BF}$ FOR AGROFORESTRY SIMULATION

$ALMANAC_{BF}$ was designed to simulate boreal forest succession, including initial stages after timber harvest, when vegetation is dominated by annual and perennial forbs and grasses. On the Canadian Boreal Plain, forest disturbance triggers successional forest regeneration, where the community transitions from one dominated by annual forbs and perennial grasses, to shrubs, until the mature forest composed of mixed or pure stands of coniferous and deciduous species develops (Smith et al., 2003; Beckingham and Archibald, 1996). For $ALMANAC_{BF}$ to be applicable to forest management, it needed to, not only accurately simulate key species growth, but also account for the successional forest dynamics without spending excessive simulation time on the complexities of forest growth.

For SWAT to simulate agroforestry impacts on water quantity and quality, the forest growth module of SWAT requires major modifications. To accurately simulate the key processes of forest hydrology impacted by forest management practices, simulations of multi-species interactions are required (Arnold and Forher, 2005). Existing forest growth models tend to be complex and data intensive (Running and Coughlin, 1988; Kimmins et al., 1999; Van Noordwijk and Lusiana, 1999; Peng et al., 2002). While simpler models exist (Landsberg and Waring, 1997), they are limited to simulating even aged monocultures. Since the largest impact on water quantity and quality in forests occurs in the first ten years after disturbance (Burke et al., 2005; Prepas et al., 2006), the $ALMANAC_{BF}$ model was developed to be integrated into SWAT as a forest disturbance and re-growth module. With the multi-species algorithms already in ALMANAC, the development of $ALMANAC_{BF}$ algorithms emphasized the successional changes in vegetation in these initial stages after disturbance.

The $ALMANAC_{BF}$ algorithms developed to simulate initial stages of boreal forest recovery after disturbance may be particularly applicable to tropical agroforestry systems. Because tropical agroforestry systems are subjected to periodic disturbance regimes, $ALMANAC_{BF}$, which accounts for periodic disturbance, is a good platform for building a model capable of modeling such systems. Tropical agroforestry applications would need to be able to simulate the environmental impacts of both annual or perennial crops as well as the successional and later, understory forest vegetation dynamics. $ALMANAC_{BF}$ contains algorithms specifically designed to describe the development of forest canopies and as well as commercial tree characteristics. Further, the relatively simple light partitioning algorithms allow $ALMANAC_{BF}$ to simultaneously simulate the overstory canopy and perennial or annual plants growing under the canopy.

2.1 Effectively Simulating Commercial Tree Characteristics

The complete $ALMANAC_{BF}$ model is described in detail elsewhere (MacDonald et al. 2008). Briefly, like crop growth in SWAT, tree growth is simulated with light interception using Beer's law, and a species-specific value of radiation use efficiency (RUE) to calculate daily potential biomass accumulation. The model uses sigmoid curves (“s curves”) based on growth degree day to describe annual growth (deciduous bud burst and conifer flush) (Phillips, 1950). Likewise, to simulate the gradual establishment of species on a site over time, sigmoid equations are used to describe long-term height and leaf area growth, using year as the dependant variable as opposed to heat units.

$ALMANAC_{BF}$ uses an empirical approach to describe forest growth based on stand structure. In natural forests, as is the case in agroforestry plantations, as forest stem density increases, individual tree size decreases (Plonski, 1974). The model uses species specific allometric equations to partition biomass into different woody and foliar biomass (MacDonald et al., 2005; MacDonald et al., 2008) by back calculating the average diameter at breast height for a tree species (DBH_i) from the stem number (Ter-Mikaelian and Korzukhin, 1997). Foliar biomass and branch biomass can then be calculated using an additional allometric equation based on simulated DBH_i.

Leaf area index is proportional to foliar biomass, which is a function of stem number. Consequently, stand productivity is proportional to stem density and the distribution of biomass among the different compartments within the tree (foliar, stem, branch and rooting systems). High density forest stands have smaller trees with a lower ratio of foliar biomass to stem biomass (and lower leaf area index). Net annual aboveground biomass production (NPP) for a specific tree species is calculated by subtracting annual foliar losses, based on the allometric calculation of foliar biomass from gross annual production (GPP) for that specific tree species. $ALMANAC_{BF}$ considers different stem densities as determined by site conditions, which then affects simulated productivity of the site.

As a consequence the commercial aspects of the forest stand can be determined (such as wood volume) and furthermore, annual nutrient uptake cycles are also simulated with the calculation and partitioning of plant biomass among the different parts of the plants (Figure 1). The simulation of biomass partitioning by different species to particular organs and tissue types changes over a plant’s lifetime. It is essential to effectively simulate these changes in order to capture the changes in nutrient requirements and nutrient partitioning over time. This aspect of $ALMANAC_{BF}$ is particularly relevant to tropical agroforestry systems interested in managing multiple species for different yield goals (green manure, wood, fruit, bark, flowers, etc.). In the agroforestry context, relationships between tree planting density, tree growth and site productivity would have to be derived from experimental data.

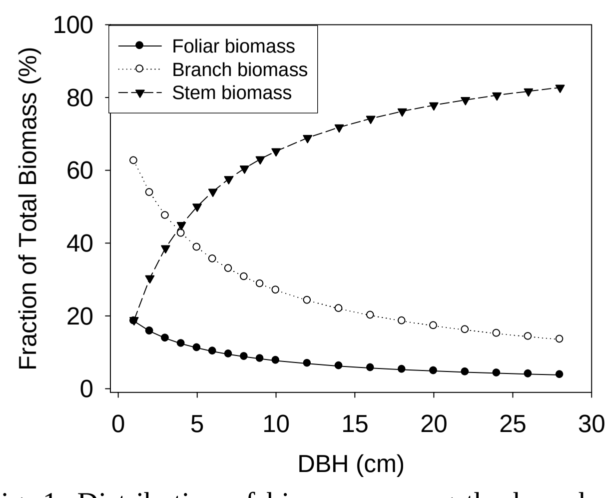

Fig. 1: Distribution of biomass among the branches, stem and leaves of a deciduous trembling aspen (*Populus tremuloides*) tree species as calculated by allometric equations in the $ALMANAC_{BF}$ model based on allometric equations from Ter-Mikaelian and Korzukhin (1997)

2.2 Multilevel Canopy Simulation Algorithms

ALMANAC's light partitioning algorithms distribute photosynthetic radiation (PAR) between different species based on species specific physiological parameters. The proportion of PAR intercepted by an individual species in the canopy is a function of its light extinction coefficient, its proportion of the total leaf area and its height (Kiniry et al., 1992). This approach, describes the filtering of PAR as it passes through the plant canopy. For species less than half the height of the tree species, the light interception is principally a function of the leaf area index of the dominant overstory tree species (Figure 2).

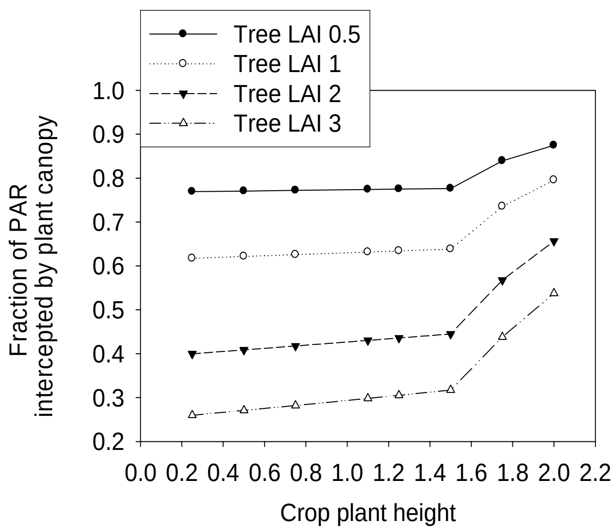

Fig. 2: Light interception of understory crop species under varying levels of leaf area index and consequently light competition by overstory trees. The leaf area is varied between 0.5 and 3 m^2 m^{-2} and the competing trees are 3 m tall and have a Beer's extinction factor of 0.45

There is also a physical effect of canopy shading on plant growth. As the height and leaf area of the upper canopy increases, the area available to shorter species with adequate light to grow becomes limited, and therefore their potential LAI decreases (Lieffers and Stadt, 1994). As canopy height increases, annual potential LAI for vegetation under the canopy cover is limited (Figure 3). Different plants have different reactions to shading and the introduction of a light sensitivity factor (LTSNS) defines how a species reacts to shading. Species with high shade tolerance tend to invest greater proportions of available resources to maintain leaf area under light stress. This factor will define the maximum potential leaf area that an understory species can reach under a given tree canopy.

In the case of boreal forest canopies, there is a gradual shift from short perennial species to trees over the first 10 years, as the over-story canopy forms. Once that occurs there is a reduction in the growth of the lower species due to light and space limitations. In the case of tropical agroforestry, a similar evolution will occur as tree species begin to develop more ample canopies over the crop species. Once again experimentation will be required to develop parameters for the tree canopies and for different crop species reactions to shading at different plant heights and canopy development.

However at the same time there is a reciprocal effect on the growth of trees due to competition during tree establishment (Figure 4). Using relatively simple algorithms the ALMANAC_{BF} model is produces a realistic simulation of the physical competition between tree species and annual or perennial species. While the model will require a certain amount of calibration and validation to be applied to tropical agroforestry problems, the fundamental algorithms required to simulate growth in complex, multi-canopy boreal agroforestry environments are sound and will provide an excellent starting point for simulating tropical agroforesty systems.

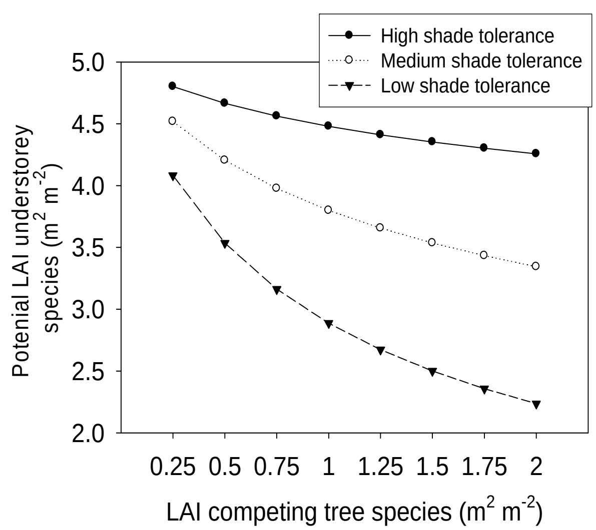

Fig. 3: Limitations to potential leaf area index for species with differing degrees of shade tolerance. The competing tree species are fixed at 10 m height and have a Beer's extinction factor of 0.45

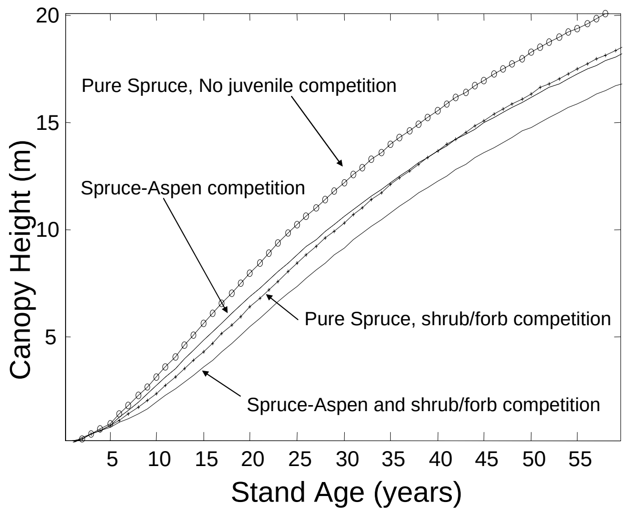

Fig. 4: Monoculture and polyculture tree growth with differing competition regimes, demonstrating tree-shrub interaction and recovery after disturbance

3. WATER AND NUTRIENT COMPETITION

ALMANAC was originally designed to simulate weeds competing with crops (Kiniry et al., 1992). ALMANAC incorporates the light competition equations of Spitters and Aerts (1983) and simulates competition among species for water and nutrients. Water balance and nutrient balance are simulated for each plant species in the system, with reductions in leaf area growth and biomass production if either water or nutrients are insufficient to meet demand. Water demand (potential evapotranspiration) for each species is based on atmospheric demand and plant leaf area cover. Demand for nutrients is based on optimum nutrient concentrations (which are species specific and vary according to development stage), rooting depth, and available nutrients in the current rooting depth of the soil.

4. THE FUTURE OF ALMANAC$_{TF}$

Agroforestry systems are incredibly complex and varied, such as those described by Reyes et al. (2008). System approaches are determined by climate, topography, economic and ecological objectives, as well as species composition. Managers determine their interacting species as well as the manner in which species interact by spatial and temporal methods, including hedgerow intercropping with annual or perennial crops, scattered trees in croplands, boundary trees, and rotational or sequential cropping systems (Rao et al., 1998). Tree-crop intercropping is driven by various goods and services objectives, making optimal management strategies harvest objective dependent (Everson et al., 2009). At present, accurate quantification of the impacts that various woody species within different management scenarios have on soil water content, nutrient cycling, and crop production across the variety of agroforestry systems is lacking (Teixeira et al., 2003).

Light is not the only limiting factor in tropical agroforestry systems. Root interactions and competition for water and nutrients are also means by which trees and understory crops interact. Possible beneficial effects of woody species on microclimate and nutrient availability for understory species during specific periods of rotational sequences may not become apparent for many years post-establishment (Rao et al., 1998). On the other hand, some nitrogen fixing legumes (*Acacia* spp.) have been shown to fix substantial amounts of nitrogen in the initial years following establishment (Khanna, 1998). Interactions between species are site-specific. For example, spatial complementarity noted between trees and crops in regards to soil water use is only apparent when trees are deep rooted and able to access a deep water source or when water is a non-limiting resources (Everson et al., 2009). Otherwise, hydraulic redistribution by deep rooted tree species may be deleterious to water availability in shallower rooted species (Burgess et al., 1998). In semi-arid tropical climates soil water depletion by hedgerow species can lead to lower yields by intercropped species (Govindarajan et al., 1996). Feldhake (2009) found that though trees modified microclimate for understory forage, the trade-off between the water savings benefit of decreased forage evapotranspiration and cost of PAR interception stress caused by the overstory were determined by plant spacing.

To apply ALMANAC to tropical systems, the necessary parameters need to be developed for pertinent species and management scenarios. These include Beer’s law coefficients, leaf area development parameters, nutrient use efficiency, radiation use efficiency, and estimates of shade sensitivity for all crop species. These physiological parameters will require validation across various climates and soils, as species interactions and management approaches in tropical agroforestry systems vary considerably due to soil fertility (Rao et al., 1998). The products and services desired from these multifunctional systems vary radically. The harvestable end goal may be a product like bark, latex, flowers, fruits, seeds, or wood, or it may be a service like forage, soil stability, biological nitrogen fixation, biodiversity maintenance, carbon sequestration, or rural socio-economic viability (Muetzelfeldt, 1995; Bengtsson et al., 2000; Everson et al., 2009). Maximizing yields of one agroforestry product or service can be deleterious to another aspect; research must be focused on the ecological and physiological trade-offs that arise in tropical agroforesty systems (Jordan et al., 2007).

With the development of physiological parameters for specific species under optimal conditions, the site specific interactions between species can be studied and thus modeled more effectively. Many of these interactions are already under study, as it is the optimizing of interactions between woody species and non-woody species that epitomizes agroforestry success (Rao et al., 1998). To effectively develop ALMANAC into $\text{ALMANAC}_{TF,}$ further work on nutrient and water competition algorithms are needed. These changes will require development and validation of below ground biomass estimates and rates of production to better model water and nutrient interactions between species.

Canopy architecture is a critical element in light, water, and nutrient competition. Trees express different architecture under different ecological conditions, including under various agroforestry applications such as hedgerow cropping as compared to scattered trees in croplands (Rao et al., 1998). Manceur et al. (2009) found that when grown under tree species with high crown volume, understory soybean crops decreased biomass allocation to structural tissues and petioles, leading to lower overall yields than under low-volume tree canopies. Further study of the effects of cropping on the geometry of tree canopies, resultant stem flow, and light interception patterns under different management systems is needed. ALMANAC_{TF} needs to be parameterized for these dynamic production systems in order to appropriately account for the allocation of biophysical resources in such systems. Furthermore, the physical impact of the presence and distribution of trees on microclimate will be quantified and specific algorithms will be developed into ALMANAC to account for these effects. Due to the compartmentalized structure of deterministic models such as ALMANAC and SWAT, these changes would be relatively easily achieved.

Finally, it is important to note that the interactions between tropical agroforestry species for light, nutrients, and water are complex and change over time as some species mature or are harvested out of the system. The use of livestock in some tropical systems increases the system complexity, including redistribution of nutrients and effects of selective grazing. The importance of collecting relevant, sequential data on a variety of tropical agroforestry management systems across a variety of climates and soils to quantitatively account for variability in theses systems cannot be over-emphasized. In addition to allowing us to better model these systems, collecting parameters relevant to ALMANAC_{TF} will further our understanding of forest dynamics and ecosystem processes as affected by current management scenarios, which will lead to better agroforestry management decisions (Bengtsson, et al., 2000).

5. CONCLUSION

Agroforestry systems combine woody perennial management with cropping systems or livestock operations, either as a simultaneous, but heterogeneous spatial mixture or in temporal sequence (Leakey, 1996). ALMANAC is capable of considering complex agroforestry systems managed in either way. ALMANAC_{BF} realistically simulated successional stages in forest growth as well as watershed scale variations in stand characteristics in mixed and pure forest canopies in Canadian Boreal forests. In tropical forest systems such as those found in Southeast Asia, simulation scenarios could be conducted and compared to forest inventory data to determine the accuracy of the current model parameters. With some modification to better fit tropical systems, the proposed ALMANAC_{TF} shows potential as a tropical forestry modeling system, capable of assisting land managers in making decisions that will improve the sustainability of land use, improve the productivity of the managed system, and provide better economic stability to the community or individuals managing the system.

SWAT's current plant growth model was developed for crops grown in monoculture (Krysanova and Arnold, 2008). Quantifying the appropriate model inputs for tropical agroforestry systems is a daunting, but necessary task. The ALMANAC model has shown tremendous flexibility and promise in new systems. Ongoing incorporation of the ALMANAC plant growth routines into SWAT will increase the robustness of the SWAT model by allowing simulation of overseeded cropping systems, Boreal forest systems, and other scenarios with mixed vegetation. Further refinement of parameters in tropical agroforestry systems will allow the development of an improved SWAT model that can be used for watershed-scale tropical agroforestry assessments. Such improvements are imperative if modelers hope to simulate the diversity of benefits and services provided by tropical agroforestry species and systems at both local and watershed scales, as well as at various temporal scales (Jose, 2009).

Continued development and integration of SWAT and ALMANAC will be driven by user-demand. Working in combination, these models may prove a valuable tool to tropical agroforestry managers interested predicting the effects of multifunctional agroforestry management techniques at field-scale and watershed scale under various climate scenarios.

REFERENCES

1. Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large area hydrologic modeling and assessment, Part I. Model development. *J. Am. Water Resour. Assoc.* 34: 73-89.
2. Arnold, J.G. and N. Fohrer. 2005. SWAT2000: current capabilities and research opportunities in applied watershed modeling. *Hydrol. Process*. 19(3): 563-572.
3. Beckingham, J. D., and J. H. Archibald. 1996. Field guide to ecosites of northern Alberta. Special Report 5. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alta.
4. Bengtsson, J., S. G. Nilsson, A. Franc, and P. Menozzi. 2000. Biodiversity, disturbances, ecosystem function, and management of European forests. *For. Eco Manag.* 132: 39-50.
5. Burgess, S. S. O., M. A. Adams, N. C. Turner, and C. K. Ong. 1998. The redistribution of soil water by tree root systems. *Oecologia* 115: 306-311.
6. Burke, J. M., E. E. Prepas, and S. Pinder. 2005. Runoff and phosphorous export patterns in large forested watersheds on the western Canadian Boreal Plain before and for 4 years after wildlife. *J. Environ. Engng. Sci.* 4: 319-325.
7. Everson, C. S., T. M. Everson, and W. van Niekerk. 2009. Soil water competition in a temperate hedgerow agroforestry system in South Africa. *Agrofor. Syst.* 75: 211-221.
8. Feldhake, C. M. 2009. Forage evapotranspiration and photosynthetically active radiation interception in proximity to deciduous trees. *Agr. Water Mngmnt.* 96: 1170-1174.
9. Gassman, P. W., M. R. Reyes, C. H. Green, and J. G. Arnold. 2007. The soil and water assessment tool: historical development, applications, and future research directions. *Trans. ASABE*. 504: 1211-1250.
10. Govindarajan, M., M. R. Rao, M. N. Mathuva, and P. K. R. Nair. 1996. Soil-water and root dynamics under hedgerow intercropping in semiarid Kenya. *Agron J.* 88: 513-520.
11. Huth, N. I., P. S. Carberry, P. L. Poulton, L. E. Brennan, and B. A. Keating. 2003. A framework for simulating agroforestry options for the low rainfall areas of Australia using APSIM. *Europ. J. Agron.* 18: 171-185.
12. Jordan, N., G. Boody, W. Broussard, J. D. Glover, D. Keeney, B. H. Mc Cown, G. McIsaac, M. Muller, H. Murray., J. Neal, C. Pansing, R. E. Turner, K. Warner, D. Wyse. 2007. Sustainable development of the agricultural bio-economy. *Science* 316: 1570-1571.
13. Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: an overview. *Agrofor. Syst.* 76: 1-10.
14. Khanna, P. K. 1998. Nutrient cycling under mixed-species tree systems in southeast Asia. *Agrofor. Sys.* 38: 99-120.
15. Kimmins, J. P., D. Mailly, and B. Seely. 1999. Modelling forest ecosystem net primary production: the hybrid simulation approach used in forecast. *Ecol. Model.* 185: 77-91.
16. Kiniry, J. R. 1998. Biomass accumulation and radiation use efficiency of honey mesquite and eastern red cedar. *Biomass & Bioenergy* 15 (6): 467-473.
17. Kiniry, J. R., and A. J. Bockholt. 1998. Maize and sorghum simulation in diverse Texas environments. *Agron. J.* 90: 682-687.
18. Kiniry, J. R., J. R. Williams, P. W. Gassman, and P. Debaeke. 1992. A general, process-oriented model for two competing plant species. *Trans. Am. Soc. Agric. Engrs.* 35(3): 801-810.
19. Kiniry, J. R., M. A. Sanderson, J. R. Williams, C. R. Tischler, M. A. Hussey, W. R. Ocumpaugh, J. C. Read, G. VanEsbroeck, and R. L. Reed. 1996. Simulating Alamo switchgrass with the ALMANAC model. *Agron. J.* 88:602-606.
20. Kiniry, J. R., C. R. Tischler, and G. A. VanEsbroeck. 1999. Radiation use efficiency and leaf CO_2 exchange for diverse C_4 grasses. *Biomass & Bionenergy* 17:95-112.
21. Kiniry, J. R., H. Sanchez, J. Greenwade, E. Seidensticker, J. R. Bell, F. Pringle, G. Peacock Jr., and J. Rives. 2002. Simulating grass productivity on diverse range sites in Texas. *J. Soil Water Conserv.* 57: 144-150.

22. Kiniry, J. R., B. L. Burson, G. W. Evers, J. R. Williams, H. Sanchez, C. Wade, J. W. Featherstone, and J. Greenwade. 2007. Coastal bermudagrass, bahiagrass, and native range simulation at diverse sites in Texas. *Agron. J.* 99:450-461.
23. Krysanova, V. and J. G. Arnold. 2008. Advances in ecohydrological modeling with SWAT – a review. *Hydrological Sci. J.* 53 (5): 939-947.
24. Landsberg, J. J., and R. H. Waring. 1997. A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance, and partitioning. *For. Ecol. Manage.* 95:209-228.
25. Leakey, R. 1996. Definition of agroforestry revisited. *Agroforestry Today* 1: 5-7.
26. Lieffers, V. J., and K. J. Stadt. 1994. Growth of understory *Picea glauca*, *Calamagrostis canadensis*, and *Epilobium angustifolium* in relation to overstory light transmission. *Can. J. For. Res.* 24**:** 1193-1198.
27. MacDonald, J. D., J. R. Kiniry, J. Arnold, R. McKeown, I. Whitson, G. Putz, and E. E. Prepas. 2005. Developing parameters to simulate trees with SWAT. In *Proc. 3rd International SWAT 2000 Conference* K. Abbaspour and R. Srinivasan. Zurich, Switzerland.
28. MacDonald, J. D., J. R. Kiniry, G. Putz, and E. E. Prepas. 2008. A multi-species, process based vegetation simulation module to simulate successional forest regrowth after forest disturbance in daily time step hydrological transport models. *J. Environ. Eng. Sci.* 7: 1-18.
29. Manceur, A. M., G. J. Boland, N. V. Thevathasan, A. M. Gordon. 2009. Dry matter partitions and specific leaf weight of soybean change with tree competition in an intercropping system. *Agriforest. Syst.* 76: 295-301.
30. McLaughlin, S. B., J. R. Kiniry, C. M. Taliaferro, and D. D. Ugarte. 2006. Projecting yield and utilization potential of switchgrass as an energy crop. *Adv. Agron.* 90:267-297.
31. Muetzelfeldt, R. I. 1995. A frameword for a modular modeling approach for agroforestry. *Agroforestry Sys*. 30: 223-234.
32. Peng, C., J. Liu, Q. Dang, M. J. Apps, and J. Hong. 2002. TRIPLEX: a generic hybrid model for predicting forest growth and carbon and nitrogen dynamics. *Ecol. Model.* 153: 109-130.
33. Philips, E. E. 1950. Heat summation theory as applied to canning crops. *The Canner* 27: 13-15.
34. Plonski, W.L. 1974. Normal yield tables (metric) for major forest species of Ontario. Ontario Ministry of Natural Resources, Toronto, Ont. 40 pp.
35. Prepas, E. E., J. M. Burke, I. R. Whitson, G. Putz, and D. W. Smith. 2006. Associations between watershed characteristics, runoff, and stream water quality: hypothesis development for watershed disturbance experiments and modeling in the Forest Watershed and Riparian Disturbance (FORWARD) project. *J. Environ. Eng. Sci.* 5 (Suppl. 1): S27-S37.
36. Rao, M. R., P. K. R. Nair and C. K. Ong. 1998. Biophysical interactions in tropical agroforestry systems. *Agroforestry Sys*. 38: 3-50.
37. Reyes, M.R. 2008. Progress report: Agroforestry and sustainable vegetable production in Southeast Asian watersheds. ASABE Paper 085105. Presented at the 2008 ASABE Annual International Meeting, 29 June to 2 July, Providence, RI.
38. Running, S. W., and J. C. Coughlin. 1988. General model of forest ecosystem processes for regional applications, hydrological balance, canopy gas exchange, and primary production processes. *Ecol. Model.* 42: 125-154.
39. Smith, D. W., E. E. Prepas, G. Putz, J. M. Burke, W. L. Meyer, and I. Whitson. 2003. The forest watershed and riparian disturbance study: a multi-disciplinary initiative to evaluate and manage watershed disturbance on the Boreal Plain. *J. Environ. Eng. Sci* 2(Suppl. 1): S1-S13.
40. Spitters, C. J. T. and R. Aerts. 1983. Simulation of competition for light and water in crop-weed associations. *Aspects Appl. Biol.* 4: 467-483.
41. Ter-Mikaelian, M.T., and M. D. Korzukhin. 1997. Biomass equations for sixty-five North American tree species. *For. Ecol. Manage*. 97: 1-24.
42. Teixeira, W. G., F. L. Sinclair, B. Howe, and G. Schroth. 2003. Soil water *In:* G. Schroth and F. L. Sinclair, eds. Trees, Crops, and Soil Fertility: Concepts and Research Methods. CABI Publishing. Wallingford, UK.Fscroth
43. Van Noordwijk, M., and B. Lusiana. 1999. WaNuLCAS, a model of water, nutrient, and light capture in agroforestry systems. *Agrofor. Syst.* 43:217-242.
44. Yun, X., J. R. Kiniry, V. Nedbalek, and W. D. Rosenthal. 2001. Maize and sorghum simulations with CERES-Maize, SORKAM, and ALMANAC under water-limiting conditions. *Agron. J.* 93: 1148-1155.

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ARCAPEX: ARCGIS INTERFACE FOR AGRICULTURAL POLICY ENVIRONMENTAL EXTENDER (APEX) HYDROLOGY/WATER QUALITY MODEL

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ABSTRACT

ArcAPEX is an ArcGIS-based user interface designed to automate the input parameterization of the Agricultural Policy Environmental eXtender (APEX) hydrologic/water quality model. The interface integrates topographic, land use, and soil spatial datasets and a built-in APEX-Parameters database that contains model parameter values required to simulate a wide range of plant growth, tillage, fertilizer, and pesticide applications over a farm/field to basin scale drainage area. Other key features of ArcAPEX include its ability to build and save alternative crop management operation schedules and options for integration directly with the Soil and Water Assessment Tool (SWAT) for large watershed simulations. The major components for the ArcAPEX interface are presented, including watershed delineation, analysis of land use and soils, weather data, input parameter definition, model run management, and SWAT model integration. An application of ArcAPEX, conducted to evaluate various agricultural best management practices for a subwatershed of Bosque River Watershed in central Texas, is described to provide a demonstration of ArcAPEX. The software also provides possibilities for watershed-scale assessments of agroforestry systems in Southeast Asia and other regions.

Keywords: *Watershed, geographical information system, hydrologic modeling, water quality, best management practice.*

1. INTRODUCTION

The Agricultural Policy Environmental eXtender (APEX) model (Williams et al., 2008a; b) is a distributed, continuous, daily time-step farm or small watershed-scale hydrologic/water quality model. It is an extension of Environmental Policy Integrated Climate (EPIC) (Williams, 1990). The model is capable of detailed field scale modeling and routing, connecting farm/field sized subareas within a watershed. The EPIC/APEX models have been tested widely for their ability to simulate different agricultural management practices at both field and watershed scales (Gassman et al., 2005; 2009).

The use of spatial datasets and geographic information system (GIS) software to parameterize hydrologic and water quality models has been in practice for well over a decade. The GIS platforms provide functionality that enables efficient integration and analysis of critical landscape physiographic data layers, such as elevation, land use, soils, and hydrography required to characterize a watershed scale model. Properly designed GIS interfaces can automate watershed delineation and hydrologic network identification, calculation of parameters that describe subbasin geometric and topographic characteristics, channel dimensions, as well as land use, soils, and slope area distributions. An excellent example is the Soil and Water Assessment Tool (SWAT) watershed model (Arnold et al., 1998; Gassman et al., 2007) which has experienced significant integration with GIS interfaces over the last 15 years, including a RASS platform (SWAT/GRASS) interface (Srinivasan and Arnold, 1994), an ArcView 3.x (AVSWAT) interface (DiLuzio et. al., 2004), and an ArcGIS (ArcSWAT) interface (Olivera et al., 2006; Winchell et al., 2008).

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The APEX model has seen a rapid progression in user interfaces within the past five years. Several non-GIS-enabled interfaces have included a DOS-based Universal Text Integration Language (UTIL) interface (Williams et al., 2004; Taylor and Bryant, 1994), and two Windows based interfaces, WinAPEX (Magre et al., 2006) and i_APEX (Gassman et al., 2009). GIS-enabled interfaces for APEX have included an ArcView 3.x-based program referred to as SWAPP to convert SWAT files to and from APEX format and simulate SWAT and APEX simultaneously (Saleh and Gallego, 2007). In addition, a modeling system combining ArcGIS and WinAPEX called WinAPEX-GIS has also been recently developed (Gassman et al., 2009). This system utilizes ArcGIS (ESRI, Redlands, California) to calculate all the GIS-based input data such as soil, land use, and topographic characteristics of the landscape. These data are stored in Access tables that are exported to WinAPEX for further defining management and other inputs.

ArcAPEX is a GIS-based user interface that integrates enhanced GIS capabilities and algorithms based upon the ArcSWAT interface with APEX databases, input, and output management within a single interface. ArcAPEX is an extension to the ArcGIS software package that has been developed using ArcObjects and the Microsoft Visual Basic .NET software development kit. The interface has been developed for use with ArcGIS versions 9.2 and 9.3.x and is compatible with the Microsoft Windows operating systems. ArcAPEX was designed to automate the parameterization of APEX model using readily available topographic, hydrologic, land use, and soils spatial datasets. In addition to automated identification of model topographic and landscape characteristics, ArcAPEX features direct integration with an APEX-Parameters database that contains plant, tillage, fertilizer, pesticide, and weather characteristics required by the APEX model. Additionally, ArcAPEX has been designed to provide direct integration with SWAT model created using the ArcSWAT interface. This framework allows the development of watershed scale models that incorporate multiple scales into the simulation, and provides consistency between the two models for calculation of parameters as well as a similar series of processing steps for users to follow when developing their models with either interface. In this framework, APEX can be implemented for more detailed simulation of farms or small subwatersheds with complex agronomic systems, while SWAT is implemented for larger subwatersheds characterized by simple agricultural systems and non-agricultural landscapes, as well as for integrating constituent (runoff, sediment, nutrient, and pesticide) contributions from all subwatersheds and simulating in-stream channel processes. The ability of APEX to simulate multiple crop/plant species may also provide the potential in the future for simulating complex tropical agroforestry systems such as those used in Southeast Asia, as discussed by Johnson et al. (2009).

The specific objectives of this paper are to: (1) describe the features and functionality of ArcAPEX interface, and (2) demonstrate application of ArcAPEX to evaluate various agricultural best management practices for a subwatershed of Bosque River Watershed in central Texas.

2. METHODOLOGY

2.1 ArcAPEX Project Components

An ArcAPEX project is built around an ArcGIS ArcMap document, several ArcGIS personal geodatabases, and the APEX model executable program (APEX0604). The ArcMap document contains the user interfaces used to develop and run the APEX model for a particular project. It also provides all map visualization for the project and spatial analysis capabilities required to calculate APEX model parameters. The first geodatabase, the APEX Parameters geodatabase, is a database accessible to one or more APEX projects. This database contains parameters that describe various crops, tillage practices, fertilizers, pesticides, weather stations, and agricultural management schedules. In addition, the database serves as a repository for metadata on the content and structure of each APEX input file and parameter. This information is used directly by the ArcAPEX interface, providing data necessary to describe model parameters within the interface and dictating how APEX model input files are generated. The second database is referred to as the APEX Project database. As the name suggests, this database is associated with a single APEX project within the ArcMap document. The Project database stores all the spatial data layers associated with the project, including subareas, reaches, outlets, and longest flow paths. In addition, this database contains tables that store information on all of the APEX model parameters that are used to write the inputs necessary for the APEX0604 model. The APEX0604 executable reads the input files generated by the ArcAPEX interface, runs the APEX model, and generates the output files in a standard ascii text format. The ArcAPEX interface is designed to be compatible with a specific version of the APEX0604 executable. The most recent and compatible version of APEX0604 is always included with the current ArcAPEX interface installation package. Documentation of the APEX0604 model is provided in Williams et al. (2008a, 2008b).

A new APEX project is initiated from within an empty ArcMap document which has the ArcAPEX extension activated. When a new project is created, the necessary directory structure and databases are generated and associated with the ArcMap document. The steps required to build an APEX simulation begin with analysis of GIS data layers, including delineation of watersheds and subareas, analysis of subarea land use and soils characteristics, and development of weather inputs. Model input tables are then built and edited by the user, if needed. These steps are described in more detail in the sections that follow.

2.2 APEX Subarea Delineation

The APEX model divides a watershed into one or more subareas. A subarea is conceptually equivalent to a field or landscape unit with homogeneous weather inputs, land cover, vegetation, soils, and agronomic practices. In this respect, an APEX subarea is functionally equivalent to a SWAT Hydrologic Response Unit (HRU). In addition, each subarea is associated with a channel for routing runoff, sediment, nutrients, and pesticides from one subarea to another. With respect to defining watershed connectivity, APEX subareas are functionally equivalent to subbasins in the SWAT model. Delineation of APEX subareas, channels, and subarea connectivity is the first step in the development of an APEX model project.

Prior to beginning the subarea delineation process, a user must make the decision as to whether the APEX simulation being developed will be a standalone application or will be integrated with a larger-scale SWAT simulation. The standalone model option is intended for use when the entire watershed of interest will be simulated using the APEX model. In this case, the subarea delineation will define the subarea boundaries and hydrologic connectivity contributing to a user defined watershed outlet(s). Subarea boundaries may be delineated based upon a digital elevation model (DEM) or by importing user defined subarea boundaries and streams. The DEM-based subarea delineation implements the single flow direction algorithm used in ESRI software (Jenson and Domingue, 1988) to generate the required flow direction and flow accumulation raster datasets used in watershed delineation. This method for subarea delineation defines subareas as essentially micro-watersheds. These micro-watersheds will often contain portions of multiple fields with different land uses or crops, however in the APEX model, the subarea must be characterized as a single land use or crop. An example DEM-based subarea delineation and underlying land cover is shown in figure 1. This shows how subareas can be made up of multiple fields, in this case, both corn and soybean.

In some situations, it may be desirable to define subareas to be closely associated with specific agricultural field boundaries. In this case, the option of importing user defined subarea boundaries and streams would be chosen in place of the DEM-based delineation of subareas. User defined subareas could easily be delineated from readily available aerial

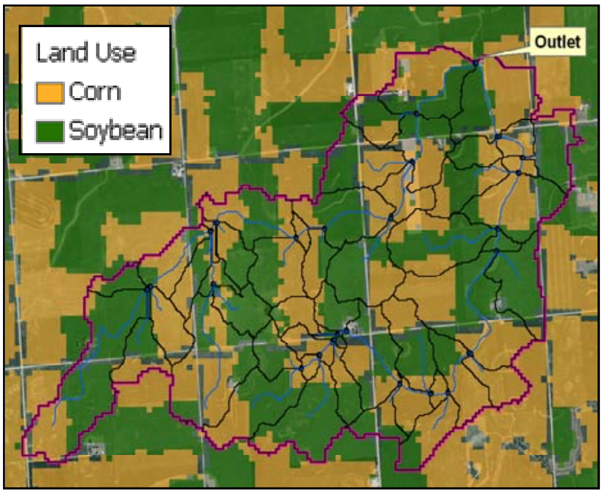


Fig. 1: DEM-based APEX subarea delineation

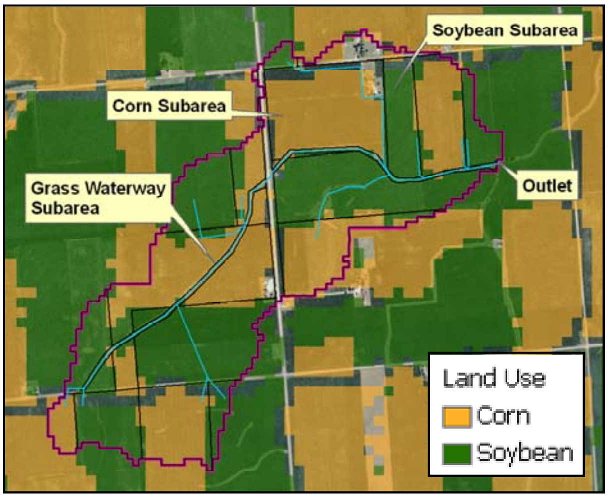


Fig. 2: User-defined APEX subarea delineation

imagery; e.g., United States Department of Agriculture-National Agriculture Imagery Program (USDA, 2009b) or other remote sensing datasets. Figure 2 shows an example APEX subareas that were delineated using the NAIP aerial imagery to more accurately reflect field boundaries. Many BMPs can be represented in a more detailed way such as the grassed waterway shown in Figure 2.

The SWAT-Integrated option is applicable when APEX will be used to simulate one or more subbasins in an existing SWAT model. This option would typically be chosen when simulation of a complex agricultural system is necessary to properly represent certain areas within a larger watershed. In this case, a user will be required to identify an existing SWAT model and choose which subbasins will be modeled with APEX. Once users have selected SWAT subbasins, the interface provides the option of importing the SWAT DEM and derived datasets or incorporating a new, usually more refined, DEM from which to base the APEX subarea delineation and calculation of subarea parameters. Both the standalone APEX model and SWAT-Integrated subarea delineations provide users a range of options when defining the size and location of subareas. Usage of the DEM-based delineation allows users to define the size of their subareas based upon a threshold drainage area that constrains the minimum size of a subarea in the watershed. Threshold drainage area is the minimum area required to begin a stream. The size of a subarea typically range from 1 to 100 ha or more depending on the geographic location. It is limited only by the degree of details to be incorporated in the model setup and the variability in the landscape. The number of subareas is limited by the computing resources and ease of data handling and analysis. Point source inputs can also be added directly to user specified subareas through an interactive tool. Users have the option of adding additional subarea outlets through a table of latitude and longitude coordinates, or by interactively specifying a location along the channel network using the GIS functionality of the interface. Reservoirs within the watershed can also be added into the model structure through the same interactive approach. Once the subarea and channel structure definition has been completed, the subarea topographic and physical characteristics, including area, slope, overland flow slope length, channel length, and channel slope are calculated by the interface.

The outputs of the APEX subarea delineation include subarea and stream spatial datasets, which are stored as feature classes within an ArcGIS geodatabase. The format of the geodatabase data model is consistent with the ArcSWAT data model (Olivera et al., 2006) and uses the watershed feature class to store subareas and the reach feature class to store streams. The attribute tables of these feature classes are used by the ArcAPEX interface to define subarea connectivity and parameters for each subarea input file. In some cases, multiple watershed outlets will be defined within a single ArcAPEX project. The APEX model refers to watersheds draining to a single outlet as “sites”. The ArcAPEX database keeps tracks of which subareas are associated with which APEX site, allowing many sites to be simulated concurrently.

2.3 Subarea Analysis

Subarea analysis characterizes the land use/land cover, soils, and slope distributions within each delineated subarea. These characteristics are critical in determining the hydrologic and agronomic response within a watershed. The two steps in the subarea analysis are the definition of land use, soils and slope input datasets, and then the selection of the most appropriate of these characteristics for each subarea.

The land use/soils/slope definition in ArcAPEX combines these three landscape properties to generate areas representing unique hydrology within each subarea. The slope data layer is a direct outcome of the subarea delineation step. The land use data layer must be provided by the user, which can be either a vector or a raster layer. The soil data layer can be extracted from the U.S. STATSGO soils database for U.S. watersheds, which is packaged and integrated with the ArcAPEX interface. Loading and defining soil properties based on the STATSGO soil database (USDA, 1994; 2006) is currently automated in ArcAPEX. Depending on the specific purpose and nature of soil variability in the location of their interest, users can either use STATSGO or import a table of soils properties into the APEX Parameters database from any other soil database, such as the U.S. SSURGO database (USDA, 1995; 2009a).

Consistent formats are maintained between the ArcAPEX and ArcSWAT soil properties database tables. Once all required input data layers and lookup tables are defined, a spatial overlay is performed to calculate the areas represented by each unique combination of characteristics within each subarea.

The ArcAPEX subarea definition step assigns a single land use, soil class, and slope class to each subarea. This is conceptually different than ArcSWAT, where multiple HRUs can be defined within each subbasin. By design, APEX subareas are intended to be smaller than a SWAT subbasin, and as previously discussed, have conceptual similarities to individual HRUs. There are three options for assigning a land use, soil, and slope class to each subarea: 1) the most dominant of each of the three landscape characteristic, 2) the most dominant unique combination of the three landscape characteristics, and 3) the user specified land use, soil, and slope class to a particular subarea.

2.4 Weather

The APEX model requires daily time series of precipitation, temperature, relative humidity, solar radiation, and wind speed. The ArcAPEX interface provides the user three options for supplying weather information: 1) Daily time series for all weather parameters provided by the user, 2) Daily time series for all weather parameters generated by APEX, and 3) Daily time series provided by the user for some parameters and generated by APEX for other parameters. The daily weather time series generated by the APEX model use station-specific monthly weather statistics and account for the interdependence among weather parameters to generate synthetic daily time series. The APEX Parameters geodatabase contains monthly weather and wind statistics for 975 stations across the United States. APEX users in countries other than the United States can import monthly weather statistics data for local weather stations directly into the ArcAPEX weather stations database, in the required format. The weather generator algorithms in APEX are also used to fill in missing data within user provided observed daily time series.

The ArcAPEX interface will identify the closest station to each subarea. The monthly weather generator stations and the user provided daily stations associated with each subarea are then written to a table contained in the APEX Project geodatabase. These data are then used to populate the APEX input files with the appropriate weather information.

2.5 APEX Input Files

The ArcAPEX interface will generate a set of initial input parameters based upon the subarea delineation, subarea land use/soils/slope analysis, and the weather data. These parameters are stored in tables within the ArcAPEX Project geodatabase. The structure of the APEX Project geodatabase has been designed so that there is generally one table that represents each of the main APEX0604 input files. The exceptions to this rule are the APEX soils input files, which are represented by two tables in the APEX Project geodatabase; one for the component level attributes and one for the layer level attributes. In addition to project specific tables, APEX0604 input files will be extracted from tables stored in the APEX Parameters database. These tables, including operations schedules, are shared between multiple APEX projects. As with the inputs generated from the APEX Project geodatabase, the inputs generated from the Parameters geodatabase are generally represented as one table per APEX input file. The operations schedule input files are an exception to this, with one table storing operation schedules and a second table storing the related individual management operations. The APEX input files and associated geodatabase tables are listed in table 1.

The ArcAPEX interface includes a user interface for editing each of the input files listed in table 1, which are integrated with metadata tables stored in the APEX Parameter geodatabase. The metadata table for each APEX input table/file provides help to the user in terms of describing each parameter and constraining the allowable values for the parameters. In addition, the metadata tables describe the formatting necessary for writing the APEX0604 text input files from the geodatabase tables. This allows APEX parameters to be efficiently added, modified, or removed from the input files without requiring changes to the interface code that reads the database and prints the input files.

The user interfaces for the tables in the APEX Parameters geodatabase (Operation Schedules, Crop, Tillage, Fertilizer, Pesticide, Monthly Weather, and Wind) allow users to add new records to the database tables. This is necessary if a user would like to simulate, for example, a crop or pesticide that is not included in the APEX Parameters database provided with ArcAPEX. These interfaces allow the user to choose an existing record (crop, pesticide, etc.) in the database upon which to base the new record, greatly simplifying the process of defining new entries in the APEX databases. The Operations Schedules database interface, one of the more complex interfaces in ArcAPEX, provides functionality for creating new operation schedules, adding, deleting, and editing operations from those schedules, and also provides the ability to upload properly formatted APEX0604 operations files (*.OPC files) into the APEX Parameters database.

2.6 APEX Model Run and Output Files

ArcAPEX contains a simple interface for running the APEX model. In cases where an APEX project contains multiple watersheds, the user may elect to run the model for one or more of the watersheds in a single APEX run. With the advent of ArcAPEX, APEX0604 was modified to generate output files in the same format generated by the SWAT model. At the conclusion of an APEX model run, users may use a built-in tool to import the output files into a Microsoft Access or Excel database for analyzing the output for individual reaches or subareas. APEX will also generate an output file containing all the flow, sediment, and nutrient time series for the outlet of APEX watershed(s) in the same format as a SWAT point source input file. It is this output file that allows the direct integration of APEX model into SWAT.

2.7 Integration with SWAT

Once an APEX model run has been completed in ArcAPEX, one must return to a SWAT model project to complete the linkage of the two models. A menu option has been added to the ArcSWAT interface that allows for the specification of APEX model outputs to replace the inputs from a set of selected SWAT subbasins. This is accomplished by replacing the loadings generated by subbasin and HRU processes in SWAT with a point source input in the SWAT channel network. The point source loadings come from the APEX watershed simulation results. The user must select the subbasins modeled with APEX and then identify the APEX output folder that contains the results of the APEX simulations. The communication between the ArcAPEX and ArcSWAT interfaces ensures that the watershed “site” IDs in the ArcAPEX project correspond with the “subbasin” IDs in the ArcSWAT project, relieving the user from needing to keep track of file names and lookups between SWAT and APEX. To complete the connection between the APEX and SWAT models, the ArcSWAT interface re-writes the SWAT ‘watershed configuration file’ (fig.fig) to insert APEX inputs as point sources in place of SWAT subbasin inputs. The fig.fig file contains information used by SWAT to simulate processes occurring within the HRU/subbasin and route the loadings through the watershed channel network. The user will always have the option of resetting the SWAT fig.fig file to its original structure which uses the SWAT subbasin simulations instead of the APEX inputs. This functionality provides a method to quickly evaluate the differences in simulations between APEX and SWAT simulated subbasins.

Table 1: APEX input files and associated database tables

APEX0604 Input File	APEX Geodatabase	Geodatabase Table(s)
APEX Control	Project	APEXCONT
APEX Site	Project	APEXSITE
APEX Subarea	Project	SUBAREA
APEX Soils	Project	APEXSOIL_COMP, APEXSOIL_LAYER
APEX Operation Schedules	Parameters	tblOPSCCOM, tblAPEXOPSC
APEX Monthly Weather	Parameters	tblWPM1MO
APEX Monthly Wind	Parameters	tblWINDMO
APEX Tillage	Parameters	tblTILLCOM
APEX Crop	Parameters	tblCROPCOM
APEX Fertilizer	Parameters	tblFERTCOM
APEX Pesticide	Parameters	tblPESTCOM
APEX PARAM	Project	APEXPARM
APEX Herd	Project	APEXHERD
APEX Print	Project	tblAPEXPRNT

3. APPLICATION

The following sections describe a study wherein ArcAPEX is applied to evaluate the water quality impacts of various agricultural conservation practices (also referred to as best management practices (BMPs)) over a watershed in central Texas. The BMPs are on-farm or in-stream activities that are designed to conserve water by reducing runoff and increasing infiltration into the soil profile, and to reduce sediment, nutrients and pesticides loss in drainage waters. The agricultural BMPs are encouraged for wider adoption in the US to preserve and/or enhance the quality of receiving waterbodies. Simulating these BMPs and assessing their impacts using watershed models is gaining wider scope due to the fact that models are efficient scientific tools to simulate the impact of potential changes in landscape and land management on downstream water quality. Moreover, due to the general complex nature of the landscape, effect of a BMP might vary from one location to another as function of soil type, land management, and climatic conditions. Also, conducting long-term experiments to monitor the effectiveness of BMPs in large watershed becomes overly expensive.

3.1 Watershed Description and Input Data

The selected area for ArcAPEX application is a subwatershed of Bosque River watershed in central Texas (Fig. 3). This subwatershed drains Tonk Creek (TC) and Wasp Creek (WC) and has a combined drainage area of 104 km^2. A DEM of 10m horizontal resolution was used as an input to establish the topographic characteristics of the watershed. A threshold drainage area of 0.55 km^2 (i.e., 6071 DEM cells), as determined by the ArcAPEX interface, was used to derive the stream network. Several additional outlets were manually added through the interface. Accordingly, a total of 102 outlets were defined that resulted in subdividing the study watershed into 102 subareas (fig. 3).

USDA-Natural Resources Conservation Service (NRCS, 2008) 2007 land use/land cover data (fig. 4(a)) and SSURGO soils data (fig. 4(b)) were used to define the subarea landuse and soil characteristics. Daily rainfall records from a rain gage station maintained by the Texas Institute of Applied Environmental Research (TIAER) at the TC monitoring site was used in this study (fig. 3). Daily minimum and maximum temperature data was obtained from the nearby cooperative weather station. Solar radiation, relative humidity, and wind data were generated based from the weather statistics from the closest weather station in the ArcAPEX Parameters geodatabase. Most of the initial parameter values were default values from the database. Corn and wheat are the major crops grown in the watershed. A three year conventionally tilled ‘corn-corn-winter wheat’ rotation was simulated on all croplands. Both rangelands and pasture lands were simulated as grazed. Rangeland was not fertilized while pasture was fertilized. Management scheduling for cropland, rangeland, and pastureland was obtained from local ‘soil and water conservation district’ personnel (A. Spencer. Personal Communication. Conservation Agronomist, USDA-NRCS, Weatherford, Texas).

The model options considered to simulate various hydrological processes were NRCS curve number (CN) method for runoff estimation, variable daily CN soil moisture index method (Wang et al., 2009) to estimate daily CN, modified rational equation to calculate peak flow, Hargreaves method to calculate potential evapotranspiration, and modified Universal Soil Loss Equation (USLE) to calculate erosion. A detailed description of the model concepts and mathematical relationships used to simulate these processes is given in Williams et al. (2008b).

The period of simulation run was January 1994 through March 2003 including January 1994 through September 1995 as model warm-up period. Calibration was performed for October 1995 through December 1999 and validation for January 2000 through March 2003. The parameters adjusted during calibration include curve number (reduced by -8% from the baseline values), parm8 (25), parm14 (0.2), parm18 (1.0), parm19 (0.01), parm29 (0.3), parm31 (0.3), parm35 (0.9), parm42 (1.2), parm46 (1.0), parm59 (3), and parm72 (0.4). The values within the parenthesis denote the actual value used for model calibration. See Williams et al. (2008a) for description of these parameters. The model simulated stream flow and water quality values were compared against the corresponding observed values at the WC monitoring station maintained by TIAER. Coefficient of determination (r^2) and Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) were used to evaluate model predicted monthly streamflow, sediment, total nitrogen, and total phosphorus loads with observed values.

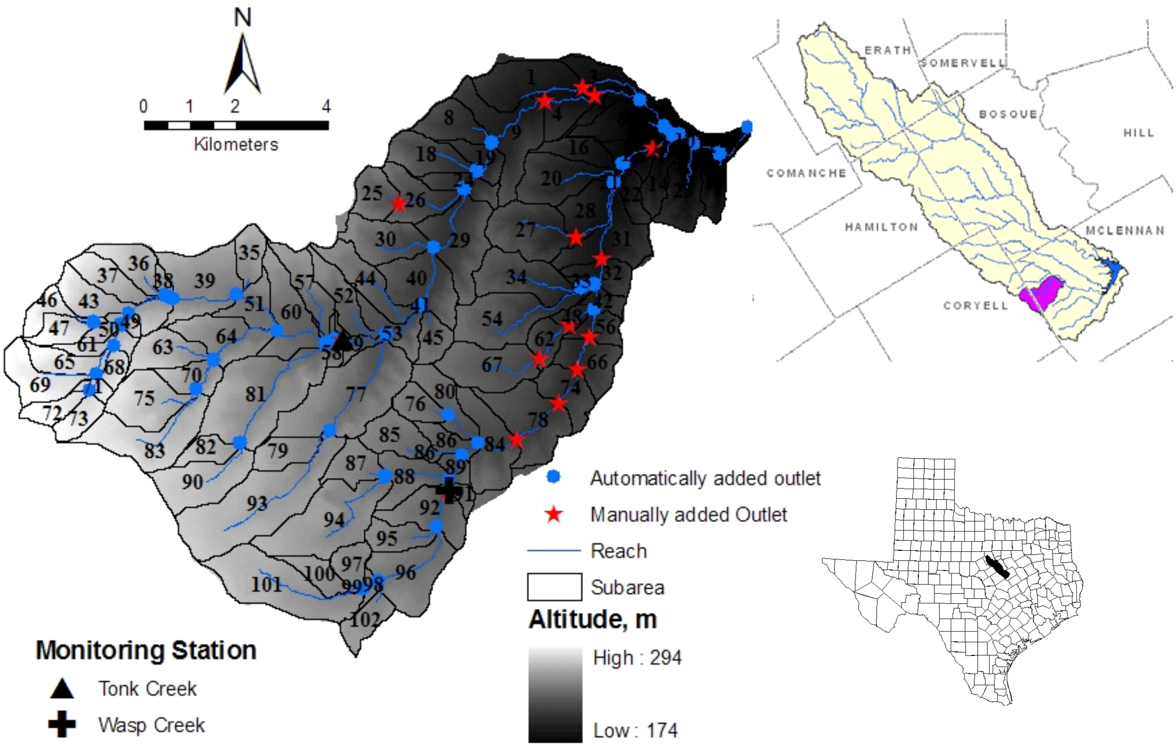
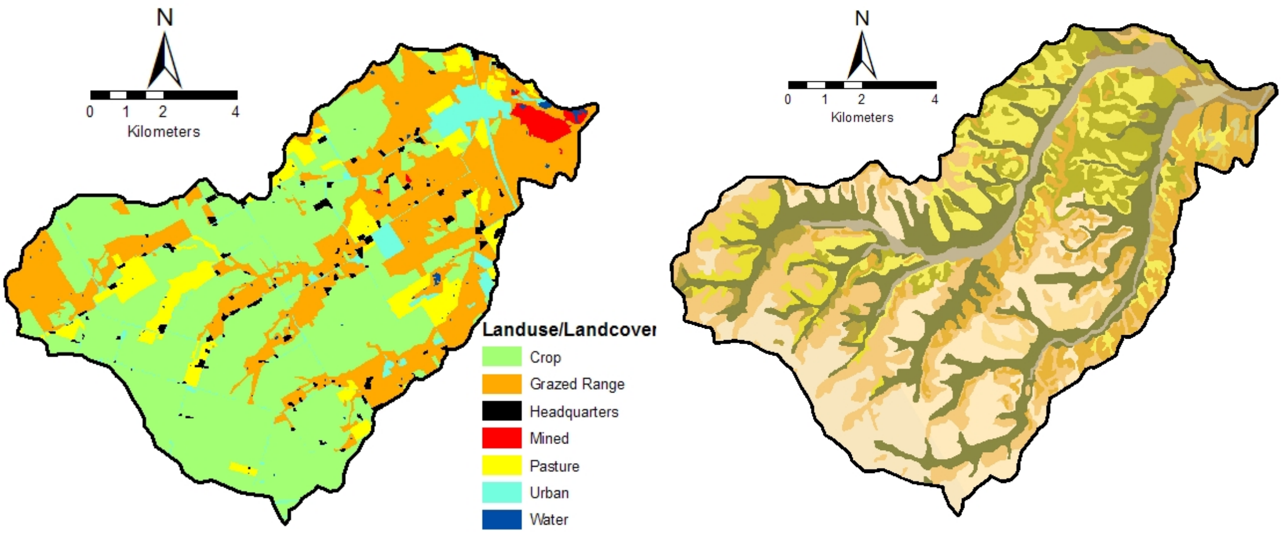


Fig. 3: Subarea delineation, stream network, and automatically and manually added outlets in Tonk Creek and Wasp Creek Watersheds (104 km^2) draining to Middle Bosque River eventually draining to Lake Waco in McLennan County in central Texas



(a) (b)

Fig. 4: Landuse/landcover (a) and SSURGO soils map (b) of the study watershed

The calibrated model was then run for a longer period (30 years, using 1977 to 2006 climate data) to establish the baseline condition against which the BMP effects were evaluated. The interface was further used to represent three BMPs: contour farming, no-till cropping, and furrow diking. Details of these practices can be found in USDA-NRCS (2007). The BMPs were simulated individually, and all inputs except the parameters used to represent a BMP were held constant.

Contouring was represented by the USLE conservation support practice factor (PEC) in *.SUB file and curve number (CN) in *.OPC file. A PEC value of 1.0 in the baseline condition was altered to 0.6 or 0.5 depending on the average upland slope of the subarea (Schwab et al., 1995; Arabi et al., 2008). The CN was reduced by 3 from the baseline condition (Arabi et al., 2008). No-till was represented in APEX by excluding all tillage operations, replacing row crop planters for corn and drills for winterwheat with no-till planters and no-till drills, and fertilizer was injected to a depth of 75 mm below the soil surface. Furrow diking was simulated by building furrow dikes during planting corn and removing them after harvest. The simulated furrow dikes were spaced 1 m apart and offset at 150 mm in height. These BMPs were simulated for all cropland subareas. There were 52 cropland subareas with a total area of 63.4 km^2 (61% of the total watershed area). For each BMP, the model was run for the same 30-year period as simulated in the baseline scenario. Model output results were then compared between the baseline and BMP scenarios. This comparison provides an assessment of the effectiveness of the BMPs in terms of reducing pollutant loadings over a multi-year period. The effectiveness of BMPs was evaluated in terms of percent reductions in average annual surface runoff, sediment, TN, and TP loadings at the subarea levels and at the watershed outlet. Load reductions at the watershed outlet include cumulative load reductions considering overland transport and routing through the stream network. The percent reduction was calculated as:

$$reduction,\% = \frac{100(baseline - postBMP)}{baseline} \qquad (1)$$

where,
baseline = long-term calibrated model run without BMP
postBMP = long-term calibrated model run with BMP

4. RESULTS

Time series of measured and simulated monthly flows at the WC monitoring site matched well during both calibration and validation periods (fig. 5), with the exception of September 1996. The r^2 and NSE statistics at WC monitoring station are summarized in table 2. Although, the model generally performed well in predicting sediment and nutrients during calibration, the model performance during the validation period was poor. This could partly be attributed to the fact that the calibration period contained higher rainfall events compared to validation period. Moreover, the drainage area at the WC station is only about 10 km^2 with an average flow of 0.03 m^3/s over the simulation period. The discrepancy between the measured and predicted values could be due to rainfall variability and the fact that rainfall records from only one rainfall station was used for the entire watershed of 104 km^2, as well as the uncertainty in model input data and measured flow and water quality data. The validation results are generally weaker than those reported by Gassman et al. (2009) for previous APEX studies and point to the need for further investigation to improve the results obtained in this study.

Table 2: Summary statistics of monthly calibration and validation results

	Calibration		Validation	
	r^2	NSE	r^2	NSE
Flow	0.71	0.55	0.66	0.63
Sediment	0.68	0.68	0.17	0.02
Total Nitrogen	0.75	0.57	0.38	0.30
Total Phosphorus	0.65	0.60	0.27	0.16

Percentage reduction in surface runoff, sediment, TN, and TP due to no-till, furrow dike, and contour farming practices at the subarea level is illustrated in figure 6. On an average annual basis, no-till, furrow dikes, and contour farming reduced runoff by 11%, 21%, and 29% respectively. Contour farming was highly effective in reducing all constituents considered compared to no-till and furrow diking. Soils in this watershed are of hydrologic group D, which are mainly clayey with very slow infiltration rates and therefore have high runoff potential. As runoff CN is a very sensitive model parameter in controlling estimated surface runoff, reducing its value by 3 to represent contour farming practice on soils of high runoff potential contributed to higher effectiveness of the practice. Further, slower infiltration capacity of the soils render no-till and furrow dikes less effective. However, no-till effectively reduced sediment by 40% (fig. 6) and TN by 29%. At the watershed outlet, no-till reduced sediment, TN, and TP by 27%, 7%, and 30%; furrow dikes by 19%, 3%, and 26%; and contour farming by 38%, 4%, and 30%, respectively. Although only the above mentioned BMPs were evaluated in the present study for demonstration purposes, various other BMPs could be simulated and assessed for their effectiveness at different spatial scales (Gassman et al., 2009).

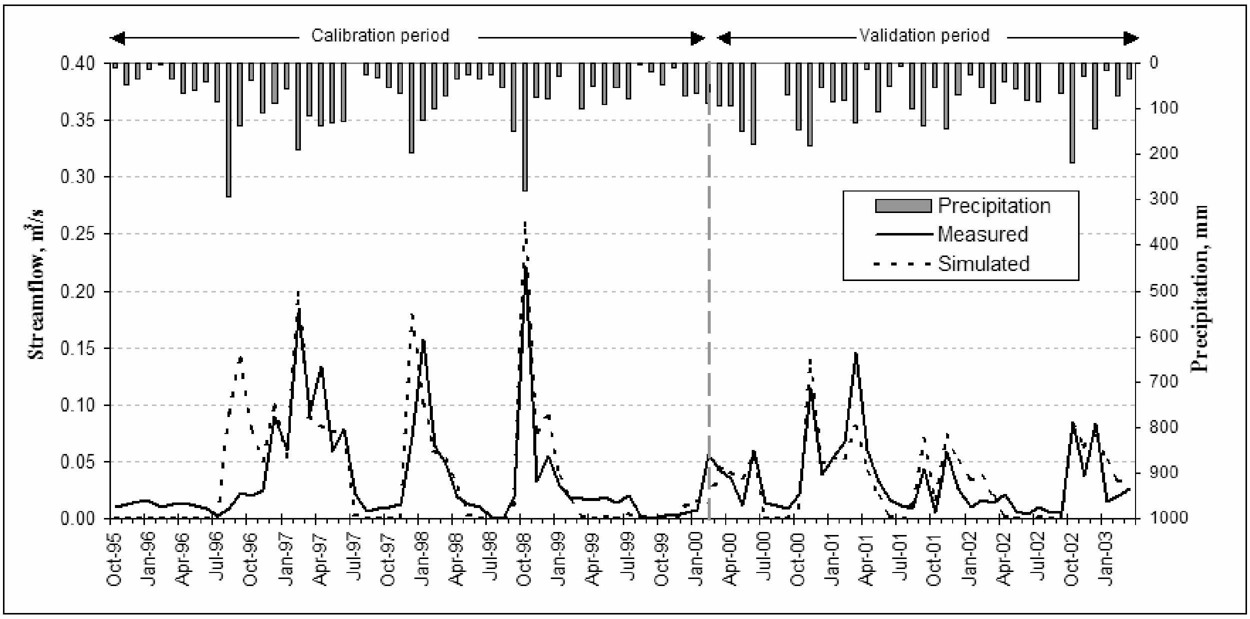


Fig. 5: Measured and simulated flows at Wasp Creek monitoring station calibration and validation periods

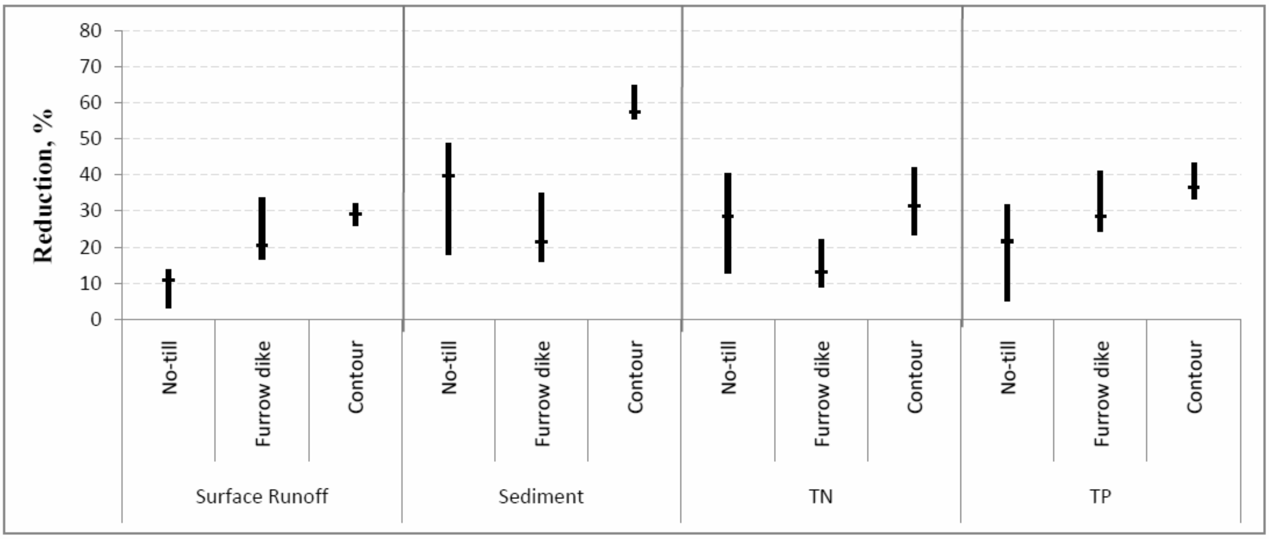


Fig. 6: Percentage reduction in surface runoff, sediment, total nitrogen (TN), and total phosphorus (TP) (mean, minimum, and maximum) due to no-till, furrow dike, and contour farming practices at the subarea level

5. CONCLUSIONS

The ArcAPEX is an ArcGIS-based user interface designed to automate the parameterization of APEX model integrating readily available topographic, hydrographic, land use, and soils spatial datasets. The interface includes an APEX-Parameters database that contains model parameterizations for a wide range of plant growth, tillage, fertilizer, and pesticide applications, as well as U.S. weather and soil data. The ArcAPEX interface and companion database allow users to very efficiently build complex models ranging in scale from the farm to watershed. Users can build and save alternative crop management operation schedules through the interface's editing dialogs, enabling the evaluation of best management practices on water quality and the environment. A key feature of the interface is the functionality it provides to directly integrate APEX simulations with watersheds modeled with SWAT. Using this modeling framework, APEX can be implemented for more detailed simulation of farms or small subwatersheds with complex agronomic systems, while SWAT can be used for larger subwatersheds with more homogeneous and less complex agricultural systems and non-agricultural landscapes, as well as for integrating constituent (runoff, sediment, nutrient, and pesticide) contributions from all subwatersheds and simulating in-stream channel processes. Together the ArcAPEX and ArcSWAT interfaces seamlessly link the APEX and SWAT modeled components.

The ArcAPEX interface was used to setup the APEX model for a 104 km^2 subwatershed of Bosque River Watershed in central Texas. Calibration and validation of the model were performed using data collected for the study watershed; those results indicate the need for further refinement of this APEX application to improve the validation accuracy. The interface was then used to represent contour farming, no-till cropping, and furrow diking BMPs and evaluate their effectiveness in reducing runoff, sediment, and nutrient loads. Other BMPs, climatic, and land use scenarios can be simulated in APEX within the ArcAPEX framework, such as those documented by Gassman et al. (2009) across a range of studies.

Improvement of ArcAPEX to support the efficient evaluation of best management practices will continue. Current plans are focused on the development of pre-built management operations schedules and best management practice scenarios for a wide range of cropping systems. These operations schedules and scenarios would be distributed as part of the APEX Parameters database and available for incorporation into APEX models developed through ArcAPEX. The vision is to streamline the scenario evaluation process to enable less sophisticated users to apply the APEX model in an intelligent way to obtain scientifically accurate and defensible results used to assist in environmental management and decision making.

Finally, the potential exists to apply APEX within ArcAPEX and/or ArcSWAT for simulation of complex agroforestry systems in southeast Asia including intercropping of tree crops and vegetables, such as the systems described by Reyes (2008). Plant competition algorithms based on the approach used in the ALMANAC model (Kiniry et al., 1992) have already been incorporated in APEX, which account for competition between multiple crops, weeds, and/or other vegetation for light, water, and nutrients. However, expanded plant parameter datasets and other improvements are needed before APEX can be applied for agroforestry systems, as discussed in detail by Johnson et al. (2009) in the context of incorporating ALMANAC multi-cropping algorithms into SWAT for simulating agroforestry systems in southeast Asia and other regions.

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REFERENCES

1. Arabi, M., J. R. Frankenberger, B. A. Engel, and J. G. Arnold. 2008. Representation of agricultural conservation practices with SWAT. Hydrol. Process. 22(16): 3042-3055.
2. Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large area hydrologic modeling and assessment part I: model development. J. Amer. Water Resour. Assoc. 34(1): 73-89.
3. Di Luzio, M., R. Srinivasan, and J. G. Arnold. 2004. A GIS-Coupled Hydrological Model System for the Water Assessment of Agricultural

Nonpoint and Point Sources of Pollution. Trans. GIS 8(1): 113-136.

4. Gassman P. W., M. Reyes, C. H. Green, and J. G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future directions. Trans. ASABE 50(4): 1211-1250.
5. Gassman, P. W., J. R. Williams, V. W. Benson, R. C. Izaurralde, L. Hauck, C. A. Jones, J. D. Atwood, J. Kiniry, and J. D. Flowers. 2005. Historical development and applications of the EPIC and APEX models. Working Paper 05-WP 397. Center for Agricultural and Rural Development, Iowa State Univ., Ames, IA. Available at: http://www.card.iastate.edu/publications/synopsis.aspx?id=763.
6. Gassman, P. W., J. R. Williams, X. Wang, A. Saleh, E. Osei, L. Hauck, C. Izaurralde, and J. Flowers. 2009. The Agricultural Policy Environmental Extender (APEX) Model: An emerging tool for landscape and watershed environmental analyses. Technical Report 09-TR 49. Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa. Available at: http://www.card.iastate.edu/
7. Jenson S. K., and J. O. Domingue. 1988. Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis. Photogramm. Eng. Rem. Sens. 54(11): 1593-1600.
8. Johnson, M-V. V., J. D. MacDonald, J. R. Kiniry, and J. G. Arnold. 2009. ALMANAC: a potential tool for simulating agroforestry yields and improving SWAT simulations of agroforestry watersheds. Inter. Agric. Eng. J. (This issue).
9. Kiniry, J. R., J. R. Williams, P. W. Gassman, and P. Debaeke. 1992. A general, process-oriented model for two competing plant species. Trans. ASAE 35(3): 801-810.
10. Magre, M. J.R. Williams, W.L. Harman, T. Gerik, J. Greiner, L. Francis, E. Steglich, and A. Meinardus. 2006. WinAPEX Users Guide Version 1.0. Temple, Texas: Blackland Research and Extension Center, Texas A& M System. Available at http://winapex.brc.tamus.edu/media/17085/winapexv0604_nov2006.pdf.
11. Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I. A discussion of principles. J. Hydrol. 10(3): 282-290.
12. Olivera, F., M. Valenzuela, R. Srinivasan, J., Choi, H. Chou, S. Koka, and A. Agrawal. 2006. ArcGIS-SWAT: A Geodata Model and GIS Interface for SWAT. J. Amer. Water Resour. Assoc. 42(2): 295-309.
13. Reyes, M. R. 2008. Progress report: Agroforestry and sustainable vegetable production in Southeast Asian watersheds. ASABE Paper 085105. Presented at the 2008 ASABE Annual International Meeting, 29 June to 2 July, Providence, RI.
14. Saleh, A., and O. Gallego. 2007. Application of SWAT and APEX using the SWAPP (SWAT-APEX) program for the Upper North Bosque River watershed in Texas. Trans. ASABE 50(4): 1177-1187.
15. Schwab, G. O., D. D. Fangmeier, and W. J. Elliot. 1995. Soil and water management systems. New Jersey: John Wiley & Sons. Pp: 108-111.
16. Srinivasan, R., and J. G. Arnold, 1994. Integration of a Basin-Scale Water Quality Model with GIS. J. Amer. Water Resour. Assoc. 30(3): 453-462.
17. Taylor, E. D. and K.J. Bryant. 1994. A universal text integration language (UTIL): making data intensive computer models easier to use. Appl. Eng. Agric. 10(4): 553-559.
18. USDA-NRCS. 1994. State Soil Geographic (STATSGO) Database: Data Use information. Miscellaneous publication 1492. Washington, D.C.: U. S. Department of Agriculture, Natural Resources Conservation Service. Available at: http://www.nrcs.usda.gov/technical/techtools/statsgo_db.pdf.
19. USDA-NRCS. 1995. Soil Survey Geographic (SSURGO) Database: Data Use information. Miscellaneous publication 1527. Washington, D.C.: U. S. Department of Agriculture, Natural Resources Conservation Service.
20. USDA-NRCS. 2006. U.S. General Soil Map STATSGO2. Washington, D.C.: U. S. Department of Agriculture, Natural Resources Conservation Service. Available at: http://soils.usda.gov/survey/geography/statsgo/.
21. USDA-NRCS. 2007. National Handbook of Conservation Practices. Washington, D.C.: U. S. Department of Agriculture, Natural Resources Conservation Service. Available at: http://www.nrcs.usda.gov/technical/standards/nhcp.html.
22. USDA-NRCS. 2008. Land use and land cover data for Tonk Creek watershed, Texas. Temple, TX: U. S. Department of Agriculture, Natural Resources Conservation Service. September 2008.

23. USDA-NRCS. 2009a. Soil Survey Geographic (SSURGO) Database. Washington, D.C.: U. S. Department of Agriculture, Natural Resources Conservation Service. Available at: http://soils.usda.gov/survey/geography/ssurgo/.
24. USDA. 2009b. United States Department of Agriculture-National Agriculture Imagery Program. Washington, D.C.: U. S. Department of Agriculture. Available at: http://www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai.
25. Wang, X., D. W. Hoffman, J. E. Wolfe, J. R. Williams, W.E. Fox. 2009. Modeling the effectiveness of conservation practices at Shoal Creek watershed, TX, using APEX. Trans. ASABE 52(4):1181-1192.
26. Williams, J. R. 1990. The erosion productivity impact calculator (EPIC) model: a case history. Phil. Trans. R. Soc. Lond. 329: 421-428.
27. Williams, J. R., R. C. Izaurralde, and E. M. Steglich. 2008a. Agricultural Policy/Environmental Extender Model User’s Manual Version 0604. BREC Report #2008-16. Blackland Research and Extension Center. 222 p. Available at: http://epicapex.brc.tamus.edu/downloads/user-manuals.aspx. Accessed 25 September 2009.
28. Williams, J. R., R. C. Izaurralde, and E. M. Steglich. 2008b. Agricultural Policy/Environmental Extender Model Theoretical Documentation. BREC Report #2008-17. Blackland Research and Extension Center. 130 p. Available at http://epicapex.brc.tamus.edu/downloads/user-manuals.aspx. Accessed 25 September 2009.
29. Williams, J. R., E. Wang, A. Meinardus, W. L. Harman. 2004. APEX2110 Users Guide. Temple, Texas: Blackland Research and Extension Center, Texas A&M University.
30. Winchell, M., R. Srinivasan, M. Di Luzio, and J. G. Arnold. 2008. Arc-SWAT 2.1 Interface for SWAT2005 - User’s guide. Temple, TX: Blackland Research Center, Texas Agricultural Experiment Station and Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service.

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STORMWATER BEST MANAGEMENT PRACTICES: REVIEW OF CURRENT PRACTICES AND POTENTIAL INCORPORATION IN SWAT

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ABSTRACT

Stormwater Best Management Practices (BMPs) are employed to mitigate high peak flow, flow volumes, and transport of pollutants from urbanized areas. Many of these structures are widely used throughout the United States, including wet ponds, stormwater wetlands, bioretention cells, level spreader – vegetative filter strips, swales, permeable pavements, green roofs, and water harvest systems. Two different metrics of effectiveness are presented: pollutant removal efficiency and effluent concentration. However, the effectiveness of many of these BMPs has been limited due to a lack of assessment and documentation. Once documented, they become a valuable source of information for modeling purposes. The possible use and form of these monitored data for modeling and how the BMPs could be represented in a watershed model is discussed. For this analysis, the Soil and Water Assessment Tool (SWAT) model is considered because of its wide use and successful track record of modeling rural watersheds throughout the world. An ongoing effort for development of urban modeling tools in SWAT is also highlighted.

1. INTRODUCTION

Urban watersheds differ from their rural counterparts in terms of more runoff per unit area. Pollutant loads from urban watersheds can be substantial, despite relatively low concentrations, because of high runoff volumes. The high runoff volumes come from impervious areas as an instantaneous response to precipitation. Stormwater management practices, also referred to as best management practices (BMPs), have been employed to mitigate runoff volumes from large precipitation events. Traditionally, these practices were mostly ponds or dry detention basins. However, newer BMPs include more vegetated systems such as stormwater wetlands, level spreader- vegetated filter strip systems, and rain gardens. Because small-scale developments are often required to manage water on-site, BMPs such as sand filters, bioretention, permeable pavement, swales, green roofs, and water harvesting systems are becoming common (Barrett 2003, Davis et al. 2009, Collins et al. 2008, USEPA 2009). Many of these practices comply with landscape requirements or serve multiple purposes such as being a parking surface or providing a water source.

Modeling urban watersheds and stormwater BMPs requires realistic capturing of flow and pollutant transport coming from impervious areas. The Soil and Water Assessment Tool (SWAT) has a long history of watershed hydrologic and pollutant prediction with the majority of the model's use being in agricultural watersheds (Williams et al. 2008; Gassman et al. 2007). The model's ability to predict water flow and pollutant removal through soil and vegetation systems, however, makes it a potential tool for urban watershed management.

SWAT already incorporates some management practice modules that can be modified for urban stormwater systems, such as wet ponds, wetlands, grassed waterways, and filter strips (Arabi et al. 2008, Arnold et al. 2001, White and Arnold, 2009). SWAT

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allows for assignment of soil and crop management parameters for a watershed. Many urban stormwater BMPs incorporate removal processes associated with ponds and dry detention in addition to using soil and vegetation for treatment. There exists an opportunity for SWAT to be expanded to incorporate many innovative urban stormwater BMPs, perhaps without a tremendous code modification investment. With the stormwater BMP simulation capability, the model could be used to analyze many what-if scenarios for urban watersheds such as the effectiveness of analyzing a group of BMPs, identifying key pollutant sources, prioritizing the mitigation measures, etc.

The purposes of this paper are to (1) present and describe the function of various innovative urban stormwater BMPs, (2) report on pollutant removal and sequestration of these BMPs for potential incorporation into SWAT, and (3) discuss some specific challenges associated with incorporating urban treatment components. The paper will conclude with a discussion of a current urban SWAT application for the city of Austin, Texas, focusing on development of urban modeling tools for SWAT.

2. URBAN STORMWATER BMPs

Urban stormwater designers utilize several stormwater practices to comply with locally managed requirements. The following practices will be discussed in succeeding sections: wet ponds, stormwater wetlands, bioretention, level spreader – vegetated filter strip systems, swales, permeable pavement, green roofs, and water harvesting systems. Other practices such as sand filters and manufactured systems have more regionally limited application in the US, and therefore are not discussed. Each practice will be described and its performance assessed.

Two basic evaluation methodologies of urban stormwater BMPs are discussed throughout this study: pollutant removal efficiencies and effluent concentrations. These evaluation methodologies are essential for understanding the effectiveness of these practices and are important data needed for future testing of urban BMP algorithms in SWAT. They may also prove necessary for direct simulation of some urban stormwater practices in the model, at least temporarily until enhanced mechanistic approaches can be developed, as discussed in more detail in the SWAT Considerations section below. Many of the pollutant removal mechanisms for stormwater BMPs are still relatively poorly characterized and therefore will not be the focus of this paper.

Removal efficiency is calculated by the following equation:

$$\text{Rem. Eff.} = 100\% \text{ x } \frac{(\text{Pollutant INFLOW} - \text{Pollutant OUTFLOW})}{\text{Pollutant INFLOW}}$$

While pollutant removal efficiencies are widely used, there are several flaws associated with this metric (Jones et al. 2009, Strecker et al. 2001). One is that percent removals can be biased by extremely clean or extremely dirty inflow. Conversely, effluent concentrations could theoretically be higher than those of the influent, meaning the BMP could be adding pollution. This has been observed for nutrient export from vegetated BMPs like bioretention and stormwater wetlands (Hunt et al. 2006; Lenhart and Hunt 2009). Both types of BMP performance metrics are reported herein: capture efficiency, expressed in per cent (%) for typical target pollutants including Total Suspended Solids (TSS), Total Nitrogen (TN), Total Phosphorus (TP), and Zinc (Zn) are provided in "a" tables for each practice, while effluent concentrations, expressed in mg/L, associated with these systems and target pollutants are noted in corresponding "b" tables.

2.1 Wet Ponds

Perhaps the most common urban stormwater management tool is the wet pond. For many years it was the preferred stormwater treatment device because of its ability to attenuate flow peaks. The use of the pond has begun to wane due to more recent regulations requiring water quality treatment in addition to or in lieu of peak runoff mitigation. However, in many US states the wet pond is still the preferred practice. SWAT simulations have been conducted on reservoirs and ponds, and the ability of SWAT to predict pond performance has been established (Prochnow et al., 2007). Wet pond pollutant reduction is predicated upon sedimentation, and many states assign total suspended solids (TSS) removal efficiencies (Strecker et al. 2001) to these systems of 80-85%, based upon expected sediment load and particle size distribution.

Wet ponds are designed such that their average depth, volume, and flow path traps the required fraction of inflow sediment. Newer pond configurations include features such as forebays, which serve as an initial sediment and gross solid storage area, and littoral shelves, which create wetland features typically around the perimeter of the structure (Figure 1).

Fig. 1: Wet Ponds with forebays (left) and aquatic shelves (left and right)

Table 1a: Wet pond pollutant removal efficiencies (in %). (NR = Not Reported)

Study	Location	TSS	TN	TP	Zn
Hathaway et al., 2007a	Charlotte, NC	63	19	15	49
Schueler, 1996	Maryland	93	50	87	27
Hathaway et al., 2007b	Charlotte, NC	56	23	41	49
Mallin et al. 2002	Wilmington, NC	65	-3	23	NR
Comings et al., 2000	Bellevue, Wash.	61	NR	19	45

Table 1b: Wet pond effluent concentrations (in mg/L)

Study	Location	TSS	TN	TP	Zn
Hathaway et al., 2007a	Charlotte, NC	29	2.2	0.10	0.026
Hathaway et al., 2007b	Charlotte, NC	27	1.32	0.14	0.028
Mallin et al., 2002	Wilmington, NC	3	0.64	0.05	NR
Comings et al., 2000	Bellevue, Wash.	9	NR	0.08	0.030

Wet ponds are the most extensively studied BMP due to their widespread use. In general they capture large amounts of gross solids, sediment and pollutants associated with sediment. Wet pond pollutant removal is summarized in Tables 1a and 1b. Other studies (Jones and Hunt 2009a, Van Buren et al. 2000) have showed that ponds have detrimental impact on thermal pollution due to direct solar radiation on the water surface, making ponds an unfavorable choice in regions with cold water fisheries.

2.2 Stormwater Wetlands

Treatment wetlands have been modeled in SWAT previously, including a 15.4 ha constructed riparian wetland in Texas (Arnold et al. 2001). Embedded in SWAT are numerous algorithms able to predict hydrologic balance within wetland systems, similar to how SWAT models ponds. Stormwater wetlands are typically large and shallow stormwater treatment basins that are mostly vegetated. The average normal pool depth in a stormwater wetland is approximately 15 cm, but the underlying topography is quite variable (Hunt et al. 2007). Created stormwater wetlands have been designed to treat watersheds exceeding 100 ha, but typically receive runoff from 10 to 30 ha watersheds. Important design elements for stormwater wetlands include planting medium and vegetation selection as well as its outlet configuration. In many states, like North Carolina (NC DENR 2007), stormwater wetlands are required to retain a portion of the water quality event (typically 2.5 cm) for at least 48 hours. The ponding allowed above normal pool is usually restricted to 30 to 40 cm (Hunt et al. 2007), thus often leading to relatively large surface areas dedicated to the treatment practice.

Stormwater wetlands employ several pollutant removal mechanisms including sedimentation, chemical sorption, filtration, and biological processes such as nitrification and denitrification. The presence of vegetation in stormwater wetlands has many benefits. Because of extensive vegetated coverage, the plants are able to filter gross solid floatables. Due to plant roots in a saturated soil zone, aerobic and anaerobic soil conditions establish in close proximity. This creates the opportunity for relatively high rates of nitrification and denitrification, making stormwater wetlands common practices in nitrogen-sensitive watersheds. Moreover, wetlands have been shown to more readily remove small sediment particles (<2 microns) to which pollutants such as phosphorus, some types of nitrogen, and fecal coliforms adhere (Bavor et al., 2001).

Tables 2a and 2b summarize stormwater wetland effects. Wetlands appear to be slightly preferable to wet ponds when treating thermal pollution due to the shade provided by the vegetated cover (Jones and Hunt 2009a, Keiser et al. 2004).

A special type of stormwater wetland is the infiltrating wetland, which is typically a small, "pocket" wetland located in permeable soils with relatively high water tables. The presence of seasonally high water tables usually prohibits the use of other small scale, or Low Impact Development, techniques such as bioretention (discussed later). Deeper water zones of these wetlands are designed to retain water during droughty periods, but much of the wetland is subject to occasionally drying out due to infiltration and ET. These wetlands would typically be located in flat, sandy soils that adjoin the Mid-Atlantic

Fig. 2: Two infiltrating wetlands located in North Carolina (a) River Bend and (b) Wilmington. In (b) the inundated deep pool is in contrast to the remaining portion of the wetland which is not saturated at the surface

Table 2a: Stormwater Wetland pollutant removal efficiencies (in %)

Study	Location	TSS	TN	TP	Zn
Lenhart and Hunt, 2009	New Bern, NC	49	36	47	NR
Johnson, 2006	Charlotte, NC	66	41	55	55
Line et al., 2008	Raleigh, NC	53	10	41	NR
Scholes et al., 1999	Dagenham, UK	35	NR	NR	71

Table 2b: Stormwater Wetland effluent concentrations (in mg/L)

Study	Location	TSS	TN	TP	Zn
Lenhart and Hunt, 2009	New Bern, NC	41	1.11	0.23	NR
Johnson, 2006	Charlotte, NC	24	1.37	0.20	0.022
Line et al., 2008	Raleigh, NC	18	1.00	0.99	NR
Line et al., 2008	Asheville, NC	31	0.94	0.12	NR

and Southeastern coasts of the United States. Infiltrating wetlands are wetter than bioretention cells, because they do not rely on a drainage infrastructure or special fill media. Examples of infiltrating wetlands are shown in Figure 2.

2.3 Bioretention

Bioretention is a filtration and infiltration BMP that is based, in part, on sand filter design (Urbonas, 1999). The typical bioretention design is an excavated basin that is underdrained by a gravel, perforated pipe envelope. Above the drainage envelope is a specialized soil, or media, into which vegetation is planted. If the vegetation is primarily trees and shrubs, then mulch is added. Bioretention stores water in a bowl that is usually up to 30-cm deep (average depth slightly lower). When the bowl fills, water will then spill over an outlet (Figure 3). A type of bioretention cell that does not employ underdrains is termed bioinfiltration (Davis et al. 2009). Bioretention has proven to provide both infiltration and a substantial amount of evapotranspiration and is probably the most commonly used structural practice as part of Low Impact Development (Davis et al. 2009). A common name for bioretention is the "rain garden." A photo of two types of bioretention cells is shown in Figure 4.

Several researchers have examined the benefits of creating a sump in the bottom of the bioretention cell (Dietz and Classen 2006, Kim et al. 2003, Hunt et al.

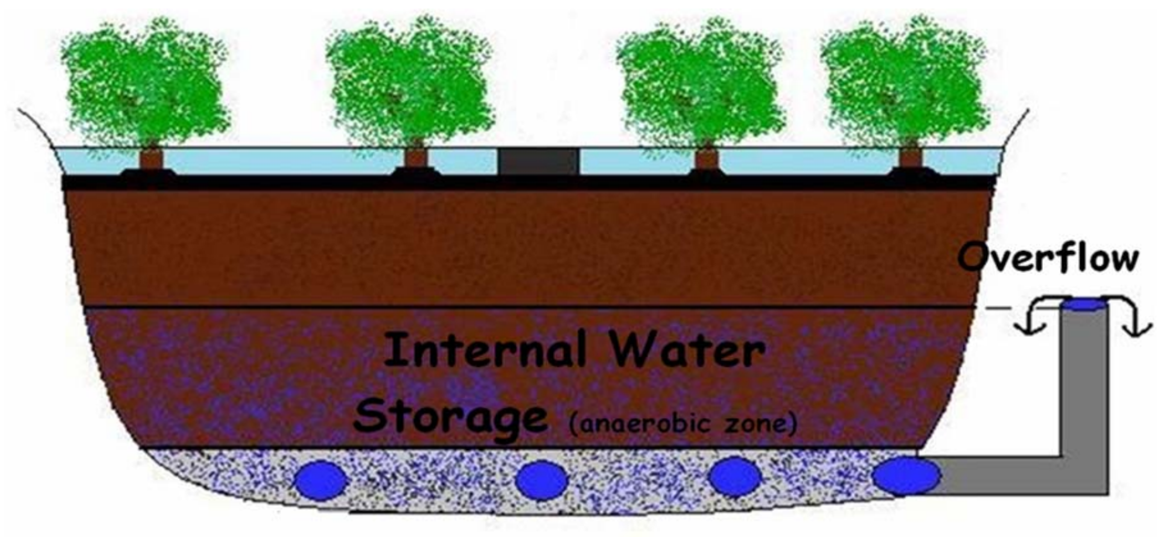

Fig. 3: Schematic of Bioretention cross section

Fig. 4: Two bioretention cells in North Carolina: an ultra-urban application in Charlotte, NC, (left) and a grassed cell located on the North Carolina State Univ. campus in Raleigh (right)

2006). Sumps, or internal water storage zones (IWS) (Davis et al. 2009), are designed to temporarily store water so that it can later infiltrate. Creating sumps is accomplished by either elevating the underdrains or installing an upturned elbow (Figure 3). Design guidance on IWS sizing is in the process of being established, but is not yet available. The inclusion of sumps can have a dramatic influence on the amount of infiltration a bioretention cell can provide.

Pollutant removal processes associated with bioretention are numerous, making this one of the most popular small-scale stormwater management practices in the United States. Bioretention employs sedimentation, filtration through a porous media, chemical sorption, and, like wetlands, several biological processes, including nitrification, and, if an IWS layer is employed or other creation of a saturated zone, denitrification. The selection of fill media in a bioretention system is a critical design element for several reasons. Because bioretention is an infiltration and filtration practice, the fill media must be permeable, with 0.007 to 0.014 mm/s (1 to 2 in/hr) a typical guide (Hunt and Lord 2006, NC DENR 2007). The composition of the fill media impacts pollutant removal (or addition) provided by the bioretention cell. Media with high phosphorus content (typical of agricultural fill soils) tend to produce phosphorus, and media with high compost levels tend to release more nitrogen as compost decomposes (Hunt et al. 2006). As a result, fill media is predominantly sand with small fractions of fines (clays + silts) and compost. Some research has examined the addition of high sorption capacity minerals to media to enhance their pollution removal ability (Davis et al. 2009); perhaps the use of "boutique minerals" may become common in the future.

Of small scale practices, bioretention has been researched most extensively, and a substantial amount of field performance data is available. A selection of studies is presented in Table 3. Jones and Hunt (2009b) found bioretention to reduce thermal loads substantially, because these systems both cool and infiltrate runoff.

2.4 Level Spreader / Vegetated Filter Strips

The use of agricultural filter strips to treat runoff is already being incorporated into SWAT (White and Arnold, 2009). However, because urban development produces so much more runoff per unit area for most events, linear level spreaders are located between the drainage area and the filter strip. Level spreaders are designed to spread flow evenly over the same grade consist of three parts: the forebay, the channel, and the vegetated filter strip (Figure 5). This allows for infiltration and some eventual ET in the downslope vegetated filter strip. The type of material used to construct urban level spreaders has not always provided diffuse flow (Hathaway and Hunt 2008), thus leading to hardened material, like concrete, being required. While simple, little design guidance is available for vegetated filter strips in the urban environment. Some efforts are underway using VFS-MOD (Munoz-Carpena and Parsons, 2004) to establish design guidelines. Vegetated filter strips are generally designed to slope perpendicularly away

Table 3a: Bioretention pollutant removal efficiencies (in %)

Study	Location	TSS	TN	TP	Zn
Hunt et al., 2008	Charlotte, NC	60	32	31	77
Hunt et al., 2006	Greensboro, NC	-170[1]	40	-240 *	98
Line and Hunt, 2009	Catawba County, NC	-198	-17	37	87
Dietz and Claussen, 2006	Haddam, CT	NR	32	-111	NR
UNH, 2006	Durham, NH	97	97%	NR	99
Davis, 2007	College Park, MD	59	NR	79	54

* Poor performance associated with low influent concentrations (TSS) and fill media with high phosphorus content.

Table 3b: Bioretention effluent concentrations (in mg/L)

Study	Location	TSS	TN	TP	Zn
Hunt et al., 2008	Charlotte, NC	20	1.14	0.13	0.017
Line and Hunt, 2009	Catawba County, NC	105	1.80	0.21	0.040
Dietz and Claussen, 2006	Haddam, CT	NR	0.80	0.06	NR
Davis, 2007	College Park, MD	18	NR	0.15	0.048

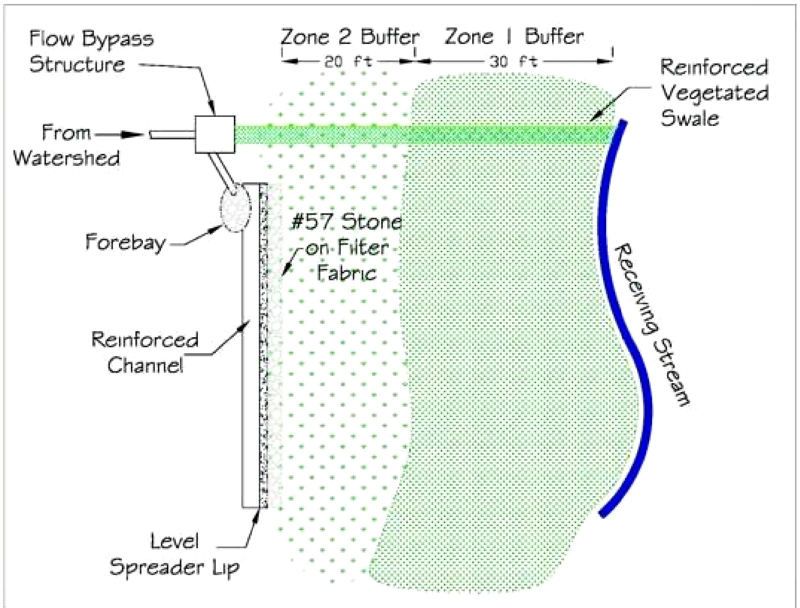

Fig. 5: Schematic of a level spreader system upslope of a riparian buffer

Fig. 6: A pair of level spreaders in Apex, NC. Each is made of structurally durable and level material: concrete (left) and metal (right)

from the level spreader and are usually grassed. Figure 5 shows a pair of level spreader/ vegetated filters in Piedmont North Carolina.

Level spreader and graded grass filter strips may often be the most appropriate BMP in locations with a seasonally high water table near the surface, which is a common occurrence in some of the flatter topographic regions along the southeast and mid-Atlantic coasts. Their use, conversely, will be more limited in steep slope applications typically found in hillier, mountainous topography.

Designed filter strips have been shown to infiltrate substantial quantities of runoff when used in conjunction with level spreaders (Line and Hunt 2009, Hunt et al. 2010). Substantial infiltration is due to vegetative filter strips being graded by design, ensuring their “levelness” and downward slope. This allows water to remain in sheet flow for much longer periods than those associated with a naturally-occurring topography. An extensive study by Hathaway and Hunt (2008) showed that level spreaders upslope of riparian buffers did not provide diffuse flow in any of the 24 level spreader/riparian buffer systems examined. In many cases the topography of the riparian buffer forced water to re-concentrate, effectively bypassing most of the riparian

Table 4a: Level Spreader – Vegetated Filter Strip pollutant removal efficiencies (in %)

Study	Location	TSS	TN	TP	Zn
Yu et al. 1998	Virginia	77	NR	38	51
Line and Hunt, 2009	Johnston County, NC	54	62	48	82
Winston, 2009	Apex, NC	63	67	62	NR
Winston, 2009	Louisburg, NC	-106*	70	67	NR

* mean removal efficiency reported. Median removal efficiency was 93%. Discrepancy explained by author as one-time fire extinguisher discharge at monitoring location

Table 4b: Level Spreader – Vegetated Filter Strip effluent concentrations (in mg/L)

Study	Location	TSS	TN	TP	Zn
Line and Hunt, 2009	Johnston County, NC	77	2.05	0.19	0.050
Winston, 2009	Apex, NC	25	0.89	0.09	NR
Winston, 2009	Louisburg, NC	10	0.85	0.16	NR

buffer's hydrologic benefits. White and Arnold (2009) discuss how SWAT accounts for this effect and allows the user to select the effective portion of the VFS that is used to convey flow and compare that to the contributing watershed area. Grassed filter strips that are evenly graded perpendicularly from the level spreader tend to keep flow from concentrating, thus allowing for increased infiltration.

Pollutant removal processes associated with level spreader – vegetative filter strips include sedimentation and chemical sorption. Filter strips can be amended with compost or other soil amendments to make these systems more permeable (Hunt et al. 2010). The few pollutant removal studies that have been conducted on level spreader systems are summarized in Tables 4a and 4b.

2.5 Swales

Swales are one of the most common stormwater practices, and serve as the "urban cousin" of grassed waterways. Modeling of grassed waterways has been a part of SWAT in recent versions (Arabi et al., 2008). Swales are inexpensive to construct, and are needed to convey water from a source to a treatment device or an exit from the property. They are usually turf covered, but can sometimes be allowed to grow with wetland vegetation. If the latter design is used, the swale must be oversized to compensate for the cross sectional area lost due to the taller vegetation and the increased flow resistance. Examples of both swale types are shown in Figure 7.

Swales rely on sedimentation, vegetative filtering, and some infiltration to reduce pollutant loads. Swale performance is extremely variable per adjoining land use. Swales associated with residential areas can *add* pollutants if domesticated animals frequent locations immediately surrounding the swale. When researched in highway environments, swales have been shown to improve pollutant loads (Tables 5a and 5b). The length of swales with respect to contributing drainage area, height and type of vegetation all impact swale performance. Swale design guidance is still coarse. As expected proportionally larger swales outperform their smaller counterparts (Deletic and Fletcher 2006).

2.6 Permeable Pavement

Permeable pavement is exactly what its name implies: pavement that allows water to pass through it rather than shed off it. It is comprised of a gravel storage layer, typically ranging in depth from 10 to 30 cm, that is overlain by a permeable surface such as pervious concrete or concrete grid pavers (Figure 8). Depending upon the location of the pavement, an underdrainage system may be used (typically in clayey in situ soil). Depending upon the rainfall intensity, rainfall volume, and existing soil infiltration rate, water then either exits the bottom of the permeable paver via soil infiltration or under drain pipe, or water will pond inside the pavement until runoff occurs. Very intense rainfall rates can produce runoff from permeable pavement surface. Some designs of permeable pavement are able to infiltrate

Fig. 7: Two swales, one dry (in Raleigh, NC) and one wet (along I-40 in eastern NC) are used to convey water

Table 5a: Swale pollutant removal efficiencies (in %)

Study	Location	TSS	TN	TP	Zn
Stagge, 2006	Maryland, USA	90	45	38	80
Backstrom, 2003	Sweden	70	NR	NR	66
Fletcher et al., 2002	Australia	57-88	40-72	12-67	NR

Table 5b: Swale pollutant effluent concentrations (in mg/L)

Study	Location	TSS	TN	TP	Zn
Stagge, 2006	Maryland, USA	11	3.6	0.35	0.093

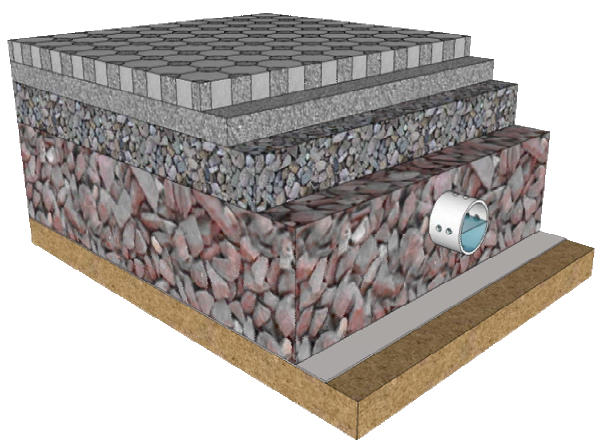

Fig. 8: Schematic cross section of Permeable Interlocking Concrete Pavers (PICP) type permeable pavement

nearly 100% of the rain that falls upon it. Examples of two permeable pavement applications are shown in Figure 9.

For runoff that passes through the pavement, many pollutants can be trapped inside the pavement or removed as the water passes out the pavement into the surrounding soil. Permeable pavement employs a few different removal mechanisms, namely filtration and chemical sorption. Little internal denitrification can occur in permeable pavement because these systems are not intended to be anaerobic. Tables 6a and 6b summarize permeable pavement pollutant removal and effluent concentrations.

Table 6a: Permeable pavement pollutant removal efficiencies (in %)

Study	Location	Type	TSS	TP	TN	Zn
Bean et al., 2007	Goldsboro, NC	PICP	33%	63%	42%	88%
Brattebo and Booth, 2003	Renton, Wash.	various	NR	NR	NR	39-69%
Collins et al., 2010	Kinston, NC	various	10-26%	NR	(36)-25%	NR

Table 6b: Permeable pavement effluent concentrations (in mg/L)

Study	Location	Type	TSS	TP	TN	Zn
Bean et al., 2007	Goldsboro, NC	PICP	8	0.05	0.77	0.008
Brattebo and Booth, 2003	Renton, Wash.	various	NR	NR	NR	0.007 – 0.013
Collins et al., 2010	Kinston, NC	various	13-15	NR	0.95-1.73	NR

Fig. 9: Pervious concrete used in Nashville, NC, (left) and pervious asphalt found in Raleigh, NC, (right) are two types of permeable pavement

Fig. 10: A turf covered green roof in Alaska is very attractive (left). A similar green roof in North Carolina would require irrigation. A succulent (sedum) vegetated green roof is shown in Kinston (right)

2.7 Green Roofs

In certain parts of the world, such as Germany and Northern Europe, green roof use is quite common, but widespread application of this technology in the USA is lacking. Green roofs essentially replace the "hardscape" of traditional roofs and can detain rainfall and later allow it to evapotranspire. Green roofs employ specialized media that partially captures water, is lightweight, stable, and supports vegetation. In variably moist, or typically dry climates, most vegetative cover are succulents. Examples of green roofs are found in Figure10.

Green roofs usually do not treat surrounding watersheds. Pollutant concentrations leaving green roofs tend to be somewhat elevated because the green roof media, like certain types of bioretention media, can leach nutrients. Research on optimal media design is ongoing. The green roof's primary stormwater benefit is runoff volume reduction. Tables 7a and 7b summarize green roof performance for North American studies.

2.8 Cisterns / Water Harvesting

Cisterns and water harvesting systems are old technologies that have found a re-birth with modern stormwater management. The systems capture rainfall (usually from rooftops) and temporarily store it for later use. Cisterns can be either above or below ground. Intended uses for cistern-stored water include irrigation, washing vehicles, toilet flushing, and laundry. A major challenge of cistern/ water harvesting systems is to fully utilize the captured water.

Cisterns can be either above or below ground (Figure 11). Underground cisterns can be quite expensive. A cistern is sized to optimize water demand met, the frequency of a dry cistern, the amount of water (and nutrients) captured, and cost

Table 7a: Green Roof pollutant removal efficiencies (in %)

Study	Location	TSS	TN	TP	Zn
USEPA, 2009	Pennsylvania	NR	NR	-720	-225
Hathaway et al. 2008	Goldsboro, NC	NR	-30	-460*	NR

* Media high in compost accounted for poor nutrient capture

Table 7b: Green Roof pollutant effluent concentrations (in mg/L)

Study	Location	TSS	TN	TP	Zn
USEPA, 2009	Pennsylvania	NR	NR	0.41	0.013
Hathaway et al., 2008	Goldsboro, NC	NR	3.91	1.03	NR

Fig. 11: Above ground (left) and below ground (right) cisterns installed in Santa Fe, New Mexico, and Fayetteville, NC, respectively

(payback period). Various solutions might capture the majority of runoff, but be quite costly. In other cases, it is important for the cistern to rarely go dry, so an otherwise over-sized cistern might be most appropriate. Cistern water is most easily used for non-potable (non-drinkable) purposes; however, with special treatment, harvested rainwater can even be consumed.

Water harvesting system pollutant removal mechanisms include sedimentation within the cistern proper, and if captured water is disposed upon a landscape, infiltration and filtration associated with flowing through soil. If cistern water is used for internal purposes, such as toilet flushing, water is then treated by a waste water system. To date there have been no water harvesting pollutant removal studies reported in literature.

3. SWAT CONSIDERATIONS

Several key points presented here can be made regarding the incorporation of urban stormwater BMPs into SWAT:

- Current efforts to develop urban BMP simulation capabilities in SWAT are focused primarily on mechanistic approaches that build on already existing filter strip (White and Arnold, 2009), impoundment, and other algorithms, such as those described in the following section. However, the previously described pollutant removal efficiencies (or alternatively BMP effluent concentrations) could be used in the model to initially represent the effects of some urban BMPs, while further research is conducted to obtain the level of understanding needed to ultimately simulate the practices in a more mechanistic fashion. Regardless of approach, it is clear that the pollutant removal efficiencies will be key data needed to test the robustness of such urban BMP routines in SWAT.
- Many urban stormwater practices treat relatively small watersheds. Small hydrologic response units (HRUs) will be needed to adequately simulate these in SWAT.
- The data requirements for representing both the size and shape of urban BMPs may be substantial. Extensive testing of future enhanced urban SWAT components will be needed to ensure these algorithms are realistically replicating urban BMP impacts.
- Many designers choose to use BMPs in series. SWAT algorithms will need to be modified to be able to simulate these types of systems.
- Modifications will also be required of existing impoundment structure routines in SWAT, to more accurately simulate the dynamics of small urban impoundment BMPs.
- Infiltration and evapotranspiration are very important goals of Low Impact Development (LID) and therefore impact design features and selection of certain urban BMPs. Modeling of BMPs must account for both of these characteristics and not simply be flow-through modules.
- Model developers should consider a modeling time step that is sub-hourly to hourly to realistically capture the flow and pollutant attenuation mechanisms of most urban BMPs. Small-sized BMPs that serve highly impervious catchments, such as LID applications, are sensitive to short duration rainfall intensities. If sub-daily weather data are not available, allocating daily precipitation to a limited number of hours (say 2-4) may be an acceptable alternative. However, daily precipitation may be acceptable for some larger scale urban applications that have less time sensitive processes.

Some additional recommendations are also listed here regarding potential simulation of some specific urban BMPs in SWAT:

- At present, a pond must be configured at the subbasin level and the portion of the subbasin that flows into the pond has to be defined. However, urban stormwater BMPs should be simulated at the HRU level, if represented as ponds in SWAT. In addition, smaller HRU sizes will be required (as noted above) because most of the stormwater BMPs are typically designed to serve small areas.
- A reservoir can currently only be sited on a main channel in the model, which drains all of the subbasins upstream of its location. This constraint would need to be removed for applications where reservoirs are used to mimic stormwater BMPs, so that drainage from only a single subbasin or selected subbasins to the BMP could be simulated.
- An “infiltrating function” would need to be inserted in SWAT, if a stormwater wetland were to be designated as an infiltrating wetland.
- SWAT modelers may choose to view permeable pavement and green roofs as a surface rather than as a BMP, essentially assigning these systems runoff coefficients such as a landscape feature (lawn or forest). Bean et al. (2007) calculated curve numbers for several different permeable pavements and found them to range from the mid-

40's to 89. The wide range of values was attributed to the design and underlying soils of the individual pavements tested. Research has indicated that green roofs are characterized by curve numbers ranging from the low to mid-80's (Hathaway et al. 2008). Both of these surfaces have curve numbers substantially lower than the values of 98 used for typical parking lot and roof tops (USDA, 1986).

- Modeling water harvesting systems may be difficult, due to the requirements for long-term precipitation and reliable and demonstrated demand data. Output from a rainwater harvesting system model could be used as input for SWAT. A few publically-available models can be accessed for this purpose (Jones and Hunt, 2009c; Coombes and Barry, 2007). One possible simulation option would be to estimate a pollutant load reduction by calculating the volume of, or a fraction of total, runoff captured in the cistern over a multi-year period.

Finally, a users' manual describing how urban and other BMPs can currently be simulated in SWAT and/or the Agricultural Policy Environmental eXtender (APEX) model is being developed and should be available for on-line distribution in late 2009 (Waidler et al., 2009).

4. ONGOING EFFORTS FOR DEVELOPMENT OF URBAN MODELING TOOLS IN SWAT

Texas AgriLife Research Scientists are currently developing selected SWAT stormwater BMP algorithms, in collaboration with City of Austin, Texas, for simulation of detention basins, wet ponds, sedimentation filtration ponds, and retention irrigation. As previously discussed, modeling stormwater BMPs often requires sub-hourly simulation time steps to realistically capture the flow and pollutant attenuation processes carried out by BMPs. However, current SWAT versions have a limited capability of sub-daily simulation; only hourly flow routing is available. Therefore, sub-hourly simulation capabilities are being developed in SWAT as a part of this study for flow, sediment routing and stormwater BMPs.

The SWAT model has been modified to simulate flow at any time step (as small as one minute). The Green and Ampt method is used for computation of infiltration and surface runoff at any time step. However, ET and soil water routing are carried out at a daily time step only. Base flow, lateral flow and tile drainage (if any) are calculated at daily time steps and distributed equally for each modeling time step within a day. Flow routing is done at any time step using Muskingum or variable storage channel routing technique. Changes were also made in the model to lag flow and pollutants realistically at the HRU level based on time of concentration. A sensitivity analysis based on Latin Hypercube Sampling-One At a Time (LHS-OAT) approach is used to identify the sensitive parameters affecting flow from a list of commonly used parameters in flow calibration. An automated procedure is developed to carry out flow calibration using sensitive parameters. The developed sub-hourly flow modeling approach is tested in an urbanizing watershed (Lost Creek Golf Course (LGA) watershed, one of the sub-watersheds of Austin, TX) and a rural watershed (Riesel, TX). The preliminary flow results after a calibration look very reasonable (in terms of model performance evaluation measures and visual comparison with observations, Figure 12) and encourage the application of SWAT model to urban watersheds.

Sub-hourly soil erosion and sediment yield model development is complete. Splash erosion is calculated based on the kinetic energy delivered by rain drops adapted from EUROSEM model (Morgan et al., 1998), and rill/inter-rill erosion is estimated using a physically based approach adapted from ANSWERS model (Dillaha et al. 1998). Three models are available for sediment routing (Brownlie, Yang, and Bagnolds). The modified SWAT model with newly added routines is expected to yield good results for urban watersheds not only for individual storm events but also for long-term simulation periods (Figure 13). Presently the testing of soil erosion and sediment yield routines are going on. In the near future, algorithms will be developed within SWAT to model stormwater BMPs with due consideration to the key points discussed in this paper. For this project, most of the stormwater BMPs will be modeled as ponds or reservoirs with simple modifications to mimic the physical processes occurring in BMPs.

5. CONCLUSIONS

Many stormwater BMPs are used throughout the USA, including wet detention ponds, stormwater wetlands, bioretention, level spreader – vegetated filter strips, swales, permeable pavement, green roofs and water harvesting systems. Exactly which BMP is selected is based upon several factors such as watershed size, relative water table elevations, and pollutant to be removed. BMPs are evaluated using several different metrics that can be useful model

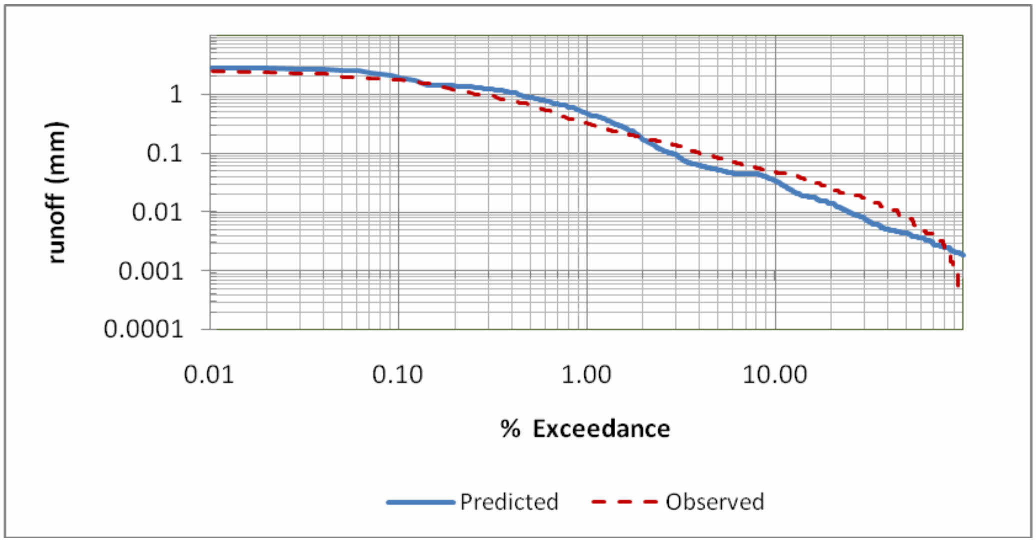

Fig. 12: Stream flow at 15-min time step for LGA watershed

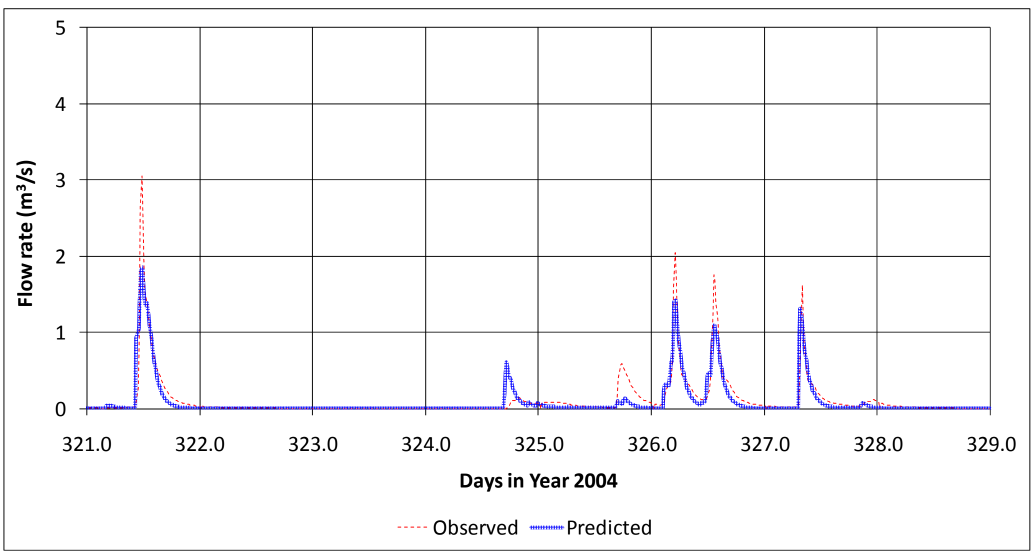

Fig. 13: Stream flow at 15-min time step for Riesel watershed

inputs, including percent removal efficiencies or effluent concentrations. Watershed models such as SWAT are beginning to incorporate urban stormwater BMPs to predict watershed hydrology and pollutant loadings. The testing of SWAT in Austin, Texas, USA, is underway, and preliminary indications are that SWAT is an accurate predictor of hydrology in urban catchments that employ stormwater BMPs.

REFERENCES

1. Arabi, M., J. Frankenberger, B. Engel, and J.Arnold. (2008). Representation of agricultural management practices with SWAT. Hydrological Processes, 22(16), 3042-3055.
2. Arnold, J.G., P.M. Allen, D.S. Morgan. (2001). Hydrological model for design and constructed wetlands. Wetlands, 21(2): 167-178.
3. Backstrom, M. (2003). Grassed swales for stormwater pollution control during rain and

snowmelt. Water Science and Technology, 48(9), 123-134.
4. Barrett, M. E. (2003). Performance, Cost, and Maintenance Requirements of Austin Sand Filters. Journal of Water Resources Planning and Management. 129(3):234-242.
5. Bavor, H. J., C. M. Davies, and K. Sakadevan. (2001). Stormwater treatment: do constructed wetlands yield improved pollutant management performance over a detention pond system? Water Science and Technology, 44(11-12), 565-570.
6. Bean, E.Z., Hunt, W.F., and Bidelspach, D.A. (2007). Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts. Journal of Irrigation and Drainage Engineering, 133 (6): 583-592.
7. Brattebo, B. O. and D. B. Booth (2003). Long-term stormwater quantity and quality performance of permeable pavement systems. Water Research 37(18): 4369-4376.
8. Collins, K. A., Hunt, W. F., and Hathaway, J. M. (2008). Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina. Journal of Hydrologic Engineering, 13 (12): 1146-1157.
9. Collins, K.A., W.F. Hunt, J.M. Hathaway. (2010). Side-by-Side Comparison of Nitrogen Species Removal for Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina. Journal of Hydrologic Engineering (in press)
10. Comings, K.J., D.B. Booth, and R.R. Horner. (2000). Stormwater Pollutant Removal by Two Wet Ponds in Bellevue, Washington. Journal of Environmental Engineering, 126(4), 321-330.
11. Coombes, P. J. and Barry, M. E. (2007). The effect of selection of time steps and average assumptions on the continuous simulation of rainwater harvesting strategies. Water Science and Technology, 55(4): 125-133.
12. Davis, A. P. (2007). Field Performance of Bioretention: Water Quality, Environ. Eng. Sci., 24(8) 1048-1063, (2007).
13. Davis, A. P., W. F. Hunt, R. G. Traver, and M.E. Clar. (2009). Bioretention technology: an overview of current practice and future needs. Journal of Environmental Engineering 135(3), 109-117.
14. Deletic, A. and T. D. Fletcher. (2006). Performance of grass filters used for stormwater treatment – a field and modeling study. Journal of Hydrology, 137(3-4), 261-275
15. Dietz, M. E., and J. C. Clausen (2006). Saturation to Improve Pollutant Retention in a Rain Garden Flow. Environ. Sci. Technol., 40, 1335-1340.
16. Dillaha, T. A., M. L. Wolfe, A. Shirmohammadi, F.W. Byne, 1998. ANSWERS 2000. Presented at the ASAE annual meeting, July 12-16, 1998, Orlando, FL. Paper No. 98-2199. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659.
17. Fletcher, T.D., L. Peljo, J, Fielding, T.H.F. Wong, T. Weber. (2002). The performance of vegetated swales for urban stormwater pollution control. Proceedings of the 9th International Conference on Urban Drainage (eds. W. Huber and E. Strecker). American Society of Civil Engineers.
18. Gassman, P.W., M.R. Reyes, C.H. Green, and J.G. Arnold. (2007). The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. Transactions of the ASABE, 50(4), 1211-1250.
19. Hathaway, A.M, W.F. Hunt, and G.D. Jennings. (2008). A Field Study of Green Roof Hydrologic and Water Quality Performance. Transactions of the ASABE, 51(1), 37-43.
20. Hathaway, J.M., W.F. Hunt, J.T. Smith, and A.M. Johnson. (2007a). City of Charlotte, NC, Monitoring Report: Shade Valley Wet Pond. City of Charlotte, NC. 27p.
21. Hathaway, J.M., W.F. Hunt, J.T. Smith, and A.M. Johnson. (2007b). City of Charlotte, NC, Monitoring Report: Pierson Pond. City of Charlotte, NC. 26p.
22. Hathaway, J.M. and W.F. Hunt. (2008). Field evaluation of level spreaders in the Piedmont of North Carolina. Journal of Irrigation and Drainage Engineering, 134(4): 538-542.
23. Hunt, W.F. and W. G. Lord (2006). Bioretention performance, design, construction, and maintenance. North Carolina Cooperative Extension, Raleigh, NC. 8 p.
24. Hunt, W. F., Jarrett, A. R., Smith, J. T. and L. J. Sharkey (2006). Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. Journal of Irrigation and Drainage Engineering. 132(6):600-608.
25. Hunt, W. F., Burchell, M. R., Wright, J. D., and Bass, K. L. (2007). Stormwater Wetland Design Update: Zones, Vegetation, Soils and Outlet Guidance. North Carolina Cooperative Extension, Raleigh, NC.
26. Hunt, W. F., Smith, J. T., Jadlocki, S. J., Hathaway, J.M., and Eubanks, P.R. (2008). Pollutant removal and peak flow mitigation by a

bioretention cell in urban Charlotte, NC. Journal of Environmental Engineering. 134(5): 403-408.
27. Hunt, W. F., J. M. Hathaway, R. J. Winston and S.J. Jadlocki. (2010). Runoff volume reduction by a level spreader- vegetated filter strip system in suburban Charlotte, NC. Journal of Hydrologic Engineering (in press).
28. Johnson, J. L. (2006). Evaluation of Stormwater and Wet Pond Forebay Design and Stormwater Wetland Pollutant Removal Efficiency. M.S. Thesis, North Carolina State University, Raleigh, NC.
29. Jones, J.E., Clary, J., Strecker, E., Quigley, M.M. (2009). 15 reasons you should think twice before using percent removal to assess BMP performance. The Journal for Surface Water Quality Professionals: Stormwater. January - February2008, (1/16/2009), undefined (accessed 1/16/2009).
30. Jones, M. P. and Hunt, W. F. (2009a). Effect of Stormwater Wetlands and Wet Ponds on Runoff Temperature in Trout Sensitive Waters. Journal of Irrigation and Drainage Engineering. (submitted)
31. Jones, M. P. and Hunt, W. F. (2009b). The effect of bioretention on runoff temperature in trout sensitive waters. Journal of Environmental Engineering, 135(8): 577-585.
32. Jones, M. P. and W. F. Hunt. (2009c). Performance of Rainwater Harvesting Systems in the Southeastern United States. Resources, Conservation, and Recycling. (in Press).
33. Kieser, M. S., Spoelstra, J. A., Feng, A., James, W., and Li, Y. (2004). Stormwater Thermal Enrichment in Urban Watersheds. IWA Publishing, London, UK.
34. Kim, H., Seagren, E. A., and Davis, A. P. (2003). Engineered Bioretention for Removal of Nitrate from Stormwater Runoff. Water Environ. Res., 75(4), 355-367.
35. Lenhart, H. A. and Hunt, W. F. (2009). Evaluating Four Stormwater Performance Metrics with a North Carolina Coastal Plain Stormwater Wetland. Journal of Environmental Engineering. (submitted)
36. Line, D. E and W. F. Hunt. (2009). Performance of a bioretention area and a level spreader-grass filter strip at two highway sites in North Carolina. Journal of Irrigation and Drainage Engineering, 135(2), 217-224.
37. Line, D. E., Jennings, G. D., Shaffer, M. B., Calabria, J., and Hunt, W. F. (2008). Evaluating the Effectiveness of Two Stormwater Wetlands in North Carolina. Transactions of the ASABE, 51(2): 521-528.
38. Mallin, M.A., S.H. Ensign, T.L. Wheeler, and D.B. Mayes. (2002). Pollutant Removal Efficacy of Three Wet Detention Ponds. Journal of Environmental Quality, 31(2), 654-660.
39. Morgan, R. P. C., Quinton, J. N., Smith, R. E., Govers, G., Poesen, J. W. A., Auerswald, K., Chisci, G., Torri, D. and Styczen, M.E. (1998). The European Soil Erosion Model (EUROSEM): A dynamic approach for predicting sediment transport from fields and small catchments. Earth Surface Processes and Landforms, 23: 527-544.
40. Munoz-Carpena, R., and J. E. Parsons. (2004). A design procedure for vegetated filter strips using VFSMOD-W. Transactions of the ASAE, 47(6), 1933-1941.
41. North Carolina Department of Environment and Natural Resources (NCDENR), Division of Water Quality. (2007). Stormwater Best Management Practices Manual. Raleigh, N.C.
42. Prochnow, S. J., J. D. White, T. Scott, and C. Filstrup. (2007). Small reservoir impact on simulated watershed-scale nutrient yield. Research Letters in Ecology. Article ID:12571.4p.
43. Schueler, T.R. (1996). Irreducible pollutant concentrations discharged from stormwater practices. Technical Note 75. Watershed Protection Techniques. 2:369-372.
44. Scholes, L. N. L., R. B. E. Shutes, D. M. Revitt, D. Purchase, and M. Forshaw. (1999). The removal of urban pollutants by constructed wetlands during wet weather. Water Science and Technology, 40(3), 333-340.
45. Stagge, J. H. (2006). Field evaluation of hydrologic and water quality benefits of grass swales for managing highway runoff. M.S. Thesis. University of Maryland-College Park, College Park, MD.
46. Strecker, E. W., Quigley, M. M., Urbonas, B. R., Jones, J. E., and Clary, J. K. (2001). Determining Urban Storm Water BMP Effectiveness. Journal of Water Resources Planning and Management, 127(3), 144-149.
47. University of New Hampshire Stormwater Center (UNHSC). (2006). 2005 Data Report, CICEET, Durham, NH. 16 p.
48. United States Department of Agriculture (USDA). (1986). Urban Hydrology for Small Watersheds. Soil Conservation Service, Technical Release No. 55. Washington, DC.
49. United States Environmental Protection Agency (USEPA). (2009). Green Roofs for Stormwater

Runoff Control. EPA/600/R-09/026. Office of Research and Development. 81 p.
50. Urbonas, B. R. (1999). Design of a sand filter for stormwater quality enhancement. Water Environment Research, 71(1): 102-113.
51. Van Buren, M. A., Watt, W. E., Marsalek, J., and Anderson, B. C. (2000). Thermal Balance of an On-Stream Storm-Water Management Pond. Journal of Environmental Engineering, 126(6), 509-517.
52. Waidler D., M. White, E. Steglich, W. Wang, J. Williams J., C.A. Jones., and R. Srinivasan. 2009. Conservation Practice Modeling Guide for SWAT and APEX. AgriLIFE Research & Extension, Texas A&M System, Urban Solutions Center, Dallas, TX (forthcoming).
53. White, M. J. and J. G. Arnold. (2009). Development of a simplistic vegetative filter strip model for sediment and nutrient retention at the field scale. Hydrological Processes. 12: 1602-1616.
54. Williams, J. R., J. G. Arnold, J. R. Kiniry, P. W. Gassman, and C. H. Green. (2008). History of model development at Temple, Texas. Hydrol. Sci. J. 53(3): 948-960.
55. Winston, R. J. (2009). Field Evaluation of Level Spreader – Vegetated Filter Strip Systems for Improvement of Urban Hydrology and Water Quality. M.S. Thesis. North Carolina State University, Raleigh, NC.
56. Yu, S. L., M. A. Kasnick and M. R. Byrne. (1993). A level spreader/vegetated buffer strip system for urban stormwater management. Integrated Stormwater Management, R. Field, M. L. O'Shea, and K. K. Chin, eds., Lewis Publishers, Boca Raton, FL. pp. 93-103.

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CONTENTS

Vol. 18, Nos. 1-2, 2009

Research Papers:

Hydrologic Evaluation of the Lower Mekong River Basin with the Soil and Water Assessment Tool Model – C. G. Rossi, R. Srinivasan, K. Jirayoot, T. Le Duc, P. Souvannabouth, N. Binh, and P. W. Gassman 1

Predicting the Effects of Land Use Change on Runoff and Sediment Yield in Manupali River Subwatersheds Using the SWAT Model – N. R. Alibuyog, V. B. Ella, M. R. Reyes, R. Srinivasan, C. Heatwole and T. Dillaha 15

Sensitivity analyses of hydrologic and suspended sediment discharge in the Abashiri River Basin, Hokkaido Region, Japan – H. Somura, I. Takeda and Y. Mori 27

Optimal Placement of Conservation Practices using Genetic Algorithm with SWAT – M. Jha, S. Rabotyagov and P. W. Gassman 41

ALMANAC: a potential tool for simulating agroforestry yields and improving SWAT simulations of agroforestry watersheds – Mari-Vaughn V. Johnson, J. D. MacDonald, J. R. Kiniry, and J. Arnold 51

ArcAPEX: ArcGIS Interface for Agricultural Policy Environmental eXtender (APEX) Hydrology/Water Quality Model – P. Tuppad, M. F. Winchell, X. Wang, R. Srinivasan and J. R. Williams.. 59

Stormwater Best Management Practices: Review of Current Practices and Potential Incorporation in SWAT – W. F. Hunt, N. Kannan, J. Jeong and P. W. Gassman 73

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Aims and Scope: The aim of this journal is to communicate advances in Agricultural Engineering, with particular reference to Asia, to practicing professionals in the field. The scope will include soil and water engineering, farm machinery, farm structures, post-harvest technology, biotechnology food processing and emerging technologies. Subjects of general interest to agricultural engineers such as ergonomics, energy, systems engineering, precision agriculture, protected cultivation, terramechanics, instrumentation, environment in agriculture and new materials are also included.

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Message from the Guest Editor and Chief Editor on this Special Issue

Printing a special issue on an emerging topic of science and technology, once in three to four years, is a good activity for an international journal to advance and promote science within professional societies. This special issue is a result of an International Conference on “SWAT Southeast Asia (SWAT-SEA) Modeling” held in Chiang Mai, Thailand on January 5-7, 2009*, which was jointly led by Dr. Attachai Jintrawet of Chiang Mai University in Thailand and Dr. Manuel Reyes of North Carolina A&T University in the U.S.A. This conference served as a catalyst for the idea of publishing a special issue of this journal. Therefore, we are extremely pleased to present Part 1 of the Special Issue of the International Agricultural Engineering Journal (IAEJ), which features seven papers that describe key Soil and Water Assessment Tool (SWAT) model development with the incorporation of most recent improvements in modeling processes and its application in solving water quality problems in several countries in Asia and the western hemisphere. Each of these peer-reviewed papers is a high quality paper and could have been published by other international journals but we are very pleased that the authors decided to publish these papers in this leading agricultural engineering journal in Asia.

SWAT is a watershed-scale water quality model that was released in the early 1990s and represents over 30 years of U.S. Department of Agriculture (USDA) model development at the Grassland, Soil, and Water Research Laboratory (GSWRL) in Temple, Texas (Arnold and Forher, 2005; Williams et al., 2008). Gassman et al. (2007) chronicle the explosive growth of worldwide applications of SWAT, which has proven to be an effective tool for assessing hydrologic and water quality problems for a wide range of watershed and environmental conditions. The global growth of SWAT conferences and workshops and ever-increasing body of literature further attests to the effectiveness of the model, as discussed in other special journal issues (Arnold and Forher, 2005; Krysanova and Arnold, 2008; Kronvang et al., 2009) and conference proceedings and compilations of peer-reviewed literature citations accessible at the SWAT website (SWAT, 2009).

The seven papers contained in Part 1 include four papers that describe applications of the model in southeast Asia and other regions, one paper that describes a new simulation interface tool, and two papers that explore emerging frontiers of SWAT applications. The papers presented here include studies that were originally presented at SWAT-SEA in Chiang Mai and additional papers that complement the theme of the special issue. More SWAT-related papers will be featured in continuation of the Special Issue in one or more forthcoming IAEJ issues.

The first article, authored by Rossi et al., describes a hydrologic application of SWAT for the Lower Mekong River Basin (LMRB), a huge system that covers over 660,000 km^2 in portions of Myanmar, Cambodia, Thailand, Vietnam, and Laos. Comparisons of predicted versus measured streamflows are reported for several dozen gauge sites in the study, which represents one of the most extensive SWAT hydrologic verification efforts reported to date in the SWAT literature. Alibuyog et al. describe next an application of SWAT for a small 2 km^2 watershed on the Island of Mindanao in the Philippines, which to our knowledge is the first application of the model in that country reported in the peer-reviewed literature. They describe several land use scenarios with a calibrated SWAT model and conclude that the results indicate that SWAT can be a useful tool for assessing a variety of land use and related studies in the Philippines. Somura et al. present a SWAT climate change assessment in the third paper for the 1,100 km^2 Abashiri River watershed located in the Hokkaido region of Japan. They describe streamflow and sediment load calibration/validation results followed by the impacts of different

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climate sensitivity scenarios on both the predicted hydrology and the sediment loads. The final featured SWAT application paper is by Jha et al., who present both streamflow and pollutant calibration/validation results as well as the results of a conservation practice targeting scenario for the intensively cropped 9,400 km^2 Raccoon River watershed located in the state of Iowa, U.S. They describe the use of an evolutionary algorithm for the targeting scenario, which is a powerful technique that is being interfaced with SWAT and other water quality models for enhanced assessments of conservation practice and/or cropping system placements.

Johnson et al. follow these four SWAT application papers with a conceptual study that presents possibilities of expanding the SWAT plant growth algorithms for application to complex Southeast Asia and other agroforestry systems. They describe how plant competition algorithms are currently being ported from the (Agricultural Land Management Alternatives with Numerical Assessment Criteria) ALMANAC model (Williams et al., 2008) to SWAT, and what types of data and other improvements are needed in order to realistically simulate the complex interactions that occur in agroforestry systems, such as competition between tree and vegetable crops. Tuppad et al. then present a new ArcGIS-based simulation interface called ArcAPEX in the sixth paper that supports stand-alone simulation applications of the Agricultural Policy EXtender (APEX) water quality model (Williams et al., 2008) and also integrated applications with SWAT. The APEX model provides options for refined management and cropping system applications including plant competition based on the ALMANAC algorithms. An example application of the interface for an APEX conservation practice assessment is presented for a 104 km^2 watershed in Texas, U.S. Finally, Hunt et al. present an array of urban stormwater best management practices (BMPs) and discuss issues and options of developing SWAT algorithms to effectively simulate those BMPs. A brief description of an ongoing SWAT study is also presented for the city of Austin, Texas, U.S., that primarily discusses developments regarding inserting routines in SWAT that can effectively capture small urban watershed processes using a sub-hourly time step.

We appreciate your interest in this Special Issue and trust that you will come away better informed about the usefulness of the SWAT model and water quality modeling and related issues in general. We also look forward to featuring additional articles in the next issue of IAEJ, both in the context of this Special Issue and in other future issues.

Sincerely,

Dr. Philip W. Gassman
Guest Editor, Special Issue IAEJ

Sincerely,

Dr. Rameshwar S. Kanwar
Chief Editor, IAEJ

References

Arnold, J.G. and N. Fohrer. 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modeling. Hydrol. Process. 19(3): 563-572.

Gassman, P.W., M. Reyes, C.H. Green, and J.G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future directions. Trans. ASABE 50(4): 1211-1250.

Kronvang, B., S.A.Borgvang and L.J. Barkved. 2009. Towards European harmonised procedures for quantification of nutrient losses from diffuse sources-the EUROHARP project. J. Environ. Monitor. 11(3): 503-505. Doi: 10.1039/b902869m.

Krysanova, V. and J.G. Arnold. 2008. Advances in ecohydrological modelling with SWAT-a review. Hydrol. Sci. J. 53(5): 939-947.

SWAT. 2009. Soil and Water Assessment Tool: SWAT. Texas A&M Unversity System, College Station, TX. Available at: http://www.brc.tamus.edu/swat/.

Williams, J.R., J.G. Arnold, J.R. Kiniry, P.W. Gassman, and C.H. Green. 2008. History of model development at Temple, Texas. Hydrol. Sci. J. 53(5): 948-960.

International Agricultural Engineering Journal

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