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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.

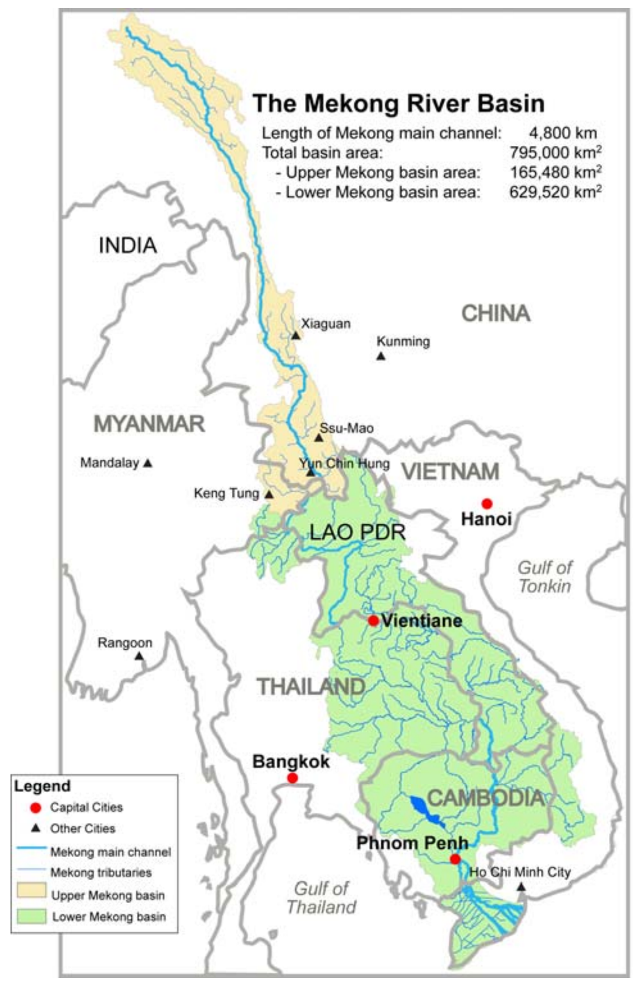

Fig. 1: The Mekong River Basin and its characteristics (MRC, 2009)

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

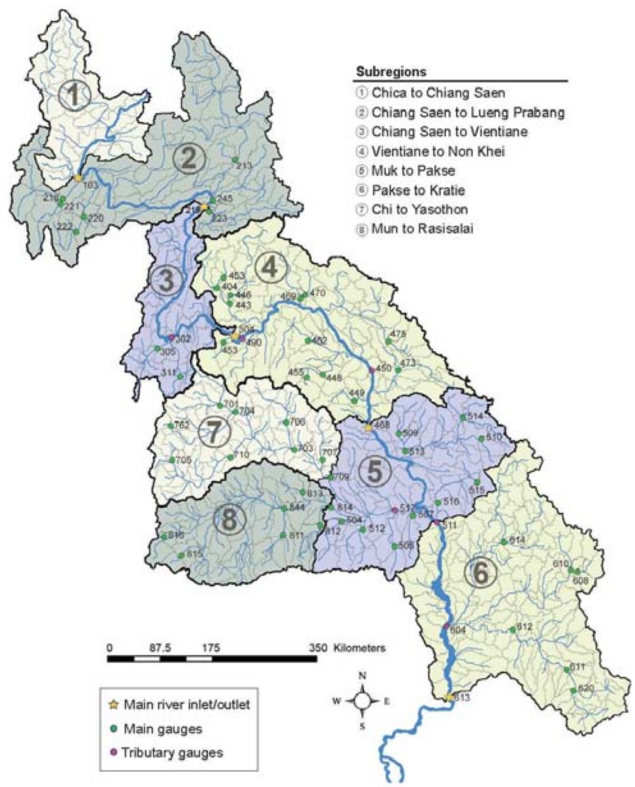

Fig. 2: Identification of the Lower Mekong River Basin subareas and gauges

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 $\geq$ 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.

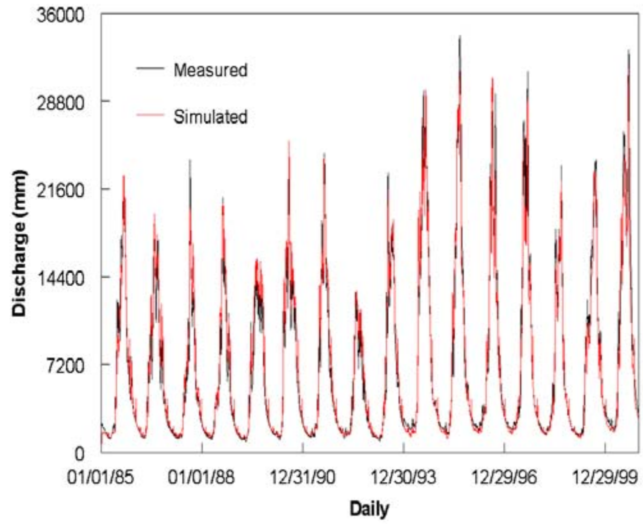

Fig. 3: Measured and simulated daily discharge for the MRB at the mainstream Gauge 450 from January 1985 through December 2000

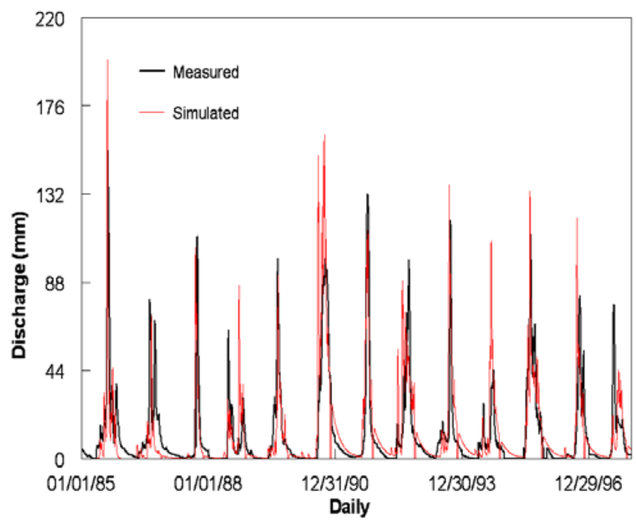

Fig. 4: Measured and simulated daily discharge for the MRB at Gauge 813, from January 1985 through December 1997, which is not directly linked to the Mekong River

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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