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2.6 Application of the SWAT Model to the Hii River Basin, Shimane Prefecture, Japan

H. Somura[1], D. Hoffman[2], J. Arnold[3], I. Takeda[1] and Y. Mori[1]

Abstract

Using a daily time step, we evaluated SWAT's discharge simulation of the Hii River basin from 1986 to 2005. The Hii River basin is in the eastern part of Shimane Prefecture, Japan. It covers an area of about 900 km^2 and the length of the river from the source to Ootsu river discharge observation station, the outlet of whole basin, is about 150 km. About 80% of the basin is forest and 10% is paddy fields. The parameters were calibrated from 1993 to 1996 and validated from 1986 to 1992 and from 1997 to 2005. The parameters were automatically calibrated and they were CANMX, ALPHA_BF, SOL_AWC, SOL_Z, CH_K2, SMFMX, GWQMN, CN2, ESCO and SLOPE. Both calibration and validation results represented fluctuations of discharge relatively well, although some peaks were overestimated by SWAT. During the calibration period, R^2 varied from 0.65 to 0.77 and NSI was from 0.64 to 0.76. During the validation period from 1986 to 1992, R^2 varied from 0.58 to 0.74 and NSI was from 0.53 to 0.74. Lastly, from 1997 to 2005, R^2 varied from 0.51 to 0.71 and NSI was from 0.38 to 0.68.

Keywords: Runoff analysis, watershed management, subbasin, lake, GIS

1. Introduction

Impact assessment of land use change, population growth/decrease and watershed development to water quantity and quality is one of the most important topics in a basin. Integrated management of water environment from river basin to downstream, such as lake, is also very important for conservation and sustainable use of its resources. In recent years, water quality in lakes has been tried to be improved by putting an adequate sewage system in place and through the development of laws and environmental standards to control pollutant loads to lake and rivers. However, water quality in lakes has not improved. One of the reasons is pollutant loading from nonpoint sources such as agricultural lands.

 Soil and Water Assessment Tool (SWAT): Global Applications, eds. Jeff Arnold, Raghavan Srinivasan, Susan Neitsch, Chris George, Karim Abbaspour, Philip Gassman, Fang Hua Hao, Ann van Griensven, Ashvin Gosain, Patrick Debels, Nam Won Kim, Hiroaki Somura, Victor Ella, Attachai Jintrawet, Manuel Reyes, and Samran Sombatpanit, pp. 211-221. This paper will be published in the Proceedings of the 4th International SWAT Conference, Delft, Netherlands, 2007. The paper is printed here with the permission of the 4th International SWAT Conference organizers. WASWC is grateful for the permission granted.

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There are lakes in Shimane Prefecture, Japan, such as Lake Shinji and Lake Nakaumi, whose water quality has not improved. The Lake Shinji and Lake Nakaumi area has been designated as one of the Wetlands of International Importance by the Ramsar Convention in November 2005.

Many researchers have studied water quality in Lake Shinji and Lake Nakaumi from several perspectives (e.g. Seike et al., 2006; Sakuno et al., 2003). Also, there are some studies done on Hii River (Takeda et al., 1996; Ishitobi et al., 1988). However, few studies have been done about runoff analysis and quantitative analysis of pollutant loads by a model in the Hii River basin. When considering watershed management and improvement of water environment in lakes, both information of lakes and rivers are necessary. Thus, we tried to represent stream flow in the Hii River basin as a first step in water environment management.

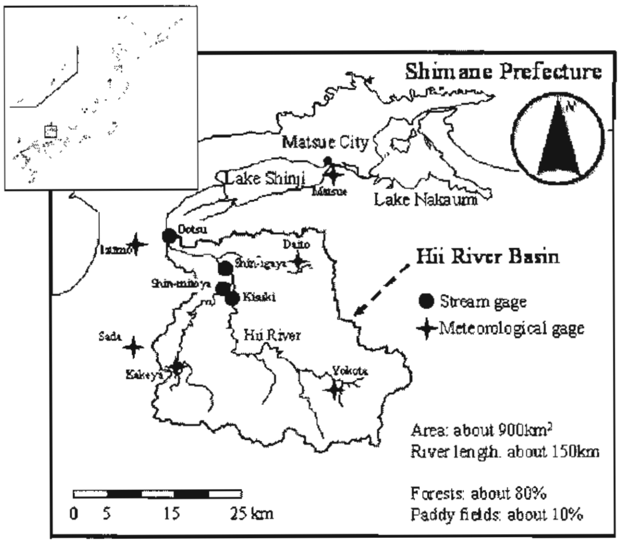

Figure 1. Location of Hii River Basin.

2. Study Area

The Hii River basin is located in the eastern part of Shimane Prefecture, Japan (Fig. 1). It covers an area of 914.4 km^2 and the length of the river from the source to the Ootsu river discharge observation station, which is the outlet of whole basin, is about 150 km. According to the Chugoku Regional Development Bureau in the Ministry of Land, Infrastructure and Transport Government of Japan (MLIT: http://www.cgr.mlit.go.jp/), yearly average discharge is about 40 m^3/s and the volume of total runoff is about 1,270 M m^3. About 80% of the land use in the basin is forest and 10% is paddy fields. As the Hii River dominates about 75% of watershed area flowing into the Lake Shinji, water quality and quantity of the river will considerably affect the lake.

3. Methodology

We tried to apply the SWAT model to this basin from 1986 to 2005 using daily time step. As a first step of application of the SWAT model to the basin, we paid attention to the discharge of the river. The Hii River basin was divided into four subbasins according to location of stream gages in the basin (Ootsu, Shin-igaya, Shin-mitoya and Kisuki). The parameters were calibrated from 1993 to 1996 and validated from 1986 to 1992 and from 1997 to 2005. The ten parameters selected by ranking based on sensitivity analysis were optimized automatically for all subbasins using daily discharge data as shown in Table 1.

Table 1. Range and optimal values of SWAT2003 calibration parameters.

Parameter name	Lower bound	Upper bound	Optimal value	Imet
CANMX: Maximum canopy storage (mmH_2O)	0.0	10.0	0.009	1
ALPHA_BF: Baseflow alpha factor (days)	0.0	1.0	0.75	1
SOL_AWC: Available water capacity of the soil layer (mmH_2O/mm soil)	-0.04	0.04	0.04	2
SOL_Z: Depth from soil surface to bottom of layer (mm)	-50.0	600	588.2	2
CH_K2: Effective hydraulic conductivity in main channel alluvium (mm/hr)	0.0	150.0	150.0	1
SMFMX: Melt factor for snow on June 21 (mmH_2O/°C-day)	2.0	8.0	2.09	1
GWQMN: Threshold depth of water in the shallow aquifer required for return flow to occur (mmH_2O)	0.0	5000.0	0.35	1
CN2: Initial SCS runoff curve number for moisture condition II	-8.0	8.0	-6.6	2
ESCO: Soil evaporation compensation factor	0.001	1.0	0.89	1
SLOPE: Average slope steepness (m/m)	0.0	0.6	0.0002	1

Note: Imet means variation methods available in auto calibration (1: Replacement of initial parameter by value, 2: adding value to initial parameter)

3.1 Brief description of SWAT model

The Soil and Water Assessment Tool (SWAT) has been widely applied for modeling watershed hydrology and simulating the movement of nonpoint source pollution. The SWAT is a physically-based continuous time hydrologic model with an ArcView GIS interface developed by the Blackland Research and Extension Center and the USDA-ARS (Arnold et al., 1998) to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex basins with varying soil type, land use and management conditions over long periods of time. The main driving force behind the SWAT is the hydrological component. The hydrological processes are divided into two phases, the land phase, which controls the amount of water, sediment and nutrient loading in receiving waters, and the water routing phase which simulates movement through the channel network. The SWAT considers both natural sources (e.g. mineralization of organic matter and N-fixation) and anthropogenic contributions (fertilizers, manures and point sources) as nutrient inputs. The SWAT delineates watersheds into subbasins interconnected by a stream network and each subbasin is divided further into hydrologic response units (HRUs) based upon unique soil / land class characteristics, without any specified location in the subbasin. Flow, sediment and nutrient loading from each HRU in a subbasin are summed and the resulting loads are then routed through channels, ponds, and reservoirs to the watershed outlet (Arnold et al., 2001). The model includes a number of storage databases (i.e. soils, land cover/ plant growth, tillage and fertilizer) which can be customized for an individual basin. A single growth model in SWAT is used for simulating all crops based on the simplification of the EPIC crop model (Williams et al., 1984). Phenological development of the crop is based on daily heat unit accumulation. The model can simulate up to 10 soil layers if sufficiently detailed information is available. The SWAT is expected to provide useful information across a range of timescales, i.e. hourly, daily, monthly and yearly timesteps (Neitsch et al., 2002).

3.2 Input data description

The SWAT requires meteorological data such as daily precipitation, maximum and minimum air temperature, wind speed, relative humidity and solar radiation data. Spatial data sets including a digital elevation map (DEM), land cover and soil maps are required. Since some gaps were present in the climate data, the weather generator included in SWAT was used, based on statistical values (average monthly values of rain, maximum and minimum temperatures, standard deviation, skew coefficient, probability of wet day following a dry day in the month, probability of wet day following a wet day, average number of rainy days in the month) and computed on the basis of available daily values.

Meteorological data was obtained from the Japan Meteorological Agency (JMA: http://www.jma.go.jp/jma/index.html). Measuring gages of precipitation, air temperature and wind speed were located in and around the basin. We chose five gages for precipitation and three gages for air temperature and wind speed. However, there is no gage monitoring relative humidity in the basin. So, relative humidity data observed in Matsue city, located about 30 km away from the basin, was used instead. Solar radiation was calculated with the Angstrom formula (FAO, 1998) by using the data measured by Shimane University (http:// www.ipc.shimane-u.ac.jp/weather/i/home.html) and actual sunshine duration in the basin obtained from the JMA because there was no monitoring gage of solar radiation in the basin. The average values of climatic data at each gage are shown in Table 2.

Table 2. Average annual precipitation and climatic variables from 1985 to 2005 at each gage.

Gage name	EL (m)	Annual Precip. (mm)	Max. Air temp. (deg. C)	Min. Air temp. (deg. C)	Wind speed (m/s)	Relative humidity (%)	Solar radiation (calculated) (MJ/m²)
Matsue	16.9	-	-	-	-	75.6 (10.0)	-
Izumo	20	1726	18.9 (8.3)	10.3 (8.1)	2.2 (1.2)	-	11.1 (7.5)
Daito	56	1778	-	-	-	-	-
Sada	100	2072	-	-	-	-	-
Kakeya	215	2046	18.0 (9.0)	8.8 (8.3)	1.3 (0.7)	-	-
Yokota	369	1765	17.2 (9.3)	7.5 (8.8)	1.2 (0.7)	-	-

Note: The values in the parenthesis indicate a standard deviation

Discharge data was prepared at four monitoring stations named Ootsu, Shin-igaya, Shin-mitoya and Kisuki in the basin. The data was furnished by the Izumo River Office in the MLIT.

DEM data was prepared with 50 m grid created from 1:25,000 topographic map of the Geographical Survey Institute.

Land use was categorized as paddy field, upland field, orchard, denuded land, forest, water and others. The land use data was obtained from the National-Land Information Office in the MLIT (http://nlftp.mlit.go.jp/). Each subbasin has almost similar land use. Forest area ranges from 59% to 87% and paddy fields area ranges from 9% to 18% spatially as shown in Table 3.

Table 3. Area and ratio of major land use in each subbasin.

Gage name	Subbasin No.	Drainage area	Subbasin			
			Area	Forests	Rice fields	Upland Fields and Orchard
		(Km²)	(Km²)	(%)	(%)	(%)
Ootsu	Sub 1	914.4	183.9	74	16	3
Shin-igaya	Sub 2	730.5	14.1	59	18	5
Shin-mitoya	Sub 3	206.8	206.8	86	9	3
Kisuki	Sub 4	509.6	509.6	87	10	2

Soil data was taken from Fundamental Land Classification Survey, a GIS soil map with a scale of 1:500,000 prepared by the MLIT (http://tochi.mlit.go.jp/tockok/index.htm) (Fig. 2). Soil type was categorized into 10 groups of 14 soils such as Dystric Rhegosols, Fluvic Gleysols, Gleysols, Haplic Andosols, Helvic Acrisols, Humic Cambisols, Lithosols, Ochric Cambisols, Rhodic Acrisols and Vitric Andosols. Internal data of each soil such as the number of layers, soil depth and physicochemical properties was prepared based on soil profile in soil map and the data colleted up by Hirai (1995).

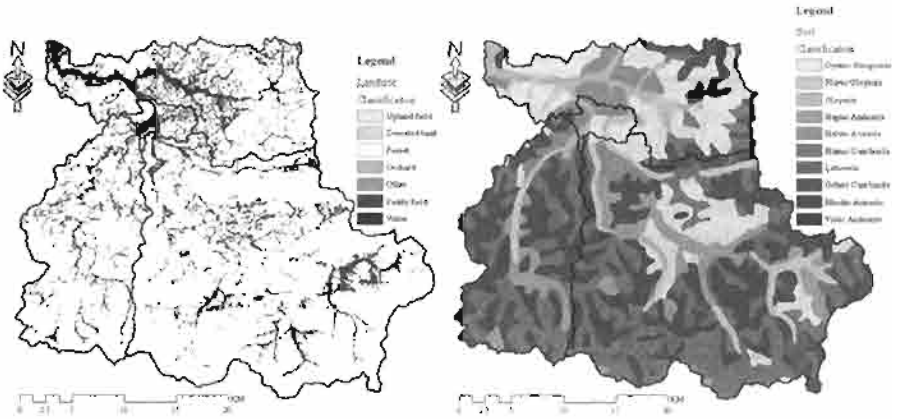

Figure 2. Land use and soil classification GIS data.

3.3 Model performance evaluation

The SWAT model was calibrated and validated using observed discharge data. The coefficient of determination (R^2) and Nash-Sutcliffe Index (NSI) were used to evaluate the model performance. The R^2 value is an indicator of strength of relationship between the observed and simulated values. The NSI value indicates how well the plot of the observed versus the simulated values fits the 1:1 line. The ranges of NSI value is between ∞ and one. If the R^2 and NSI values are less than or very close to zero, the model performance is considered unacceptable or poor. If the values are equal to one, then the model prediction is considered to be perfect.

$$NSI = 1.0 - \left(\frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{cal,i})^2}{\sum_{i=1}^{n} (Q_{obs,i} - \overline{Q}_{obs})^2} \right)$$

(Nash-Sutcliffe Index)

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

4. Results and Discussion

The model was applied to the Hii River basin, which has a low density of stream flow and climatic gages. The simulated and observed statistics for calibration and validation are shown in Table 4. The calibration procedures formulated consist of finding the most appropriate parameters for hydrologic routing model component. In this stage, the best fit was achieved with R^2 of 0.65 at subbasin 1, 0.75 at subbasin 2, 0.77 at subbasin 3, and 0.69 at subbasin 4. The best fit was done with

NSI of 0.64 at subbasin 1, 0.74 at subbasin 2, 0.76 at subbasin 3, and 0.67 at subbasin 4 for daily discharge. During the validation period (1986-1992), R^2 varied from 0.58 to 0.74 and NSI did from 0.53 to 0.74. From 1997 to 2005, R^2 varied from 0.51 to 0.71 and NSI did from 0.38 to 0.68. During the whole simulation period, subbasin 3, which is an independent subbasin, showed a relatively high reproducibility among the subbasins. Similarly, subbasins 2 and 4 also gave satisfactory simulation results except during the latter validation period (1997-2005) particularly for subbasin 4.

Simulated and observed discharge on a daily time step is shown in Figure 3. The gray line is observed flow and dotted black line is simulated flow. It is apparent that both results of calibration and validation at each subbasin captured the fluctuations of discharge relatively well, although some peaks were overestimated. This is particularly true on the 20th of October 2004, when the basin was struck by a big typhoon No. 23 and the observed precipitation was about 150 mm as observed at Yokota rain gage (a total of about 200 mm for 2 days), 120 mm at Kakeya rain gage (a total of 165 mm for 2 days), and 100 mm at Daito rain gage (a total of 150 mm for 3 days). Therefore, the simulated discharge during that day at all subbasins became big, particularly at subbasin 4. If the simulated results on that day were ignored, the NSI value would increase to 0.48 from 0.38.

Table 4. Simulated versus observed statistics for the Hii River calibration and validation.

	Calibration period		Validation period			
	1993-1996		1986-1992		1997-2005	
	R^2	*NSI*	R^2	*NSI*	R^2	*NSI*
Sub 1	0.65	0.64	0.58	0.53	0.51	0.50
Sub 2	0.75	0.74	0.67	0.60	0.64	0.62
Sub 3	0.77	0.76	0.74	0.74	0.71	0.68
Sub 4	0.69	0.67	0.70	0.69	0.59	0.38

Yearly averages for the water balance components are shown together with overall average for the simulated period in Table 5. The overall average of simulated river discharge (1,321 mm) was about 90% of observed average discharge (1,473mm). The average water balance is broken down as follows: precipitation 1,818 mm, percolation 921 mm, actual ET 428 mm, potential ET 985 mm, base flow 859 mm, lateral soil flow 400 mm, and surface flow 62 mm. It is considered that base flow accounts for about 65% and lateral flow does for about 30% of water yield in the simulation.

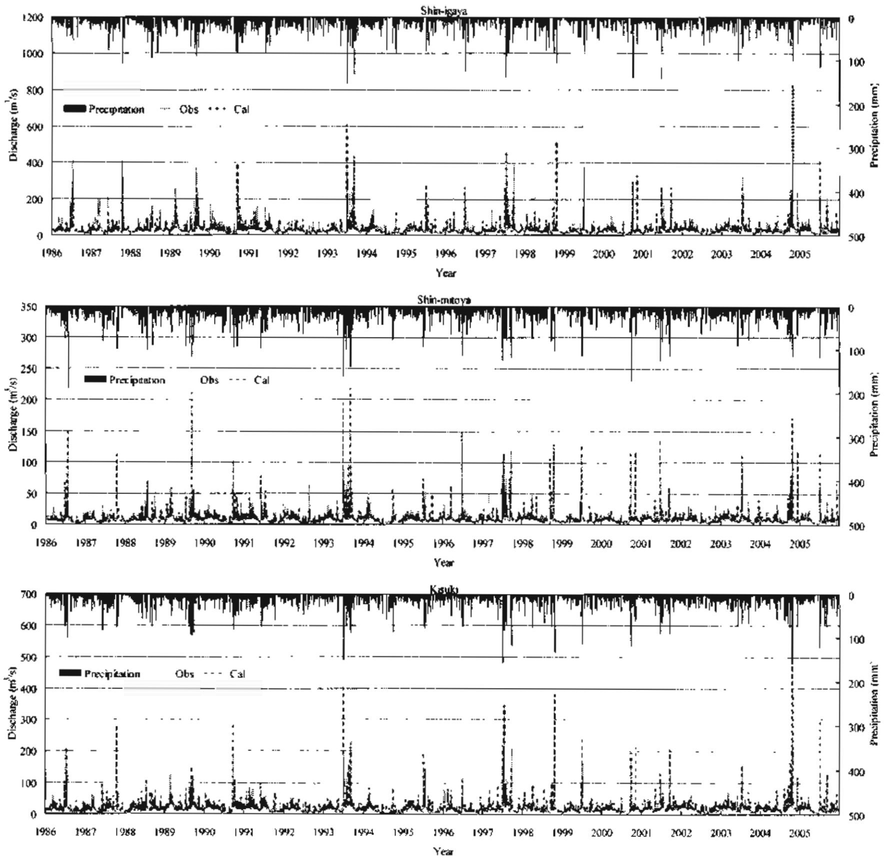

Figure 3. Simulated and observed discharge on a daily time step (calibration: 1993-1996, validation: 1986-1992 and 1997-2005).

By using the model parameter values used in the simulation, we tried to estimate the change in maximum and minimum discharge at each subbasin in case the annual total precipitation decreased or increased by 20% as shown in Table 6. The maximum and minimum flows were computed during the 20-year simulation period, keeping the other parameters constant. It was calculated that the maximum discharge at subbasin 1 became 1,200 m^3/s if the total precipitation amount increased by 20%. On the other hand, the maximum discharge became 558 m^3/s if the precipitation amount decreased by 20%. The minimum discharge at subbasin 1 became 3.76 m^3/s if the precipitation amount increased by 20% and 2.1 m^3/s if the amount decreased by 20%.

Table 5. Yearly averages of simulated water balance.

Year	Precip. (mm)	Sur flow (mm)	Lat. flow (mm)	Base flow (mm)	Perco. (mm)	Soil water (mm)	Actu. ET (mm)	Poten. ET (mm)	Water yield (mm)
1986	1649	59	366	760	808	77	412	1112	1185
1987	1819	64	385	828	868	68	511	1152	1277
1988	1768	34	406	858	934	69	392	862	1298
1989	2193	76	498	1096	1169	71	436	889	1670
1990	1916	54	419	890	975	75	467	1053	1363
1991	1843	37	406	899	950	73	443	874	1342
1992	1475	8	323	730	778	71	381	954	1061
1993	2258	148	505	1079	1169	79	426	835	1732
1994	1340	23	263	649	665	78	388	1122	935
1995	1877	58	430	890	979	72	376	932	1378
1996	1607	45	340	738	789	68	474	944	1123
1997	2189	113	490	1043	1112	73	467	1005	1646
1998	1862	80	391	886	911	73	479	908	1357
1999	1707	52	367	757	862	73	425	919	1176
2000	1545	68	320	725	749	'69	413	1053	1113
2001	1996	54	449	912	1018	71	473	1004	1415
2002	1621	10	365	792	855	74	381	996	1167
2003	2017	57	457	961	1044	73	465	899	1475
2004	1998	130	434	891	929	72	480	1129	1455
2005	1674	81	390	797	862	72	285	1066	1268
Ave.	**1818**	**62**	**400**	**859**	**921**	**72**	**428**	**985**	**1321**

Table 6. Change in maximum and minimum discharge due to decrease / increase of total precipitation amount (-20 %, 0% and +20 %).

	Maximum flow (m^3/s)			Minimum flow (m^3/s)		
	-20%	0	+20%	-20%	0	+20%
Sub 1	558	876	1200	2.1	2.87	3.76
Sub 2	546	832	1120	1.5	2.07	2.70
Sub 3	133	218	311	0.3	0.55	0.82
Sub 4	440	656	872	0.9	1.32	1.72

Table 7. Yearly averages of simulated water balance components due to decrease/increase of total precipitation mount (-20 % and +20 %).

Year	Precip. (mm)	Sur. flow (mm)	Lat. flow (mm)	Base flow (mm)	Perco. (mm)	Soil water (mm)	Actu. ET (mm)	Poten. ET (mm)	Water yield (mm)
-20 %	1454	29	304	654	704	72	413	988	987
+20 %	2181	109	494	1059	1132	73	439	983	1662

In addition, the maximum discharge values resulting from precipitation of different return periods were estimated for each subbasin (Fig. 4). The precipitation at various probabilities was calculated using the software made by the Public Works Research Institute. Rainfall duration was set to 24 hours when calculating the rainfall intensity. Simulation period was 1 year and daily average precipitation for 21 years from 1985 to 2005 was prepared. Results showed that the highest monthly to yearly rainfall ratio occurred in July. Hence, the precipitation of a given probability was set on the day when the highest amount of rainfall was recorded in July. As a result, the maximum discharge was 1,490 m^3/s at subbasin 1, 1,340 m^3/s at subbasin 2,424 m^3/s at subbasin 3, and 906 m^3/s at subbasin 4 in case of 200-year return period. However, rainfall will continue for several days. Thus, maximum discharge will also continue to increase.

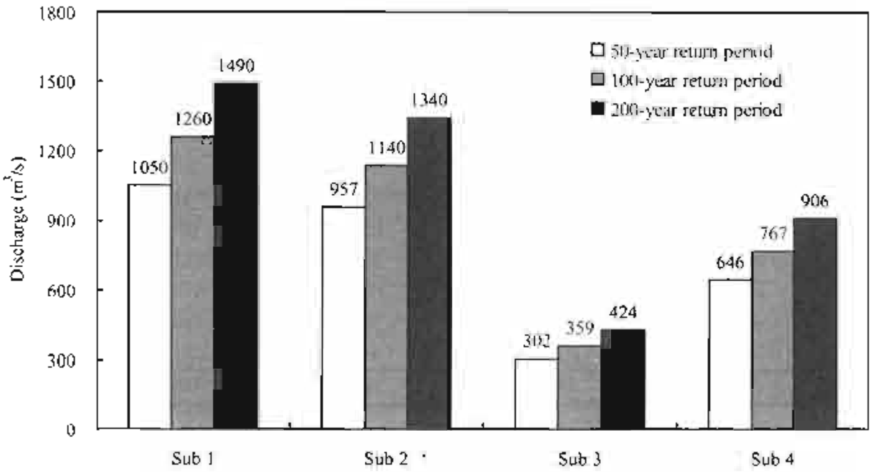

Figure 4. Maximum discharge at each subbasin due to precipitation of different return periods (rainfall duration was set to 24 hours).

5. Conclusion

The SWAT model performed well in simulating the general trend of river discharges at all subbasins over time for daily time intervals. Thus, this study showed that the SWAT model can be used for Japanese mountainous river basins. However, for more accurate modeling of hydrology and simulation of water quality, a large effort will be needed to improve the quality of available information concerning soils, land use, agricultural activity and climate of the basin.

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2.7 Development and Applications of SWAT-K (Korea)

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Abstract

In Korea, accurate hydrological component analyses for proper water resources planning and management have become an urgent issue. To evaluate the variation and properties of the hydrological components and to produce well defined hydrologic model, SWAT-K (Korea) has been established with the financial support from the Sustainable Water Resources Research Center for 21st Century Frontier Research Project by MEST (Ministry of Education, Science and Technology). SWAT-K is the modified version of SWAT considering variation of water cycle structure (natural and artificial) and surface-groundwater interaction and so on. Major achievements are integrated surface-groundwater model SWAT-MODFLOW, Temporally Weighted Averaged CN technique, improved reservoir operation module, integrated SWAT-SWMM, modified EVT module SWAT-EVT and so forth. SWAT-K studies have been focused on two major topics. One thing is an accurate estimation of hydrologic components for proper planning and management of water resources in Korea and another is making the effective tool for water quality management in the watershed. SWAT-K is expected to be a useful tool for water resources planning and be a basic tool for TMDL management in Korea.

Key Words: SWAT- K (Korea), water resources planning, hydrological component analysis, TMDL management

1. Introduction

In Korea, accurate hydrological component analyses for proper water resources planning and management have become an urgent issue. As existing water budget model has some sources of errors, there have been many limitations in water resources planning and management due to incorrect input of water budget in Korean watershed.

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To evaluate the variation and properties of the hydrological components and to produce well defined hydrologic model, SWAT-K (Korea) has been established with the financial support from the Sustainable Water Resources Research Center for 21st Century Frontier Research Project by MEST (Ministry of Education, Science and Technology). SWAT-K is the modified version of SWAT considering variation of water cycle structure (natural and artificial) and surface-groundwater interaction and so on. Major achievements are as below.

- SWAT-MODFLOW (Kim et al., 2008): integrated surface-groundwater model;
- Temporally Weighted Averaged CN technique (Kim and Lee, 2008): enhancement of runoff volume estimation by SWAT;
- SWAT-ROM (Kim et al., 2006b): improved reservoir operation module in SWAT;
- SWAT-SWMM (Kim and Won, 2004a,b): integrated modeling for urban watershed; and
- SWAT-EVT (Kim and Kim, 2004): modified EVT module for Korean watershed.

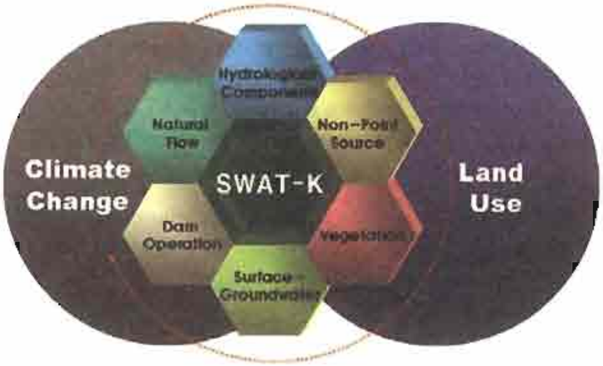


Figure 1. Overview of SWAT-Korea.

There have been a large number of applications involving use of SWAT-K in Korea. Brief descriptions of these studies have been presented below.

2. On the characteristics of flow duration curve according to the operation of multi-purpose dams in Han River basin, Korea

In Korea, about 70% of total rainfall is concentrated from June to September. Therefore, multi-purpose dams should store the water as well as reduce peak river flow during flood season, and they play an important role of original water supply, which stably provides the stored water to the downstream basin during dry seasons. Consequently, improving flow pattern to the downstream river is one of essential objectives for multi-purpose dam operations. However, there is no specific dam operation report on how large an effect of improving flow pattern is really indicated on the downstream river and with which amount of water storage the water supply is being attained. Accordingly, this study aimed to analyze and evaluate characteristics of flow pattern change depending on the operation of the Soyang and Chungju multi-purpose dams centered on Paldang dam which is located downstream of two larger dams. For this purpose, dam operation technique by using SWAT-K model is applied considering flow rate before and after dam construction. Also, it is aimed to quantitatively analyze and evaluate the virtual water storage effect of Soyang and Chungju dams.

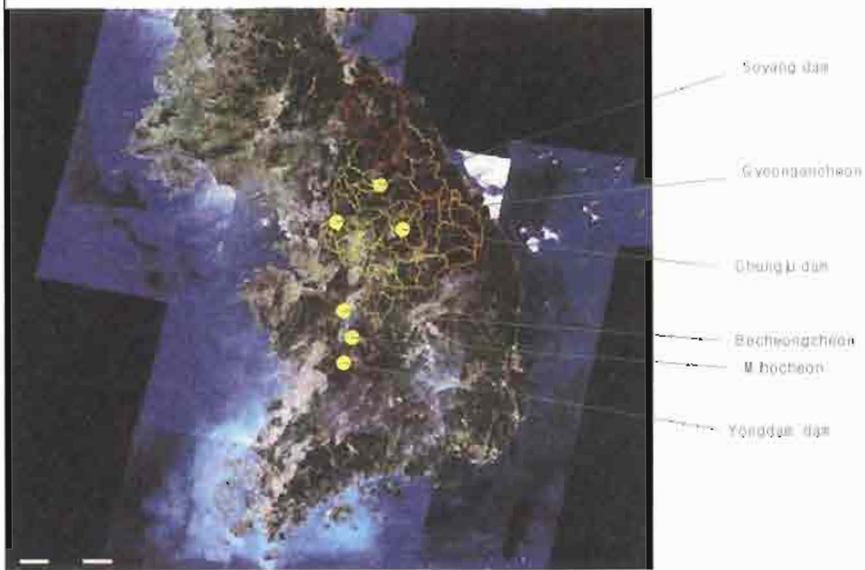


Figure 2. Study watersheds for SWAT application in Korea.

2.1 Concept and procedure for evaluating the characteristics of flow pattern changes depending on reservoir operation

The concept is that it is able to evaluate the storage shape and the storage operation in two multi-purpose dams as well as the evaluation of a flow pattern change, when being able to simulate runoff in the basin without Soyang and Chungju dams. Generally, the conceptual rainfall-runoff model, like the Tank model, the runoff simulation in the ungaged basin is very difficult and, moreover, the simulation on the basin of including reservoir is almost impossible. Fortunately, MEST (2004) had fully proven the application to the basin of including reservoir or the ungaged basin, through SWAT-K model, which is the modified version of SWAT (Arnold et al., 1993; Neitsch et al., 2001). Of course, a reservoir operation model is included in the SWAT itself, but this should be modified for application to Korean watershed. Consequently, SWAT-K's reservoir module is modified to apply the operation of each reservoir when a number of reservoirs are located within the basin. The following are the procedures that analyzed the flow pattern change in the Paldang dam by using this model:

(1) By using SWAT-K, applicability of model is examined by comparing the simulated runoff of upper basin of Paldang dam with the daily inflow of Paldang dam by forming the measured release of the upper stream basin of Soyang, Chungju and Hwacheon dams can be considered in a model.
(2) The daily inflow of the Paldang dam is simulated through the measured inflow of the Soyang and Chungju dams, through the measured release of Hwacheon dam, and through the runoff simulation in the remaining basin. At this time, it evaluates by subdividing an individual impact of the Soyang and Chungju dams.
(3) Performs the flow pattern analysis on a system of flow rate materials by scenario depending on the operation of the multi-purpose dam.
(4) Discusses the characteristics of two multi-purpose dams by using the result of flow pattern analysis.

2.2 Present status and runoff simulation of subject basin

As the Han River basin is located in the central part of the Korean Peninsula, and is the largest river with basin area of 26,919 km^2, river length of 481.7 km, average basin width of 54.4 km, and basin shape factor of 0.111, it possesses about 26.4 % of the entire area of 99,237 km^2 in South Korea. The basin area in the upper stream of Paldang dam is 23,800 km^2, within the basin is located 3 multi-purpose dams and 7 dams for hydroelectric power generation, for flood control, and for water supply (Fig. 3).

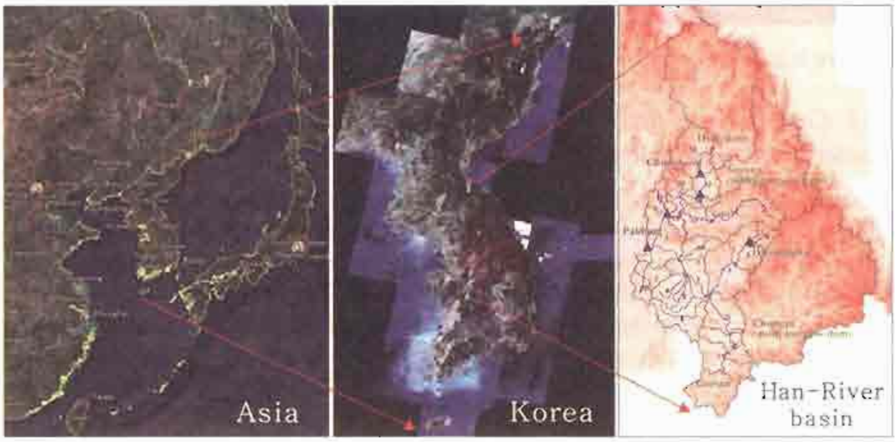


Figure 3. Present status of the subject basin.

For the purpose of SWAT-K modeling, daily based hydrometeorologic data from 16 weather stations are collected. Also, a digital thematic map is made up of Digital Elevation Model (DEM) from Korea Water Resources Corporation, land use map from Ministry of Environment, and soil map from Rural Development Administration.

Aiming to more exactly analyze a change in the flow duration curve at a spot of Paldang dam according to the operation of two multi-purpose dams, among the upper stream basins, the upper stream basin of Soyang, Chungju, Hwacheon, and Goesan dams were applied to a model by using the observed release and inflow data in each dam. Therefore, reservoir operations (target release) of Chuncheon, Uiam, and Cheongpyeong dams are performed in the North Han River system. The SWAT-K model is a physically based model, thus only its parameter is physically set, but optimization or other artificial manipulation is not easy.

Accordingly, parameter correction is virtually the same as the procedure of validation, and the correction comes to be attained within the physically proper range. Parameter calibration was performed using the observed and simulated daily inflows at the Paldang dam site during 1986~2000.

As shown in Figure 4, in consequence of performing the comparison of 1:1 in the observed value and the simulated value in daily units, the simulated value was indicated to be very good in coefficient of determination (R^2), which is about 0.91. To evaluate the water-budget balance of total runoff, it was compared the observed value and the simulated value in the accumulated inflow from the year of 1987 as shown in Figure 5(a). Given the attempt to consider objectives of a study aiming to analyze a change in runoff volume, the model, which is being currently applied, is excellent and efficient. Meanwhile, given the attempt to compare flow duration curve on the measured flow rate and the simulated flow rate in the Paldang dam, it can be seen to be almost consistent as shown in Figure 5(b).

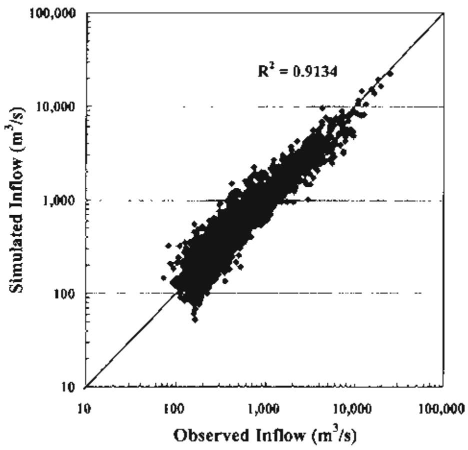


Figure 4. Comparison between the observed inflow and the simulated inflow at Paldang dam.

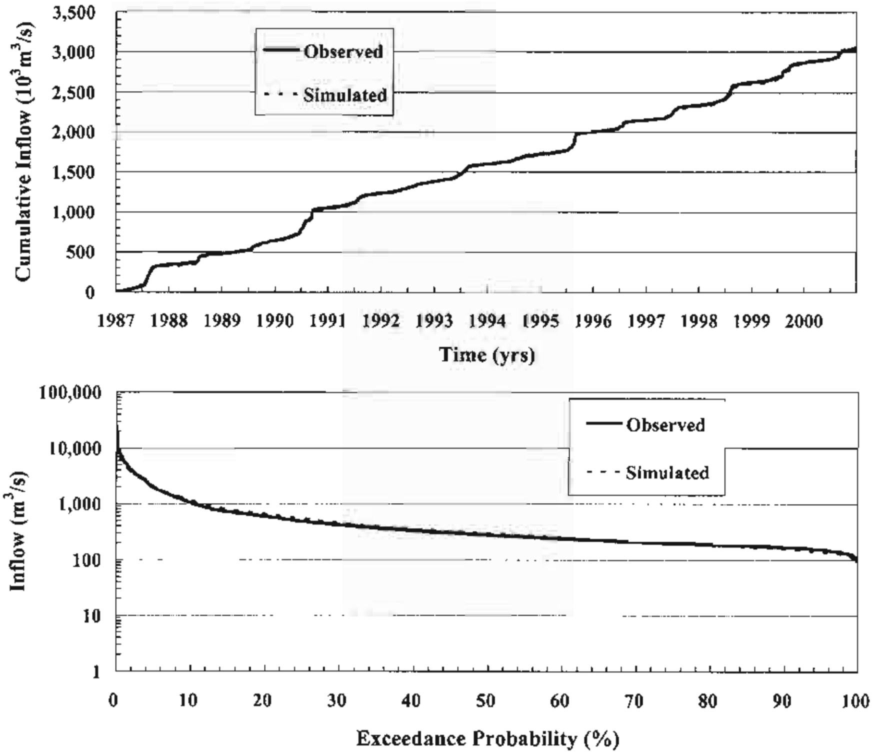


Figure 5. Comparison the measured-simulated inflow at Paldang dam: (a, upper) cumulative inflow; (b, lower) flow duration curve.

2.3 The flow pattern change and the evaluation of storage effect depending on reservoir operation

For Soyang and Chungju dams, runoff simulation was performed by using the observed release data when the operation of a dam is carried; on the other hand runoff simulation was performed by using the inflow data when the operation of a dam is not carried. Through forming this scenario, it can really inquire into even each of characteristics in Soyang and Chungju dams, and accordingly, can evaluate all the roles in two dams, thereby having analyzed flow pattern change at the Paldang dam by making up three scenarios as in Table 1.

As Figure 6 indicates the results of analyzing flow pattern change, it could quantitatively analyze the effect of multi-purpose dams in flood season and drought season, and confirm a point of time for improvement in flow pattern due to the operation of multi-purpose dams, by each scenario.

Table 1. The conditions of input materials by scenario and the situations of basin.

Scenarios	Input		Situations of basin
	Soyang dam	Chungju dam	
Current basin	Release	Release	When operation of Soyang and Chungju dams is proceeded
Scenario 1	Inflow	Release	When there is no Soyang dam
Scenario 2	Release	Inflow	When there is no Chungju dam
Scenario 3	Inflow	Inflow	When there are no Soyang and Chungju dams

In case of scenario 1 aiming to analyze the effect of Soyang dam on flow duration curve for a spot of the Paldang dam in the current basin situation, it can judge the effect of the Soyang dam, which reduced the peak flow as for high flow rate more than average 17.3 % (63 days) and improved flow pattern as for low flow rate less than it, during the simulation period. In other words, focusing on Paldang dam, the effect of operating the Soyang dam was indicated to store water in 9.1 billion tons over about 63 days every year and to regulate flow pattern during drought season. As the case of Scenario 2 that analyzed the effect of the Chungju dam, it could confirm the effect of improving flow pattern in a dam with a high flow rate and low flow rate as for average 7.7% (28 days). The period of storing water is shorter than the Soyang dam, but in case of storage capacity, it was shown that water in about 12.5 billion tons is stored in a high flow rate, and then flow pattern is improved again during the drought season, thereby having been indicated to be greater in the effect of improving flow pattern due to the Chungju dam, seeing the centering on the Paldang dam. Finally, given the case of scenario 3 that was aimed to simultaneously analyze the effect of the Soyang and Chungju dams, it brought about the effect of improving flow pattern in the remaining period, after storing water for the period of average 14.7% (54 days).

This is indicated to be the storage period due to the composite impacts of the Soyang and Chungju dams, and the storage capacity shows the storage effect about 21.6 billion tons, which are the sum total of two dams. The effective storage capacity in the Soyang and Chungju dams is 19 billion tons and 18 billion tons, respectively, thus the effective storage capacity in two dams is approximately 37 billion tons. However, it is known that the role in two dams can be averagely integrated into the storage effect of approximately 21.6 billion tons per year.

This is the first study of attempting to prove that this can be solved by using SWAT-K model, by paying attention to the fact that there has been no analysis on an effect of operating a dam due to the difficulty of interpreting flow pattern changes in the downstream river after constructing a dam.

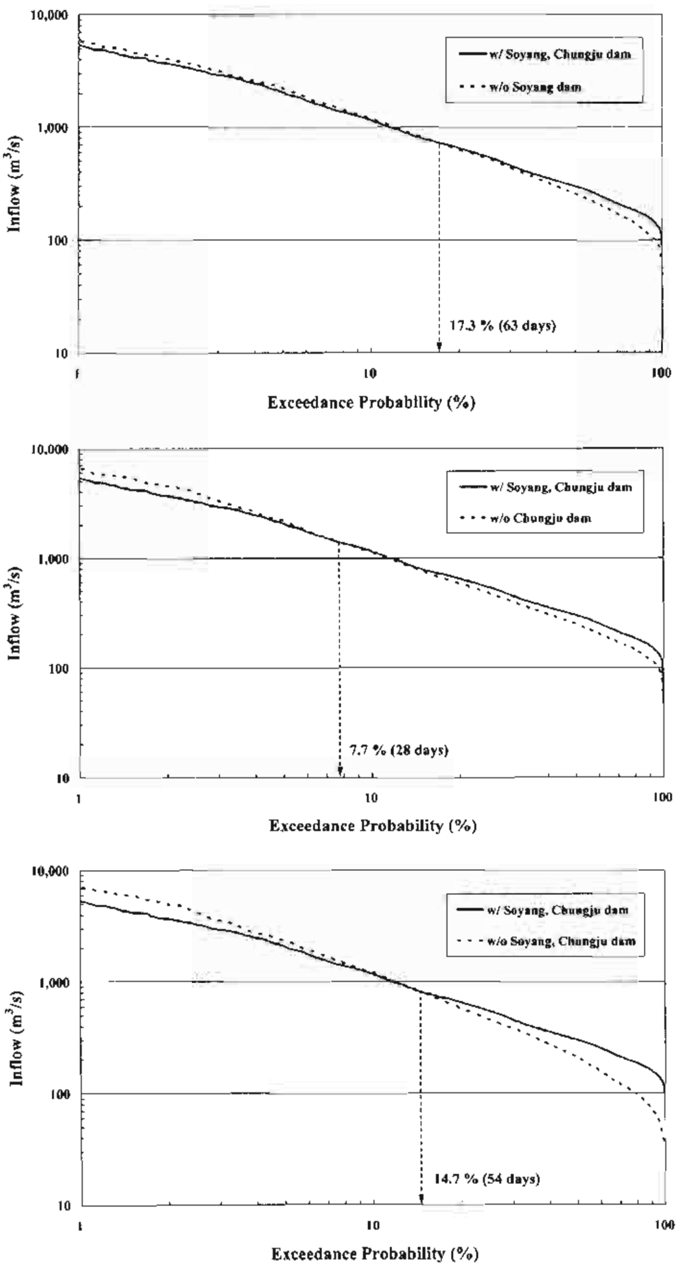


Figure 6. Analysis on flow pattern change by scenario: (a-upper) = Scenario 1, (b-middle) = Scenario 2, Lower - (c-lower) = Scenario 3.

3. Integrated modeling of surface water and groundwater by using combined SWAT-MODFLOW

Up until now, hydrologic component analysis in Korea has concentrated on surface water management, so problems related to groundwater were not dealt with in a rigorous manner. Additionally, the groundwater model was not adequately linked to surface water analysis, and thus the main focus was primarily on aquifer management. For instance, groundwater recharge could not be considered in terms of hydrological processes, which are directly related to precipitation, evapotranspiration and surface runoff. Groundwater recharge rate was an input to the groundwater model and thus has been determined from trial and error during calibration. The best solution for solving this problem is the construction of a long-term rainfall runoff model, which can effectively produce an integrated analysis for both the groundwater and surface water (Kim et al., 2006a). The main factors to consider for these kinds of models are: the land use, surface runoff, and other factors such as climate change. It is essential for the model to be able to examine the hydrologic effects and, at the same time, allowing hydraulic interaction between surface water and groundwater. To compute the quantity of groundwater runoff determined by runoff analysis from the watershed, SWAT (Arnold et al., 1993; Arnold et al., 1998) model and MODFLOW (McDonald and Harbaugh, 1988) model were fully combined (Kim et al., 2004a,b).

Although SWAT has its own module for groundwater components, the model itself is semi-distributed and thus distributed parameters such as hydraulic conductivity distribution could not be represented. Moreover, it causes difficulties in expressing the spatial distribution of groundwater levels. One of the most essential components of an efficient groundwater model is the accuracy of recharge rates amongst the input data. The conventional groundwater flow analysis performed by MODFLOW often overlooks the accuracy of the recharge rates that are required inputs to the model. Consequently, there is considerable uncertainty in the simulated runoff results. To overcome these disadvantages, we developed subroutines which exchanges flow data between the cells in MODFLOW and the HRUs (hydrologic response units) of SWAT. HRUs are defined by overlaying soil and land use and lumping similar soil/land use combinations. On the basis of these modifications, the groundwater model in SWAT was replaced with MODFLOW. Therefore, it was possible to establish a fully combined modeling program which is able to form a linkage in each time step. Sophocleous et al. (1997, 1999) already presented the development and implementation of a computer model SWATMOD which is capable of simulating the flow of surface water by SWAT, and groundwater and stream aquifer interactions by MODFLOW on a continuous basis for the Rattlesnake Creek basin in south-central Kansas.

In this study, the integrated SWAT-MODFLOW model (Kim et al., 2008) is described and tested in the Gyeongancheon watershed in Korea, where the area of the basin is 259.2 km^2. As shown in Figure 7, this drainage basin is divided into 9 subbasins, and the area of each subbasin ranges from 7 to 60 km^2. The channel length of each subbasin ranges from 5 to 20 km. AVS2000 (DiLuzio et al., 2001) was used to automate the development of model input parameters. Daily precipitation for Suwon gaging station that covers the entire watershed were obtained from the hydrologic database of MLTM (Ministry of Land, Transport and Maritime Affairs). Daily values of maximum and minimum temperatures, solar radiation, wind speed, and relative humidity were collected from the weather service data of KMA (Korea Meteorological Administration). Land use digital data (1:25,000) from the National Geographic Information Institute of MLTM were used. The detailed soil association map (1:25,000) from the NIAST (National Institute of Agricultural Science and Technology) was used for selection of soil attributes. Thirty-eight hydrologic soil groups within the Gyeongancheon watershed were used for analysis. Relational soil physical properties such as texture, bulk density, available water capacity, saturated conductivity, soil albedo etc. were obtained from the Agricultural Soil Information System (http://asis.rda.go.kr) of NIAST (2005).

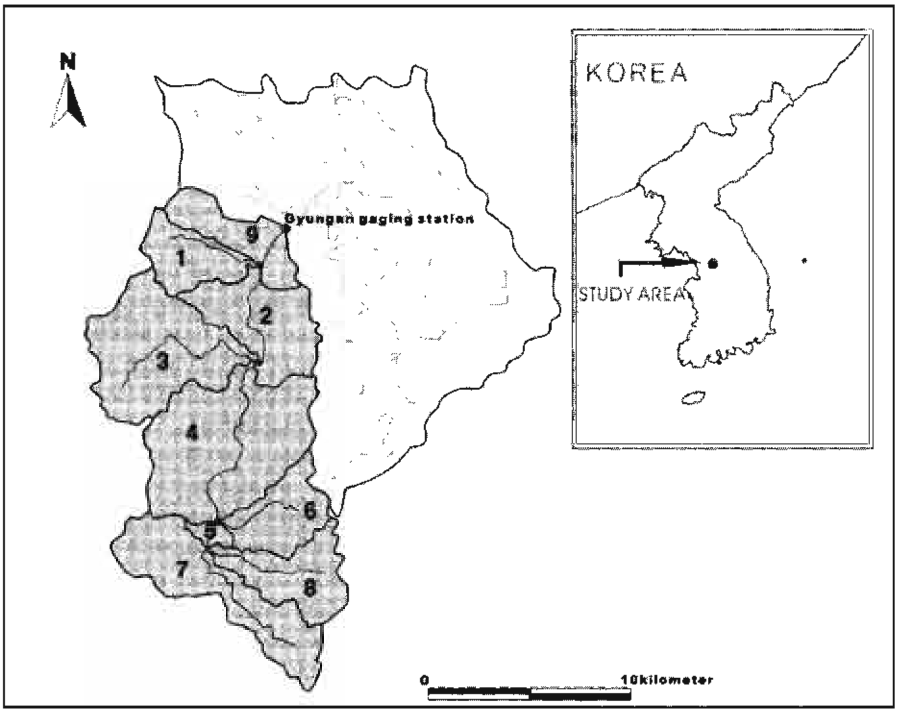


Figure 7. Division of subbasins of Gyeonganchneon watershed.

HRUs in SWAT are formed based on the hydrologic soil group and land use. However, due to the semi-distributed features of SWAT, spatial locations of each HRU within subbasins is not determined. Hence, to reflect HRU locations to MODFLOW, spatially distributed HRUs using the DEM, with a cell size of 300 m, are used to match the discretized watershed with MODFLOW grids. An HRU-Grid conversion tool is made for this purpose. Within MODFLOW, the aquifers are represented as two layers, discretized into a grid of 126 rows and 123 columns. Groundwater information from National Groundwater Information Management and Service Center was used to determine the aquifer characteristics for MODFLOW inputs. Hydraulic conductivity in alluvial aquifer is 2.113×10^{-3} cm/sec. Additionally, an assumption was made, according to a literature by Freeze and Cherry (1979), that the specific yield ranges from 0.1 to 0.3. Conductance of river bed was determined as one-tenth of the alluvial aquifer by trial-and-error procedure. The watershed boundaries were designated as no-flow cells. Recharge was distributed according to SWAT simulation outputs for each day. River-aquifer interaction was simulated using a RIVER package for MODFLOW. River stage of MODFLOW is imported from SWAT's daily simulation outputs.

Daily stream flow for year 1990 was calibrated against measured daily stream flow. Inputs to the model are physically based (i.e. based on readily observed or measured information). Several variables such as ESCO, AWC, CN2 were used for calibration. For the groundwater model, primary calibration parameters were the aquifer hydraulic conductivity and storativity. The hydraulic conductivity, the storativity and river bed conductance were then optimized by trial-and-error procedure. These variables were optimized by minimizing the low flow error during dry season. Calibration was performed on total stream flow. If simulated and measured flows are within 10%, the calibration is terminated. Observed and calibrated flows are shown in Figure 8(a). Total flow for the entire basin yielded an R^2 of 0.79. During 1991, daily stream flows were simulated by SWAT-MODFLOW model at the Gyungan gaging station in order to verify the performance of the calibrated SWAT-MODFLOW. The hydrograph was plotted using a log scale in order to emphasize the quality of low flow simulation. Figure 8(b) shows the SWAT-MODFLOW simulation during 1991. Total flow for the entire basin yielded an R^2 of 0.655 and Nash-Sutcliffe model efficiency of 0.647.

SWAT-MODFLOW is a grid based model, capable of calculating the spatially distributed groundwater table as shown in Figure 9. Figure 9 shows the distributions of groundwater head at 500, 800, 1000 days after running SWAT-MODFLOW. The gradual changes are shown in the figure.

The advanced pumping module, which is added to the SWAT-MODFLOW, is initially tested to Gyeongancheon watershed in Korea. For this purpose, the transfer command should be inserted to the data file We located a single discharge well at a certain cell (column=68, row=43) of MODFLOW in subbasin 4. The source is the shallow aquifer in subbasin 4, and the destination is the reach of subbasin 1.

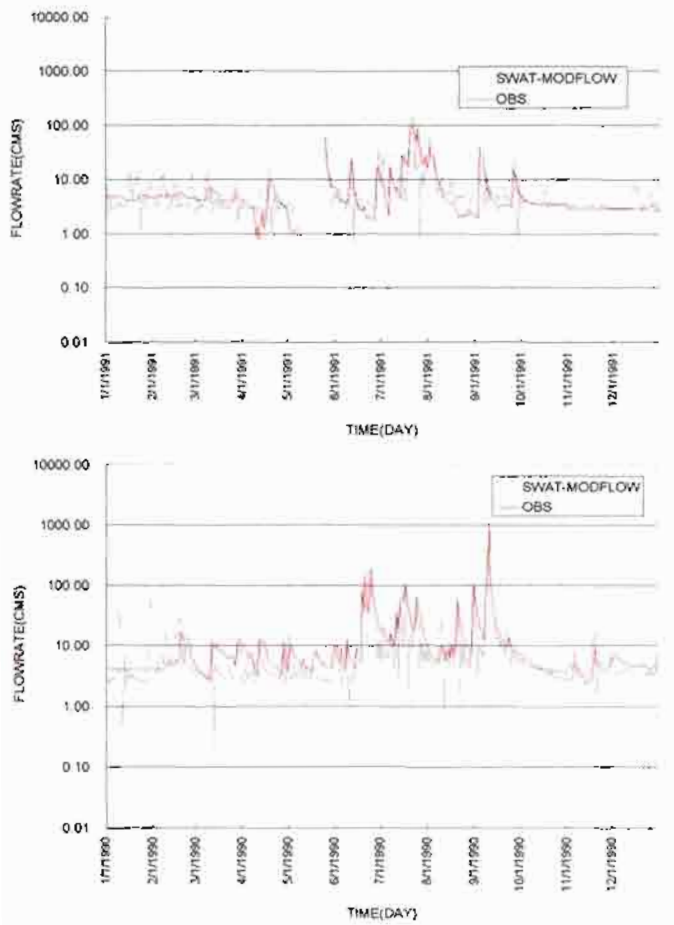
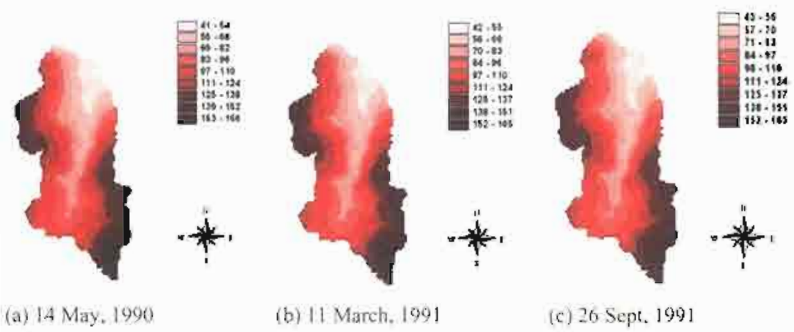
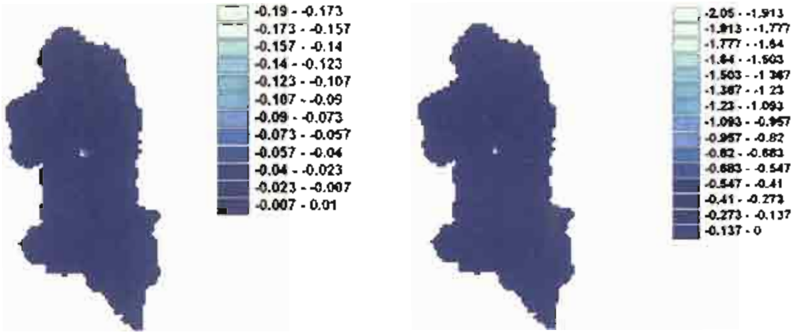


Figure 8. Simulation results by SWAT-MODFLOW (Kim et al., 2006): (a-upper) Calibration, (b-lower) Verification.



(a) 14 May, 1990 (b) 11 March, 1991 (c) 26 Sept, 1991

Figure 9. Spatial distribution of groundwater head simulated by SWAT-MODFLOW.



(a) pumping rate Q=100CMD (Unit: m) (b) pumping rate Q=1000CMD (Unit: m)

Figure 10. Groundwater drawdown contour lines.

Two pumping scenarios, 100 m^3/day and 1,000 m^3/day, are applied. The groundwater variation and water budget variation according to pumping were examined. Figure 10 shows the groundwater drawdown contour lines with pumping rates of 100 m^3/day and 1,000 m^3/day.

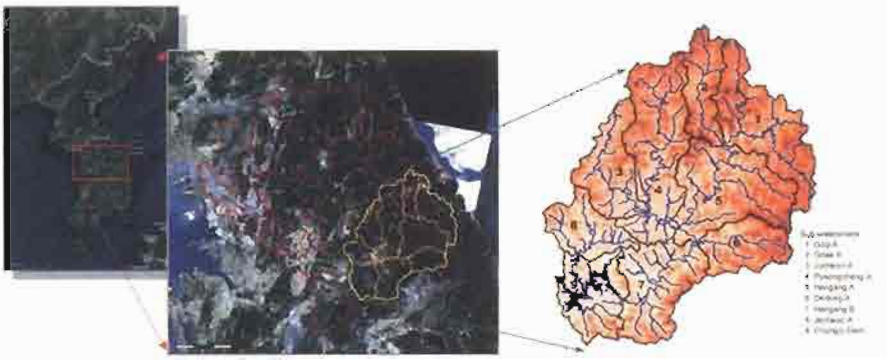
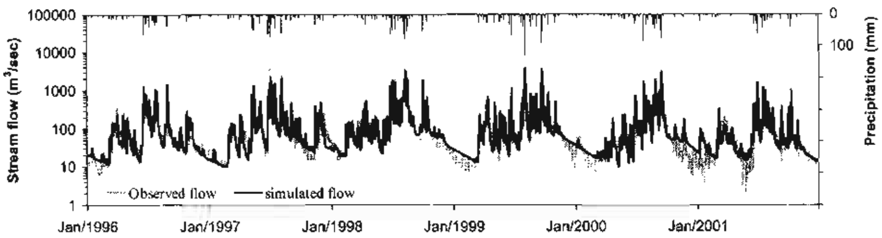
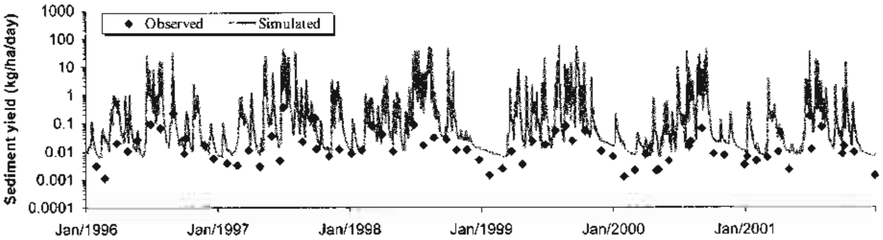


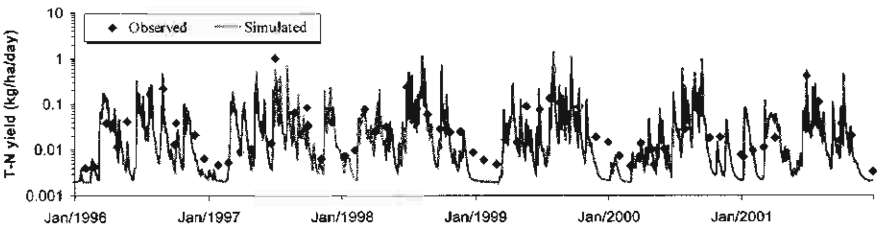
Figure 11. Han River basin and Chungju dam watershed.



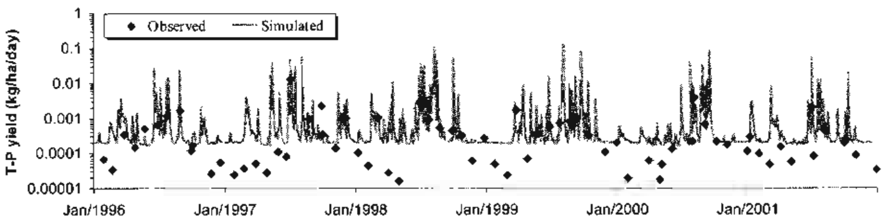
(a) Stream flows



(b) Sediment



(c) T-N



(d) T-P

Figure 12. Calibration results of daily stream flows, sediment, T-N, and T-P loads at Chungju dam (Kim et al., 2007; Kim and Kim, 2008).

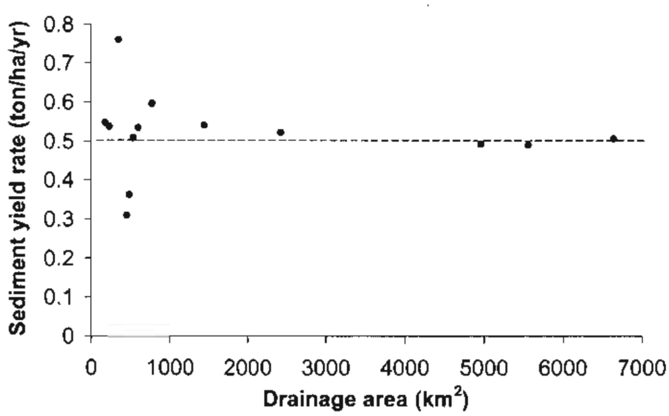


Figure 13. Sediment yield rates with drainage areas (Kim et al., 2007).

These results demonstrate that the advanced pumping module in the combined SWAT-MODFLOW model could effectively describe the water transfer in the watershed. Consequently, the combined SWAT-MODFLOW is introduced and applied to Gyeongancheon watershed in Korea. As model is fully combined, it is very useful to compute surface and groundwater components altogether. The application demonstrates a combined model which enables an interaction between saturated zones and channel reaches. This interaction plays an essential role in the runoff generation in the Gyeongancheon watershed. The comprehensive results show a wide applicability of the model that represents the temporal-spatial groundwater head distribution.

4. Watershed sediment and water quality modeling with SWAT-K

SWAT-K was applied to the Chungju dam upstream watershed through calibration and validation with physically based inputs and parameters, in order to quantify sediment, nitrogen, and phosphorus loads throughout the watershed, and investigate impacts of soil conservation practices.

The Chungju dam watershed is located in the main stream of the Han River basin, and covers 6,648 km^2 (6.7% of whole area of South Korea) with 375 km in length. For application of SWAT-K model, the watershed was divided into nine sub-watersheds based on TMDL unit-watershed of MOE (Ministry of Environment) (see Fig. 11), in which streamflow and water quality data have been measured at about 8-day intervals since August of 2004.

Figure 12 shows the calibration results for daily stream flows, sediment, total nitrogen (T-N), and total phosphorus (T-P) yields at Chungju dam site, the main outlet of the watershed, which accounts for reliable and accurate modeling in long-term periods.

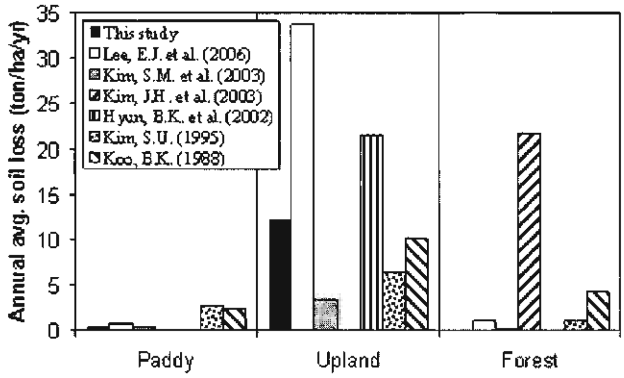


Figure 14. Annual average soil loss according to land use (Kim et al., 2007).

(a) T-N

(b) T-P

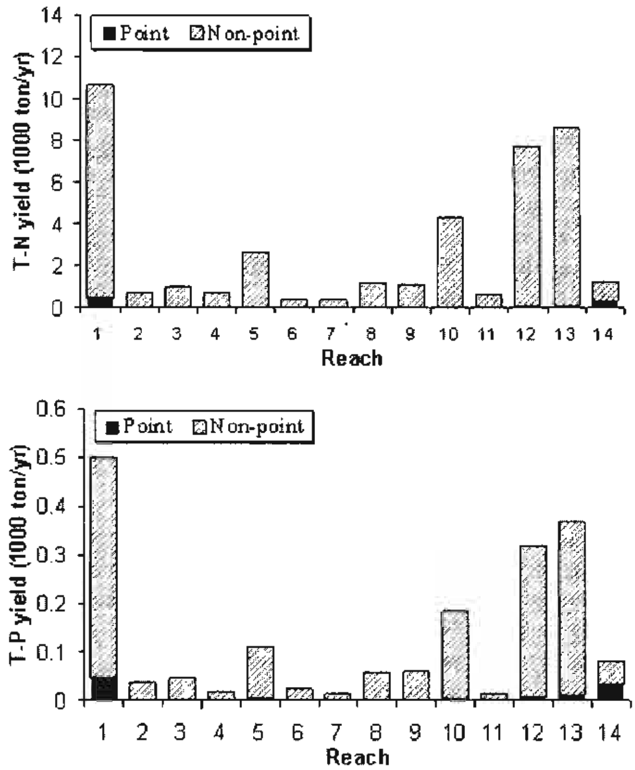
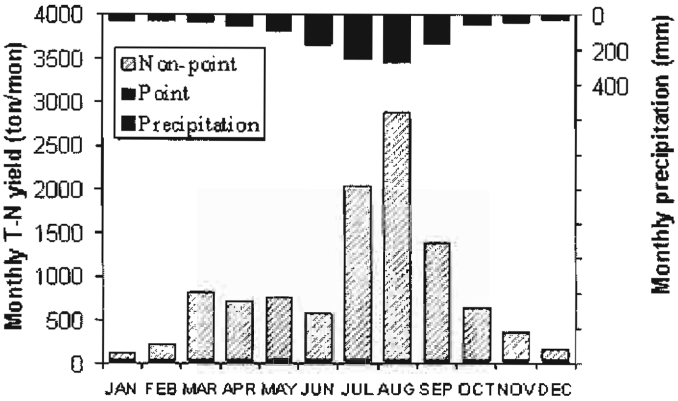
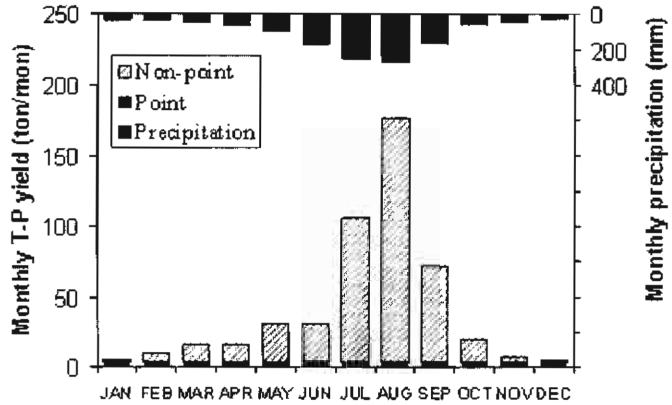


Figure 15. Pollutant yields of each reach with point and nonpoint sources (Kim and Kim, 2008).



(a) T-N



(b) T-P

Figure 16. Monthly pollutant loads with point and nonpoint sources (Kim and Kim, 2008).

We could understand the spatial distribution of sediment yields in the watershed from the investigation on relationship between sediment yield rates and drainage areas in each watershed (see Fig. 13). And we could roughly estimate the amount of sediment yields and pollutant loads generated from each vegetation type (see Fig. 14).

In addition, we could grasp that in most forested upstream sub-watersheds of the Chungju dam upstream watershed, pollutant loadings from point sources are low, and total loadings by point and nonpoint sources are also insignificant. On the other hand, in #14 sub-watershed including Jecheon city, the loadings by point sources are relatively considerable (see Fig. 15). For the whole watershed, point sources account for 9% of T-N loads, and 16% of T-P loads.

Monthly nonpoint source loadings concentrated on rainy summer season, while point source loadings kept nearly constant throughout the year (see Fig. 16).

And also, we applied conservation practices to the paddy fields and upland areas in order to evaluate the impact of BMP, and we could see decrease of 18% in sediment yields, 5% in T-N loads, and 19% in T-P loads from the Chungju dam upstream watershed (see Fig. 17).

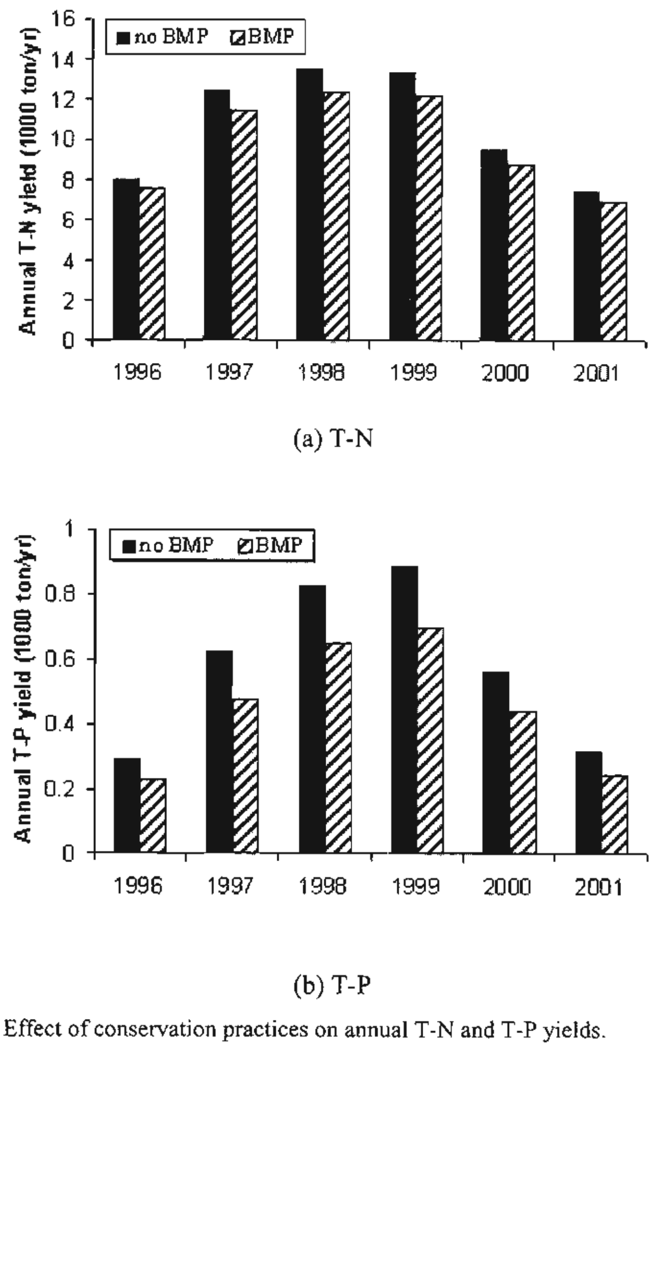
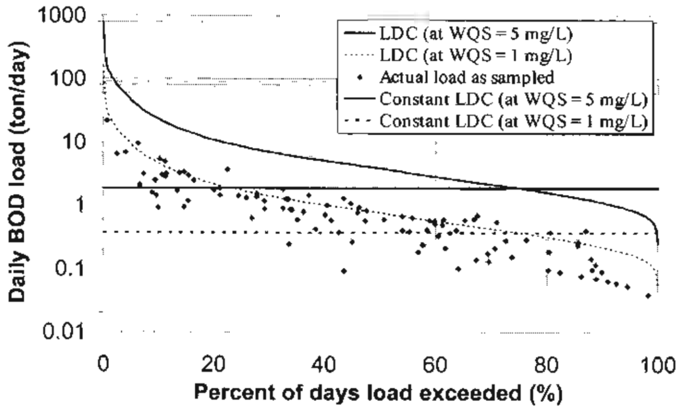
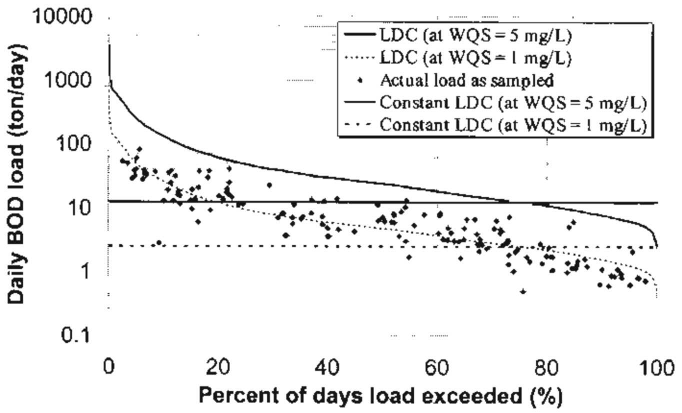


Figure 17. Effect of conservation practices on annual T-N and T-P yields.



(a) Golji A



(b) Hangang B

Figure 18. TMDL test-evaluation by load duration curve.

SWAT-K was used to estimate flow duration curve (FDC) and standard flow for deriving LDC at each sub-outlet. In the Han River basin, TMDLs system currently is not in operation for most areas including the study watershed, and targeted WQS also has not been established yet, therefore we assumed WQS as 5 mg/L (corresponding to 'normal' in "Stream water quality level" by MOE), and 1 mg/L ('very good') for BOD, and performed test-evaluation of TMDLs with LDC and measured data for each sub-watershed. Figure 18 is an example result at Golji A in upstream and Hangang B in downstream, in which solid-lined and dotted-lined curves present LDCs obtained with WQS of 5 mg/L and 1 mg/L respectively, and parallel solid and dotted lines are allocated loads from the existing "averaged 10-year low flow". From the results we could more efficiently and reasonably evaluate the TMDLs using LDC accounting for seasonal varying nonpoint pollutant loads and flows through the year. In the future, it could be useful to perform TMDLs evaluation for allocated loads of nonpoint pollutants such as T-N or T-P including BOD in the watershed carrying out TMDLs system (Kim and Kim, 2009).

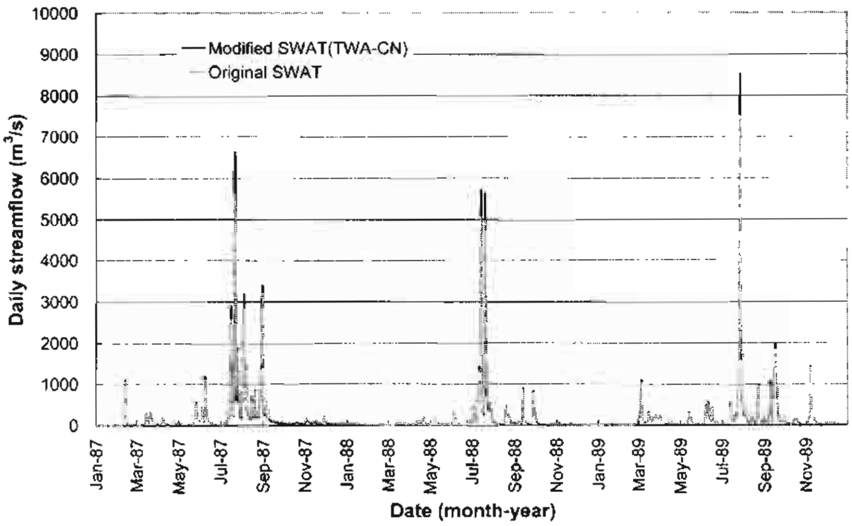


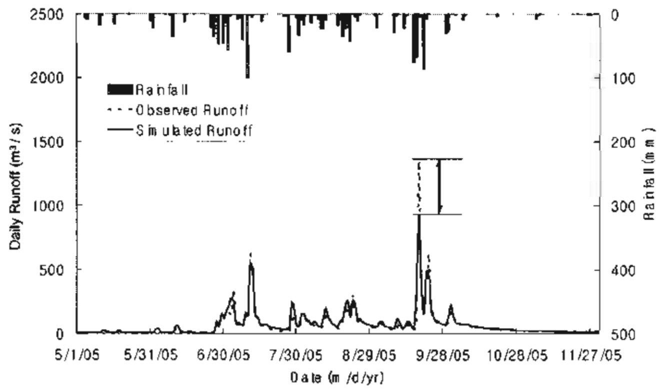
Figure 19. Comparison of streamflows simulated by original and modified versions of SWAT.

5. Enhancement of the runoff module in SWAT

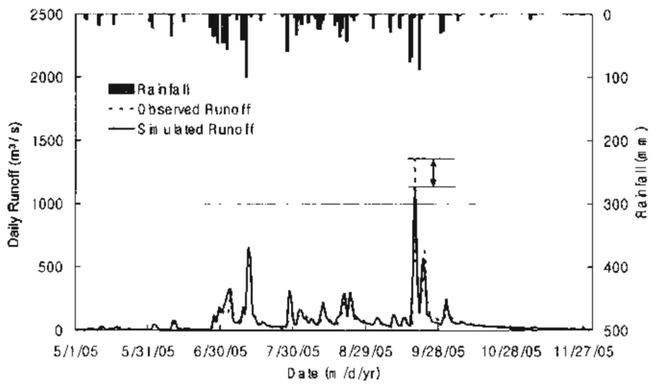
Two modules in SWAT have been improved to provide better prediction of daily hydrographs. One is the enhanced surface runoff module which is incorporated with the temporally weighted average curve number (TWA-CN) method and the other is the additional channel routing module that is based on the nonlinear storage equation.

SWAT uses a procedure that links retention parameter with available water capacity of soil and uses the SCS runoff curve number method for estimating surface runoff depth. However, SWAT's weakness in predicting high and peak flows has been reported in recent articles. SWAT has a tendency to underestimate peak flows in high rainfall periods especially for lots of watersheds in South Korea.

Therefore, for providing better prediction of daily high and peak flows, the runoff module in SWAT has been enhanced by incorporating the TWA-CN method that is capable of reflecting the effect of the amount of rainfall for a given day as well as the antecedent soil moisture condition (Kim and Lee, 2008). In the modified version of SWAT with TWA-CN, the daily surface runoff volume is determined as a function of the weighted sum of CN_t at the end of the previous day and $CN_{t+\Delta t}$ at the end of the current day.



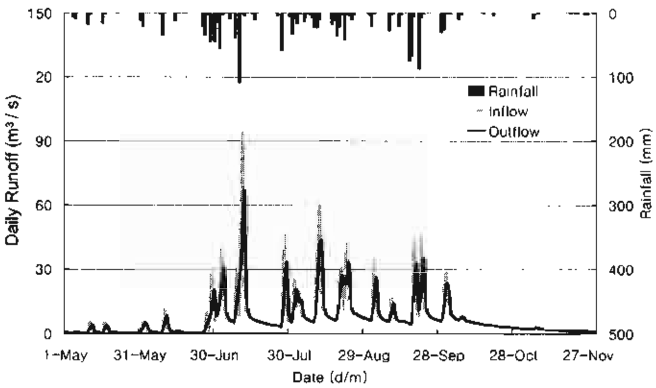
(a) Original version of SWAT



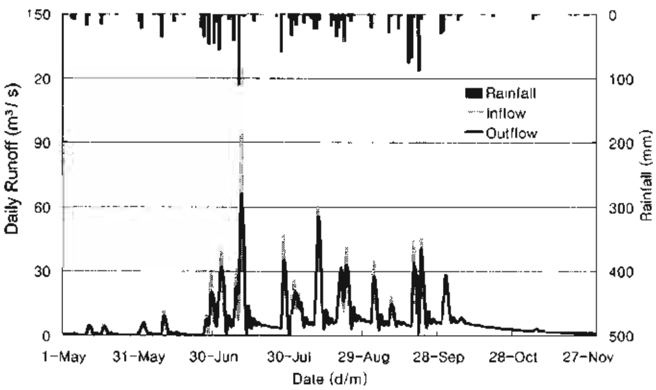
(b) Modified version of SWAT

Figure 20. Comparison of observed and simulated daily streamflow (Kim and Lee, 2008).

To assess the performance of the enhanced runoff module, the modified version of SWAT with TWA-CN method was applied to the Chungju dam watershed which is located in the middle of South Korea and covers a drainage area of 6,654 km^2. Figure 19 shows the hydrographs simulated by original and modified versions of SWAT. It is obvious that the peaks by modified SWAT are about 10-20% higher than those by original SWAT.



(a) over attenuation



(b) unstable signal

Figure 21. Routed flow by SWAT for a subbasin of Mihocheon basin.

Simulation was also conducted for the Mihocheon basin (1,869 km^2) located in the middle of South Korea to illustrate another performance of the modified version of SWAT with TWA-CN. Figures 20(a) and 20(b) show the results simulated by original and modified versions of SWAT, respectively. Figure 20(a) shows a satisfactory concurrence between measured and simulated hydrographs but it reveals a tendency to underestimate some of the peak flows. Even after a comprehensive calibration process, the original SWAT was not able to correctly reproduce the high flows for the Mihocheon basin. While using the modified

SWAT, as shown in Figure 20(b), an improved correspondence between the observed and predicted daily runoff was achieved. Visual inspection of the daily hydrographs shows the magnitude of peak flows simulated with reasonable accuracy.

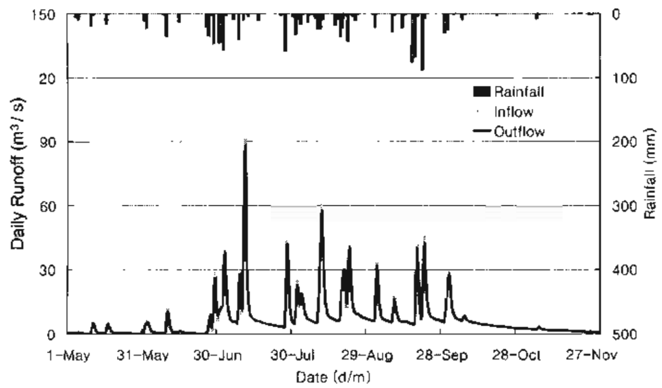


Figure 22. Routed flow by modified SWAT for a subbasin of Mihocheon basin.

Sometimes the channel routing module used in SWAT can be inappropriate for runoff simulation in small catchments that has a short travel time of much less than a day. As shown in Figures 21(a) and 21(b), simulated hydrographs showed an over attenuation of peak flow or a false signal during the recession periods when SWAT was applied to short tributaries within the Mihocheon River. This is due to the mathematical restriction of the Muskingum routing method in SWAT, which makes it difficult to calibrate routing parameters.

In order to enhance the channel routing module in SWAT for small catchments, an alternative routing technique in which Manning relationship is combined with a simple channel reach continuity equation has been added to the water routing module in SWAT. The advantage of the new routing technique is that parameters are readily available from channel morphological data and that it is applicable to small catchments. Figure 22 shows the routed flow by the modified version of SWAT. A little attenuation is found and the hydrograph is free from instability errors and produces realistic flow.

6. Assessment of forest vegetation effect on water balance in a watershed

To evaluate the effect of forest vegetation on the long-term water balance in a watershed, semi-distributed and physically based parameter model, SWAT was applied to the Bocheong watershed, and the variation of hydrological components such as evapotranspiration, surface flow, lateral flow, base flow, and total runoff was investigated with coniferous and deciduous forests, respectively. First, SWAT model was modified to simulate the actual plant growth pattern of coniferous trees that have the uniform value of leaf area index all the seasons of the year. The modified model was applied to the watershed that is assumed to have only one land cover in the whole watershed, and the variation of the water balance components was investigated for each land cover. It was found that coniferous forest affected the increase in evapotranspiration and decrease in runoff more than deciduous forest. However, the age and the density of stand, the location, and soil characteristics and meteorological conditions including the tree species should be also considered to examine the effect more quantitatively and to reduce the uncertainties in simulated output from the hydrological model (Kim and Kim, 2004).

7. Runoff estimation from two mid-size watersheds using SWAT model

SWAT model was applied to estimate daily stream flow for Yongdam and Bocheong watersheds in Korea. The model was calibrated and validated for the two watersheds and a new routine was added to analyze runoff process in paddy fields. The model efficiencies for two watersheds were 0.77 and 0.65 for the calibration period, and 0.76 and 0.50 for the validation period, respectively. It showed that water balance method simulated the runoff from paddy fields more precisely than CN method in SWAT. As a result, the SWAT model is applicable to Korean watersheds, and more accurate estimation is possible using daily water balance method in paddy fields (Kim et al., 2004).

8. The development of coupled SWAT-SWMM model

8.1 Model development

From the continuous long-term rainfall-runoff standpoint, the urbanization within a watershed causes land use change due to the increase in impervious areas, the addition of manmade structures, and the changes in river environment. Therefore, rainfall-runoff characteristics change drastically after the urbanization. Due to these reasons, there exists the demand for rainfall-runoff simulation model that can quantitatively evaluate the components of hydrologic cycle including surface runoff, river flow, and groundwater by considering urban watershed characteristics as well as natural runoff characteristics. In this study, continuous long-term rainfall-runoff simulation model SWAT-SWMM is developed by coupling semi-distributed continuous long-term rainfall-runoff simulation model SWAT with RUNOFF block of SWMM, which is frequently used in the runoff analysis of urban areas in order to consider urban watershed as well as natural watershed. The coupling of SWAT and SWMM is described with emphasis on the coupling scheme, model limitations, and the schematics of coupled model (Kim and Won, 2004a).

8.2 Model characteristics and evaluation

The continuous long-term rainfall-runoff simulation model SWAT has an advantage of being able to account for various land use. However, SWAT lacks the capability of simulating the drainage characteristics of urban area. On the other hand, SWMM, which is the most popular model for runoff analysis of urban watershed, has the advantage of being capable of considering surface and drainage characteristics in urban area, but SWMM cannot easily account for land use other than urban area within a watershed. In this study, SWAT-SWMM model, which builds on the strengths of SWAT and SWMM, has been applied to the Osan River Watershed which is a tributary watershed to the Gyung-Ahn River. From the application, the results from coupled SWAT-SWMM model has been compared to the ones from SWAT for each hydrologic component such as evapotranspiration, surface runoff, groundwater flow, and watershed and channel discharge, and the runoff characteristics of two models for each hydrologic component has been discussed (Kim and Won, 2004b).

9. An evaluation of snowmelt effects using SWAT in Chungju dam Basin

The objective of this study is to evaluate the snowmelt effects on the hydrological components, especially on the runoff, by using the soil and water assessment tool (SWAT) which is a continuous semi-distributed long-term rainfall-runoff model. The model was applied to the basin located in the upstream of the Chungju dam. Some parameters in the snowmelt algorithm were estimated for the Chungju basin in order to reflect the snowmelt effects. The snowmelt effects were assessed by comparing the simulated runoff with the observed runoff data at the outlet of the basin. It was found out that the simulated runoff with consideration for the snowmelt component matches more satisfactorily to the observed one than without considering snowmelt effect. The simulation results revealed that the snowmelt effects were noticeable in March and April. Similar results were obtained at other two upstream gaging points. The effect of the elevation bands that distribute temperature and precipitation with elevation was analyzed. This study also showed that the snowmelt effect significantly affects the temporal distribution as well as quantity of the hydrological components. The simulated runoff was very sensitive to the change of temperature near the threshold temperature that the snowmelt can occur. However, the reason was not accounted for this paper. Therefore, further analyses related to this feature are needed (Kim et al., 2006).

10. Analysis of the characteristics of low-flow behavior based on spatial simulated flows

The drought flow analysis for small and medium sized river is very difficult because of the scarcity of drought flow observation data. This study concerns the generation of areal simulated flow from SWAT-the semi distributed hydrologic model, the estimation of drought flow and the analysis of its areal characteristics. The SWAT model is set up for the Chungju dam basin and is verified by comparing the observation-simulation daily flow of dam site with upper stream station. The specific flow rate of mean drought flow is increased with the area, which is identified from the slope of each subbasin and the areal characteristics of saturated hydraulic conductivity. It is also proved that the drought flow can be overestimated using observed flow data by comparing with previous results. This method can represent more reasonable drought flow than thereby areal-specific flow rate method. The physical characteristics of drought flow also can be evaluated by these results (Kim et al., 2007).

11. A new method of estimating groundwater recharge for sustainable water resources management in Korea

In Korea, there have been various methods of estimating groundwater recharge, which generally can be subdivided into three types: base flow separation method by means of groundwater recession curve, water budget analysis based on lumped conceptual model in watershed, and water table fluctuation method (WTF) by using the data from groundwater monitoring wells. However, groundwater recharge rate shows the spatial-temporal variability due to climatic condition, land use and hydrogeological heterogeneity, so these methods have various limits to deal with these characteristics. To overcome these limitations, we present a new method of estimating recharge based on water balance components from the SWAT-MODFLOW which is an integrated surface-groundwater model. Groundwater levels in the interest area close to the stream have dynamics similar to streamflow, whereas levels further upslope respond to precipitation with a delay. As these behaviors are related to the physical process of recharge, it is needed to account for the time delay in aquifer recharge once the water exits the soil profile to represent these features. In SWAT, a single linear reservoir storage module with an exponential decay weighting function is used to compute the recharge from soil to aquifer on a given day. However, this module has some limitations expressing recharge variation when the delay time is too long and transient recharge trend does not match to the groundwater table time series, the multi-reservoir storage routing module that represents more realistic time delay through vadose zone is newly suggested in this study. In this module, the parameter related to the delay time should be optimized by checking the correlation between simulated recharge and observed groundwater levels. The final step of this procedure is to compare simulated groundwater table with observed one as well as to compare simulated watershed runoff with observed one. This method is applied to Mihocheon watershed in Korea for the purpose of testing the procedure of proper estimation of spatio-temporal groundwater recharge distribution (Chung et al., 2007).

12. Estimation of runoff curve number for Chungju dam watershed using SWAT

The objective of this study is to present a methodology for estimating runoff curve number (CN) using SWAT model which is capable of reflecting watershed heterogeneity such as climate condition, land use, soil type. The proposed CN estimation method is based on the asymptotic CN method and particularly it uses surface flow data simulated by SWAT. This method has advantages to estimate spatial CN values according to subbasin division and to reflect watershed characteristics because the calibration process has been made by matching the measured and simulated streamflows. Furthermore, the method is not sensitive to rainfall-runoff data since CN estimation is on a daily basis. The SWAT based CN estimation method is applied to Chungju dam watershed. The regression equation of the estimated CN that exponentially decays with the increase of rainfall is presented (Kim et al., 2009).

13. Enhancement of coupling between soil water and groundwater in integrated SWAT-MODFLOW model

This study presents the effects of temporally varied groundwater table on hydrological components for the Musimcheon basin. To this end, the SWAT-MODFLOW model in which the groundwater module of SWAT is replaced with MODFLOW model has been used with a modification to enhance the coupling between the water content in soil profile and the groundwater in shallow aquifer. The variable soil layer construction technique (VSLT) is developed in the present work to represent the direct interaction of soil water and groundwater more realistically, and then the VSLT is incorporated into SWAT-MODFLOW model. In VSLT, when the simulated groundwater table rises within the soil zone, the soil layers below the water table is regarded as a portion of the shallow aquifer, so that those layers are excluded from the initially defined soil zone and are governed by the MODFLOW. From the simulation tests for the interested basin, the improved SWAT-MODFLOW model with VSLT is found to correctly capture the spatial distributions of overland flow, soil moisture, evapotranspiration according to the groundwater table variation (Kim et al., 2009).

14. The variation of probability flood according to the flow regulation by multi-purpose dams in Han River basin, Korea

The purpose of the present study is to evaluate the variation of probability flood according to the flow regulation by multi-purpose dams (Soyang and Chungju) in the Han River basin, Korea. SWAT-K was used in order to generate regulated and unregulated daily streamflows upstream of Paldang dam. Simulated flow regulated by the Soyang and Chungju dams was calibrated by comparison with the observed inflow data at Paldang reservoir. Generally the ratio of flood flows to daily streamflows is known to decrease with drainage area in a watershed.

Regulated and unregulated flood flows were obtained from the relationship between flood flows and daily streamflows. Extreme Type I distribution was applied for flood frequency analysis and L-moment method was used for parameter estimation. This is a novel approach capable of understanding the variation in flood frequency with dam operation for the relatively large watershed scale, and this will help improve the applicability of daily stream flow data for use in flood control as well as in water utilization (Kim and Lee, 2009).

15. Conclusion

As discussed above, SWAT-K studies have been carried out and some studies are going on. Especially our research is focused on two major topics. One thing is an accurate estimation of hydrologic components for proper planning and management of water resources in Korea and another is making the effective tool for water quality management in the watershed. Ministry of Land, Transport and Maritime Affairs performs the long-term water resources planning and management in Korea. For this purpose, verified and effective hydrologic model is essential. SWAT-K is expected to be a useful tool for this planning because it could analyze the hydrologic components according to the natural and artificial variation of watershed such as land use as well as the climate change. In addition, as Ministry of Environment operates Total Maximum Daily Load (TMDL) management system, it is essential to have an accurate and effective modeling technique for non-point source evaluation and estimation in watershed basis. SWAT-K is expected to be a basic tool for TMDL management. Therefore the future of SWAT-K is very promising.

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2.8 Predicting the Effects of Land Use on Runoff and Sediment Yield in Selected Sub-watersheds of the Manupali River Using the ArcSWAT Model*

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Abstract

The quantitative prediction of environmental impacts of land use changes in watersheds could serve as basis for developing sound watershed management schemes, especially for Philippine watersheds with agroforestry systems. ArcSWAT, a river basin scale model developed to quantify the impact of land management practices on water, sediment, and agricultural chemical yields, was parameterized and calibrated in selected Manupali River sub-watersheds with an aggregate area of 200 ha to simulate the effects of land use on runoff volumes, sediment yield and streamflows.

Calibration results showed that ArcSWAT can adequately predict peaks and temporal variation of runoff volumes and sediment yields with Nash and Sutcliffe coefficient (NSE) ranging from 0.77 to 0.83 and 0.55 to 0.80, respectively. Simulation of land use change scenarios using the calibrated model showed that runoff volume and sediment yield increase by 3% to 14% and 200% to 273%, respectively, when 50% of the pasture area and grasslands are converted to agricultural lands. Consequently, this results to decrease in streamflows by 2.8% to 3.3%, with the higher value indicating a condition of the watershed without soil conservation intervention. More seriously, an increase of 15% to 32% in runoff volume occurs when the whole sub-watershed 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

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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 newly opened often productive forest lands. The Manupali River watershed is a typical example of the many watersheds in the country today that had undergone land conversion and presently undergoing environmental degradation and causing off-site pollution and heavy sedimentation of rivers, reservoir and hydropower dams.

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 that had attracted many migrants from all over the country and pursue profitable economic activities in agriculture. Agriculture has become so extensive that it eventually led to the conversion of forest lands and grasslands into corn and other cropped land. Recently, expansions of sugar, banana, and corn cultivation at low altitudes and of vegetable and corn at higher altitudes have occurred substantially at the expense of perennial crops (Lapong, 2005). With the favorable 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 altitude areas and more steeply sloping lands.

Obviously, intensive cultivation of annual crops coupled with the increase use of fertilizer, pesticides and other chemicals on vegetable crops cause serious soil erosion, aggravated by poor soil conservation practices. Soil erosion results to soil nutrient depletion or soil fertility reduction with 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 serious threat to aquatic life (Ella, 2005) and may create health problems for farm families and those living downstream. Moreover, soil erosion may result in several serious 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

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found in watershed such as the Manupali River watershed will generate substantial soil erosion and in the long run worsen the poverty of upland farmers as well as generate downstream costs (Paningbatan, 2005).

Developing a quantitative prediction model for assessing the environmental impacts of land use changes specifically on runoff and sediment yield in watersheds is therefore of paramount importance. It can serve as basis for developing policy interventions and for developing sound watershed management schemes, while ensuring the sustainability of the economic activities of the people.

Among the most widely used computer simulation modeling techniques for predicting runoff and sediment yield include the Soil and Water Assessment Tool (SWAT) model. However, this model has not yet been used in the Philippines particularly for predicting land use impacts. In fact, with the exception of the WEPP model application in small Philippine upland watersheds by Ella (2005), no other published report on the use of modern computer simulation modeling techniques for predicting hydrologic impacts of land use change in the Philippines exists.

Hence, this study was conducted to determine the effects of various land use patterns on runoff, and sediment yield in selected sub-watersheds of the Manupali River using the ArcSWAT model. Specifically, it aimed to parameterize, calibrate and use the ArcSWAT model in simulating the effects of various land use patterns on runoff and sediment yields.

ArcSWAT is a physically-based, river basin scale 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 over long period of time that runs on a daily time step. Major model components describe processes associated with water movement, sediment movement, soils, temperature, weather, plant growth, nutrients, pesticides and land management (Arnold et al., 1998). The watershed is subdivided into hydrologic response units (HRUs), which is a sub-watershed 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) developed by Williams and Berndt (1977).

2. Methodology

2.1 Description of study area

The Kiluya and Kalaignon are two sub-watersheds within the Manupali River watershed in Lantapan, Bukidnon, Philippines (Fig. 1). It encompasses a total area of about 200 ha and it is a typical area that practice intensive cultivation of corn and vegetables crops. The topography is rolling to hilly, and ranges in elevation from 900 m above mean sea level at the outlet of the two sub-watersheds to about

2,000 m at their upstream peak. Soils in these sub-watersheds are predominantly clayey due to the extent of fine-grained volcanic rocks, various sedimentary derivatives and pyroclastics (BSWM, 1985). Rainfall is evenly 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°C to 28°C. Relative humidity ranges from 86 to 98 percent. 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.

2.2 Preparation of the ArcSWAT 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 map called the DEM map with pixel size of 10 m x 10 m using the topographic tool of ENVI 4.5. ArcSWAT used the DEM map to delineate the sub-watersheds and generate the slope map of the test watershed.

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 agricultural (29.5%), pasture/grasses (53.0%), forest (16.8%), and footpath (0.7%).

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, 2005; 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 ArcSWAT from previous weather data obtained from the automatic weather station of SANREM-CRSP installed at the study site. Time series of observed runoff volume and sediment yield were obtained from the work of Lapong (2005) and were used to calibrate the model.

2.3 Model development and calibration

ArcSWAT 2005 version 2.1.2a was 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 sub-watersheds namely, lower and upper Kiluya and lower and upper Kalaignon within the ArcSWAT interface. Each sub-watershed was further subdivided into hydrologic response units (HRU) by overlaying the slope map, generated from the DEM, with the soils and land use maps.

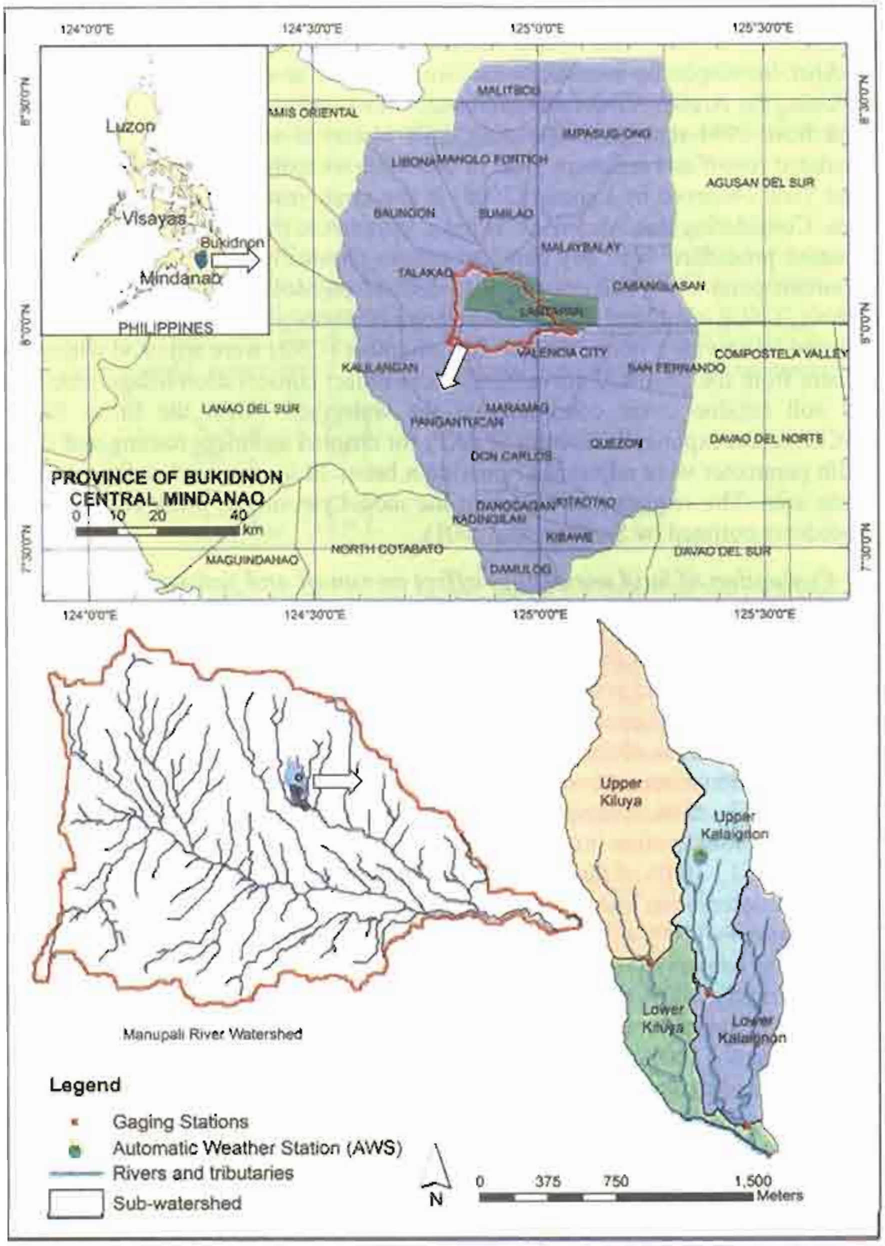

Figure 1. The Manupali River watershed and test sub-watersheds showing the locations of gaging stations and automatic weather station (AWS) and its location in the province of Bukidnon, Philippines.

The three major land uses were further subdivided into more specific land uses to better represent the spatial variation of vegetation in the watershed (Table 1). Also, the slope map was subdivided into four classes (Table 2).

Using the ArcSWAT default parameters, the watershed conditions were simulated from 1994 through 2004 using daily historical weather information. The simulated runoff and sediment yield in 2004 was compared to the runoff and sediment yield observed by Lapong (2005) in the same year in the same gaging stations. Considering that ArcSWAT is not a 'parametric model' with a formal optimization procedure to fit any data and it uses physically-based inputs, only few important parameters that are not well-defined physically such as runoff curve number, USLE cover and management factor (C factor), and infiltration rate 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 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. (2001).

2.4 Evaluation of land use change effect on runoff and sediment yield

In order to develop sound management schemes of protecting the watershed and to have clear picture of the impact of land use changes specifically on runoff volume, streamflows, and sediment yield, the calibrated model was run to simulate eight land use change scenarios. Land use change scenarios are:

Scenario 1 - 50% of the present grasslands are converted to agricultural lands with soil conservation intervention;

Scenario 2 - 50% of the present grasslands are converted to agricultural lands without soil conservation intervention;

Scenario 3 - 100% of the present grasslands are converted to agricultural lands with soil conservation intervention;

Scenario 4 - 100% of the present grasslands are converted to agricultural lands without soil conservation intervention;

Scenario 5 - 100% of the present grassland and 50% of the present forest are converted to agricultural lands with soil conservation intervention;

Scenario 6 - 100% of the present grassland and 50% of the present forest are converted to agricultural lands without soil conservation intervention;

Scenario 7 - 100% of the present grassland and 100% of the present forest are converted to agricultural lands with soil conservation intervention; and

Scenario 8 - 100% of the present grassland and 100% of the present forest are converted to agricultural lands without soil conservation intervention.

For developing the scenarios, the key processes and related model parameters such as crops grown, P factor of USLE, infiltration rate, runoff curve number, and filter width were modified in the appropriate ArcSWAT input files. An USLE P factor of 0.6 and 1.0 were used in simulations to reflect the condition of the watershed with and without soil conservation intervention, respectively. Filter width of 10 m was m was provided in all simulation scenarios to partly reflect the vegetable agroforestry (VAF) technology being advocated by the Sustainable Agriculture and Natural Resources Management (SANREM) project. The microclimate effect of the VAF however was not simulated in this study. The simulated runoff volumes and sediment yields at the various scenarios were used as guide in developing recommendations for the sustainable management of the watershed.

2.5 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 sub-watersheds were evaluated by the coefficient of determination (R^2). Also, the efficiency of the model was evaluated using the Nash and Sutcliffe (1970) equation given as

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

where E is the efficiency of the model, X_{mi} and X_{pi} are the measured and predicted values, respectively and $\bar{X}_m$ is the average measured values. A value of E=1.0 indicates a perfect prediction while negative values indicate that the predictions are less reliable than if one had used the sample mean instead. In addition, the root mean square error (RMSE) was used to evaluate how much of the prediction overestimates or underestimates the measured values. In each scenario, the mean runoff volume, streamflow and sediment yield over a 5-year simulation excluding a six-year precondition simulation period were obtained and used to assess the impact of the land use change.

Table 1. Land use classification of the study area.

LANDUSE	AREA (ha)	% 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	199.8	100.0

Table 2. Slope classification of the study area.

Slope (%)	Area (ha)	% of Total
0-8	45.4	22.71
8-18	0.1	0.03
18-30	57.6	28.82
Above 30	96.7	48.44
TOTAL	199.8	100.0

Table 3. Comparison between the simulated and observed runoff volumes in the four sub-watersheds.

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 4. Comparison between the simulated and observed sediment yield in the four sub-watersheds

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

3. Results and Discussion

3.1 Prediction of runoff volume

The daily simulated runoff volumes in each of the four sub-watersheds were lumped into weekly totals and compared with the measured runoff volumes in the area. Results show that the simulated and measured runoff volumes at the four sub-watershed outlets matched well (Fig. 2). **Further agreement between measured and simulated runoff volumes at the four sub-watershed outlets are shown by the coefficient of determination, R^2, ranging from 0.87 to 0.90 (Table 3). The adequacy of the ArcSWAT model to simulate the runoff volumes is also indicated by high NSE values ranging from 0.77 to 0.83.** The adequacy of the model is further indicated by its clear response to extreme rainfall events resulting in high runoff volumes (Fig. 2). These results indicate that hydrologic processes in ArcSWAT are modeled realistically and can be extended to simulate other hydrologic process including peak flows and streamflows at various land use change scenarios.

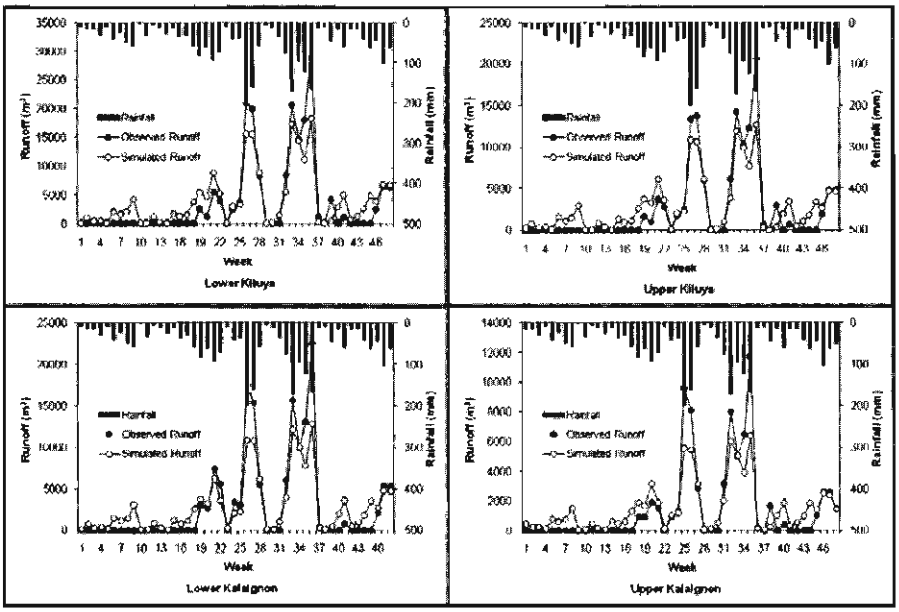

Figure 2. Observed and calibrated simulated runoff volumes at the four sub-watersheds superimposed with the weekly rainfall amount in the study area.

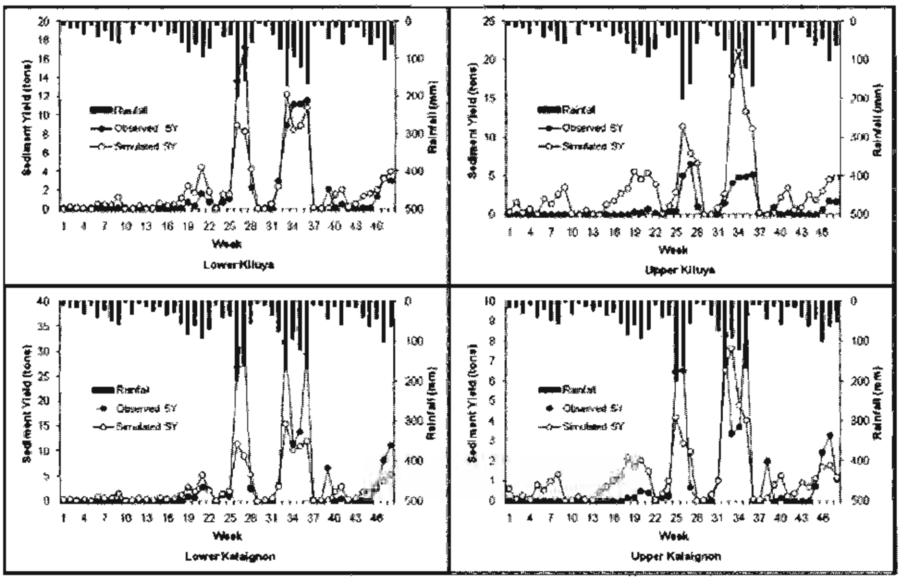

Figure 3. Observed and simulated sediment yields at the four sub-watersheds superimposed with the weekly rainfall amount in the study area during calibration period.

3.2 Prediction of sediment yield

Temporal variations of sediment yields at the four sub-watershed outlets are shown in Figure 3. It shows that the time of peak of sediment yields was adequately captured and in general shows a good agreement between the simulated and observed sediment yield with R^2 ranging from 0.58 to 0.82 (Table 4). With the exception of Upper Kiluya, the model also showed adequacy to predict the temporal distribution of sediment yield in the study area with Nash and Sutcliffe coefficient (NSE) ranging from 0.55 to 0.80 (Table 4).

In spite of the adequacy of the model to simulate sediment yields, close observation of the results shows that the model tends to overestimate the sediment yield in the upper sub-watersheds particularly in Upper Kiluya and underestimates the peak of sediment yields in the lower sub-watersheds. This behavior of the simulated sediment yields indicates high deposition of sediments as they travel along the channel. This was partly addressed in ArcSWAT by adjusting the linear factor (SPEXP) and exponential factor (SPCON) for channel sediment routing to their maximum values of 0.01 and 2, respectively. The remaining difference between the simulated and observed values may also be attributed to the channel erosion, especially during high flows, and other factors which the present model did not adequately capture. Nevertheless, the overall adequacy of the model to simulate sediment yields in the watershed indicates its usefulness to predict the effects of land use changes in the study area.

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 more runoff volumes, sediment yields and streamflows. Results of the simulations show 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. More seriously, an increase of 15% to 32% in runoff volume occurs when the whole sub-watershed under study 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 the fact 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 means that 37% to 42% of the annual rainfall is likely to be lost as surface runoff. On the other hand, 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 condition 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. Furthermore, there will be a significant decrease in groundwater baseflow due to reduced infiltration. This impacts the wildlife and fish in the streams and also the water supply of the watershed especially during dry periods.

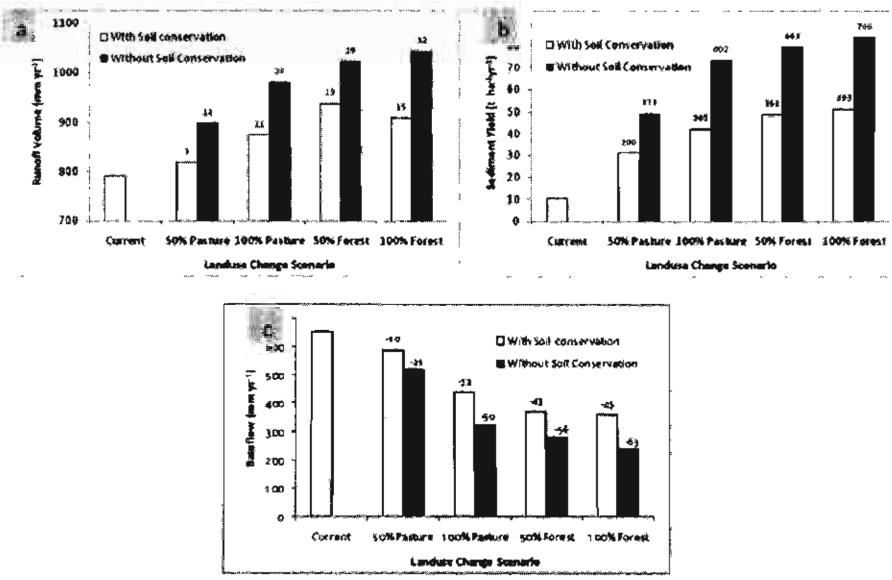

Figure 4. Simulated runoff volume (mm yr^{-1}), sediment yield (t ha^{-1} yr^{-1}), baseflow (mm yr^{-1}) in the study area as affected by percentage pasture and forest areas converted to agricultural land. The numbers on top of the bars indicate the percentage change from its current value.

It should be noted that more dramatic increase in runoff volumes can be expected in the test watershed than our simulation results. This is because we assumed in all simulations that converted areas are planted with agricultural crops all year round. Such assumption is considerably valid since only about 1.5 to 1.75 percent of the total existing agricultural areas is classified as fallow (Lapong, 2005). On the other hand, despite this assumption, a dramatic increase in sediment yields 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. 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 $ha^{-1}yr^{-1}$. Again, this dramatic increase in sediment yields could be even worse when portions of the converted areas to agricultural lands are left fallow and bare. Our simulation results show that 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, simulation results show that conversion of pasture, grasslands and forest to agricultural land use will result to decrease in baseflow (defined as stream water yield less surface runoff) to 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 content, all of which lead to greater infiltration and lower surface runoff. 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 has 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 and economic effects not only to the communities living in the study area but also those living at the 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 should be considered in policy implementation.

4. Summary and Conclusions

The ArcSWAT model was parameterized and calibrated in selected Manupali River sub-watersheds in the Philippines with an aggregate area of 200 ha to simulate the effects of land use on runoff volumes, sediment yield and streamflows. Results showed that ArcSWAT adequately predicted the runoff volumes of the test watershed with NSE ranging from 0.77 to 0.83. Both the peaks and temporal variation of runoff volumes at the four sub-watersheds of the test watershed were adequately captured by the model. Likewise, with the exception of Upper Kiluya, the model adequately predicted the sediment yields of the test watershed with NSE ranging from 0.55 to 0.80.

In order to develop sound management schemes for protecting the watershed and to have clear picture of the impact of land use changes specifically on runoff volume, streamflows and sediment yield, the calibrated model was also run to simulate eight land use change scenarios. Results showed that converting pasture, grasslands and forest to agricultural crops will likely result in increased runoff volumes, increased sediment yields, and decreased streamflows. 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 result to decrease in streamflows by about 45% to 63%. More seriously, an increase of 15% to 32% in runoff volume is likely to occur when the whole sub-watershed under study is converted to agricultural land. This accounts for 39% to 45% of the annual rainfall to be lost as surface runoff. Such condition will cause significant soil erosion depleting soil nutrients, sedimentation of reservoirs, and flooding of low lying areas at the downstream.

These simulated effects of pasture and forest conversion to agricultural crops clearly indicate an alarming situation of watersheds elsewhere having the same land use pattern as our test watershed. Efforts should therefore be exerted to address forest conversion to agricultural crops. In our test watershed, we 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 done. Finally, alternative livelihood opportunities for the upland farmers should be considered in policy implementation.

While simulation results are subject to further validation, this study showed 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.

Acknowledgments

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2.9 Hydrological Modeling with SWAT under Conditions of Limited Data Availability: Evaluation of Results from a Chilean Case Study

Alejandra Stehr[1], Patrick Debels, Francisco Romero and Hernan Alcayaga

Abstract

Water resources from the Biobío basin are of high strategic importance for economic development in Chile, both at the regional level as well as for the country as a whole. Advances in the capacity to describe and predict - in a spatially explicit manner - the impact of climate and anthropogenic forcing on the hydrology of the Biobío River basin are therefore urgently required. The work presented in this manuscript pretends to set the basis for future modeling applications within Biobío by analyzing the applicability of a readily available modeling tool, the SWAT model, to a subbasin of it. Modeling results show that the model performs well in most parts of the study basin. The SWAT model application for the Vergara basin confirms that SWAT is a useful tool and can already be used to make preliminary assessments of the potential impacts of land use and climate changes on basin hydrology.

Keywords: hydrological modeling, SWAT, calibration, Chile, Biobío

1. Introduction

The integrated management and adequate allocation of water resources between different water uses under changing conditions of land use and climate are major challenges which many societies already face, or will have to face during the next decades (Simonovic, 2002). In this context, the analysis of the impact of land use and climate changes on river hydrology and surface water availability can be addressed by means of spatially distributed rainfall-runoff model applications (Harrison and Whittington, 2002; Eckhardt and Ulbrich, 2003; Haverkamp et al., 2005). Well-known models that are commonly applied at the basin scale are the Hydrologic Simulation Package Fortran (HSPF; Holtan and Lopez, 1971), the Système Hydrologique Européen (SHE; Abbott et al., 1986a,b), the Soil and Water Assessment Tool (SWAT; Arnold et al., 1998) and the Hydrologic Engineering Centre Hydrologic Modeling System (HEC-HMS; HEC, 2000), amongst others.

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These models that produce hydrographs as well as water yields and provide possibilities for continuous simulation can be operated at different time steps, and have varying numbers of input parameters (Mishra and Singh, 2004). However, for practical applications in meso- or macro-scale basins, in Chile as well as in many other places of the world, available meteorological data will restrict choice to those models that offer possibilities for using daily (or coarser) data for performing water balance calculations. Most applications of the previously described models found today in the literature correspond to case studies from the developed world, where data availability may be very different from those typically encountered elsewhere.

In Central Chile, the Biobío basin (24.371 km^2) is of high strategic importance for economical development, both at the regional and the national level. The continuously growing pressures on the basin's water resources, together with the need to preserve its unique aquatic biodiversity, make it very difficult to achieve a consensus-based and sustainable equilibrium between availability and demand, unless a better understanding of basin hydrology and of its sensitivity to climate variability and changes in climate and land use can be provided. Advances in the capacity to describe and predict - in a spatially explicit manner - the impact of climate and anthropogenic forcing on the hydrology of the Biobío River basin are therefore urgently required. In this context, the work presented herein attempts to set the basis for future modeling applications within the Biobío basin, by analyzing the applicability of the SWAT model (Arnold et al., 1998; Neitsch et al., 2002a,b) to the Vergara basin (4.265 km^2), a subbasin of the Biobío River system that is especially important for the forestry industry (plantations). Selection of SWAT for this project was based on the following: it is an existing, readily available and well-documented modular modeling tool. Its graphical user interface (GUI), AVSWAT (Di Luzio et al., 2002), comes embedded in the popular and widely used GIS environment ArcView 3.2 (ESRI, 1999). Both the availability of good manuals as well as the ArcView-based GUI are aspects that make the model also attractive to potential end-users, such as government agencies and decision-makers. With SWAT, basic applications can be built for hydrological modeling and later extended, e.g. for analyzing water quality issues as well. An additional interesting aspect of SWAT is the ongoing development that is taking place, with contributions coming from different groups, from different parts of the world. SWAT also offers different options for calculating runoff and evapotranspiration, each option having different requirements with regard to input data. This is important, as in Chile, just as in many other places in the world, meteorological data are typically available at the daily time step only. By using the SCS Curve Number approach for runoff calculations and the Hargreaves method for evapotranspiration (both offered by SWAT - see The SWAT Model Section), this limitation can be easily addressed. Departing from the former analysis, one of our goals was to test the practical applicability of SWAT on a case study basin for which data availability can be described as "typical of many Chilean basins". It is thought that interpretation of the results obtained from this case study holds the potential for users from other parts of the world to evaluate the appropriateness of this tool - under similar conditions of basin characteristics and data availability - for their specific water resources applications.

2. Selection of the Study Area

The Biobio River basin is the third largest Chilean basin. It is located in central Chile, between 36°45'-38°49'S and 71°00'-73°20'W. The basin stretches from the continental divide in the east (Andes, Chilean-Argentinean border) to the Pacific Ocean in the west. It covers approximately 3% of the Chilean continental territory, and is influenced by the temperate climates of the south as well as by the Mediterranean climate of central Chile. Due to its location in a climatic transition zone, the study area is rich in biodiversity, which is characterized by a high degree of species endemism. At the same time, the area constitutes the country's most important centre for forestry activities (both pulp mills and exotic species forestry plantations) and contains a major portion of the Chilean agricultural soils. The basin also plays a predominant role in the national energetic supply (hydroelectricity), and its main river, the Biobio, is the principal provider of drinking water for one of Chile's major cities: Concepción (population: 700,000).

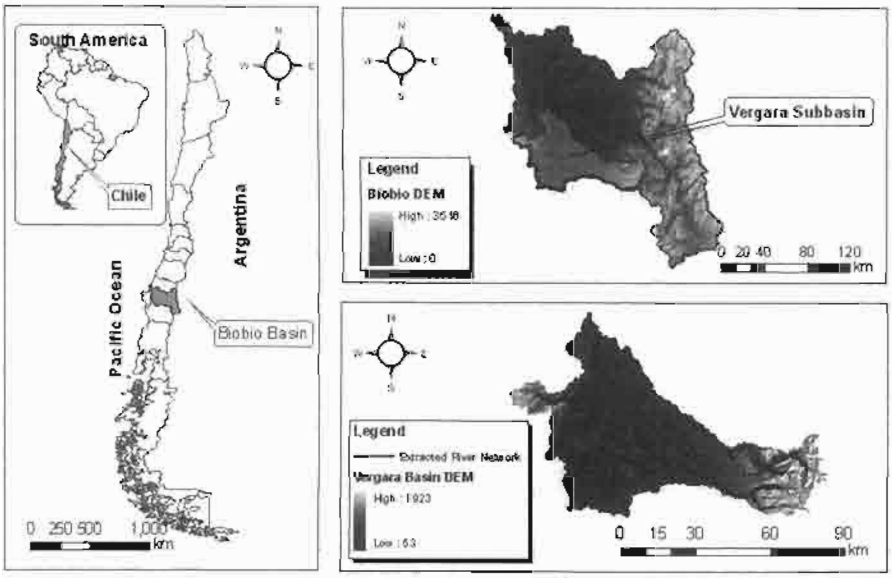

Figure 1. Location of the Biobio and Vergara basins.

The flow regime of the Biobio River is pluvio-nival, with a very marked difference in discharge between dry and wet season: maximum and minimum monthly mean values near the mouth are 1,823 and 279 m^3/s during the months of July (winter, wet season) and February (summer, dry season), respectively. In the central valley part of the basin (where most agricultural activities take place), irrigation practices are very important during the Austral summer.

The main tributaries to the Biobío are the Duqueco, Bureo, Vergara and Laja rivers. Together these rivers drain 50% of the basin's total surface area. The rainfall-runoff modeling application described in this paper focuses on one of these subbasins: the Vergara River basin. This subbasin has an area of 4,265 km^2, covering approximately 17% of the total surface area of the Biobío basin. It is located in the southern part of the Biobío basin (Fig. 1), between 37°29'-38°14'S and 71°36'-73°20'W. Maximum and minimum mean monthly discharges occur during July and February-March respectively (Table 1). Its selection as a test area for the application of the SWAT model is based on: (a) the availability of a typical set of basic input data which should allow for the model to be calibrated and validated; (b) the absence of either hydropower infrastructure or major irrigation works; and (c) the reduced amount of snowfall in the basin, and the consequent small contribution of snowmelt to total river discharge. These last two aspects are considered important: the snowmelt contributions, as well as the presence of major flow deviations and/or abstractions, would require special attention during the modeling, due to their impact on the timing and magnitude of observed discharge values. This would require additional processes to be modeled, and thus further complicate the calibration and validation process (more uncertainty involved; more parameters that have to be tuned). The philosophy behind the selected approach here is that if the model can be successfully applied to a relatively 'simple' test-case such as the Vergara basin, then in successive steps more complex subbasins may be addressed, e.g. those where one or a (progressive) combination of several of the features mentioned above are represented. Once all successive modeling steps have been successfully completed, then finally the modeling of the entire Biobío basin may be attempted. The former should be considered as a long-term goal, as current conditions of availability of data (e.g. related to snow water equivalent) still constitute a serious constraint. However, in the short term, the selected subbasin constitutes an interesting test case for evaluating impacts of land use change on basin hydrology, as major conversions between agriculture and forestry land use have been experienced in this area over the past decades.

Table 1. Mean monthly discharges (m^3/s) at the different control points in the Vergara basin.

	Tijeral	Rehue	Mininco	Renaico
Maximum	153.70 (July)	16.79 (July)	43.57 (July)	90.17 (June)
Minimum	7.52 (February)	0.28 (February)	2.16 (February)	6.71 (March)
Mean	56.32	5.85	16.21	42.66

3. The SWAT Model

Development of the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998; Neitsch et al., 2002a,b) was started in the 1990s at the United States Department of Agriculture (USDA). SWAT is a process-based and spatially semi-distributed hydrological and water quality model designed to calculate and route water, sediments and contaminants from individual drainage units (subbasins) throughout a river basin towards its outlet. It is a versatile tool that has been used in many parts of the world to predict the impact of management practices on water, sediment and agricultural chemical yields in large complex basins with varying soils, land use and management conditions, over long periods of time (Eckhardt et al., 2005).

A complete description of the SWAT model can be found in Neitsch et al., (2002a,b). Below, we limit ourselves to a short overview of the most relevant aspects related to the hydrology component, as this has been the main focus of attention in the presented work.

Within the SWAT conceptual framework, the representation of the hydrology of a basin is divided into two major parts: (a) the land phase of the hydrological cycle, and (b) the routing of runoff through the river network. For modeling the land phase, the river basin is divided in subbasins, each one of which is composed of one or several hydrological response units (HRUs), which are areas of relatively homogeneous land use/land cover and soil types. The characteristics of the HRUs define the hydrological response of a subbasin. For a given time step, the contributions to the discharge at each subbasin outlet point is controlled by the HRU water balance calculations (land phase). The river network then connects the different subbasin outlets, and the routing phase determines movement of water through this network towards internal control points, and finally towards the basin outlet (Neitsch et al., 2002a).

For the land phase water balance, within SWAT evapotranspiration can be calculated using one of either three methods: Penman-Monteith, Hargreaves or Priestley-Taylor. The Penman-Monteith method offers a better process description, but has high input data requirements which for practical applications will be hard to fulfil in many parts of the world. Although less physically based, the Hargreaves or Priestley-Taylor methods have the advantage of less stringent input data needs; under minimal conditions of data availability, the Hargreaves method can even be used with temperature time series as the only required measured input (Heuvelmans et al., 2005). For surface runoff calculations, SWAT gives the user two alternatives: (a) the use of the Soil Conservation Service curve number (SCS CN) procedure, and (b) the Green and Ampt infiltration method. For the latter method, input data at a finer-than-daily time resolution are required, whereas the CN method is lumped over time (Johnson, 1998); the SCS CN approach can typically be applied using daily rainfall values. Runoff contributions from snowmelt can be incorporated by means of a temperature index, a method commonly used in water resources management applications (Walter et al., 2005).

Due to this flexibility, SWAT has been used in many parts of the world (USA, Europe, India, New Zealand, etc.; Abu El-Nasr et al., 2005; Cao et al., 2006; Gosain et al., 2005; Govender and Everson, 2005; Tripathi et al., 2006). However, at present, almost no case study applications of SWAT in Latin America have been documented in the international scientific literature.

4. Data Sources

4.1 GIS data layers

The 90m-resolution topography data from the Shuttle Radar Topography Mission (SRTM DEM, final version) were used as a basis for the modeling process (Fig. 1). The GIS layer representing land use/cover in the basin (Fig. 2) was based on an interpretation of aerial photographs (scale 1:70 000/1:115 000 from 1996-1998; CONAMA-CONAF-BIRF, 1999), combined with information from the "Chilean Inventory of Native Vegetation Resources". The methodology used is based on the land occupation map developed by the Centre of Phytosociological and Ecological Studies L. Emberger, Montpellier, France (Etienne and Prado 1982; CONAMA-CONAF-BIRF, 1999). The GIS layer representing the different soils in the basin (Fig. 3) was obtained from the "Agrological Study of the VIII and IX Region" (CIREN, 1999a,b).

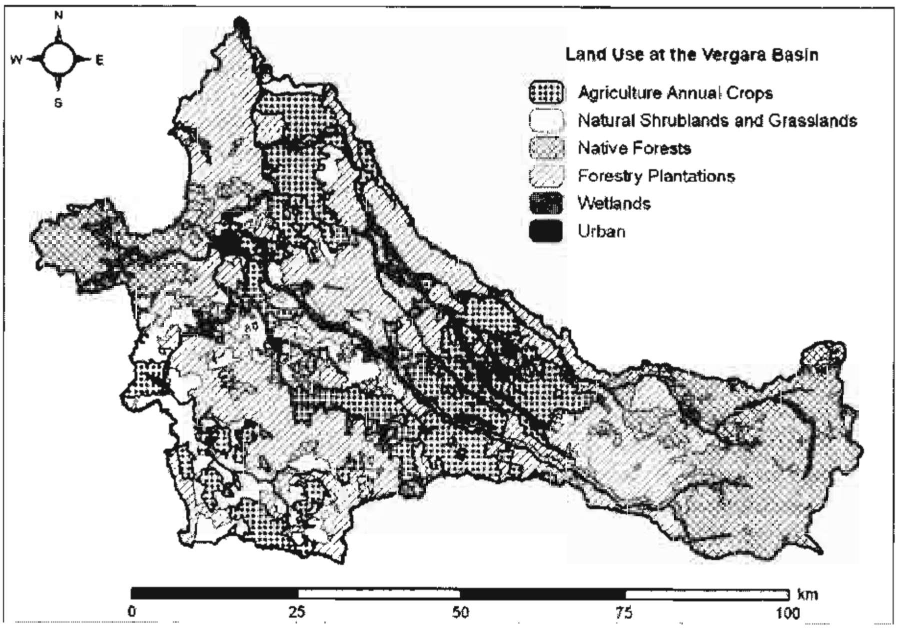

Figure 2. Land use/cover.

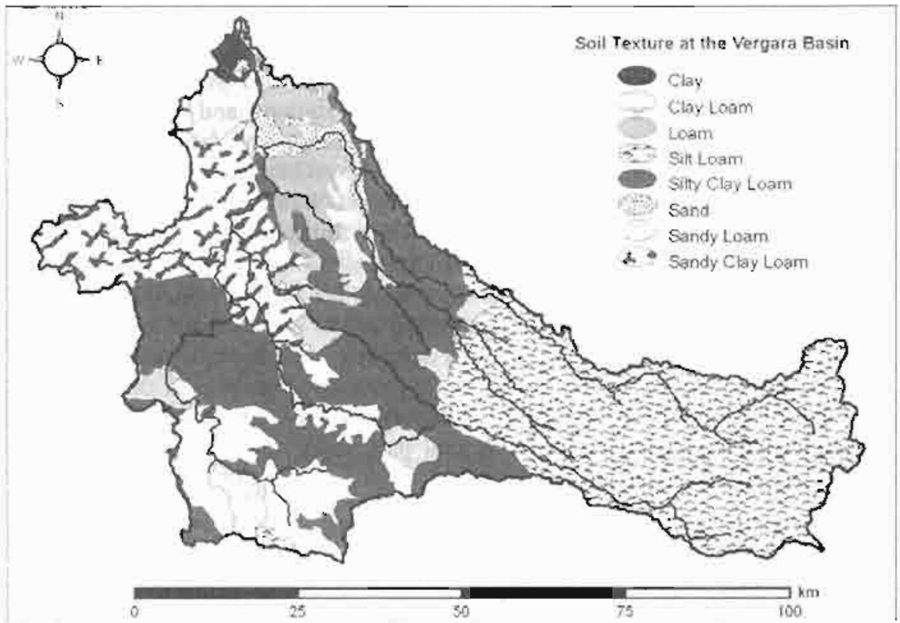

Figure 3. Soil types for the Vergara.

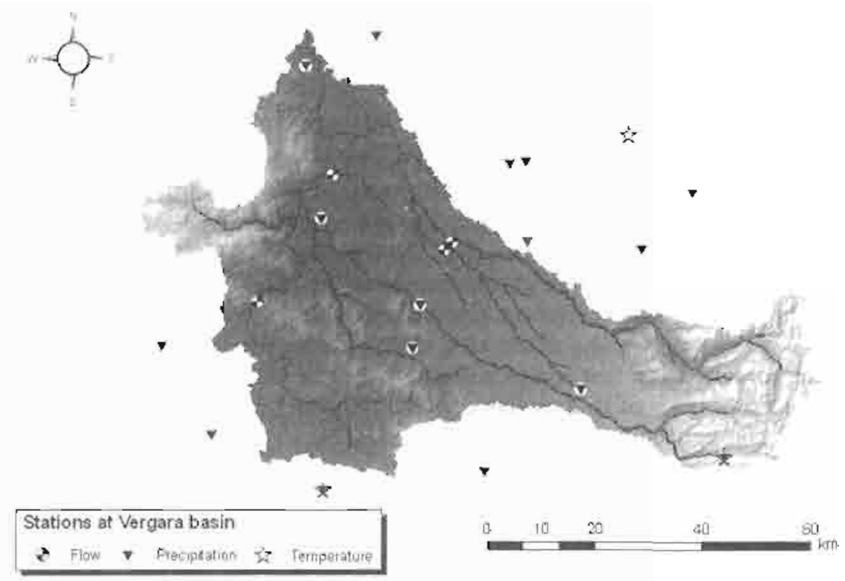

Figure 4. Meteorological and gaging stations used for modeling (the figure also shows the river network extracted by means of the SWAT GIS interface).

4.2 Time series

Input data sets available for the study area consisted of 11 years of time series (1992-2002) of daily precipitation, observed at 16 stations, and temperature, observed at 3 stations, respectively (Fig. 4). Additionally, flow data from four gaging stations located within the basin were used for calibration and validation purposes. Data sets were obtained from the National Water Databank (*Banco Nacional de Aguas*) of the Chilean General Water Directorate (DGA), as well as from private forestry companies that operate meteorological stations in the zone. In correspondence with the available input data, the SCS CN approach and the Hargreaves method were used for calculating runoff and evapotranspiration, respectively. Station density may be low as compared to densities typically encountered in many parts of the developed world (for some examples of densities, see e.g. Samaniego and Bárdossy, 2005). However, they are representative of general Chilean conditions (especially the central part), and similar to those of many other parts of Latin America and the world.

5. Model Configuration

One of the first steps in model setup consists of the identification of the calculation units (or HRUs) for the water balance. For this purpose, the river network for the Vergara basin was extracted from the digital elevation data (DEM), using standard analytical techniques contained in the AVSWAT GIS interface (a minimum upstream contributing area of 50 km^2 was used as a threshold value for defining river cells). In total 51 subbasins were defined and 272 HRUs (unique land use/soil combinations within subbasins) were generated.

5.1 Land use and soil type

Due to the lack of locally established values for the parameters (such as SCS CN, LAI, etc.) that describe the hydrological characteristics of the different land use types in the basin, each locally observed crop or land use type was associated with a "crop/land use type" contained in the SWAT model database. For most cases, locally grown crops were also contained in the SWAT database. For those local crops/land uses that were not represented in this model database, the parameter values corresponding to the most closely related land use types from the database were used as a first approximation. As can be seen in Figure 2, the most important major types of land use/cover in the basin are: forestry plantations, native forest and agriculture, covering 40, 23 and 22% of the total basin area, respectively.

For each soil series, the hydrological group - which is required for the application of the CN method - was derived from the description of soil texture (Fig. 3) contained in the "Agrological Study of the VIII and IX Region" (CIREN, 1999a,b). This was done in agreement with the recommendations given by the USDA (1986). Conductivity values were obtained from Liu et al. (2002, cited in Campos, 2005), horizon depth from CIREN (1999a,b), and the available water capacity was estimated using Soil Water Characteristics calculator (Saxton and Willey, 2005; Saxton and Rawls, 2006).

5.2 Snow

In the upper part of the basin, where snowfall may occur during winter, ten elevation bands were considered. Parameterization of the snowmelt module (e.g. mean air temperature at which precipitation is equally likely to be rain or snow, threshold temperature for snow melt, maximum and minimum melt factors) was done based on data from the Chilean literature (Peña et al., 1985; Escobar, 1992). The precipitation and temperature lapse rates were obtained using the available meteorological data sets.

6. Calibration and Validation

The SWAT model includes a large number of parameters that describe the different hydrological conditions and characteristics across the basin. During a calibration process, model parameters are subject to adjustments, in order to obtain model results that correspond better to discharge rates observed in the field. The range of parameter values used in the calibration process must be physically plausible (Eckhardt et al., 2005), so that the model can be applied afterwards for assessing the impact of change scenarios and/or management options.

Time series of discharge data from four limnigraph stations ('control points') were used for calibration and validation purposes. One of the stations corresponds to a subbasin (Rehue) that is nested in a bigger subbasin (Tijeral), which is also gaged. Together, the four stations cover 80.5% of the total drainage area of the Vergara basin (Fig. 5). For the calibration period, the model was run using rainfall and temperature data from 1998-2002 as input. The first 2 years of the modeling period were reserved for 'model warm-up'.

Prior to the calibration exercise, a sensitivity analysis was executed for each control point, in order to determine the eight parameters to which the model results are most sensitive. At each point, these eight parameters are then used in the calibration process. A ranking of the 'most sensitive' parameters, determined by means of a LH-OAT analysis (Latin Hypercube Sampling - One at A Time; incorporated in the latest model version, SWAT2005) (van Griensven et al., 2006) is given in Table 2.

An automated calibration procedure implemented in SWAT2003 called PARASOL (Parameter Solution Method; van Griensven and Bauwens, 2003) was applied separately to each one of the four subbasins. This procedure used the Shuffle complex evolution algorithm as optimization method, which is a global search algorithm for the minimization of a single function for up to 16 parameters (Duan et al., 1992). It combines the direct search method of the simplex procedure with the concept of a controlled random search, a systematic evolution of points in the direction of global improvement, competitive evolution and the concept of complex shuffling (van Griensven and Bauwens, 2003).

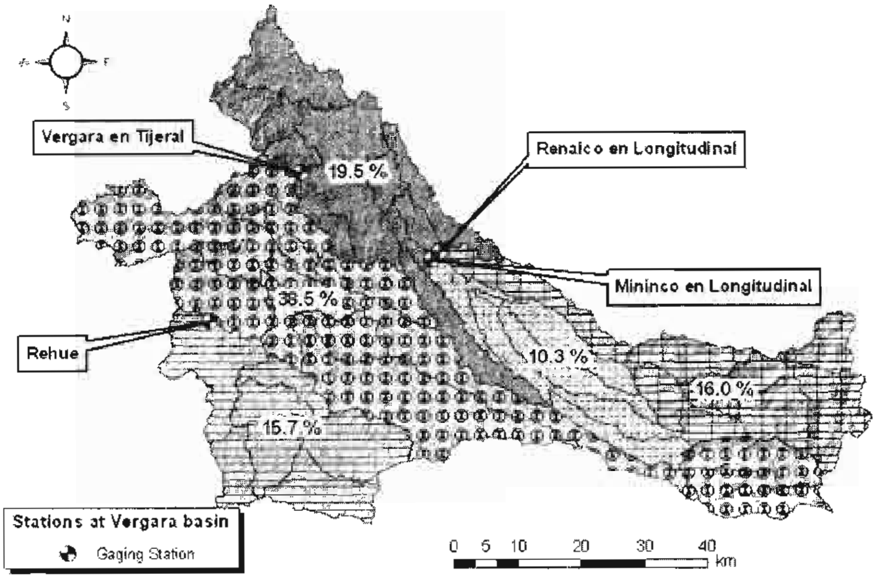

Figure 5. Location of the four gaging stations used for calibration and validation stations and percentage of the total basin area cover by each one of them (Rehue and Tijeral are nested).

Table 2 Ranking of the eight most sensitive parameters per subbasin (1= most sensitive) and their variation range for autocalibration.

Parameter	Description	P1	P2	P3	P4	Range
GWQMN	Threshold water depth in the shallow aquifer for flow	2	3	4	2	0–5000 mm
GW_REVAP	Groundwater revap coefficient*		4		8	0.02–0.20
ESCO	Soil evaporation compensation factor	7	6	6	7	0–1
SLOPE	Average slope steepness	8			5	-5% to 5 %
CN2	Initial SCS CN II value	1	2	1	1	−15% to 15%
SOL_AWC	Available water capacity	3	5	2	4	−10% to 10 %
GW_DELAY	Groundwater delay		8			0–50 days
rchrg_dp	Deep aquifer percolation fraction	4	1	3	3	0.5–1
canmx	Maximum canopy storage	6		5		0–10 mm
sol_k	Saturated hydraulic conductivity	5		8	6	−10% to 10 %
sol_z	Soil depth		7	7		−25% to 25%

To obtain the optimum solution the sum of the squares of the residuals (SSQ) was used; this is similar to the mean square error method (MSE), as it aims to match a simulated series to a measured time series. The parameters and variation range considered in the autocalibration are given in Table 2. The upper and lower bound of: GWQMN, GW_REVAP, ESCO, GW_delay, canmx and Sol_z were selected considering the default values cited by Van Liew et al. (2005) and the range of SLOPE, rchrg_dp, sol_K, CN2 and SOL_AWC were selected on the basis of the results of previous SWAT calibration studies (e.g. Eckhardt et al., 2005; Van Liew et al., 2005; Srinivasan, personal communication, 2005).

Table 3 Statistical indicators used to evaluate model performance.

Name	Formula	Name	Formula
Relative root Mean square error	$\mathrm{RRMSE}=\sqrt{\frac{\sum_{i=1}^{n}(S_i-O_i)^2}{n}}\frac{1}{\overline{O}}$	Goodness of fit	$R^2=\left[\frac{\sum_{i=1}^{n}(O_i-\overline{O})(P_i-\overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\overline{P})^2}}\right]^2$
Mean absolute error	$ABSERR=\frac{\sum_{i=1}^{n}\lvert O_i-S_i\rvert}{n}$	PBIAS	$PBIAS=\frac{\sum_{i=1}^{n}(O_i-S_i)}{\sum_{i=1}^{n}O_i}100$
Nash-Sutcliffe modelling efficiency	$EF=\frac{\sum_{i=1}^{n}(O_i-\overline{O})^2-\sum_{i=1}^{n}(S_i-O_i)^2}{\sum_{i=1}^{n}(O_i-\overline{O})^2}$		O_i: observed streamflow (m^3/s) S_i: simulated streamflow (m^3/s) $\overline{O}$: Mean observed streamflow during evaluation period (m^3/s)

Table 4 Statistical indicators of model performance (monthly output) calculated at the different control points within the Vergara basin: model calibration / model validation.

Index	Tijeral	Rehue	Mininco	Renaico
RRMSE	0.30 / 0.31	0.51 / 0.63*	0.50 / 0.33	0.82 / 0.42
ABSERR	11.64 / 8.24	1.99 / 2.15*	6.31 / 2.98	24.16 / 9.12
EF	0.93 / 0.93	0.82 / 0.75*	0.72 / 0.92	0.54 / 0.82
R^2	0.96 / 0.93	0.88 / 0.80*	0.76 / 0.94	0.71 / 0.83
PBIAS	11.78 / 2.77	21.35 / 32.75*	8.32 / 9.13	32.04 / 7.88

Additionally, the surface lag time (SURLAG) for flow routing was also included in the calibration process, in this case the variation range (0.5-10) was chosen considering recommendations done by Van Liew et al. (2005). In the case of the nested subbasins Rehue and Tijeral, calibration was done first for the 'internal' basin.

Even though the SWAT performs the simulation at a daily level, model calibration was evaluated at monthly level. The statistical indicators used for evaluating model performance are: relative root mean squared error (RRMSE); mean absolute error (ABSERR); the Nash-Sutcliffe modeling efficiency index (EF); the goodness-of-fit (R^2) and the % of deviation from observed stream flow (PBIAS). Table 3 gives the equations used for calculating these indicators, whereas Table 4 gives the value obtained for each one of these indicators during the calibration period. The closer the values of RRMSE and ABSERR to zero, and those of R^2 and EF to unity, the better the model performance is evaluated (Abu El-Nasr et al., 2005). For PBIAS, the optimal value is 0; a negative value indicates an overestimation of observed discharge values, whereas a positive value indicates underestimation. Van Liew et al. (2005) specify the following criteria for interpreting model performance:

(a) An absolute value for PBIAS of less than 20% is considered 'good', values between ±20% and ±40% are considered 'satisfactory', and those greater than ±40% are considered 'not satisfactory'; and

(b) An EF index value greater than 0.75 is considered 'good', values between 0.75 and 0.36 are considered 'satisfactory' and values below 0.36 are considered 'not satisfactory'.

From the results shown in Table 4, it can be seen that best model performance is obtained for the subbasin that closes at Tijeral (i.e. the biggest of the studied subbasins). The poorest results are obtained for Renaico, which has a relatively bigger proportion of its surface area within the Andes, and for which the representativeness of available weather stations may be bad. Overall performance for Rehue (a subbasin of Tijeral) is poorer than for Tijeral as a whole, but water yield for Rehue is proportionally much lower than for the remaining part of the Tijeral basin, so pre-calibration of the Rehue model has a relatively low impact on calibration and model performance at Tijeral. In general the performance over the 3-year calibration period ranges from 'very good' to 'satisfactory' according to the criteria mentioned above.

6.1 Validation

For model validation, a time series of discharge data from the 1992-1999 period was used. Again, the first 2 years from this period were discarded for the evaluation of model performance, as they were considered to correspond to 'model warm-up'. The evaluation was thus based on output generated for the years 1994-1999. Table 4 gives the values of the different statistical indicators. It can be seen that for the Renaico subbasin (and to a lesser extend for Mininco), model performance during validation is substantially better than during the calibration period. A possible explanation can be found in the extreme discharge rates observed during the calibration period (Fig. 6); such extreme discharges are typically (still) not well represented by the model.

7. Discussion of Results

The accuracy of model results was evaluated at the four control points for which time series of observed discharge data were available. Evaluation was done by means of different statistical indicators and by a visual interpretation of observed versus modeled (calibration and validation) discharge time series (Fig. 6). Best model performance (Table 4) was obtained for the Tijeral subbasin, where the Nash-Sutcliffe index (EF) calculated from monthly runoff values was 0.93 for both the calibration and validation period. The EF index for other subbasins ranged from 'good' to 'satisfactory' for the calibration period; based on this same index the model performance was 'good' for all subbasins during validation. For the indicator PBIAS, Tijeral and Mininco present a good performance, whereas Rehue and Renaico can be considered satisfactory. However, over the long term as well as for the peak flows the model typically underestimates the runoff. One possible explanation for this may be found in an inadequate description of the

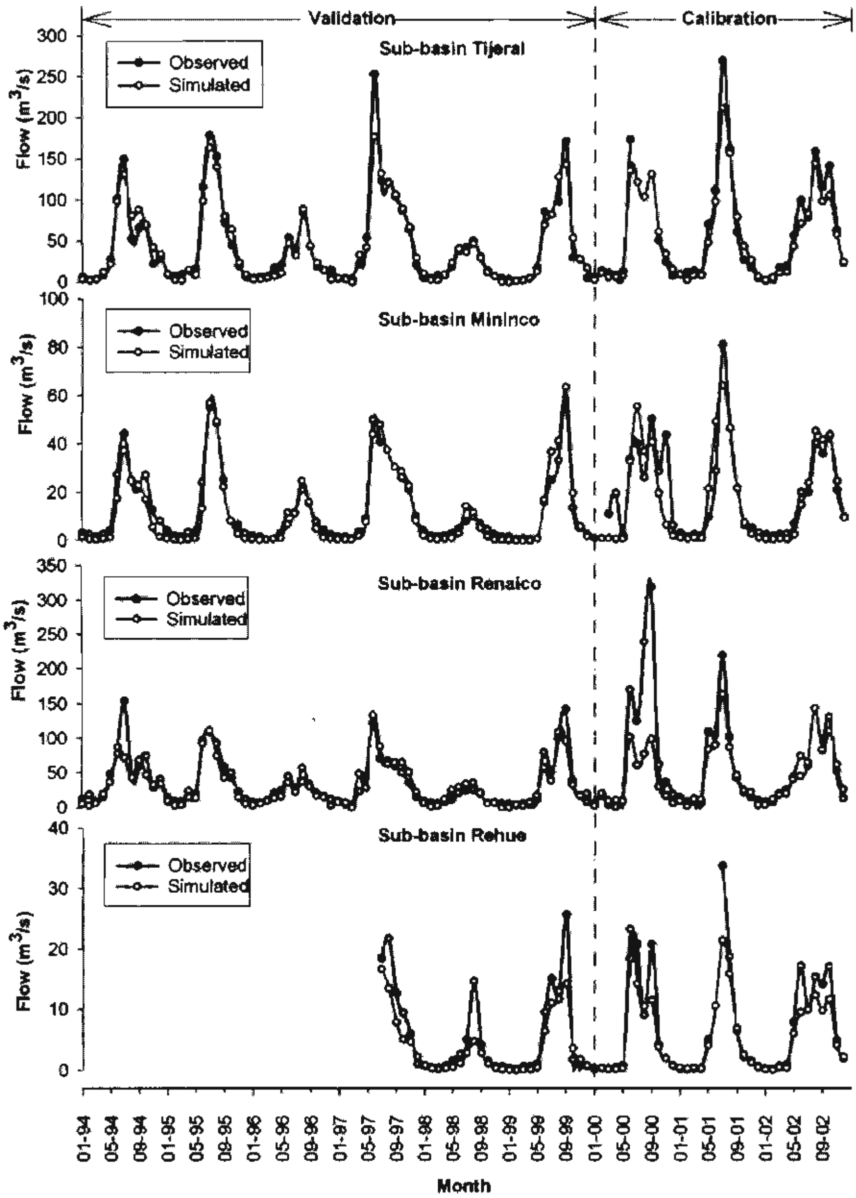

Figure 6. Calibration and validation model results (monthly output) at the different control points.

rainfall input field, caused by the limited number of available meteorological stations, as well as by their poor representation in areas of higher altitudes (orographic effects). It is relevant to remember in this context that climate information represents the main forcing data for a hydrological model (Hattermann et al., 2005). Even when the importance of spatial variability of rainfall in simulating runoff was recognized already more than three decades ago (Osborn and Keppel, 1966; Rodda, 1967; Dawdy and Bergman, 1969), the assumption of uniform rainfall over relatively large surface areas remains a common practice in many hydrological modeling applications (Chaubey et al., 1999). In this context, discrete improvements in model performance may still be expected from the testing of alternative interpolation techniques, rather than by using the 'nearest neighbor' assignment (~Thiessen Polygons), which is the standard method in AVSWAT. For this reason, future research on the Vergara basin will include an evaluation of the effects of better descriptions of the spatially variable rainfall input fields, using methods such as: inverse distance weighting, kriging, co-kriging, radial basis functions, etc. (Hevesi et al., 1992; Daly et al., 1994; Martínez-Cob, 1995; Hutchinson, 1998, 2000; Goovaerts, 2000; Hattermann et al., 2005).

For the Tijeral subbasin, which represents 54% of the study area, the total volumetric error over the calibration and validation period was approximately 12% and +3%, respectively. The volumetric error for the other subbasins ranged from +8 to +32% (calibration set) and from +8 to +33% (validation set).

Model performance was further analyzed separately for the period of low flows (November-April) and high flows (May-October). Table 5 shows the Nash-Sutcliffe EF and PBIAS calculated from pooled monthly output data for the dry and rainy season respectively, for the three stations for which the long validation time series were available. According to EF, in all the subbasins the model performed better during the high flow period than during the low flow period. Results for the low flow period in the Renaico subbasin were not satisfactory according to this parameter. PBIAS was good for both periods in Tijeral and Renaico, but was not satisfactory for the low flow period in Mininco. In this context, it can be noted that of the three stations included in the analysis, Mininco also has the lowest mean monthly discharge values for the low flow period.

Table 5. Statistical index for the validation period, separately evaluated for the low flow (November-April) and high flow (May-October) periods.

Basin	EF		PBIAS	
	Low	High	Low	High
Tijeral	0.69	0.89	−3.14	3.62
Mininco	0.63	0.89	47.72	1.96
Renaico	0.24	0.71	5.21	8.47

The sensitivity analysis showed a high sensitivity of model results to the SCS CN2 parameter (Table 2). National or regional databases relating CN to local land use/cover and/or soil types are currently not available for Chile. Development of such a database based on (a) local empirical data combined with (b) the results from modeling applications may improve both model performance as well as its usefulness for practical management purposes. It may be worthwhile to further analyze the spatial and temporal variability of CN2 as well as the pre-specified ranges used in the calibration process. Substantial additional research at the national level will be required in this area. In the currently used version of the AVSWAT model, the standard option included for describing the spatial variability of rainfall fields (assignment of nearest station rainfall value to each subbasin) is rather simplistic. Improvements in this area by means of the testing of different interpolation techniques (e.g. Hattermann et al., 2005) may further contribute to better model performance, especially where orographic effects are important. Potential improvements, however, will depend at least partially on the local availability of weather station data (especially critical at higher altitudes) and on the length and quality of the available time series.

8. Conclusions

Under local conditions of data availability, the performed SWAT model application for the Vergara basin confirms that SWAT is a useful tool that can already be used to make preliminary assessments of the potential impact of land use and climate changes on the hydrology of this basin. These assessments will consequently be based on the best currently available knowledge for the study area. However, further improvements in model performance should be sought. Meanwhile, when using outcome from the model, the limitations inherent in the modeling approach used should be taken into account.

The present work should be considered as a first step in the development of a bigger model application involving the entire Biobío basin. However, current conditions of data availability do not yet allow such an application. Current results can already be used to establish priorities for obtaining additional field data sets, which should allow such an application in the long term.

Future research on the Vergara model itself should address the aspects of spatial variability of rainfall fields, inter- and intra-annual variability of CNs and the development of a regional/national database relating CN to local land use/cover types.

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2.10 Continental Scale Simulation of the Hydrologic Balance

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Abstract

This paper describes the application of a continuous daily water balance model called SWAT (Soil and Water Assessment Tool) for the conterminous U.S. The local water balance is represented by four control volumes; (1) snow, (2) soil profile, (3) shallow aquifer, and (4) deep aquifer. The components of the water balance are simulated using 'storage' models and readily available input parameters. All the required databases (soils, land use, and topography) were assembled for the conterminous U.S. at 1:250,000 scale. A GIS interface was utilized to automate the assembly of the model input files from map layers and relational databases. The hydrologic balance for each soil association polygon (78,863 nationwide) was simulated without calibration for 20 years using dominant soil and land use properties. The model was validated by comparing simulated average annual runoff with long-term average annual runoff from USGS stream gage records. Results indicate over 45 percent of the modeled U.S. are within 50 mm of measured, and 18 percent are within 10 mm without calibration. The model tended to underpredict runoff in mountain areas due to lack of climate stations at high elevations. Given the limitations of the study (i.e. spatial resolution of the databases and model simplicity), the results show that the large-scale hydrologic balance can be realistically simulated using a continuous water balance model.

Keywords: surface water hydrology, modeling/statistics, evapotranspiration, plant growth, geographic information systems

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1. Introduction

The renewable water resources for the conterminous United States are derived from an average annual precipitation of 760 mm. Seventy percent of this rainfall is consumed through evaporation and transpiration. The remaining 30 percent of precipitation constitutes an average annual runoff of about 230 mm (WRC, 1978). Management and utilization of these resources depends upon the spatial distribution of rainfall, location of reservoirs, evapotranspiration (ET) potential, soil and groundwater storage, and water quality. All of these factors vary from basin to basin. Continental-scale maps representing some of the above components have been prepared such as annual runoff (Langbein, 1980) and precipitation-evaporation (Winter, 1990). While important in illustrating regional trends, these studies do little toward assessing the potential interaction of the components of the water balance. Basin-scale assessments have been made to determine the adequacy of water supply regions (WRC, 1968, 1978; Hirsch et al., 1990) and make projections based on estimates of population and land use, but again are not designed to account for interactions between the components of the system. Projections are made by predicting average values into the future without regard to potential thresholds or feedback loops within the system.

Water balance models attempt to predict the partitioning of water among the various pathways inherent to the hydrologic cycle (Dooge, 1992). Early models developed in the 1940s are essentially bookkeeping procedures that estimate the balance between inflow (precipitation and snowmelt) and outflow (ET, stream flow, and groundwater) (Alley, 1984). While generalized global water balance maps have been prepared, they often lack the necessary scale to be useful in even the simplest modeling efforts (UNESCO, 1978). More advanced water balance models have been used to assess the effects of land management, seasonal irrigation demands, prediction of stream flow and lake levels, recharge to the groundwater system, groundwater storage, and as a means of assessing the impact of vegetation on water yield (runoff, soil flow, and groundwater flow) and sediment yield (Chiew and McMahon, 1990; Winter, 1981; Essery, 1992; Thomas et al., 1983; Bultot et al., 1990; Arnold et al., 1993). Robbins Church et al. (1995) developed a simple water balance equation using measured precipitation and runoff to compute ET and runoff precipitation ratios for the northeast United States. More recently, general circulation models (GCMs) have linked atmospheric models to land-surface water balance models and emphasized the importance of the land based hydrologic cycle to global energy fluxes (Wood et al., 1992), and conversely, the effects of atmospheric contaminants ($C0_2$), on land surface runoff (Miller and Russell, 1992). Recent research on the land based component of the water balance using simplified inputs of potential evapotranspiration and soil water holding capacity (0.5 degree resolution) have shown the importance of soil storage control in the regional water balance (Milly, 1994). Liang et al. (1994) used a simple 2-layer soil storage model with a vegetation component to model surface water and energy fluxes for GCMs.

The SWAT model (Arnold et al., 1998) provides the modeling capabilities of the HUMUS (Hydrologic Unit Model of the United States) project (Srinivasan et al., 1993). The major components of the HUMUS project are: (1) SWAT to simulate surface and subsurface water quality and quantity; (2) a Geographic Information System (GIS) to collect, manage, analyze, and display the spatial and temporal inputs and outputs (Srinivasan and Arnold, 1994); and (3) relational databases required to manage the non-spatial data (Fig. 1). HUMUS simulates the hydrologic budget, sediment and nutrient movement for approximately 2,100 8-digit hydrologic unit areas as delineated by the USGS. Findings of the project are being used in the Resource Conservation Act (RCA) Assessment conducted by the Natural Resources Conservation Service. Planning scenarios include agricultural and municipal water use, tillage and cropping system trends, and fertilizer/ manure management.

The purpose of this study is to present findings of the HUMUS continental-scale modeling effort of all the major river basins of the conterminous United States as they relate to regional runoff and water supply. This modeling effort has been validated against average annual runoff using all existing gaging stations of the USGS. The modeled results allow assessment of spatial variations in runoff of the conterminous United States. If runoff can be simulated with reasonable accuracy, the model can then be validated for sediment and nutrient yields for further NRCS national agricultural policy scenarios. Results should also allow for more accurate assessments of the effects of land use changes and water management initiatives as well as provide a tool for parameterization of GCMs.

2. Theoretical Framework

2.1 Overview

The overriding objective of this study is to develop the most realistic physical representation of the water balance possible while utilizing data that is readily available for large regions of the U.S. This requires that model input parameters are physically based and that calibration is not attempted. Most model input parameters are physically defined such as topography (slopes and flow lengths), soil properties (texture, bulk density, saturated conductivity, etc.) and plant characteristics (biomass to energy conversions, maximum height and rooting depth, etc.). Some of the relationships used in the model, such as the curve number, are based on physical properties such as soil type and land use and do not require calibration (i.e. measured stream flow and ET are not required). However, there is often considerable uncertainty in model inputs due to spatial variability and measurement errors. In most watershed studies, inputs are allowed to vary within a realistic uncertainty range for calibration and validation then is performed on another period of data. In this study, the model was only validated using average annual runoff.

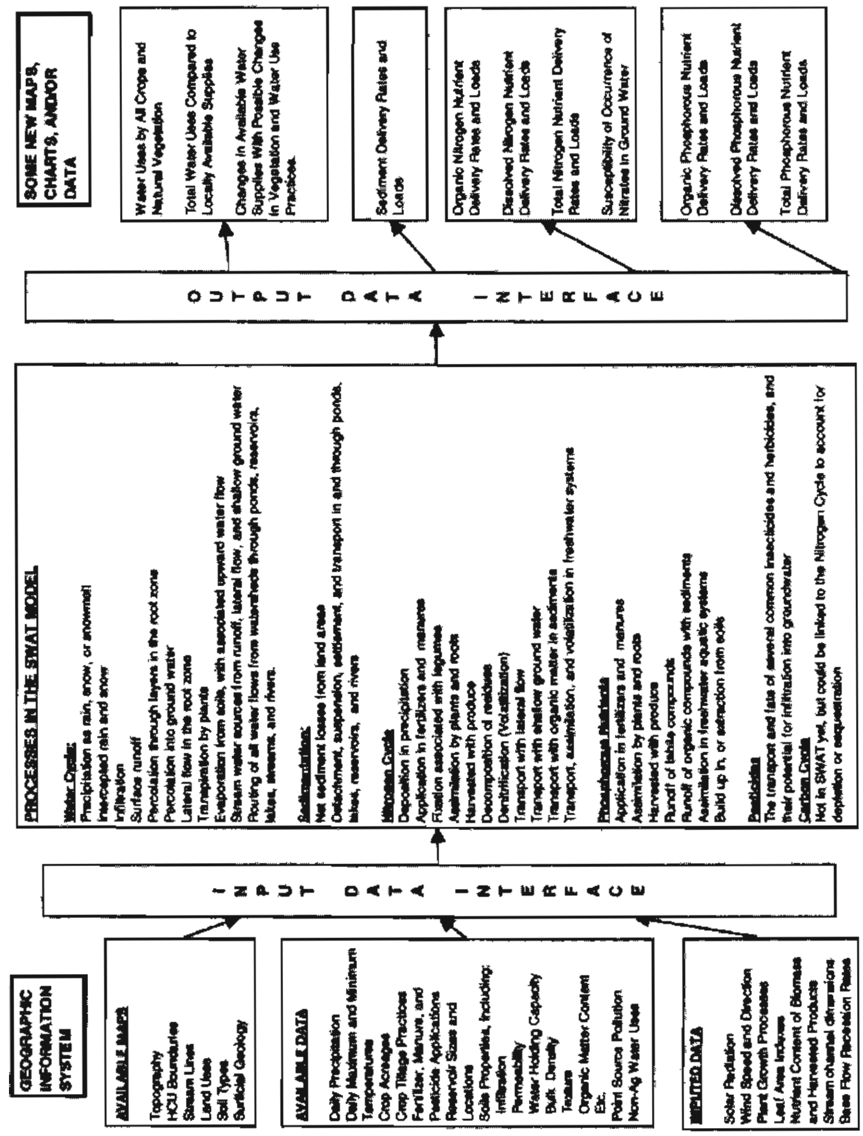

Figure 1. The HUMUS Project System.

The other main objective of this study is to develop the ability to simulate the impact of climate and land use changes on the water balance. Climate change scenarios include projected annual and seasonal changes in precipitation, temperature, and CO_2. Land use scenarios include vegetative changes (i.e. forest to agricultural land) and cropping system changes. This requires the ability to simulate tillage systems and nutrient/pesticide application scenarios.

2.2 Spatial and temporal variability

A common approach in simulating the water balance of large areas is to subdivide the area into homogeneous modeling subareas. Although there are numerous discretization schemes that are possible, we chose to use soil associations as the basis for modeling subareas. The dominant (by area) soil series, and the corresponding physical properties, for each soil association polygon were used. While, there is considerable variability in soil hydraulic properties even at relatively small scales (Warrick and Nelson, 1980), some lumping of soil properties must be made since available regional-scale data bases do not include sufficient spatial detail.

Vertical variability within the polygon is modeled by dividing the water balance into three control volumes: the soil profile, shallow aquifer, and deep aquifer. The soil profile can be subdivided further to account for soil horizons that may have a significant impact on percolation, surface runoff, and root growth. The shallow aquifer is directly below the soil profile and is assumed to (1) actively circulate groundwater and respond rapidly to changes in discharge and recharge, (2) have relatively short travel times, and (3) supply a large percentage of baseflow to the stream (Moody, 1990). Seepage from the shallow aquifer recharges the deep aquifer. The deep aquifer does not contribute to stream flow in the model.

To represent temporal variability, the model continuously updates the water balance on a finite time step (one day). Thus, the model can run continuously for many years and describe annual and seasonal variability. A long-term regional database of weather data at subdaily time steps is not currently available at similar spatial resolution as daily weather data. Also, a monthly time step cannot account for the variation in individual surface runoff events within the month. Daily weather data is readily available and daily stochastic weather generators (for a point) have been parameterized and such an approach has been in use for many years (Richardson, 1981).

2.3 Description of algorithms

Water storage is divided into four distinct components as shown in Figure 2: (1) snow profile (above the ground surface), (2) soil profile (0-2 m), (3) shallow aquifer (2-50 m), and (4) deep aquifer (> 50 m). Equations and detailed descriptions are found in Arnold et al. (1998).

Snow cover. The control volume for snow cover is bounded above by the snow-atmosphere interface and below by the snow-soil interface. The mass balance of water in the snow control volume consists of snow fall, snow melt and sublimation.

Soil profile. The upper boundary of the soil profile is the soil-atmosphere (or soil-snow if snow is present) interface. The lower boundary corresponds to the average rooting depth of the vegetation. This normally coincides with the depth that the soils have been characterized in soil surveys and is less than 2 meters. Since a modeling subarea is considered homogeneous, the horizontal extent of the soil control volume is irrelevant (soil heterogeneity and topographic effects are neglected). However, it should be noted that horizontal water flux between subareas is not considered. Processes simulated include: surface runoff, lateral soil flow, percolation, evapotranspiration, soil temperature, plant growth, and management (irrigation, fertilization and residue management).

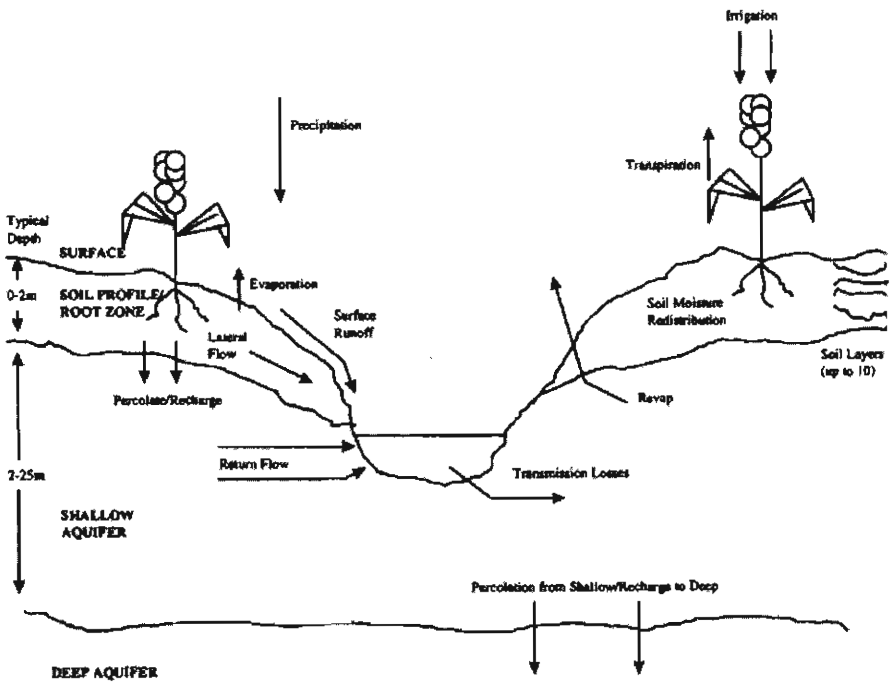

Figure 2. Schematic of subbasin hydrologic balance.

Shallow aquifer. Ground water flow systems can be classified into three types of depth and proximity to surface drainage features: (1) shallow, (2) intermediate, and (3) regional flow systems (Toth, 1963). The shallow flow systems: (1) actively circulate groundwater and respond rapidly to changes in discharge and recharge, (2) have relatively short travel times, and (3) supply a large percentage of base flow to the stream (Cannon, 1989). The shallow groundwater flow component in SWAT is intended for general use where extensive field work to obtain inputs (pump tests, etc.) is not feasible and thus the model must use readily available inputs. For more detailed, site-specific studies, Sophocleous et al. (1999)

have linked SWAT to MODFLOW, a two-dimensional groundwater flow model.

The shallow aquifer control volume is bounded above by the soil-shallow aquifer interface and below by the interface with the deep aquifer. Typical depth of the shallow aquifer is 2-25 m and processes simulated include return flow, plant water uptake, percolate to the deep aquifer, and water withdrawals. A complete description of the groundwater flow component is found in Arnold et al. (1993).

Deep Aquifer. It is assumed that there is no interaction between the deep aquifer and the stream. Also, no underflow is allowed to occur from one modeling subarea to another. Processes simulated in the deep aquifer are percolate from the shallow aquifer and water withdrawals.

3. Previous Model Validation

Ideally, we would like to validate all simulated components of the hydrologic balance (surface runoff, groundwater flow, ET, recharge, etc.) with measured estimates for the entire U.S. Unfortunately, measured estimates of the individual components of the hydrologic balance are not generally available. However, the SWAT model has been compared against measured components of the hydrologic balance at several locations throughout the U.S. Table 1 shows the location, reference, basin area, and validated components for each location. These locations represent a wide range of soils, land use, climate, and topography. The most comprehensive testing was performed for three basins in Illinois (Arnold and Allen, 1996). Schicht and Walton (1961) used precipitation, stream flow, and groundwater level data to ascertain groundwater recharge, runoff, and ET for all three basins. This data was then compared against SWAT simulated results with reasonable agreement.

A component of the model that has had limited testing is ET. Monthly simulated ET was compared against measured ET from lysimeters growing corn and bluegrass. The impact of irrigation on annual ET and corn yields at Bushland, Texas, was simulated by the model illustrating corn yield response to increasing volumes of irrigation water (Arnold and Williams, 1985). Arnold and Stockle (1991) demonstrated the models ability to simulate dryland wheat yields under extreme differences in climate and soil conditions. While the runoff validation in this study only compares average annual values, it is important to note that the model has been validated against monthly time series and is capable of simulating seasonal variability. Numerous studies (Table 1) confirm that this modeling approach is capable of simulating realistic monthly time series of runoff, and several other components of the hydrologic balance across the U.S.

Table 1. Model validation studies.

Location	Reference	Drainage Area (km^2)	Water Yield/ Streamflow	Soil Water	Surface Runoff	Base Flow	Soil ET	GW ET	GW Recharge	Plant Biomass
1. Middle Bosque River, Texas	Arnold *et al.* (1993)	471	X		X	X			X	
2. Coshocton, Ohio	Arnold and Williams (1985)	lysimeter					X			
3. Bushland, Texas	Arnold and Williams (1986)	field plot					X			X
4. Riesel, Texas Sonora, Texas	Savabi *et al.* (1989) Savabi *et al.* (1989)	1.3 4.1	X X	X X			X			
5. Seco Creek, Texas	Srinivasan and Arnold (1994)	114	X							
6. Neches River Basin, Texas	King *et al.* (1999)	25,032	X							
7. Colorado River Basin, Texas	King *et al.* (1999)	40,407	X							
8. Lower Colorado, Texas	Rosenthal *et al.*	8,927	X							
9. White Rock Lake, Texas	Arnold and Williams (1987)	257	X							
10. North Carolina	Jacobson *et al.* (1995)	4.6	X		X					
11. Goose Creek, Illinois	Arnold and Allen (1996)	246	X	X	X	X	X	X	X	
12. Hadley Creek, Illinois	Arnold and Allen (1996)	122	X	X	X	X	X	X	X	
13. Panther Creek, Illinois	Arnold and Allen (1996)	188	X	X	X	X	X	X	X	
14. Goodwin Creek Watershed, Mississippi	Binger *et al.* (1996)	21.3	X							
15. Watersheds in: Oklahoma, Ohio, Georgia, Idaho, Mississippi, Vermont, Arizona	Arnold and Williams (1987)	9.0-538	X							
16. Bushland, Texas Logan, Utah Temple, Texas	Arnold and Stockle (1991)	field plot								X

4. Application

The model presented in the section entitled 'Theoretical Framework' was tested for its ability to reproduce components of the annual water balance. The test region is the entire conterminous United States. The first part of this section describes how the input variables were estimated. All the required databases (soils, land use and DEM) were assembled at 1:250,000 scale. A GIS interface

(Srinivasan and Arnold, 1994) was utilized to automate the assembly of the model input files from map layers and relational databases. The hydrologic balance for each soil association polygon (78,863 nationwide) was simulated for 20 years using dominant soil and land use properties. Channel and impoundment routing were not simulated and thus inputs were not developed.

4.1 Estimation of inputs

Digital Elevation Model (DEM) attributes – Overland slope and slope length for each subbasin was estimated using the 3-arc second DEM. Overland slope was estimated using the neighborhood technique (Srinivasan and Engel, 1991) for each cell and calculating an average slope for the entire subbasin.

Land use attributes – The USGS-LUDA (land use/land cover) data (USGS, 1990) were used to develop plant inputs to the model. The dominant land use was used for each subbasin and a plant parameter database was used to characterize each crop. The broad classification used in the LUDA was urban, agriculture/ pasture, range, forest, wetland, and water as categories. A heat unit scheduling algorithm was used to find probable planting dates of a land use based on location (latitude and longitude) of a subbasin, monthly mean temperature, and land use type. Due to lack of information about specific crops from the LUDA database, this study used corn as the agricultural crop across the U.S., which was thought to be appropriate since corn is the major crop grown in many parts of the U.S. and since it will have a similar impact on the water balance as other summer crops.

Soils attributes – The STATSGO-soil association map (USDA, 1992) was used for selection of soil attributes for each subbasin. Each polygon contains multiple soil series, and the areal percentage of each is given (without regard to spatial location). The dominant soil series (largest area) was selected by the GIS interface. Once the soil series was selected, the interface extracted the properties for the model from a relational database. Soil physical properties include texture, bulk density, saturated conductivity, available water capacity, and organic carbon. The curve number (CN) was assigned to each subbasin, based on land use and the hydrologic soil group of the dominant soil series.

Irrigation attributes – This study used the STATSGO database to identify locations using irrigation due to lack of spatial irrigation databases showing irrigated agricultural areas. STATSGO reports irrigated crop yield for any crop in this table, and if the land use (from the USGS-LUDA) was agriculture, the entire subbasin was assigned as irrigated agriculture. Figure 3 shows the location of irrigated agriculture identified through above process. Using this irrigation layer the input interface created input parameters for automated irrigation application for each subbasin. The model automatically irrigates a subbasin and replenished soil moisture to field capacity when the crop stress reaches a user defined level.

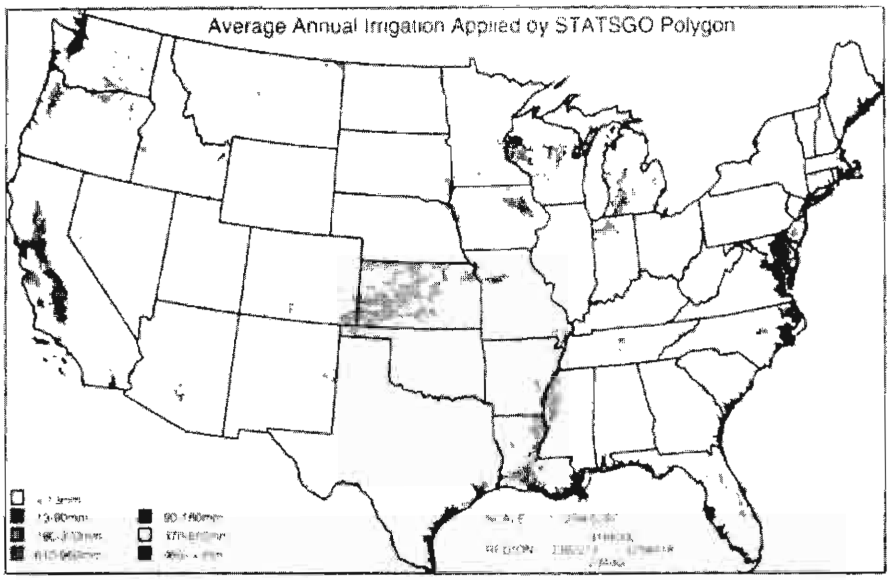

Figure 3. Location and amount of annual irrigation water applied.

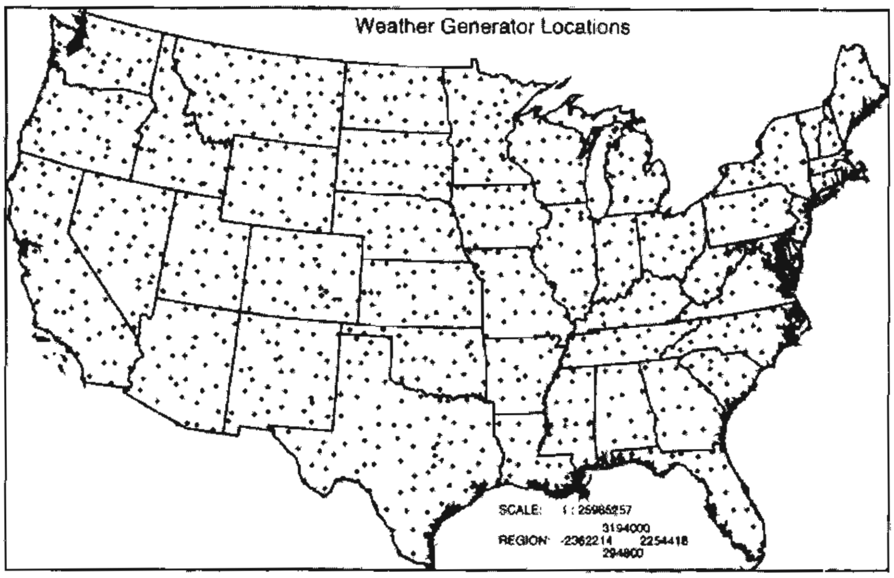

Figure 4. Location of weather generator parameter sites.

Weather attributes – The model utilized monthly weather generator parameters from approximately 1,130 weather stations to simulate daily precipitation, maximum and minimum temperatures, solar radiation, wind speed, and relative humidity. The GIS interface selected the nearest weather station for each subbasin. (Fig. 4). The interface also extracted and stored the monthly weather parameters in a model input file for each subbasin.

4.2 Comparisons with observed runoff for entire U.S.

The model was run for 20 years to obtain average annual values of runoff to compare against observed runoff. Observed runoff was determined by Gebert et al. (1987) from measured stream flow from 5,951 gaging stations that were unaffected by reservoirs, diversions or return flow. This analysis covered the entire U.S. for the period 1951-1980. Modeled runoff is defined as the sum of surface, lateral flow from the soil profile, and groundwater flow from the shallow aquifer which corresponds to observed runoff determined by Gebert et al. (1987). The model assumes that groundwater flow returns within the subbasin and that there is no net groundwater inflow or outflow. No calibration was performed and model inputs were taken without modification from the existing databases. Stream flow and potential ET were not used in developing model inputs. The modeled and observed annual runoff estimates are shown in Figures 5a and 5b. The large-scale features of the observed runoff are apparent in the simulated runoff. High values of runoff are observed from the Northeast States through the Appalachian mountain, down to the northern coast of the Gulf of Mexico. Runoff decreases from east to west between the Mississippi River and the Rocky Mountains. The high runoff of the Pacific Northwest rainforest is also simulated by the model.

The difference between observed and simulated runoff is shown in Figure 6. Negative values identify areas where the model overpredicts while positive numbers signify model underprediction. The model has a general tendency to underpredict runoff in mountain areas. This is evident in Figure 6 in the Appalachian Mountains and the western U.S. This is attributed to the lack of weather data in higher elevations. Typically, weather stations in the western U.S. are located in the valleys that generally have lower precipitation. There was no attempt in this study to correct precipitation and temperature for elevation. The model tends to overpredict runoff in areas that are irrigated (see Fig. 3). This may be due to previous assumption used in the model where irrigation was applied to the entire subbasin when the database reports that cropland within that subbasin may be irrigated. This is the limitation of the irrigation database as well as using only the dominant soil and land use for each subbasin. It should be noted that the spatial resolution of the simulated runoff (Fig. 5b) is considerably finer than the observed runoff (Fig. 5a). Some discrepancies in the two maps may be due to lack of resolution in the observed runoff, fewer stations, and more smoothing of the data set.

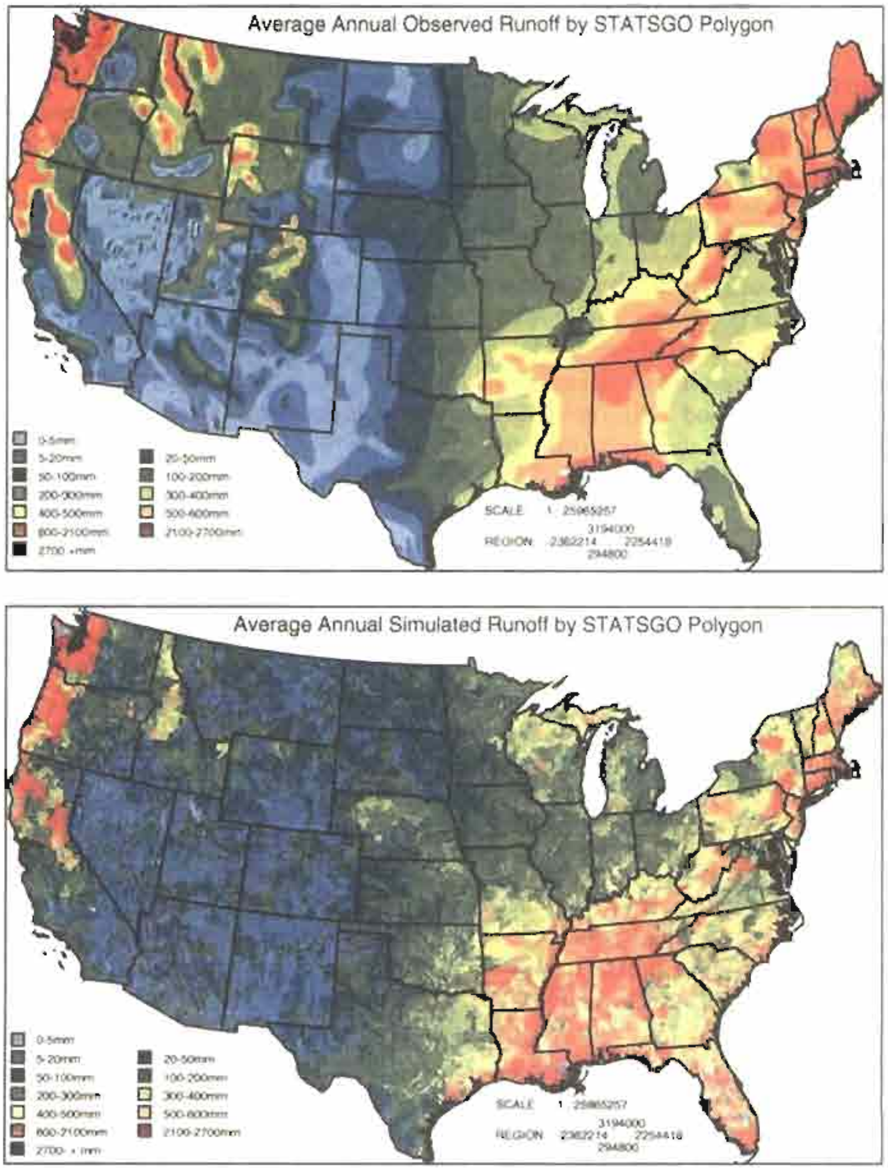

Figure 5. (a) Observed average annual runoff for U.S. from USGS stream flow records (top); and (b) Simulated average annual runoff for U.S. (bottom).

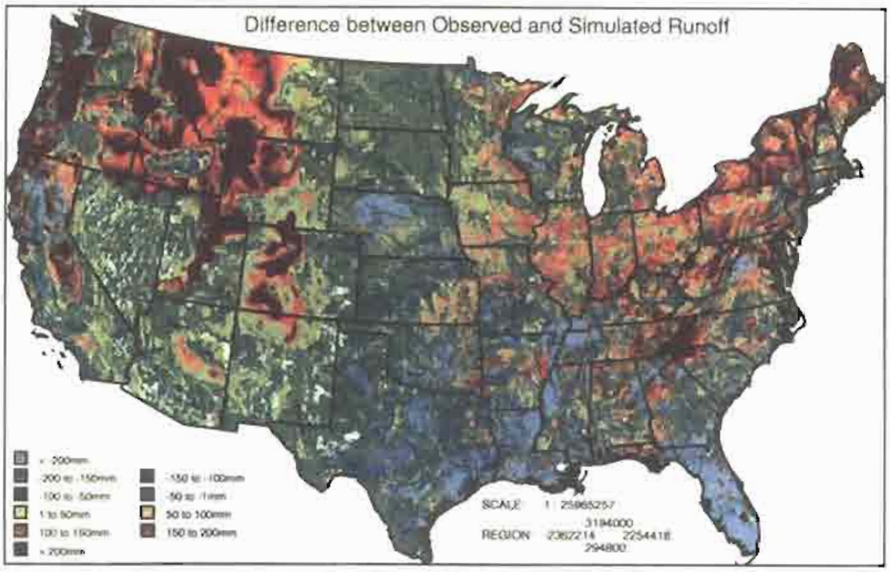

Figure 6. Difference between observed and simulated averaged annual runoff.

Summation of runoff errors show that over 45 percent of runoff difference between modeled and observed falls within 50 mm and 18 percent fall within 10 mm. This compares well considering input uncertainty and the fact that no calibration was performed. It also compares favorably with others studies (Milly, 1994). The simple water balance model of Liang et al. (1994) produced major errors in peak runoff. However, the purpose of evaluation was to provide evidence that the model is producing a reasonable soil water balance to GCMs. For that purpose the runoff simulations of Liang et al. (1994) were judged adequate.

Regression analysis was performed by state (Fig. 7) and by soil association polygon (Fig. 8). Average runoff by state compares well with a regression slope of 0.95 and R^2 of 0.18. The R^2 determined by comparing measured and simulated runoff for each of the 78,863 soil association polygons was lower at 0.66. The model displayed a general tendency to underpredict subareas with high runoff. This is again attributed to both the use of only the dominant soil in each polygon and a lack of more precise irrigation database.

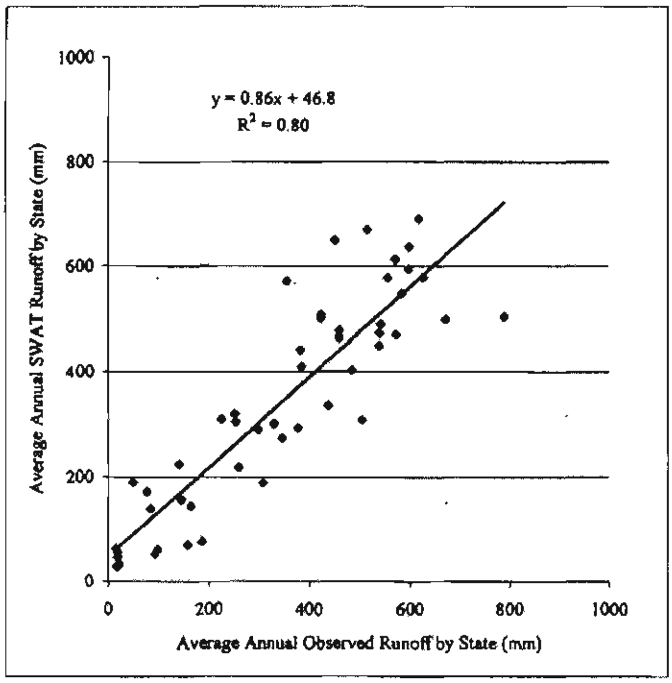

Figure 7. Regressiion of observed and simulated runoff by state.

Figure 9 shows simulated potential and actual ET. Although validation was not performed, expected large-scale features were evident and potential ET compares favorably to the method of Thornwaite (Legates and Willmott, 1990).

4.3 Limitations and implications for future studies

Databases. There are several limitations of the databases used in this study. Soil properties for each series are reported as a range and the midpoint was selected for model input. Within each soil association polygon only areal percentages of soil series are given without regard to spatial position within the polygon. Selecting the dominate soil to represent the entire polygon can cause runoff errors of 30 percent or more (Arnold, 1992). Using the dominant land use for each subbasin can similarly impact model output as the runoff is a function of soil and land use combinations.

Another database limitation involves the location of the weather stations. Elevation and orographic effects are not considered since the vast majority of the weather stations in the coterminous U.S. are located near airports or in valleys next to cities and not distributed in the higher elevations. This can significantly affect the hydrologic balance and is the probable reason for the discrepancies between measured and predicted runoff in the western mountain areas.

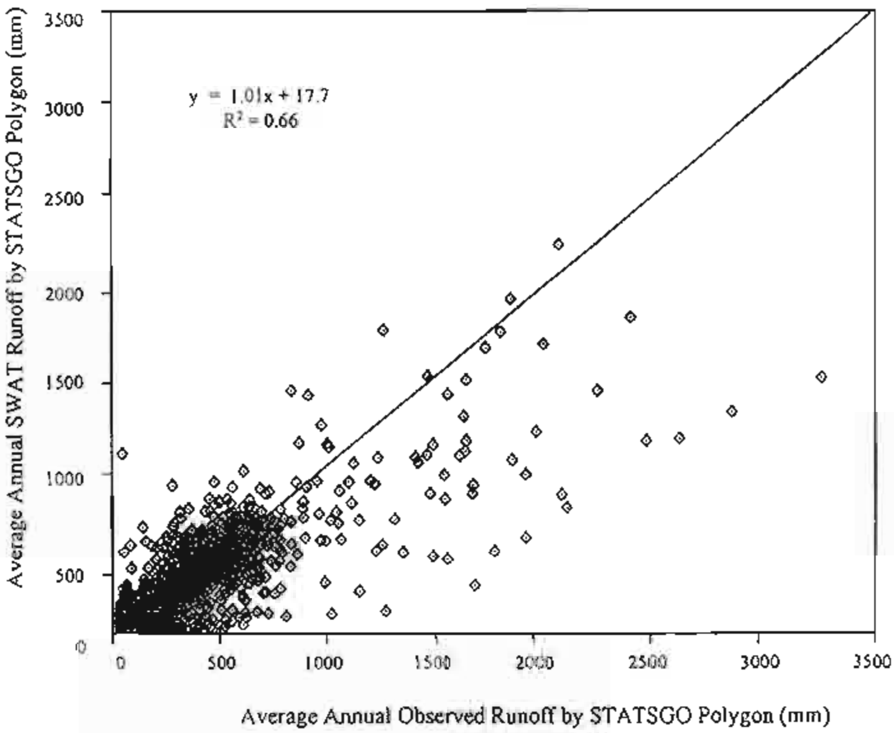

Figure 8. Regression of observed and simulated runoff by soil association polygons.

Model algorithms. Selection of a rainfall runoff model is a compromise between model complexity and available input data. While more complex models may better represent the physical processes, the assumption that they lead to more reliable results has been questioned (Loague and Freeze, 1985). They have shown that the simpler, less data intensive models provided as good or better prediction than the physically based models. An empirical model is a representation of data and has no real theoretical basis. A physically based model is one that has a theoretical basis and whose parameters and variables are measurable in the field (Beven, 1983). In reality, many empirical relationships are used for parameter esti-mation by the 'physically based' models (Wilcox et al., 1990). The SCS runoff equation is basically an empirical model that came into common use in the 1950s and is the product of more than 20 years of studies of rainfall-runoff relationships from small rural watersheds. The model was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types (Rallison and Miller, 1981). No other rainfall-runoff model has been used as successfully or as often on ungaged rangeland adequate procedure to use in regional estimates of runoff.

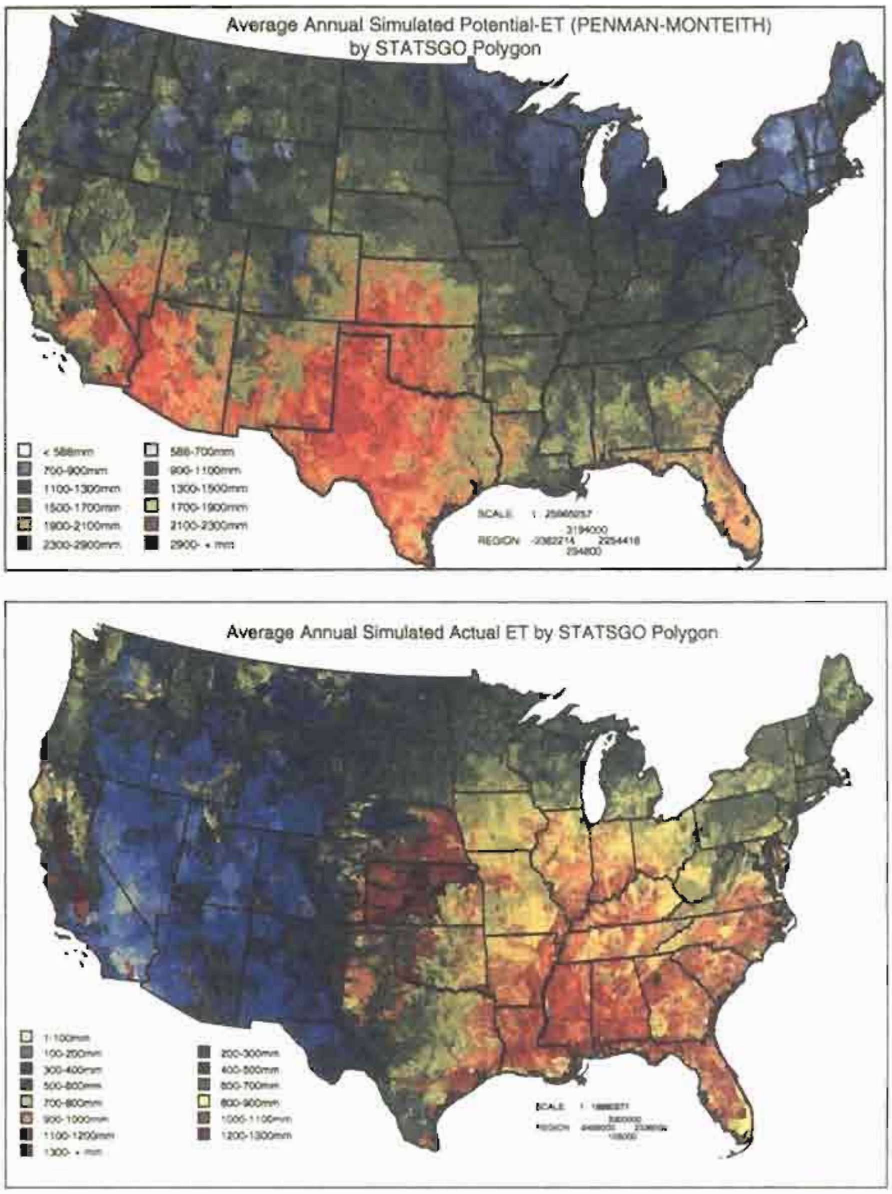

Figure 9. (a) Average annual simulated potential ET for U.S. (top); and (b) Average annual simulated actual ET for U.S. (bottom).

Other model components (snow melt, soil water routing, and shallow aquifer storage) are also rather simplistic and may not be representative of the actual flow system. However, inputs are readily available for large regions and the algorithms have provided reasonable results without calibration. It also has been assumed that there is no deep flow from one subbasin to another. While this assumption is incorrect, it is not believed to cause major error in the overall model output due to the small percentage of the overall water budget involved in recharging the deep aquifer system.

5. Summary

This paper describes the application and validation of a model of continuous daily water balance. The local water balance was represented by four control volumes; (1) snow, (2) soil profile, (3) shallow aquifer, and to a lesser extent (4) deep aquifer and the components of the water balance were simulated using 'storage' models and readily available input parameters. The model operates on a daily time step and is able to predict seasonal variations, which are important for water resources planning. The control volumes have been found to be critical in timing of flows, surface runoff occurs in hour to days, soil lateral flow in days to weeks, shallow aquifer in months to years, and deep aquifer flow (not simulated) in years to decades.

It is also important to simulate management/land use and climate scenarios since the model is being used by NRCS in national agricultural policy planning and by EPA in TMDL (Total Maximum Daily Load) analysis. Algorithms are included to simulate plant growth including the impact of various land use and cropping systems on the hydrologic balance. The impact of climate is also considered including precipitation, temperature which directly effects plant growth (indirectly ET), snow fall and melt, and soil temperature. Carbon dioxide concentration directly impacts ET and plant biomass growth.

The model was validated by comparing simulated average annual runoff (20 year model simulation) with long-term average annual runoff from USGS stream gage records. Comparisons show that over 45 percent of the conterminous U.S. within 50 mm of measured, and 18 percent within 10 mm. This was accomplished without calibration. Given the errors associated with model inputs (spatial variability, measurement errors, etc.), these results appear realistic. In this study, at the continental scale, only average annual runoff was validated. Examples of previous model validation at numerous sites across the U.S. were used to show that the model was capable of simulating other components of the hydrologic balance (surface runoff, groundwater flow, and ET) and of producing monthly and daily time series of runoff.

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Part 3

Using SWAT Software

3.1 MapWindow Interface for SWAT (MWSWAT)

Prepared by Luis F. Leon

June 2007

(Slightly modified for this book and its accompanying DVD)

MWSWAT (MapWindow SWAT)

Step by Step Setup for the San Juan (Mexico) and Linthipe Watersheds (Malawi)

Contents

Figures:

1. Environment and Tools Required

1. Microsoft Windows (any version, as far as we are aware)
2. Microsoft Access, as the interface uses an Access database
3. A tool like WordPad or NotePad that enables you to read ASCII text files.
4. A tool like WinZip that can uncompress .zip files

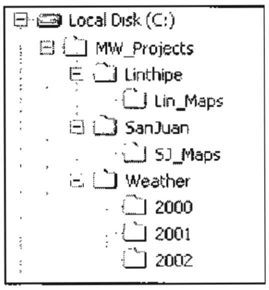
2. Installation

- Install MapWindow by running **MapWindow46SR.exe** (which is version 4.6) found in the DVD under *Software\MapWindow_GIS*, or a later version if available from www.mapwindow.org. Use the default folder *C:\Program Files\MapWindow* as the installation folder.

- Install MWSWAT by running **MWSWAT.exe**, found in *Software\MWSWAT*. It will create a folder *C:\Program Files\MapWindow\Plugins\MWSWAT* containing

- **createHRU.dll** and **MWSWAT.dll** - these constitute the MWSwat plugin
- **mwswat.mdb** - a database that will be copied for new projects
- **crop.dat, fert.dat, pest.dat, till.dat, urban.dat** - SWAT data files, in a subfolder *Databases*
- **swat2005.exe** - this is the SWAT executable
- **SWAT2005**.mdb - SWAT reference data, in the subfolder *Databases*
- A collection of weather generator (.wgn) files in the subfolder *Databases\USWeather*

- From the folder *Global_Weather_Data* in *Software\MWSWAT\DATA*, get **stnlist.txt** and **2000.zip** to **2005.zip**. Place stnlist.txt and the zip files in one folder (e.g. *Weather*) and unzip them. You will get subfolders *2000* to *2005*. The weather data includes precipitation and temperature data.



- From the folder *SWATEditor*, found in *Software*, unzip the installation archive SwatEditor_Install_2.1.2bRelease.zip and run **Setup.exe** to install the SWAT input file editor. Use the default folder *C:\Program Files\SWAT\SWAT 2005 Editor* as the installation folder.

- Create a folder to store the digital source data (e.g. *SJ_Maps* sub-folder under each project directory) and refer to the geo-processing document. This is where the DEM, landuse, and soil grids generated according to that document should be placed.

3. Structure and Location of Source Data

The "Step by Step Geo-Processing and Set-up of the Required Watershed Data for MWSWAT (MapWindows SWAT)" document (*Geo-Process.pdf*) describes the pre-processing of digital map data (DEM, Landuse and Soil). The document may be found in *Software\MWSWAT\MWSWAT_Manual.* Following that document you can create the required DEM, landuse and soil maps for the two watersheds by clipping and reprojecting the appropriate files from global data. Alternatively, for the San Juan example, you may prefer to skip this step and instead unzip the *Geo_processed.zip* archives in the *SJ_Maps* folder found in *Software\MWSWAT\DATA*. (The Linthipe example set can be downloaded from http://www.waterbase.org/.)

After either geo-processing or unzipping the archives you should have at least the following maps available. For the San Juan watershed in *SJ_Maps*: *sj_dem_clip_utm.asc*, *sj_land_clip_utm.tif*, *sj_soil_clip_utm.tif*, and *sj_washd_utm.shp*. For the Linthipe watershed in *Lin_Maps*: *lin_dem_clip_utm.asc*, *lin_land_clip_utm.tif*, *lin_soil_clip_utm.tif* and *lin_out.shp*.

4. Structure and Location of Output Data

We will be establishing a project called *Proj*, say, in a folder *F*. This will automatically create:

1. A folder *F\Proj* containing the project file *proj.mwprj*. If we later want to reopen the project this will be the file we look for. This folder also contains the project database *proj.mdb*.

2. A folder *F\Proj\Scenarios\Default\TxtInOut* that will contain all the SWAT input and output files.

3. A folder *F\Proj\Source* that will contain copies of our input maps and a number of intermediate maps generated during watershed delineation.

4. If we choose to save a SWAT run as *Run1*, for example, then a folder *F\Proj\\Scenarios\Run1\TxtInOut* will be created (a copy of *F\Proj\Scenarios\Default\TxtInOut*).

5. Setup for Mexico: San Juan River Watershed

1. Start **MapWindow** and check that you have plugins "**Watershed Delineation**" and "**MWSWAT**" available. Both these should be checked in the **Plug-ins** menu.
2. Start **MWSWAT**.
3. The main MWSWAT interface will be displayed. Click the box *New Project*.

4. A browser will be displayed requesting a name for the new project. Type **SJ_MWSwat** in the text box labeled *File name* (under the *SanJuan* folder) See Figure 1.

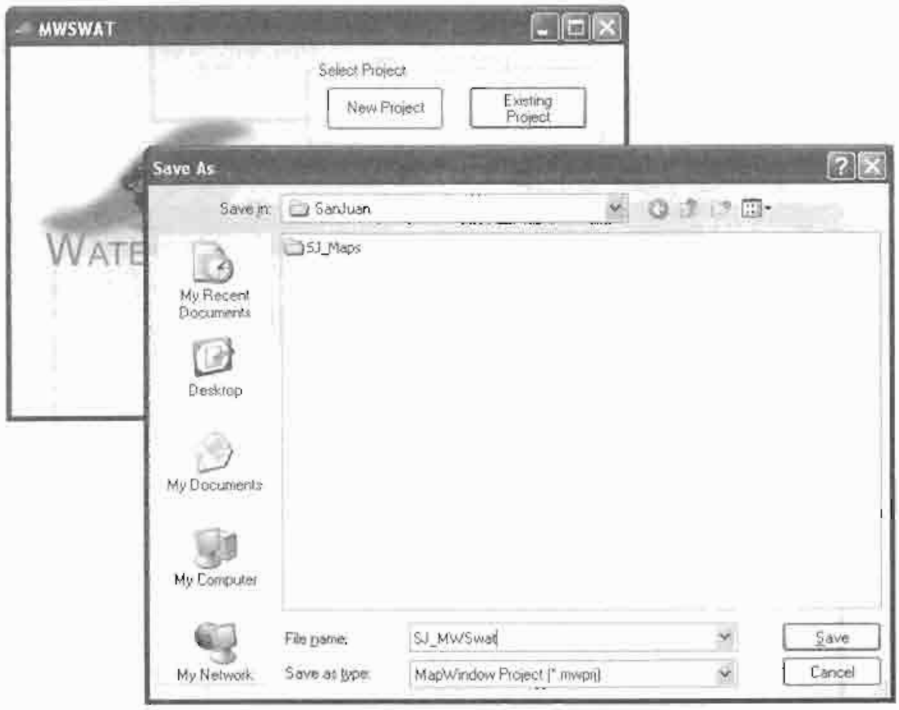


Figure 1: Naming a project

At this point you get a reminder (Figure 2) that (1) all your maps should be in an equal area projection (probably, but not necessarily, UTM)[1]; you also need to make sure that the map's units of measure are meters, and (2) that the Watershed Delineation plugin needs to be selected. If some of your maps need re-projecting you can use the MapWindow *GIS Tools* plug-in to do it.

Some of your files may not come with associated projection information, and MapWindow will ask if they have the right projection. If you are sure they have the same projection as your other files you just confirm that they should be loaded and given the same projection as the rest of the project.

If you are ready to proceed with MWSWAT, click *OK*.

[1]While UTM is not truly an equal area projection, it is close enough in most cases for SWAT.

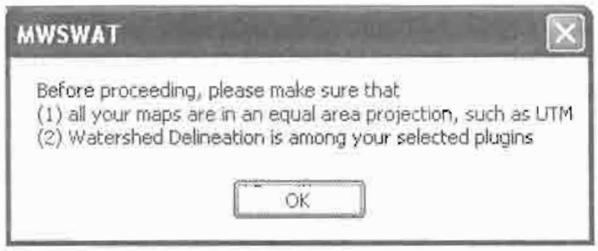


Figure 2: Reminders

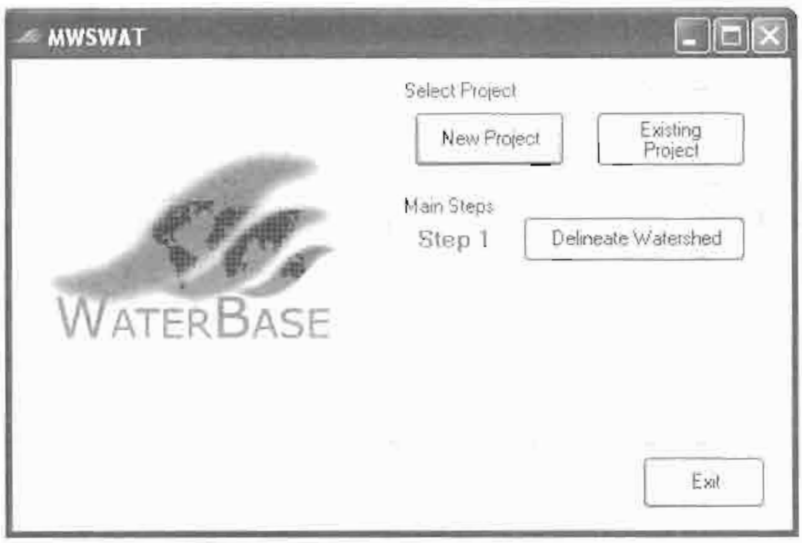


Figure 3: About to do step 1

The interface now presents a step-by-step configuration to be followed in order to prepare the SWAT simulation, starting with Step 1 (Figure 3).

5. If you need to set up some database tables for your project, this is a good time to do it, as the database has just been created in the *SJ_MWSwat* folder. See section 8 on *Using Your Own Data*.

5.1 Step 1. Process DEM (Watershed Delineation)

6. To start the automatic watershed delineation click the *Delineate Watershed* button. When the prompt box is opened *Select Base DEM*.
7. Browse to the *SJ_Maps* folder in *Software\MWSWAT\DATA* and open the file *sj_dem_clip_utm.asc* (Figure 4)

8. Click the *Process DEM* button to load the DEM file and activate the *Automatic Watershed Delineation* plug-in. This may take a few minutes.

Figure 4: Selecting the DEM

9. The name of the elevation map grid will be displayed in the *DEM* text box on the *Automatic Watershed Delineation* (AWD) dialog box. Make sure the *Elevation Units* are *Meters* (and that this is appropriate for your DEM!) and that the *Burn-in Existing Stream Polyline* option is not checked. For this watershed we have a shape file we will use as a focusing mask; select the *Use a Focusing Mask* option, click the *Use Grid or Shapefile for Mask* option if not already marked, click the file selection icon, and find and open the file *sj_washd_utm.shp* in the *SJ_Maps* folder, and click the first *Run* button (Figure 5). The first part of the watershed delineation tool will be run. This can take a few minutes.

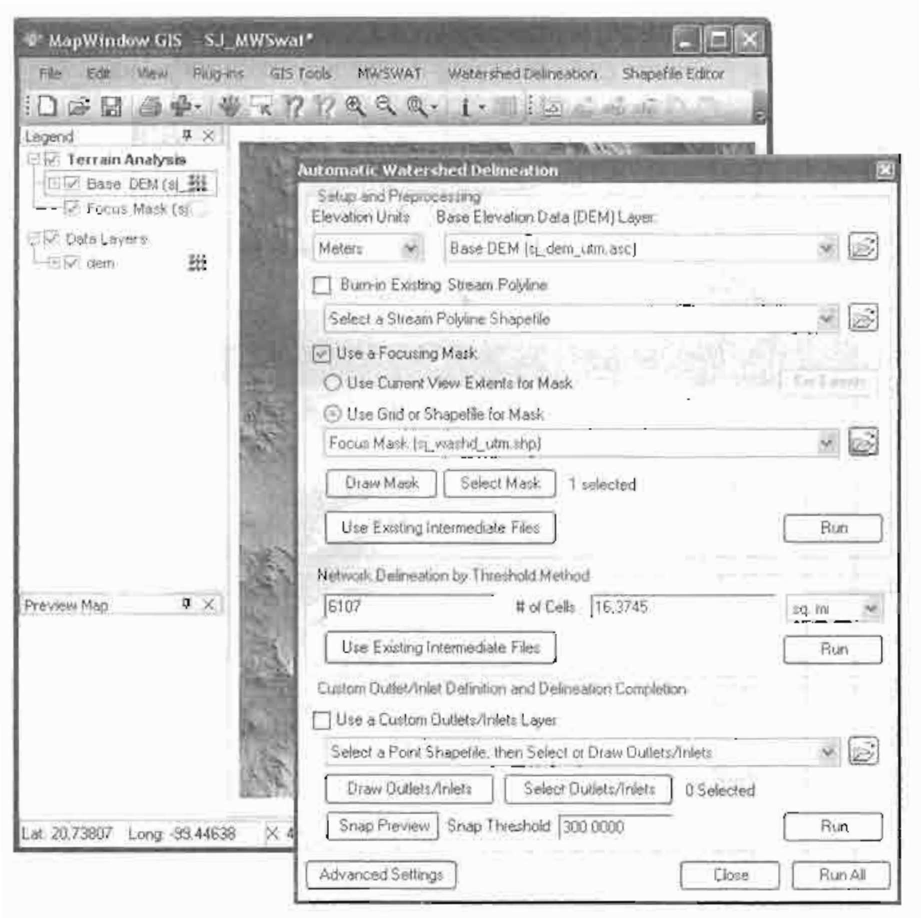


Figure 5: Preprocessing the DEM

10. The threshold size for subbasins is set next. It can be set by area, in various units such as sq km or hectares, or by number (#) of cells. Change the threshold method to use sq km, change the number of sq km to 50, and press *Enter*: the number of cells will be adjusted to the corresponding value (7200). Now click the second *Run* button to delineate the stream network. This can take a few minutes, and when complete the MapWindow display will be as illustrated in Figure 6. (You may have to move the Focus Mask entry above the Base DEM entry in the Legend panel to get exactly this view.)

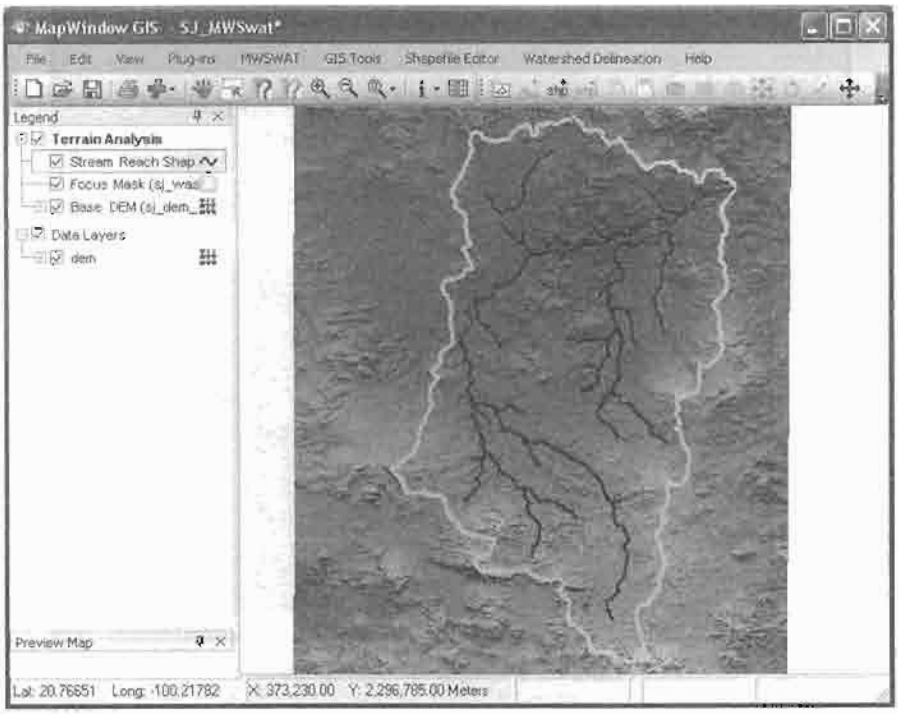


Figure 6: Stream networks displayed

11. To complete the watershed delineation we need to select an outlet point, which will be in the form of a shapefile. In the AWD form make sure that *Use a Custom Outlets/Inlets Layer* is checked, and use MapWindow to zoom into the area of the map where you want to locate the outlet. Click *Draw Outlets/Inlets.* Confirm in the new window that pops up that you want to create a new outlets/inlets shapefile, and in the next dialogue give it the name sj_out. Use the mouse to mark the outlet point on the MapWindow display (where the stream network meets the mask boundary), and click *Done* (Figure 7).

12. *n version 4.4 of AWD there was a bug which causes the network delineation parameters to be reset when the Outlets/Inlets shapefile is selected If this happens, reset the number of cells to 7200 and press Enter.*

13. Then in the AWD form click the third *Run.* The outlets and subbasin delineation will be performed, which can take a few minutes, and the MapWindow display will show the river network draining to the outlet point and the subbasin boundaries. The AWD part is now completed and you can *Close* the AWD form (Figure 8).

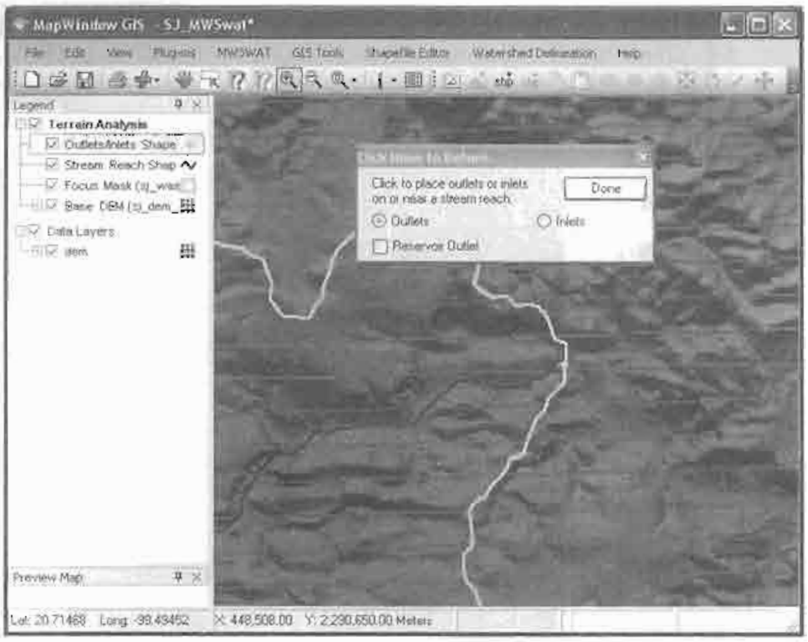


Figure 7: Defining the outlet point

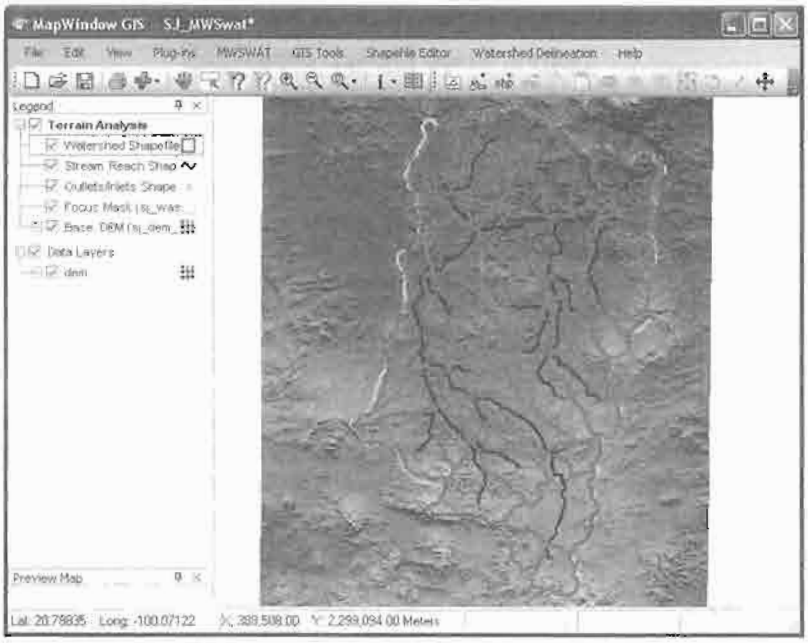


Figure 8: Watershed delineation complete

14. The MWSWAT interface will mark the *Process DEM* as done and enable the second step (Figure 9).

It is strongly recommended to save the project (via the menu of MapWindow) at this stage.

Figure 9: About to do step 2

5.2 Step 2. Create HRUs

15. Having calculated the basins, we want to calculate the details of the Hydrological Response Units (HRUs) that are used by SWAT. We can divide basins into smaller pieces each of which has a particular soil/ landuse(crop)/slope range combination.

16. To do this we click *Create HRUs*, select *sj_land_clip_utm.tif* as the *Landuse Map*, select *sj_soil_clip_utm.tif* as the *Soil Map*, select *global_landuses* as the *Landuse Table*, and select *global_soils* as the *Soil Table*. . The last two will take a few seconds as the relevant database tables are read.

17. We will form HRUs based on slope as well as landuse and soil. We add an intermediate point for slopes (e.g. 10) to divide HRUs into those with average slopes for 0-10% and those with average slopes in the range 10% to the top limit. Type 10 in the box and click *Insert*. The *Slope bands* box shows the intermediate limit is inserted.

18. To read in the data from the DEM, landuse, soil and slope maps and prepare to calculate HRUs, click *Read* (Figure 10). This may take a few minutes.

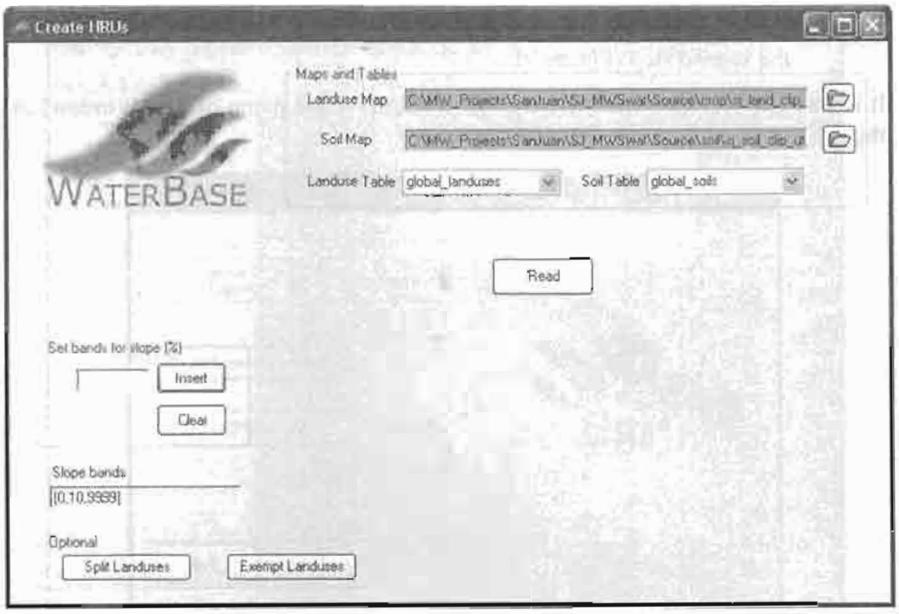


Figure 10: Ready to read the maps

19. After reading the grids you will notice a number of changes to the MapWindow display (Figure 11):

- The subbasins have been numbered.
- A Slope bands map has been created and added. This allows you to see where the areas of the two slope bands selected for this project are located. If no intermediate slope limits are chosen this map is not created.
- The legends for the landuse map sj_land_utm and the soil map sj_soil_utm include the landuse and soil categories from the SWAT database.
- A shapefile FullHRUs has been created and added. This allows you to see where in each subbasin the potential Hydrological Response Units (HRUs) are physically located. If, for example, we zoom in on subbasin 15, in the Legend panel select (left button) FullHRUs, open its attribute table (right button), set the mouse to Select (MapWindow toolbar ) and click on the box just above the number 15 in the map, then we get a view like Figure 12. We see that this potential HRU is composed of two parts, has the landuse FOEN, the soil I-K-E-c-4749, and the slope band 0-10. Its area of 396.5ha is only 4.1% of the subbasin. Close the Attribute Table Editor.

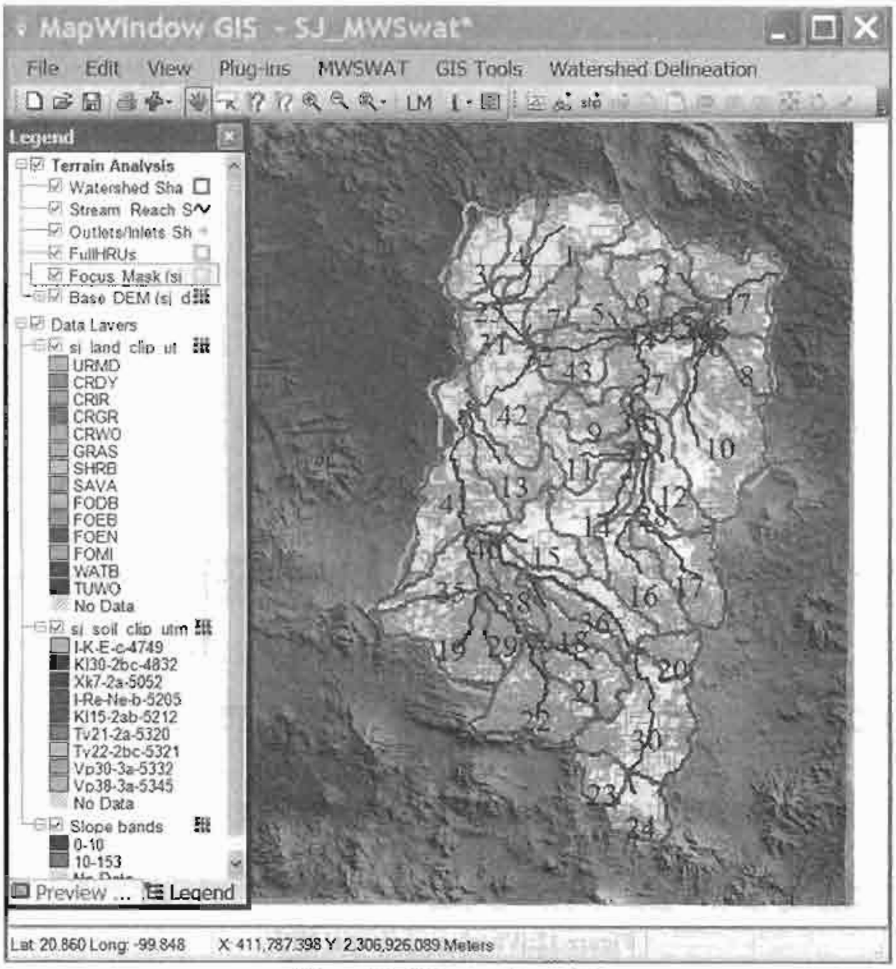


Figure 11: After reading grids

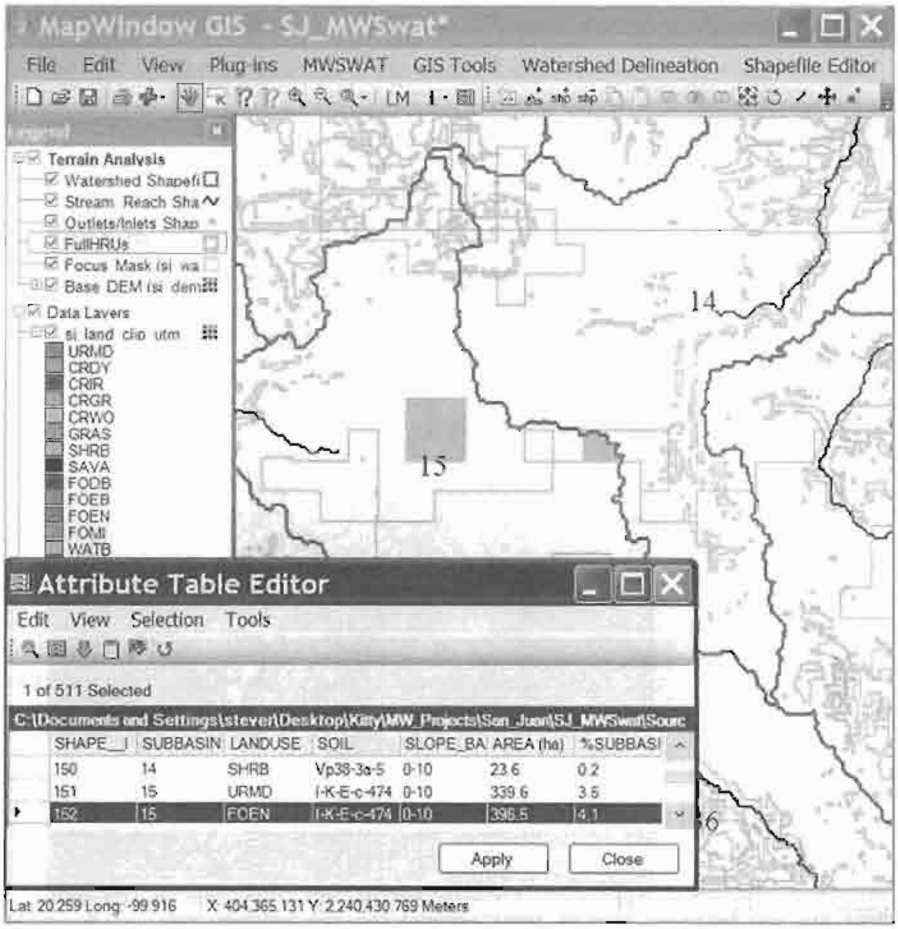


Figure 12: Viewing a potential HRU

20. Before we continue with HRU definition, if we look at the main MWSWAT window we see that a new item *Reports* is available and we can choose to view just two reports at this point, which are the *Elevation* and *Basin* reports. The elevation report gives information about how much land is at each elevation from the lowest to the highest, both for the watershed as a whole and for each subbasin (Figure 13). The basin report lists the landuse, soil and slope-band areas for each subbasin (Figure 14).

Elevation report for the watershed Thursday, December 13, 2007 12:08:48 AM

Statistics: All elevations reported in meters

Minimum elevation: 1575

Maximum elevation: 3313

Mean elevation: 2228.76787366251

Standard deviation: 302.515630179528

Elevation	% area up to elevation	% area of watershed
1575	0.00	0.00

Figure 13: Elevation report (start)

		Area [ha]	%Watershed	%Subbasin
Subbasin 47		15081.24	3.65	
Landuse				
	SHRB	6943.05	1.68	46.04
	GRAS	8138.19	1.97	53.96
Soil				
	Vp30-3a-5332	3127.78	0.76	20.74
	Kl30-2bc-4832	11297.21	2.73	74.91
	Xk7-2a-5052	656.25	0.16	4.35
Slope				
	0-10	6952.08	1.68	46.10
	10-153	8129.16	1.97	53.90

Figure 14: Basin report (fragment)

21. At this point we have the options to split landuses, and to exempt landuses, both of which will affect how HRUs are defined.

- Splitting landuses allows us to define more precise landuses than our landuse map provides. If, say, we know that in this basin 60% of the CRIR (Irrigated cropland and pasture) is used for corn, we could split CRIR into 60% CORN and 40% CRIR (Figure 15).
- Exempting landuses allows us to ensure that a landuse is retained in the HRU calculation even if it falls below the thresholds we will define later. For example, we might decide to exempt the urban landuse URMD (Figure 16).

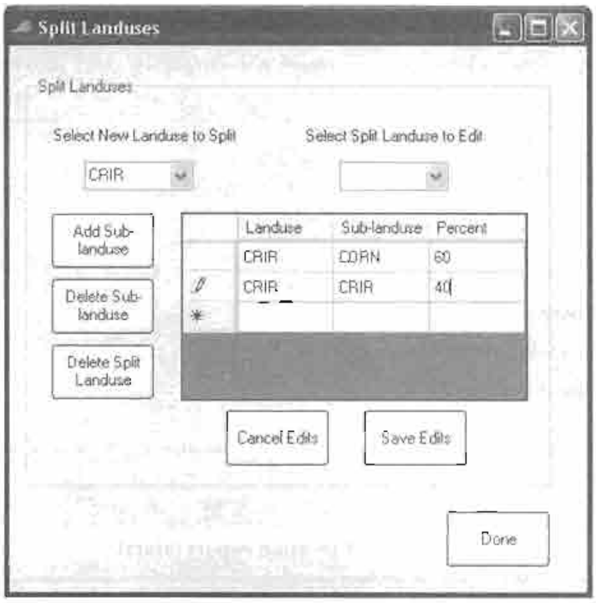


Figure 15: Splitting a landuse

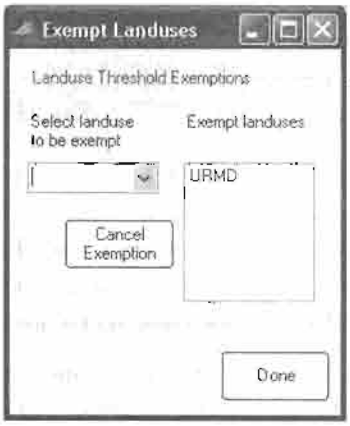


Figure 16: Exempting a landuse

In this example we will not split or exempt any landuses. Now we need to exclude HRUs that are insignificant by considering percentage thresholds or area thresholds. This is the "multiple" HRU option. The "single" option just uses each basin as one HRU, giving it the dominant soil, landuse and slope range for that basin.

22. Once all the data has been read in and stored, the *Single/Multiple HRU* choice is enabled. Select *Multiple HRUs*, and then select *By Percentage*. Now select thresholds for landuse, soil and slope. The idea of this option is that we will ignore any potential HRUs for which the landuse, soil or slope is less than the selected threshold, which is its percentage in the subbasin. The areas of HRUs that are ignored are redistributed proportionately amongst those that are retained. The value of 33 as the maximum we can choose for landuse indicates that there is a subbasin where the max value for a landuse is 33%: if we chose a higher value than 33% we would be trying to ignore all the landuse categories in that subbasin. Hence 33% is the min across the subbasins of the max landuse percentage in each subbasin. Select 20% for landuse, by using the slider or by typing in the box, and click *Go*. The interface then computes the min-max percentage for a soil as 51%. Select 10 for Soil, click *Go*, 5 for slope, and click *Create HRUs* (Figure 17). It should report 195 HRUs formed in 47 subbasins. Click *OK*.

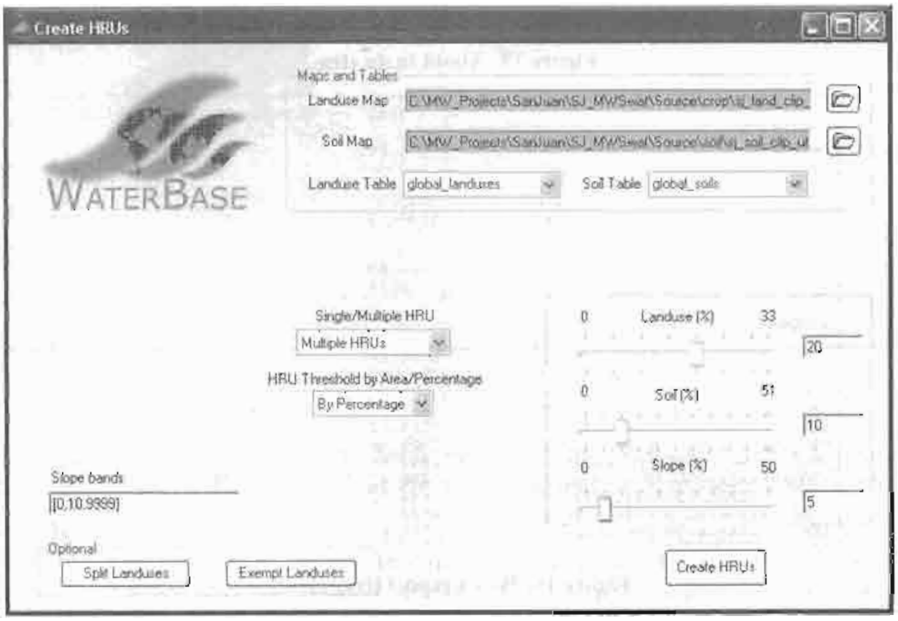


Figure 17: Creating multiple HRUs by percentage

23. *Create HRUs* is now reported as done and the third step is enabled (Figure 18). If you look at the *Reports* now available you will find that there is an *HRUs* report that only includes the landuses, soils and slope bands left after HRU selection, and also gives details of the HRUs that have been formed (Figure 19). If you wish to change the HRU thresh-

olds then you can click the *Create HRUs* button again, change the thresholds and/or the landuses to be split or exempted, and rerun the *Create HRUs* step.

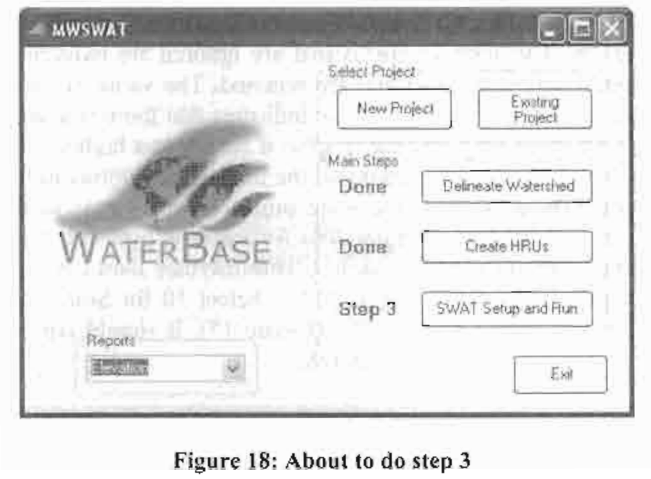


Figure 18: About to do step 3

		Area [ha]	%Watershed	%Subbasin
Subbasin 47		15081.24	3.65	
Landuse				
	SHRB	6943.05	1.68	46.04
	GRAS	8138.19	1.97	53.96
Soil				
	Vp30-3a-5332	3210.49	0.78	21.29
	K130-2bc-4832	11870.75	2.87	78.71
Slope				
	0-10	7011.57	1.70	46.49
	10-153	8069.67	1.95	53.51
HRUs:				
188	SHRB/Vp30-3a-5332/10-153	800.00	0.19	5.30
189	SHRB/Vp30-3a-5332/0-10	1384.72	0.33	9.18
190	SHRB/K130-2bc-4832/10-153	2366.66	0.57	15.69
191	SHRB/K130-2bc-4832/0-10	2391.66	0.58	15.86
192	GRAS/Vp30-3a-5332/10-153	381.45	0.09	2.53
193	GRAS/Vp30-3a-5332/0-10	644.32	0.16	4.27
194	GRAS/K130-2bc-4832/10-153	4521.55	1.09	29.98
195	GRAS/K130-2bc-4832/0-10	2590.87	0.63	17.18

Figure 19: HRUs report (fragment)

24. It is strongly recommended to save the project (via the menu of MapWindow) at this stage.

5.3 Step 3. SWAT Setup and Run

25. At this point almost everything is ready to write the SWAT input files and run SWAT. Click *SWAT Setup and Run* (Figure 20).

Figure 20: SWAT Setup and Run form

26. The first thing to do on this form is to set the period for the SWAT run. Select 1 January 2000 as the *Start date* and 31 December 2001 as the *Finish date*.

27. Next we have to choose the source of weather data. Click the *Choose* button for *Weather Sources*. MWSWAT is set up to use actual weather data for maximum and minimum temperature and precipitation, and a weather generator file that will simulate other weather factors (solar radiation, wind speed, and relative humidity). So you need to provide a weather generator file for your basin, and data for precipitation and temperature. Normally for the first run you would choose the option *Global files*, and choose *Global_Weather_Data\stnlist.txt* as the *Weather Stations File*. Then MWSWAT looks for the nearest 6 weather stations in that file, generates the temperature and precipitation data for them, and

then associates each subbasin with the nearest weather station from amongst those six. We have in this case decided to use just one of those six as the weather station for the whole watershed, and adopting the procedure described in Section 7.8, have made a local list of stations, *sanjuan1.txt* (containing just one station entry copied from *Global_Weather_Data\stnlist.txt*) in the *SJ*_Maps folder, and copied the two files *765850.pcp* and *765850.tmp*, made in the *TxtInOut* folder in an earlier run using the global files option, to the *SJ_Maps* folder. 765850 is the station identifier of the weather station with an entry in *sanjuan1.txt*. The local files option allows us to control more precisely what weather stations are used, and also means that the setup is much faster as the .pcp and .tmp files do not need to be created.

28. Choose *SJ_Maps\sj.wgn* as the *Weather Generator File* (Figure 21). Click *Done*.

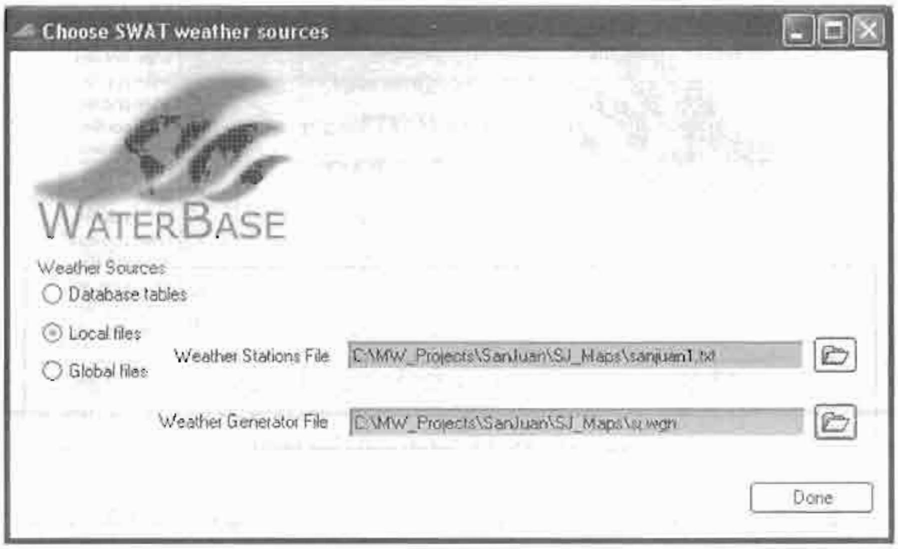


Figure 21: Choosing weather sources

29. Click *Write all files* in the list box (Figure 22) and click the *Write files* button. This can take a few minutes, especially if your simulation covers several years, but is fast in this case as the weather data is prepared already.

30. The interface reports that the SWAT input files are written. They can be found in the *TxtInOut* folder. Click *OK*.

31. Click *Run SWAT* to launch the SWAT executable in a DOS prompt window (Figure 23).

Figure 22: About to write the SWAT input files

Figure 23: Running SWAT

32. When done a message box will say that SWAT was run successfully, or that it failed. Click *OK*.

33. To see what happened if it failed you need to rerun in a DOS command window. To do this:

- Copy the file

  C:\Program Files\MapWindow\Plugins\MWSWAT\swat2005.exe

  to the project's *TxtInOut* folder.

  - Start a DOS command window (use start menu -> *Run...* , type *cmd* and click *OK*, or use start menu -> *All Programs* -> *Accessories* -> *Command Prompt*).
  - Use the *cd* command to change to the project's *TxtInOut* folder.
  - Use the command *swat2005* to run SWAT in this window. The error message will remain visible and will specify the line of SWAT code where the error occurred. The error message may suggest which SWAT input file needs to be checked, or you may be able to get more information from examining the SWAT source code, but probably you will need to report the problem to WaterBase technical assistance.

34. You can save the SWAT run if you wish using the *Save run* button. This in fact copies *F\Proj\Scenarios\Default\TxtInOut* to *F\Proj\Scenarios\Save1\TxtInOut* if you choose to save as *Save1*. If *Save1* already exists it is overwritten. This button is live as soon as the *SWAT Setup and Run* form is opened, so you can if you wish use the form to save an earlier run before you start writing the files for this one. (But note that if you changed the watershed delineation or the HRU parameters the report files will be wrong, so in this case you should do the save manually before starting the interface.)

35. You can use the *Edit files* button to run the SWAT Editor to edit any of the input files and database files if you wish. See Figure 24. Note that the parameters for the editor should be set as follows:

- SWAT Project Geodatabase: *F\Proj\Proj.mdb*
- SWAT Parameter Geodatabase:

C:*Program Files\MapWindow\Plugins\MWSWAT\Databases\SWAT2005.mdb*

  - SWAT Executable folder:

  C:*Program Files\MapWindow\Plugins\MWSWAT*

  (Note the final "\", which must not be omitted.)

For information on using the SWAT Editor, see chapters 9 through 15 of the *ArcSWAT_Documentation.pdf* in *Software\SWATEditor* on the DVD.

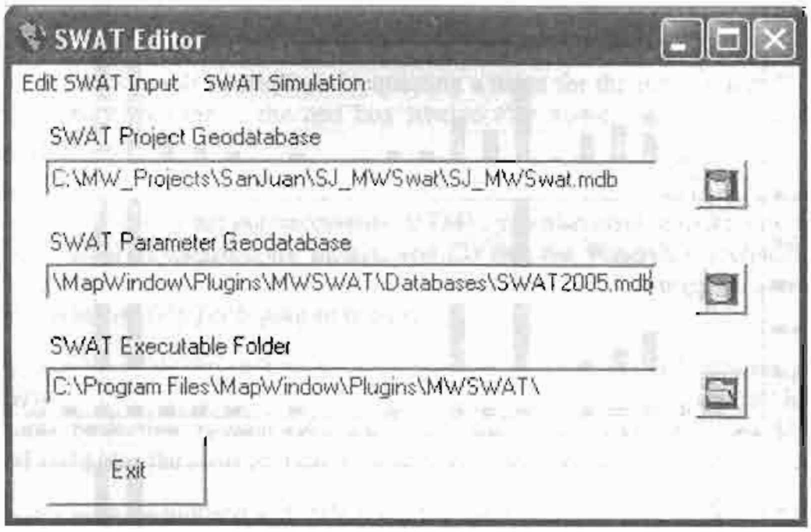


Figure 24: SWAT Editor

From the reach output file, the monthly values for the outlet were extracted and the following plots (Figure 25) created (note: precipitation values for San Juan are for the two nearest rain gauges).

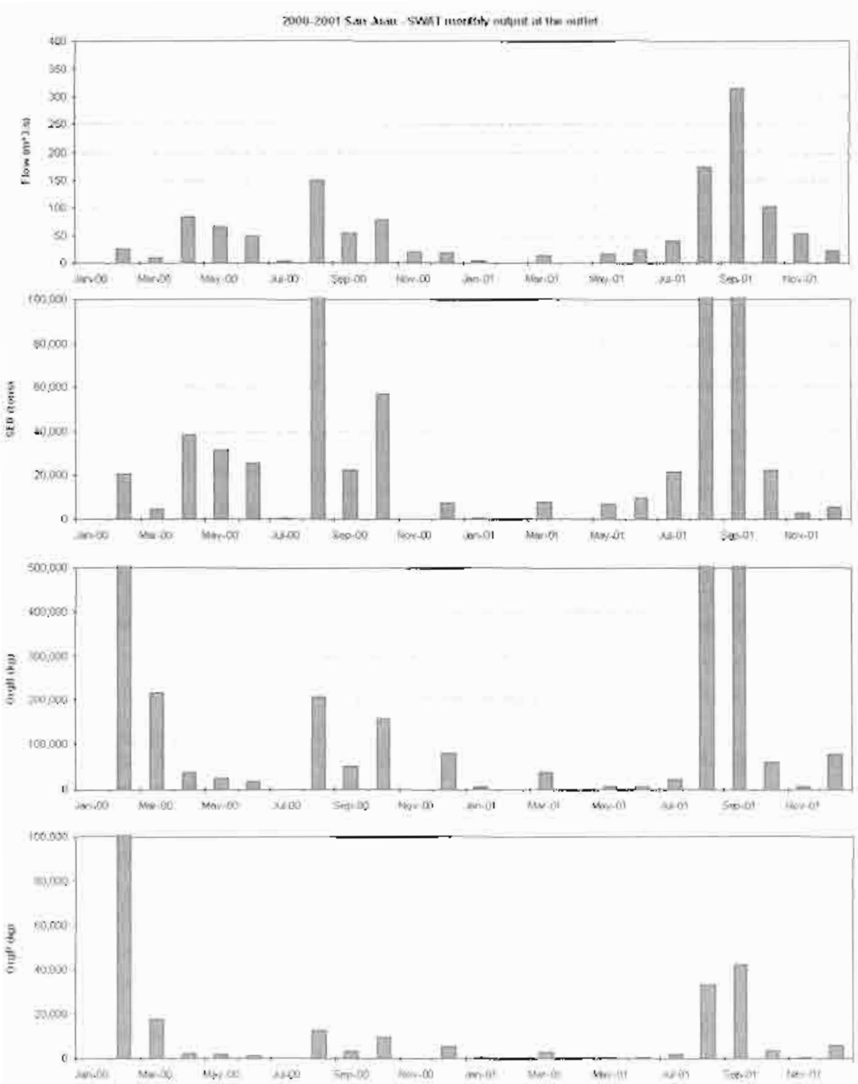


Figure 25: San Juan output plots

6. Setup for Malawi: Linthipe Watershed

Note: Be sure to read Sections 1-3 of this document before beginning the Linthipe Watershed setup. Example data for Linthipe is not available on the DVD, but may be downloaded from Waterbase at http://www.waterbase.org/download_mwswat.html.

1. Start MapWindow and check that you have plugins "Watershed Delineation" and "MWSWAT" available. Both these should be checked.
2. Start **MWSWAT**.
3. The main interface will be displayed. Click the box beside *New Project*.
4. A browser will be displayed requesting a name for the new project. Type **Lin_MWSwat** in the text box labeled *File Name* (under the *Linthipe* folder).

At this point you get a reminder that (1) all your maps should be in an equal area projection (probably, but not necessarily, UTM)[1]; you also need to make sure that the maps units of measure are meters, and (2) that the Watershed Delineation plugin needs to be selected. If some of your maps need re-projecting you can use the MapWindow *GIS Tools* plug-in to do it.

Some of your files may not come with associated projection information, and MapWindow will ask if they have the right projection. If you are sure they have the same projection as your other files you just confirm that they should be loaded and given the same projection as the rest of the project.

If you are ready to proceed with MWSWAT, click *OK*.

The interface now presents a step-by-step configuration to be followed in order to prepare the SWAT simulation, starting with Step 1 (Figure 26).

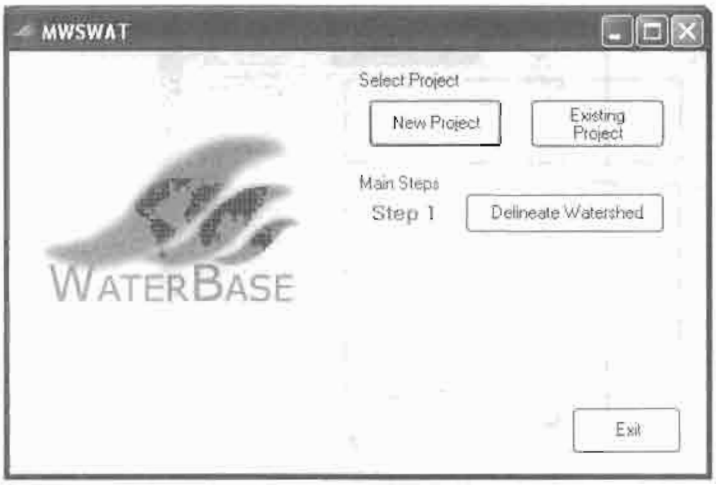


Figure 26: About to do step 1

[1]UTM, while not truly an equal area projection is close enough in most cases for SWAT.

5. If you need to set up some database tables for your project, this is a good time to do it, as the database has just been created in the *Lin_MWSwat* folder. See section 8 on *Using Your Own Data*.

6.1 Step 1. Process DEM (Watershed Delineation)

6. To start the automatic watershed delineation click the *Delineate Watershed* button. When the prompt box is opened *Select Base DEM*.

7. Browse to the *Lin_Maps* folder and open the file *lin_dem_clip_utm.asc* (Figure 27).

8. Click the *Process DEM* button to activate the *Automatic Watershed Delineation* plug-in. This will also load the DEM grid, which may take a few minutes.

Figure 27: Selecting the DEM

9. The name of the elevation map grid will be displayed in the *DEM* text box on the *Automatic Watershed Delineation* (AWD) dialog box. Make sure the *Elevation Units* are *Meters* (and that this is appropriate for your DEM!) and that the *Burn-in Existing Stream Polyline* and *Use Focusing*

Mask options are not checked. The threshold size for subbasins is set next. It can be set by area, in various units such as sq km or hectares, or by number (#) of cells. Change the threshold method to use sq km, change the number of sq km to 150, and press Enter: the number of cells will be adjusted to the corresponding value (18646).

10. To complete the watershed delineation we need to select an outlet point, which will be in the form of a shapefile. In the AWD form make sure that *Use a Custom Outlets/Inlets Layer* is checked, and browse for the file *lin_out.shp*.

11. *In version 4.4 of AWD there was a bug which causes the network delineation parameters to be reset when the Outlets/Inlets shapefile is selected. If this happens, reset the number of cells to* 18646 *and press Enter* (Figure 28).

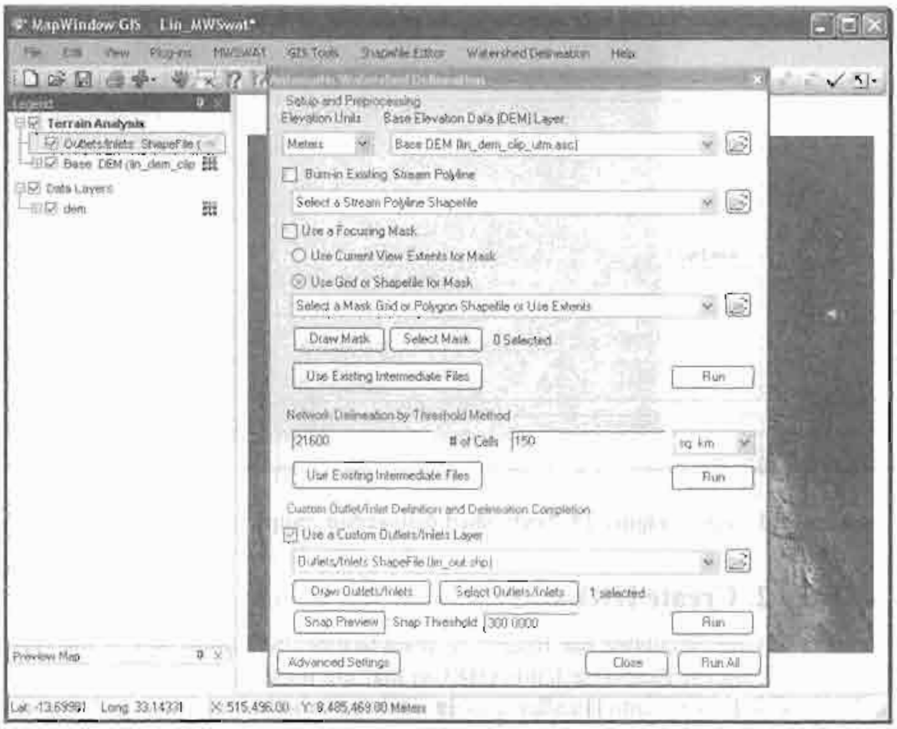


Figure 28: Running Automatic Watershed Delineation

12. Click *Run All*. All the watershed delineation steps will be performed, which can take a few minutes, and the MapWindow display will show the river network draining to the outlet point and the subbasin

boundaries. The AWD part is now completed and the AWD form will be closed automatically. (Figure 29).

13. The MWSWAT interface will mark the *Process DEM* as done and enable the second step. It's strongly recommended to save your project at this point.

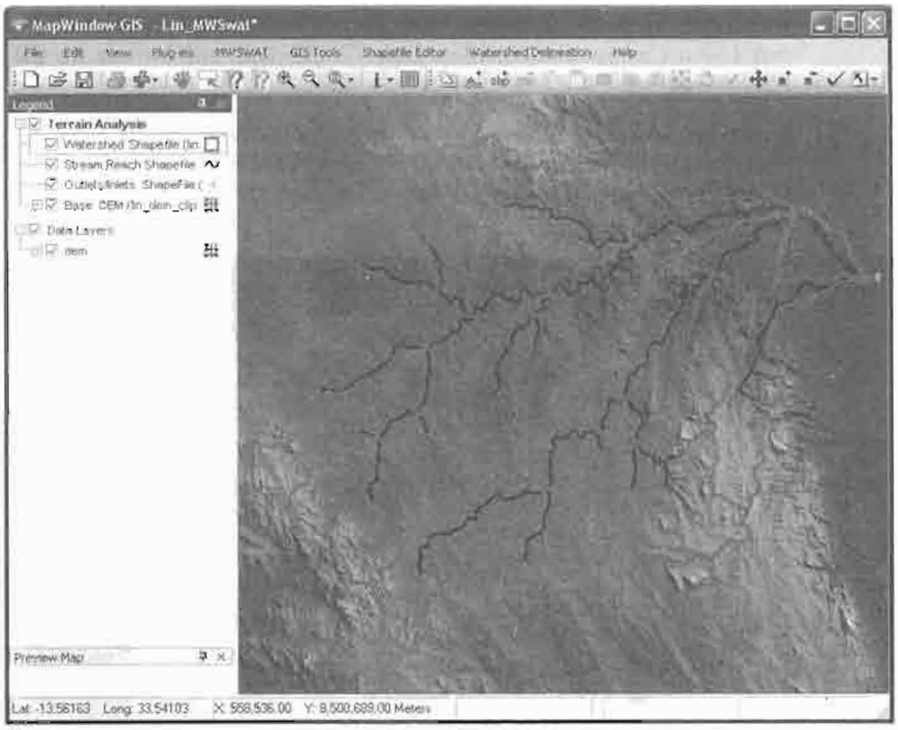


Figure 29: Watershed delineation complete

6.2 Step 2. Create HRUs

14. Having calculated the basins we want to calculate the details of the Hydrological Response Units (HRUs) that are used by SWAT. We can divide basins into smaller pieces each of which has a particular soil/landuse(crop)/slope range combination.

15. To do this we click *Create HRUs*, select *lin_land_clip_utm.tif* as the *Landuse Map*, select *lin_soil_clip_utm.tif* as the *Soil Map*, select *global_landuses* as the *Landuse Table*, and select *global_soils* as the *Soil Table*. The last two will take a few seconds as the relevant database tables are read.

16. We will form HRUs based on slope as well as landuse and soil. We add an intermediate point for slopes (e.g. 10) to divide HRUs into those with average slopes for 0-10% and those with average slopes in the range 10% to the top limit. Type 10 in the box and click *Insert*. The *Slope bands* box shows the intermediate limit is inserted.

17. To read in the data from the DEM, landuse, soil and slope maps and prepare to calculate HRUs, click *Read* (Figure 30). This may take a few minutes.

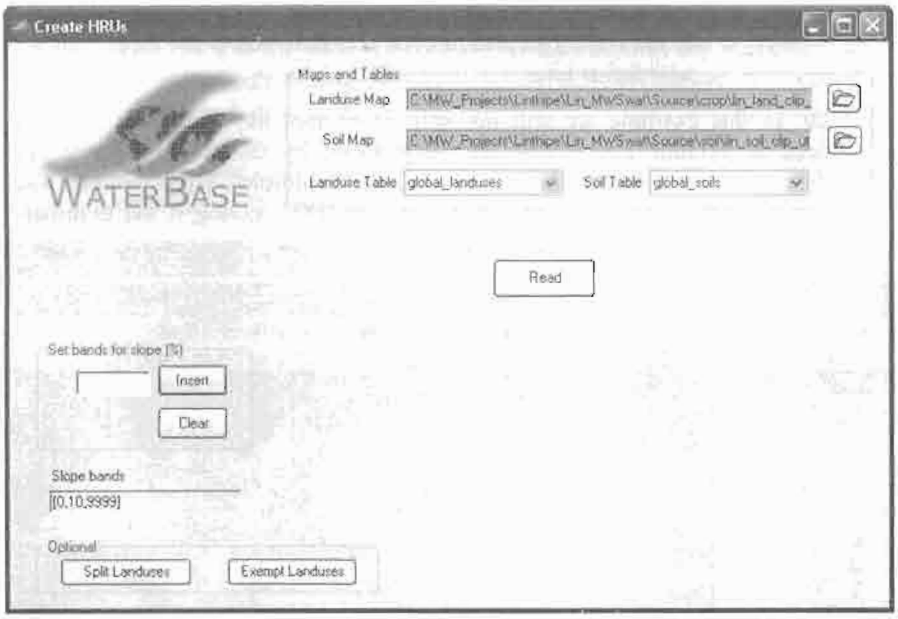


Figure 30: Ready to read the maps

18. After reading the grids you will notice a number of changes to the MapWindow display (Figure 31):

    a. The subbasins have been numbered.

    b. *Slope bands* map has been created and added. This allows you to see where the areas of the two slope bands selected for this project are located. If no intermediate slope limits are chosen this map is not created.

    c. The legends for the landuse map *lin_land_clip_utm* and the soil map *lin_soil_clip_utm* include the landuse and soil categories from the SWAT database.

d. A shapefile *FullHRUs* has been created and added. This allows you to see where in each subbasin the potential Hydrological Response Units (HRUs) are physically located.

19. At this point we have the options to split landuses, and to exempt landuses, both of which will affect how HRUs are defined.

a. Splitting landuses allows us to define more precise landuses than our landuse map provides.

b. Exempting landuses allows us to ensure that a landuse is retained in the HRU calculation even if it falls below the thresholds we will define later.

20. In this example we will not split or exempt any landuses. Now we need to exclude HRUs that are insignificant by considering percentage thresholds or area thresholds. This is the "multiple" HRU option. The "single" option just uses each basin as one HRU, giving it the dominant soil, landuse and slope range for that basin.

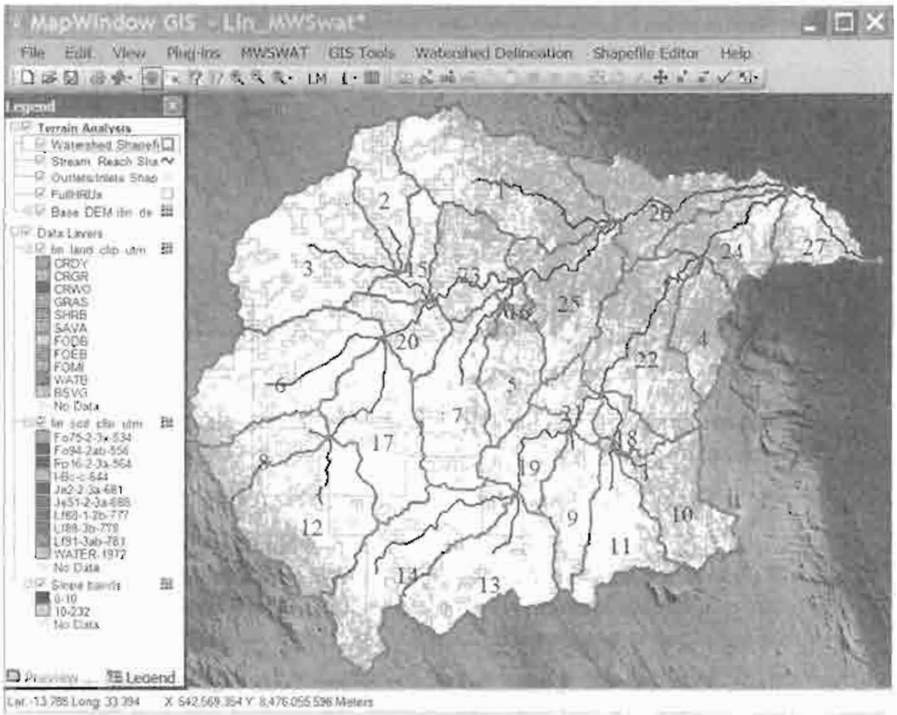


Figure 31: After reading grids

21. Once all the data has been read in and stored, the *Single/Multiple HRU* choice is enabled. Select *Multiple HRUs*, and then select *By Percentage*. Now select thresholds for landuse, soil and slope. The idea of this option is that we will ignore any potential HRUs for which the landuse, soil or slope is less than the selected threshold, which is its percentage in the subbasin. The areas of HRUs that are ignored are redistributed proportionately amongst those that are retained. The value of 34 as the maximum we can choose for landuse indicates that there is a subbasin where the max value for a landuse is 34%: if we chose a higher value than 34% we would be trying to ignore all the landuse categories in that subbasin. Hence 34% is the minimum across the subbasins of the maximum landuse percentage in each subbasin. Select 20% for landuse, by using the slider or by typing in the box, and click *Go*. The interface then computes the min-max percentage for a soil as 37%. Select 10 for Soil, click *Go*, 5 for slope, and click *Create HRUs* (Figure 32). It should report 120 HRUs formed in 27 subbasins. Click *OK*.

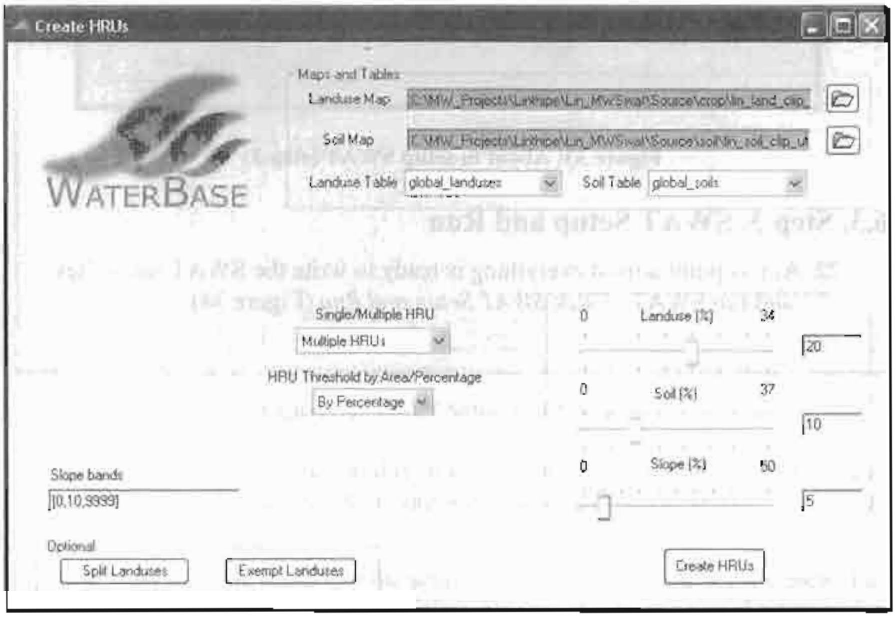


Figure 32: Creating multiple HRUs by percentage

Create HRUs is now reported as done and the third step is enabled (Figure 33). If you look at the *Reports* now available you will find that there is an *Elevation* report that gives information on the elevation profile of the basin and each subbasin, a *Basins* report that lists the landuse, soil and slope-band areas for each subbasin and also an *HRUs* report that only includes the landuses, soils and slope bands left after HRU selection, and also gives details of the HRUs that have been formed. If you wish to change the HRU thresholds then you can click the *Create HRUs* button again, change the thresholds and/or the landuses to be split or exempted, and rerun the *Create HRUs* step.

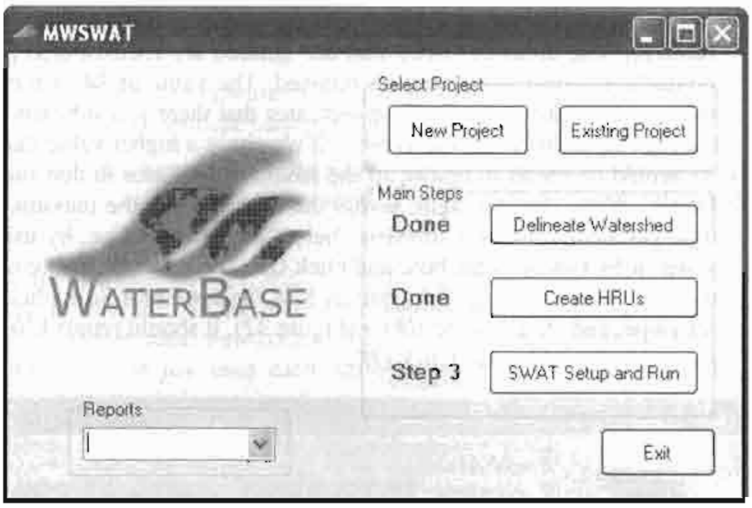


Figure 33: About to setup SWAT (step 3)

6.3. Step 3. SWAT Setup and Run

22. At this point almost everything is ready to write the SWAT input files and run SWAT. Click *SWAT Setup and Run* (Figure 34).

Figure 34: SWAT Setup and Run form

23. The first thing to do on this form is to set the period for the SWAT run. Select 1 January 2000 as the *Start date* and 31 December 2001 as the *Finish date*.

24. Next we have to choose the source of weather data. Click the *Choose* button for *Weather Sources*. MWSWAT is set up to use actual weather data for maximum and minimum temperature and precipitation, and a weather generator file that will simulate other weather factors (solar radiation, wind speed, and relative humidity). So you need to provide a weather generator file for your basin, and data for precipitation and temperature. Choose the option *Global files*, choose *Global_Weather_Data\stnlist.txt* as the *Weather Stations File* and *Lin_Maps\lin.wgn* as the *Weather Generator File* (Figure 35). Click *Done*.

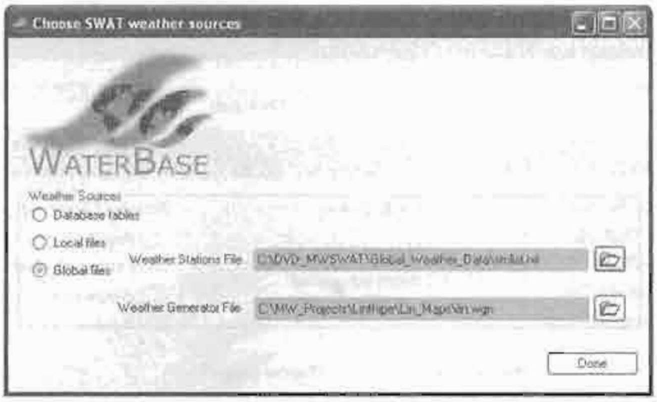


Figure 35: Choosing weather sources

25. Click *Write all files* in the list box (Figure 36) and click the *Write files* button. This may take a few minutes, especially if your simulation covers several years.

Figure 36: About to write the SWAT input files

26. The interface reports that the SWAT input files are written. They can be found in the *TxtInOut* folder. Click *OK*.

27. Click *Run SWAT* to launch the SWAT executable in a DOS prompt window (Figure 37).

Figure 37: Running SWAT

28. When done a message box will say that SWAT was run successfully, or that it failed. Click *OK*.

29. To see what happened if it failed you need to rerun in a DOS command window:

    a. Copy the file

    C:\Program Files\MapWindow\Plugins\MWSWAT\swat2005.exe

    to the project's *TxtInOut* folder.

    b. Start a DOS command (use start menu -> *Run...*, type *cmd* and click *OK*, or use start menu -> *All Programs* -> *Accessories* -> *Command Prompt*).

    c. Use the *CD* command to change to the project's *TxtInOut* folder.

    d. Use the command *swat2005* to run SWAT in this window. The error message will remain visible and will specify the line of SWAT code where the error occurred. The error message may suggest which SWAT input file needs to be checked, or you may be able to get more information from examining the SWAT source code, but probably you will need to report the problem to WaterBase technical assistance.

30. You can save the SWAT run if you wish using the *Save run* button. This in fact copies *F\Proj\Scenarios\Default\TxtInOut* to *F\Proj\Scenarios\Save1\TxtInOut* if you choose to save as *Save1*. If *Save1* already exists it is overwritten. This button is live as soon as the *SWAT Setup and Run* form is opened, so you can if you wish use the form to save an earlier run before you start writing the files for this one. (But note that if you changed the watershed delineation or the HRU parameters the report files will be wrong, so in this case you should do the save manually before starting the interface.)

From the reach output file, the monthly values for the outlet were extracted and the following plots created (Figure 38).

7. Rerunning MWSWAT

You may want to rerun the interface because you want to change some of the parameters. This section explains how to do so.

1. Start MapWindow and make sure that the plugins *MWSWAT* and *Watershed Delineation* are selected. Start *MWSWAT*.

2. Click *Existing Project* and open the project file *F\SJ_MWSwat\SJ_MWSwat.mwprj* (remember that we started the new project *SJ_MWSwat* in folder *F*).

3. The *Process DEM* step is marked as already done. You can rerun it if you want to use a new DEM, change the subbasin threshold, or move the outlet point, or add additional inner inlets, reservoirs, or outlets.

4. In the *Create HRUs* step you will find that the landuse and soil maps are already set to the files you used before (or, rather, the copies that were made of them and stored in the project folder tree) and the database tables are set to *global_landuses* and *global_soils*. These can be changed if you want to use different maps.

5. Assuming you keep the same landuse and soil maps, you are offered the options to *Read from previous run* or *Read from maps*. The former is much faster, and can be used unless you want to change the slope limits. Changing the slope limits requires a re-read of the maps because cells are allocated to potential HRUs by their subbasin number, landuse type, soil type, and slope range.

6. After reading or rereading you are offered the same choice as before between removing insignificant HRUs by percentages or area thresholds, and the values you used last time are preselected. You can switch between area and percentage, you can change the values, and you can change landuse splits and exemptions, or you can just immediately click *Create HRUs*, keeping the old values.

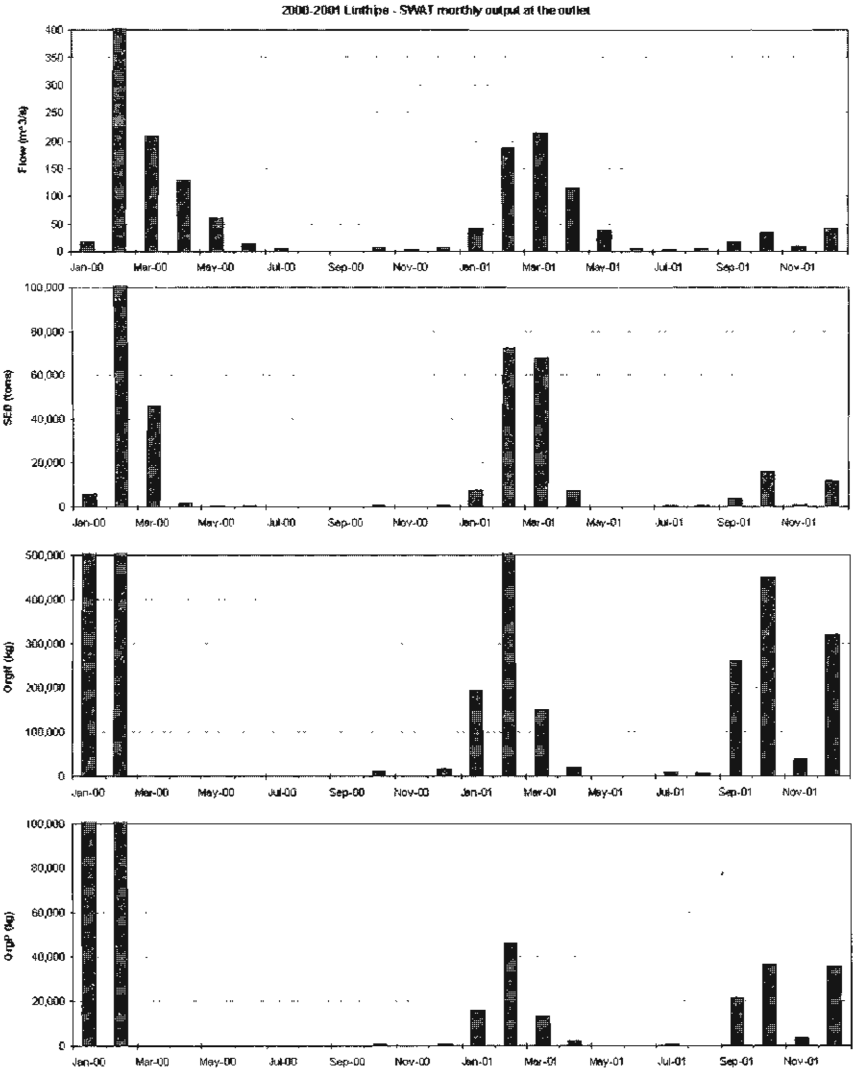


Figure 38: Linthipe output plots

7. You can now start the final form *SWAT Setup and Run*. Here you can change the Start and Finish dates, the weather sources, and any other of the options shown.

8. There are three ways to select the weather sources:

- You can use the global weather data that is supplied on the DVD. This provides a worldwide list of weather stations *stlnlist.txt.* In the folder *Global_Weather_Data* containing *stnlist.txt* there are subfolders *2000, 2001* etc containing data for each year. In the *Choose SWAT weather sources* form choose the option *Global files* and find the *stnlist.txt* file for the *Weather Stations File.* MWSWAT will later select the six weather stations closest to your basin, and then from them select the one nearest to each subbasin. It will also create precipitation and temperature files for each weather station for use by SWAT. This is what we did when we ran for the first time.

- You can reuse the files generated by using the previous option as follows. In the *TxtInOut* folder you will find files of the form *nnnnnn.pcp* and *nnnnnn.tmp. nnnnnn* is a weather station identifier from *stnlist.txt.* Create a new file, *sj_list.txt,* say, in SJ_Maps, and cut and paste the relevant lines from *stnlist.txt into it.* It does not matter if you insert some header lines first: MWSWAT will only start reading at the first line starting with 6 digits. You don't need to use all six weather stations for which *.pcp* and *.tmp* files exist, and you can use different weather stations if you wish (but make sure there is data for them in *yyyy/JAN.txt*, where *yyyy* is your start year). If you have put into your weather stations list only stations for which there are *.pcp* and *.tmp* files in *TxtInOut*, copy these files to *SJ_Maps* and in your next run you can use the *Local files* option in the *Choose SWAT weather sources* form, selecting *sj_list.txt* as your *Weather Stations File.* When this option is chosen only those stations in the weather stations file are used, and the *.pcp* and *.tmp* files are looked for in the same folder as the weather stations file.

  If you have in your weather stations list some stations for which you do not have *.pcp* and *.tmp* files in *TxtInOut* then copy *sj_list.txt* to the same folder as *stnlist.txt* and next time use the *Global files* option but with *sj_list.txt* as the weather stations file.

- The third alternative is to use tables in the database *SJ_MWSwat.mdb*, which you will find in the *F:\SJ_MWSwat* folder. The first run will generate a table *weather_sources* , six tables *pcpnnnnnn*, and six tables *tmpnnnnnn*. These tables can be reused by selecting *Database tables* as the weather source, and *weather_sources* as the table.

  Note that if you use different start or end dates in later runs you must ensure with the local or database options that your precipitation and temperature files or tables include the whole simulation period, and with the global option that the *Global_Weather_Data* folder has sub-folders for all the years required.

You can also use the *SWAT Editor* to edit any of the SWAT input files. The SWAT Editor is described in its own documentation and in further detail in chapters 9-15 of the *ArcSWAT_Documentation.pdf*, both of which can be found in *Software\SWATEditor* on the DVD.

8. Using Your Own Data

The data supplied with MWSWAT is obtained from the web, and you may have your own data which you want to use. This section explains how to do so.

8.1 DEM

The digital elevation map (DEM) is selected at the start of the interface. It can be any resolution, but (a) it must be projected to an "equal area" projection, or to a projection such as UTM which comes close enough to equal area in most cases – use MapWindow's *GIS Tools* plugin to do any reprojection – and (b) the elevations must be in meters.

8.2 Landuse and Soil Maps

You can substitute your own landuse and/or soil maps. This is a little more complicated since you have to provide the information on how the categories of landuse or soil that your maps use are to be interpreted by SWAT. For each differently categorized landuse or soil map that you use you have to prepare a table like *global_landuses* or *global_soils* and put it into either *C:\Program Files\MapWindow\Plugins\MWSWAT\mwswat.mdb* or the project database *Proj.mdb* in the *Proj* folder. In the first case it will be copied into every new project database, but you must be careful to keep it and replace it if you ever reinstall MWSWAT. In the second case it will only be used on the particular project. The project database is created (by copying *mwswat.mdb*) by the *New Project* action, so after this, before *Step 1*, is the best time to add any extra tables you need for a particular project.

1. In the case of a landuse map, the table should have the string *landuse* in its name. Then it will be offered as an option for a landuse table. It must have the same structure as the table *global_landuses* in *mwswat.mdb*. So it must contain at least the columns LANDUSE_ID (type Long Integer) and SWAT_CODE (type Text). The LANDUSE_ID corresponds to the values in the landuse grid. It is possible that more than one of your LANDUSE_IDs maps to the same SWAT_CODE, where your data makes more distinctions than are

supported by SWAT. The SWAT_CODE strings are 4 letters long and all the ones used in your map must be found in a table *crop* (or a table *urban* if the SWAT_CODE starts with a 'U') found in

a. The project database, or
b. The SWAT reference database

These databases are examined in this order.

2. In the case of a soil map, the table should have the string *soil* in its name. Then it will be offered as an option for a soil table. You should copy the structure of the table *global_soils* in *mwswat.mdb*. So it must contain at least the columns SOIL_ID (type Long Integer) and SNAM (type Text). The SOIL_ID corresponds to the values in the soil grid. You may map more than one of your soil categories to the same SWAT soil, where your data makes more distinctions than are supported by SWAT, but this is much less likely than it is for landuses. All the the SNAM strings you use must be found in a table *usersoil* found in

   a. The project database, or
   b. The SWAT reference database

   MWSWAT uses by default *global_soils* whose characteristics are defined in the table *usersoil* defined in *mwswat.mdb* and hence in your project database. If you need to define your own soils then you need to rename *usersoil* in the project database to something else (when the default will be the *usersoil* table in the SWAT reference database) and, if the SWAT reference table is not appropriate, replace it with another table of the same name and design. Or you can just add your own soils to *usersoil*, provided they have new names.

8.3 Weather Sources

You can also use the database option in *Choose weather sources* to use your own precipitation and temperature data if you have it. You need to prepare and put into your project database:

1. A table containing weather station data like *weather_sources*, with columns (at least) STATIONID, LATITUDE, LONGITUDE and ELEVATION. The first of these is type Text, the other three are type Double. The table should have a name that includes the string *weather* (but should not be called *weather_sources* or it is likely to be overwritten at some point by MWSWAT.)

2. For each STATIONID *id* in the first table there should be a table called *pcpid* and a table called *tmpid*. Each of these must have an column OID of type *Integer* that is marked as an index (with no duplicates) containing 1, 2, 3 etc., a column DATE of type *Text*, and the dates in this column must be consecutive days in one of four formats:

    a. Julian date *yyyyddd*

    b. *yyyy/mm/dd*

    c. *dd/mm/yyyy*

    d. *mm/dd/yyyy*

    MWSWAT decides which format is being used, using the first two dates in the table in the case of non-Julian dates.

    These tables can start and end with any date, not necessarily the first or last date of a year.

3. The tables called *pcpid* must have a column PCP of type Double giving the precipitation in mm on that day. The value -99 indicates missing data.

4. The tables called *tmpid* must have columns MAX and MIN of type Double defining the maximum and minimum temperatures on that day in degrees Celsius. -99 indicates missing data.

Text files with comma (or some other character)-separated values, or of fixed format, can be easily imported to make the *pcpid* and *tmpid* tables.

3.2 Step by Step Geo-Processing and Setup of the Required Watershed Data for MWSWAT (MapWindow SWAT)

Luis F. Leon

December 2007

(Slightly modified for this book and its accompanying DVD)

Contents

1. Source Data

1.1 DEM Source Data

1.1.1 SRTM Processed 90m Digital Elevation Data Version 3:

Format: ArcView Ascii Grid Files in 5° x 5° tiles (Lat/Long, decimal degrees)
Source: http://srtm.csi.cgiar.org/
Metadata included in header:

ncols 6000
nrows 6000
xllcorner -120
yllcorner 25
cellsize 0.000833333333333
NODATA_value -9999

Contents of the Readme file:

PROCESSED SRTM DATA

The data distributed here are in ARC GRID format, in **decimal degrees** and **datum WGS84**. They are derived from the **USGS/NASA SRTM** data. CIAT have processed this data to provide seamless continuous topography surfaces. Areas with regions of no data in the original **SRTM data have been filled** in using interpolation methods. A full technical report on this method is in preparation.

DISTRIBUTION

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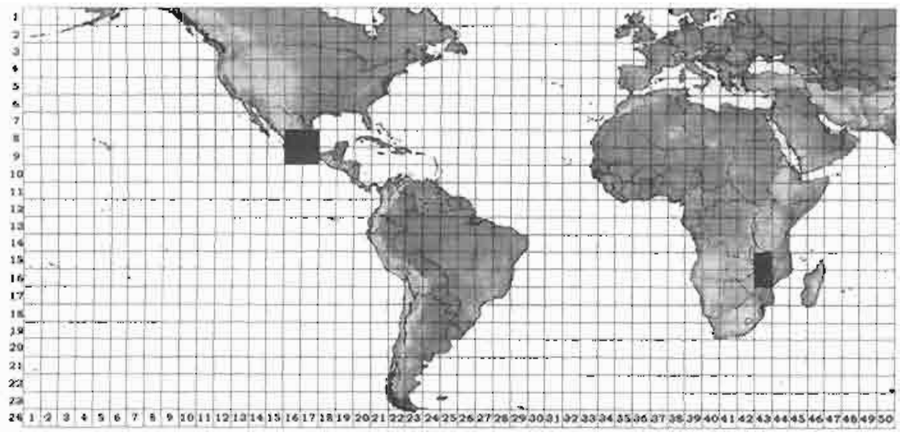
ACKNOWLEDGMENT AND CITATION

We kindly ask any users to cite this data in any published material produced using this data, and if possible link web pages to the CIAT SRTM website (http://gisweb.ciat.cgiar.org/sig/90m_data_tropics.htm).

Citations should be made as follows:

Hole-filled seamless SRTM data V1, 2004, International Centre for Tropical Agriculture (CIAT), available from http://gisweb.ciat.cgiar.org/sig/90m_data_tropics.htm

Downloaded Data



Tiles for Mexico:

srtm_16_08

srtm_16_09

srtm_17_08

srtm_17_09

Tiles for Malawi:

srtm_43_15

srtm_43_16

From the header info on each of these tiles, a simple shape file was created to quickly identify the required tiles when the user zooms in the area of interest (see World_Data_Grids folder and ZIP file).

The zipped DEM files for the San Juan example, such as ***srtm_16_08.zip***, as well as for Cambodia, Indonesia, Laos, Malaysia, Philippines, Thailand, and Vietnam are packaged in the DVD under *Software\MWSWAT\DATA\DEMs*. DEMs for other areas can be downloaded from **http://srtm.csi.cgiar.org/**. We use the

ArcInfo ASCII format. The suggested location to prepare the clipped versions to use in MWSWAT is a temporary folder (e.g. *C:\temporary\dems*). Once the DEM is merged and/or clipped for the area of interest it is strongly suggested to move the resulting output grid (*filename*.asc) to the MW_project location.

1.1.2 Basic Supporting Geographic Data:

HYDRO1k Elevation Derivative Database: http://edc.usgs.gov/products/elevation/gtopo30/hydro/index.html

Format: ArcView Shapefile Format (Lambert Azimuthal Equal Area projection)

Documentation: http://edc.usgs.gov/products/elevation/gtopo30/hydro/readme.html

Drainage Basins:

Africa - http://edcftp.cr.usgs.gov/pub/data/gtopo30hydro/af_bas.tar.gz

Origin (Longitude = 20° E ; Latitude = 5° N)

Asia - http://edcftp.cr.usgs.gov/pub/data/gtopo30hydro/as_bas.tar.gz

Origin (Longitude = 100° E ; Latitude = 45° N)

Australasia - http://edcftp.cr.usgs.gov/pub/data/gtopo30hydro/au_bas.tar.gz

Origin (Longitude = 135° E ; Latitude = 15° S)

Europe - http://edcftp.cr.usgs.gov/pub/data/gtopo30hydro/eu_bas.tar.gz

Origin (Longitude = 20° E ; Latitude = 55° N)

North America - http://edcftp.cr.usgs.gov/pub/data/gtopo30hydro/na_bas.tar.gz

Origin (Longitude = 100° W ; Latitude = 45° N)

South America - http://edcftp.cr.usgs.gov/pub/data/gtopo30hydro/sa_bas.tar.gz

Origin (Longitude = 60° W ; Latitude = 15° S)

The above files are already projected in latitude-longitude and available in the distribution DVD under the ***Global_Basins_latlong*** folder *in Software\MWSWAT\Data*. The vertices were also smoothed with 500m threshold.

Format: ArcView Shapefile Format (lat/long)

Projected Basins:

Africa – af_bas_ll_r500m.zip

Asia – as_bas_ll_r500m.zip

Australasia – au_bas_ll_r500m.zip

Europe – eu_bas_ll_r500m.zip

North America – na_bas_ll_r500m.zip

South America – sa_bas_ll_r500m.zip

It is suggested to unzip the contents of the files to a folder in the user's hard drive (e.g. *C:\unu_waterbase\Global_Basins_latlong*). The above figure, with the basins in different color for each continent, was created with MapWindow.

1.2 Landuse Source DATA:

The landuse data was provided by Dr Karim Abbaspour of Eawag (http://www.eawag.ch/index_EN):

Landuse data was constructed from the USGS Global Land Cover Characterization (GLCC) database (http://edcsns17.cr.usgs.gov/glcc/glcc.html). This map has a spatial resolution of 1 kilometre and 24 classes of landuse representation. The parameterization of the landuse classes (e.g. leaf area index, maximum stomatal conductance, maximum root depth, optimal and minimum temperature for plant growth) is based on the available SWAT landuse classes and literature research.

Pre-processing note:

Due to the huge size of the uncompressed files, after importing the file with ArcView the grids were divided into tiles for each continent. The resulting files were still rather slow to load and manipulate in MapWindow, and were therefore resampled at half the original resolution. Both the original and resampled (*newres*) tiles are available on the DVD. We think that there will typically be little difference in the results from SWAT between the two resolutions. When you are starting to use MapWindow and MWSWAT we suggest you use the resampled tiles. It is possible to get much better speed with the original tiles if you hide their display before clipping, but this is likely to be confusing to new users. We give an explanation of this in the sections on generating landuse maps.

Files exported as GeoTiff raster (distributed in the DVD – folder Software\MWSWAT\DATA\Global_Landuse_Data):

- North America – na_landuse.zip, na_landuse_newres.zip (na_land_1, na_land_2, na_land_3)
- South America – sa_landuse.zip, sa_landuse_newres.zip (sa_land_1, sa_land_2)
- Europe & Asia – ea_landuse.zip, ea_landuse_newres.zip (ea_land_1, ea_land_2, ea_land_3, ea_land_4)
- Africa – af_landuse.zip, af_landuse_newres.zip (af_land_1, af_land_2)
- Australia & Pacific – ap_landuse.zip, ap_landuse_newres.zip (ap_land_1)

1.3 Soil Source DATA:

The soil data was provided by Dr Karim Abbaspour of Eawag (http://www.eawag.ch/index_EN):

Soil map was produced by the Food and Agriculture Organization of the United Nations (FAO, 1995). Almost 5000 soil types at a spatial resolution of 10 kilometres are differentiated and some soil properties for two layers (0-30 cm and 30-100 cm depth) are provided. Further soil properties (e.g. particle-size distribution, bulk density, organic carbon content, available water capacity, and saturated hydraulic conductivity) were obtained from Reynolds et al. (1999) or by using pedotransfer functions implemented in the model Rosetta (http://www.ars.usda.gov/Services/docs.htm?docid=8953).

Reynolds, C.A., Jackson, T.J., Rawls W.J., 1999. Estimating available water content by linking the FAO soil map of the world with global soil profile database and pedo-transfer functions. Proceedings of the AGU 1999 spring conference. Boston, MA.

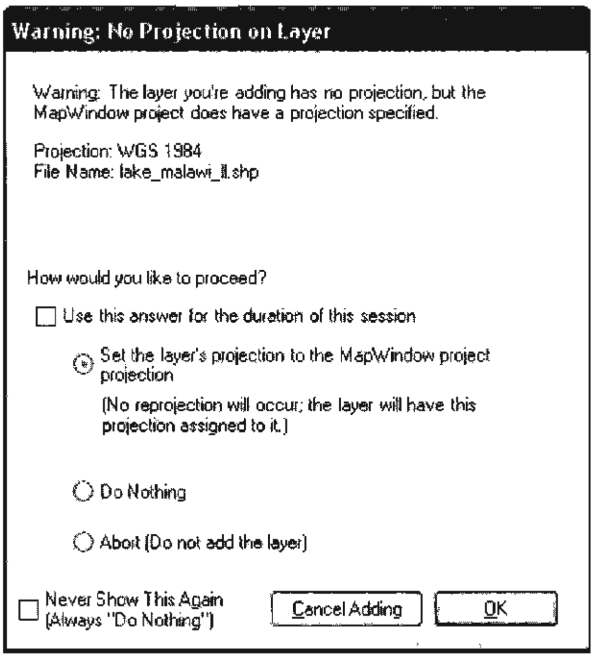
Files exported as GeoTiff raster (distributed in the DVD – folder: Software\MWSWAT\DATA\Global_Soil_Data):

- North America – na_soil.zip (na_soil_1, na_soil_2, na_soil_3)

- South America – sa_soil.zip (sa_soil_1, sa_soil_2)
- Europe & Asia – ea_soil.zip (ea_soil_1, ea_soil_2, ea_soil_3, ea_soil_4)
- Africa – af_soil.zip (af_soil_1, af_soil_2)
- Australia & Pacific – ap_soil.zip (ap_soil _1)

1.4 Note on Projection Warnings

Sometimes when adding a layer to MapWindow you may see a warning like the following:



This is because one of the maps already added has projection information, which has set the current project projection, and the new map does not. To be safe you can select *Cancel Adding*, and use *File\Settings* to look at the *Project Projection*. For a lat/long projection this should say (for the maps we are using) Geographic Coordinate Systems, World, and WGS 1984. For a UTM projection it should say (again for the maps we are using) Projected Coordinate Systems, Utm - Wgs 1984, and WGS 1984 UTM Zone plus either 14N (for San Juan) or 36S (for Linthipe). Provided the new layer is intended to be lat/long or UTM respectively you can select the default action of setting the new layer's projection to the MapWindow project projection. This, as the associated text indicates, does not change the layer data, it merely stores an extra .prj file for the layer being added.

If you are adding a new layer that has a different projection from the current project projection, for example as the result of reprojection, then you get a similar warning titled *Projection Mismatch*. In this case the best thing to do usually is *Cancel Adding*, then clear all layers (which removes the current project projection) before adding the differently projected layer.

2. Setup for Mexico: San Juan River Watershed

2.1 Elevation maps (DEMs)

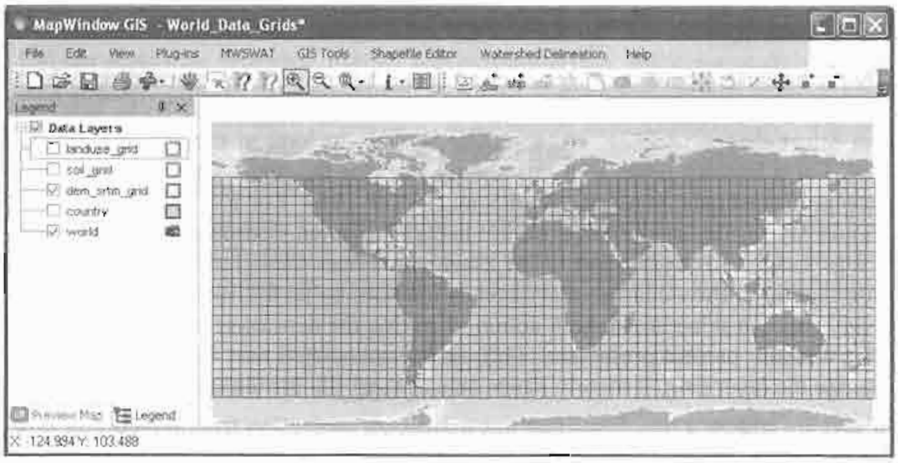
2.1.1 Pre-Process of DEM Data

Objective: Merge and clip the SRTM files for the area of interest.

As an alternative to the derivative basins files, the users may have available their own map data for the region. In this example, there are additional datasets for watersheds, surface water (i.e. lakes and dams) and rivers for the San Juan River watershed. (additional shape files: ***sj_washd_ll, sj_water_ll*** & ***sj_rivers_ll***; all in lat long). These are found in the DVD in *Software\MWSWAT\DATA\ SJ_Maps*.

Clip DEM for Area of Interest:

- Click the *Open Project* button on the MapWindow toolbar and navigate to *Software\MWSWAT\DATA\World_Data_Grids* Open the project file, *World_Data_Grids.mwprj*.
- In *Software\MWSWAT\DATA*, unzip *Global_Basins_latlong/ na_bas_ll_r500.zip* and *SJ_Maps\GeoProcessed*. Add the following layers  : ***Global_Basins_latlong\na_bas_ll_r500m.shp*** (lat long basins) and ***SJ_Maps\sj_washd_ll.shp*** (user watershed file, just for reference purposes).



- Zoom in to the required level and create a shape file with a rectangle around the area of interest. To make such a rectangle:

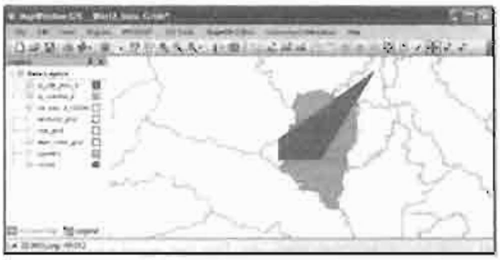
1. Use  to open a new shapefile.

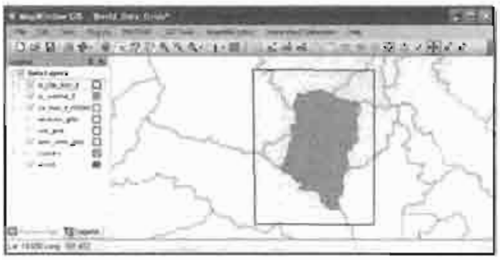
2. Using the button by the Filename textbox, navigate to the *SJ_Maps* folder and set the new shapefile's name to *sj_clip_box_ll.shp* and its type to *Polygon*

3. Click *OK* on the warning about the extents of the new shapefile.

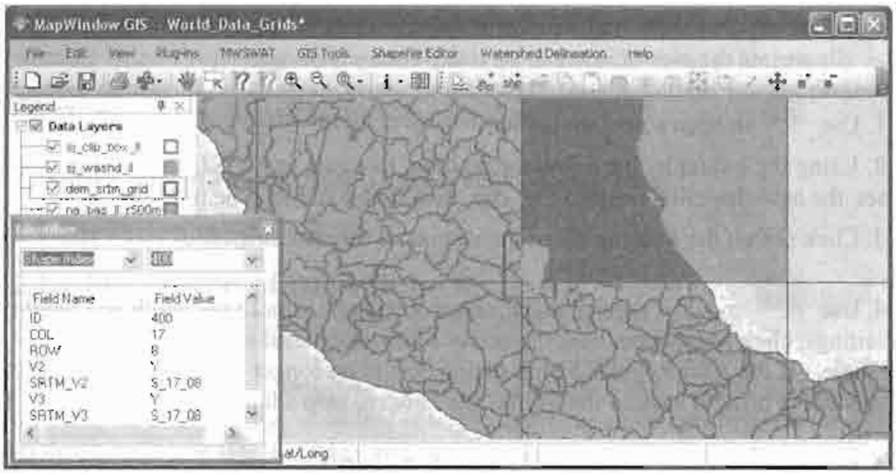
4. Use  to add a regular shape, select Rectangle, ignore the width and height settings, click somewhere near the center of the watershed to place the initial rectangle. If the Add Regular Shape dialog box is no longer visible, find it on the task bar to bring it back to the front.Click *Done* to stop adding shapes.

5. Make sure the new rectangle is selected, then click on  to move the vertices of the initial rectangle one by one so that it easily includes the watershed. The next two pictures show (a) the situation after moving the first vertex and (b) the situation after moving all four vertices and setting *Show Fill* for the shapefile to false. To do this, use the right mouse button on the legend entry for *sj_clip_box_ll*, select *Properties*, and change *Show Fill*.

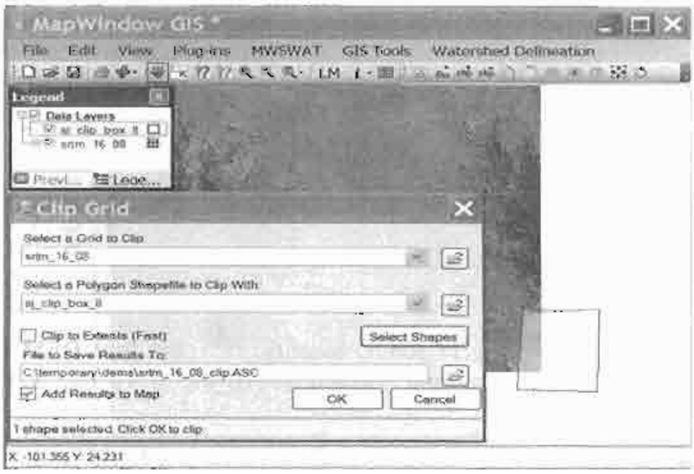




- With the ***dem_srtm_grid*** active, identify  the four DEM files that needed to be clipped and merged (S_16_08, S_16_09, S_17_08 & S_17_09).

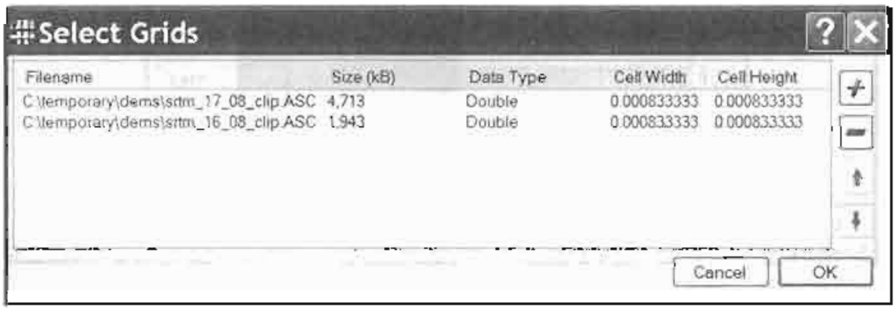


- Close MapWindow: do NOT save the changes to the project.
- Unzip *srtm_16_08.zip* and move *srtm_16_8.ASC.* to the folder, *temporary\dems.* Now add it as a view (being patient – it takes a few minutes). Also add the shapefile *SJ_Maps\sj_clip_box_ll.shp* found in *Software\MWSWAT\DATA*.
- Make sure that *GIS Tools* is selected as a Plug-in, and select *GIS Tools\Raster\Clip Grid With Polygon*. Select the dem grid to clip and the box shapefile to clip with.
- Don't check the Clip to Extents (Fast) option and select the shape (clip box), press *Done* when the box is highlighted. Note that the output file name is created for you (keep this default name and location: *temporary\dems\srtm_16_8_clip.ASC*). Click *OK* to clip.

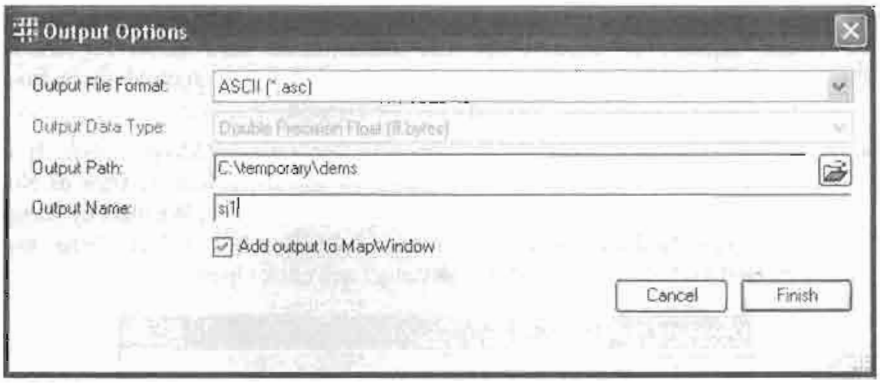


- When the clipping is done, remove the large dem layer (*srtm_16_8.ASC*) and repeat the process for the other three tiles (*srtm_16_9.ASC, srtm_17_8.ASC, & srtm_17_9.ASC*). Don't forget to remove them from the view after clipping, leaving only the clipped files.
- Merge the four clipped grids with *GIS Tools\Raster\Merge Grids*. It is possible to merge all four in one step, but this often leaves strips of No-Data cells at the joins. It is safer to merge two at a time. We start by merging *srtm_16_8_clip.ASC* and *srtm_17_8_clip.ASC*. Select these two clipped grids (press Ctrl while selecting) and click Open.

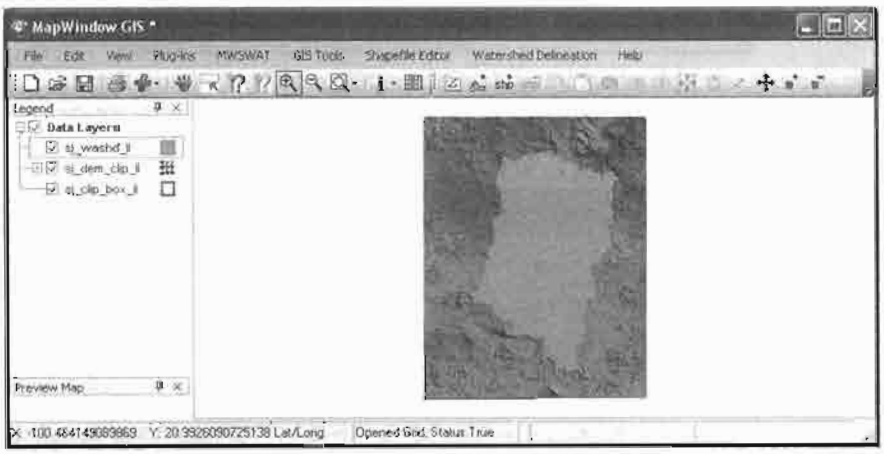
- When done, the Select Grids window will display the information for each of the files.



- Click OK to start merging. Name the result sj1.



- Click Finish and remove the clipped layers from the view. In the same way merge ***srtm_17_9_clip.ASC*** and ***srtm_16_9_clip.ASC*** to make ***sj2.asc***, and finally merge ***sj1.asc*** and ***sj2.asc*** to make ***sj_dem_clip_ll.asc***. Reload the watershed layer (*Software\MWSWAT\DATA\SJ_Maps\sj_washd_ll.shp*) and use  to zoom to that layer to verify the extents. This *sj_dem_clip_ll.asc* is the final DEM product that, when projected to UTM (see below) will be used in MWSWAT.



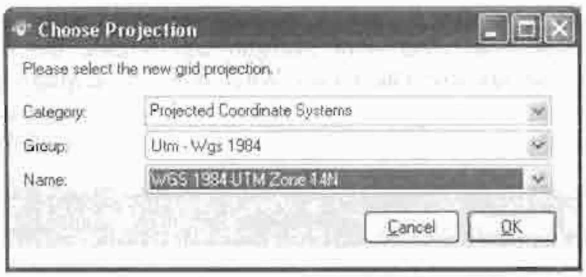
2.1.2 Re-project DEM to UTM

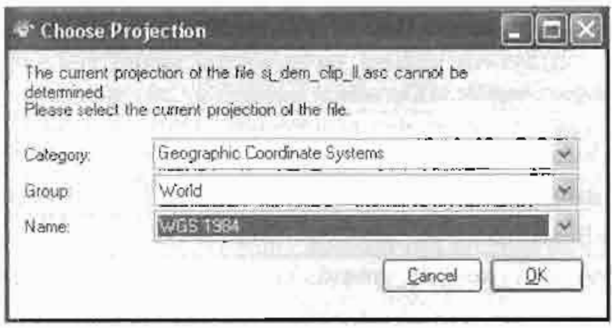
Objective: Re-project the clipped DEM files to UTM and re-clip for the area of interest.

Due to the fact that MWSWAT needs meter units and an equal area projection to perform slope and area calculations, the clipped DEM need to be re-projected to UTM coordinates. (While UTM is not truly an equal area projection, it is close enough for SWAT in most cases.) In this example, there is an additional dataset for the San Juan River watershed already projected in UTM. (additional shape file: ***sj_washd_utm***: Zone 14N).

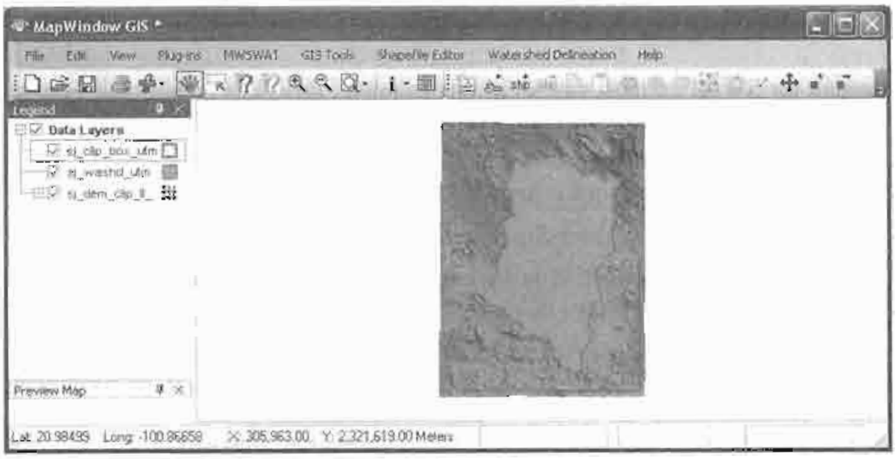
Re-project DEM and re-clip for Area of Interest:

- Select *GIS Tools\Raster\Reproject Grids.*
- Select the clipped DEM in lat/long (***temporary\dems\sj_dem_clip_ll.asc***), and when loaded click OK to re-project.
- Choose projection details: Projected Coordinate System, Datum WGS 1984 and Zone 14N and the current projection values if MapWindow couldn't determine them (Geographic Coordinate, World Projections, Datum: WGS 1984).

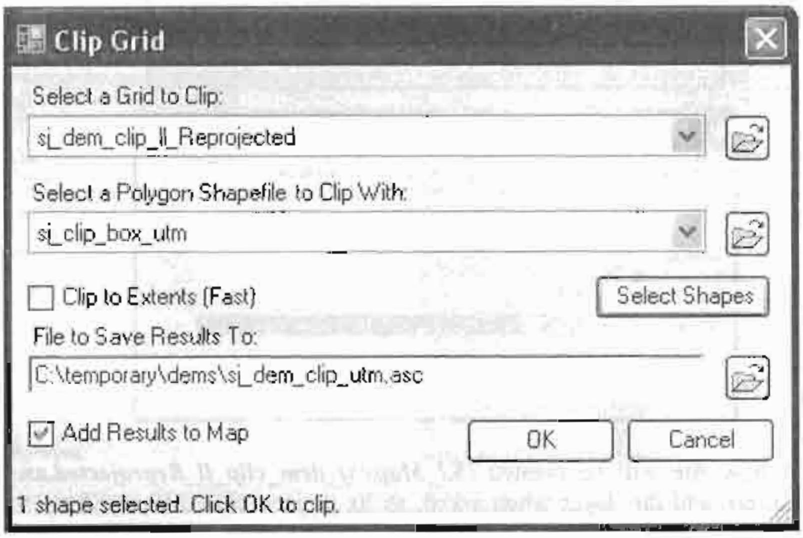




- A new file will be created (***SJ_Maps\sj_dem_clip_ll_Reprojected.asc***). Do not add this layer when asked, as its projection is different from the current one. Clear all layers and then add the layer **SJ_Maps\sj_dem_clip_ll_Reprojected.asc**. Also add the watershed in UTM (***SJ_Maps\sj_washd_utm.shp***).
- Create a new clipping box in this UTM view (this will remove all the missing values generated with the rotation of the grid when re-projected).



- Clip the re-projected dem with the UTM clip box. Select *GIS Tools\Raster\Clip Grid With Polygon* and rename the output file as ***sj_dem_clip_utm.asc***. OK to clip. When done, close MapWindow (do not save project changes) and copy the file ***sj_dem_clip_utm.asc*** to the project folder as this is going to be the DEM to be used with MWSWAT.



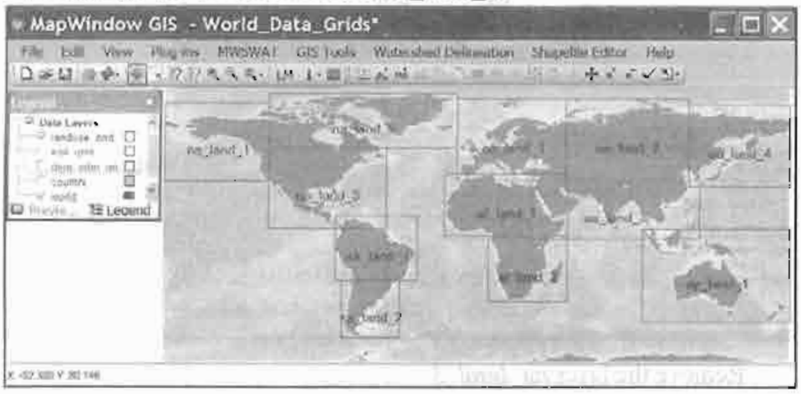
2.2 Landuse Data

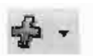
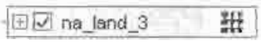
2.2.1 Pre-Process of Landuse Data

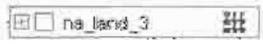
Objective: Clip the Landuse file for the area of interest.

Clip Landuse for Area of Interest:

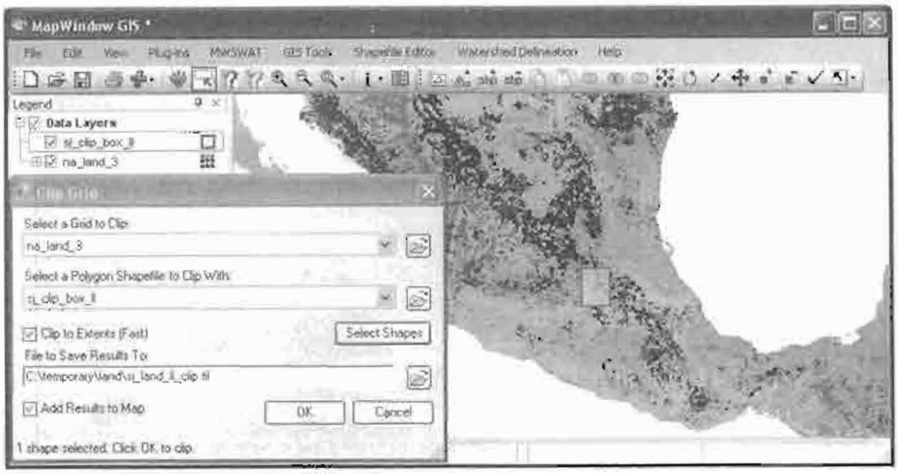
- Open the project ***World_Data_Grids.mwprj*** again. This shows that the tile we need for our area of interest is ***na_land_3***.



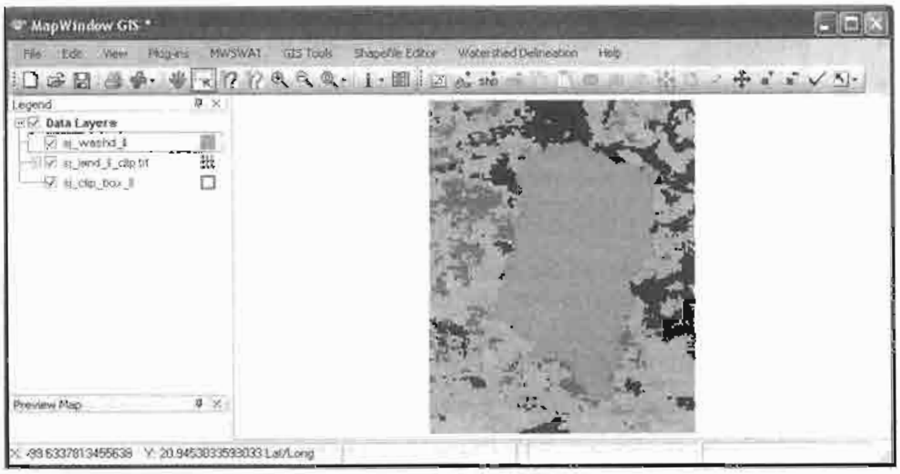
- Extract ***na_land_3.tif*** together with the corresponding .bmp, .bpw and .mwleg files from ***na_landuse_newres.zip*** (found in the DVD in the ***Software\MWSWAT\DATA|Global_Landuse_Data***). Store them in, say, ***temporary\land***.
- Close MapWindow. Do NOT save the project data.
- Add Layer  and select: ***temporary\land\ na_land_3.tif***.
- *Hint: you can choose instead of **na_landuse_newres.zip** to use the tile from **na_landuse.zip**, the original landuse files. These tiles are large and take some time to display, and are also slow to react to any changes in the display. So as soon as such a tile is loaded, remove the tick from its legend, i.e. change* 

to 

This removes the display of the map. You can still proceed with the following steps of loading a clip box and clipping, but you can't see so clear- ly what is happening.
- Add the layer for the clip box (***SJ_Maps\sj_clip_box_ll.shp***).
- Select *GIS Tools\Raster\Clip Grid With Polygon*. Select the landuse layer and the box to clip with from the ones just loaded into the view.
- Check the Clip to Extents (Fast) option and select the shape (clip box), press Done when the box is highlighted. Note that the output file name is created for you. Rename this to: ***temporary\land\sj_land_ll_clip.tif***. Click OK to clip.



- Remove the layer *na_land_3*.
- Use  to zoom to the layer of *sj_clip_box_ll*, and use Add Layer  to reload the watershed layer (***SJ_Maps\sj_washd_ll.shp***) to verify the extents. This ***sj_land_ll_clip.tif*** is the final landuse product that, when projected to UTM (see below) will be used in MWSWAT.



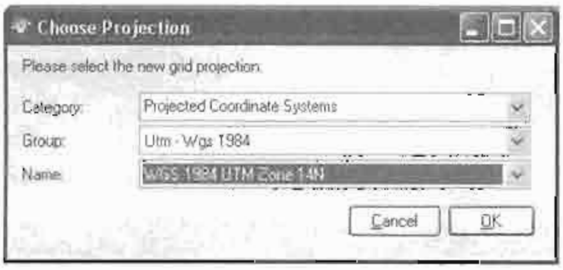
2.2 Re-project Landuse to UTM

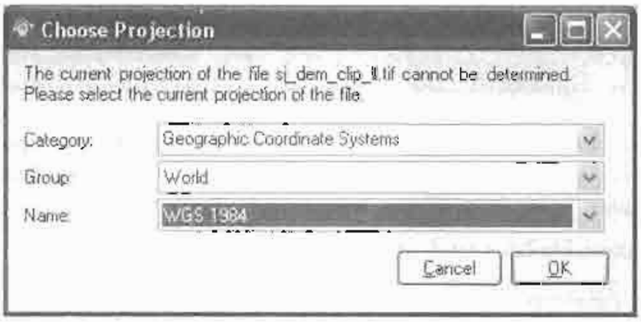
Objective: Re-project the clipped landuse file to UTM and re-clip for the area of interest.

Due to the fact that MWSWAT needs meter units and an equal area (or close to equal area) projection to perform area calculations, the clipped landuse file needs to be re-projected to UTM coordinates. In this example, there is an additional dataset for the San Juan River watershed already projected to UTM. (additional shape file: *sj_washd_utm*: Zone 14N).

Re-project Land and re-clip for Area of Interest:

- Clear all the layers and select *GIS Tools\Raster\Reproject Grids.*
- Open the clipped landuse file in lat/long (***temporary\land\ sj_land_ll_clip.tif***). When loaded click OK to re-project.
- Choose projection details: Projected Coordinate System, Datum WGS 1984 and Zone 14N and the current projection values if MapWindow couldn't determine them (Geographic Coordinate, World Projections, Datum: WGS 1984).





- A new file will be created (***temporary\land\sj_land_clip_ll_Reprojected.tif***). Do not add the layer when asked, as it has a different projection, but clear all layers and then add it. Also add the watershed in UTM (***SJ_Maps\sj_washd_utm.shp***).
- Load the clipping box in UTM view (***SJ_Maps\sj_clip_box_utm.shp***) to re-clip and remove all the missing values generated with the rotation of the grid when re-projected.

- Clip the re-projected landuse with the UTM clip box. Select *GIS Tools\Raster\Clip Grid With Polygon* and rename the output file as ***sj_land_clip_utm.tif***. OK to clip. When done, close MapWindow (do not save project changes) and copy the file ***sj_land_clip_utm.tif*** to the project folder as this is going to be the landuse file to be used with MWSWAT.

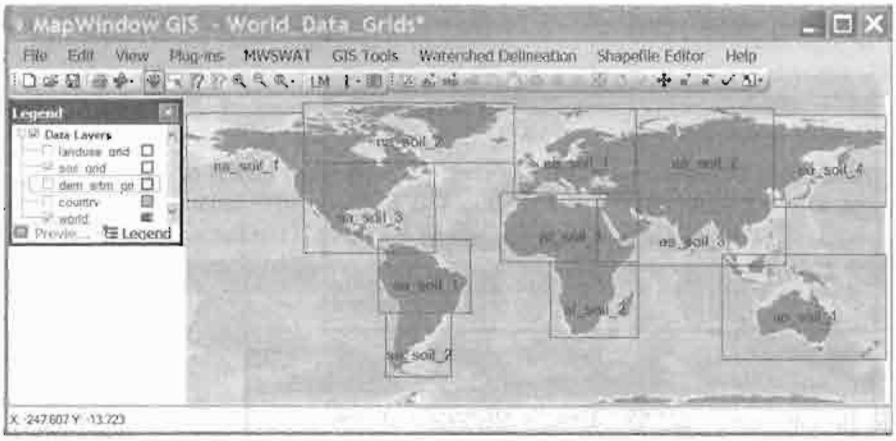
2.3 Soil Data

2.3.1 Pre-Process of Soil Data

Objective: Clip the Soil file for the area of interest.

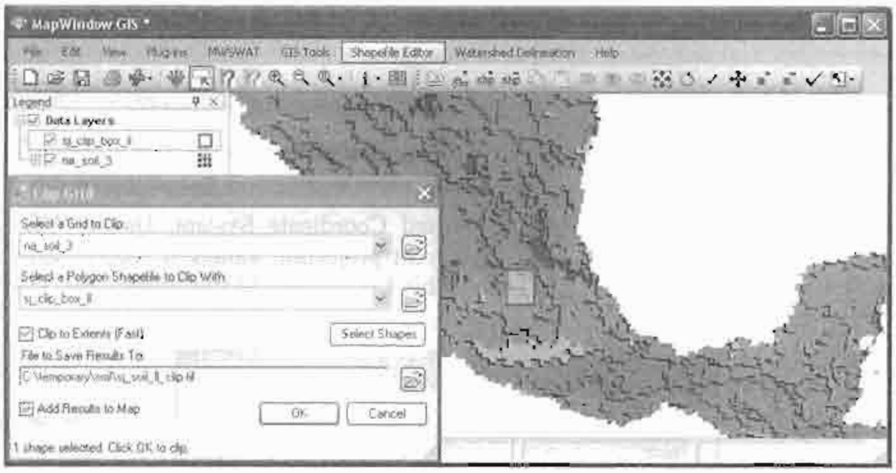
Clip Soil for Area of Interest:

- Open the project ***World_Data_Grids.mwprj*** again. This shows that the soil tile we need is *na_soil_3*.

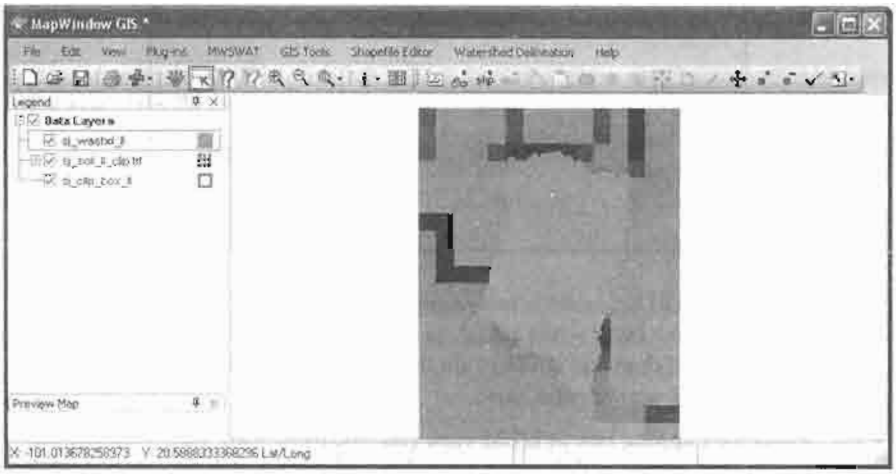


- Extract *na_soil_3.tif* together with the corresponding .bmp, .bpw and .mwleg files from *na_soil.zip* (found in the DVD in the folder ***Global_Soil_Data***). Store them in, say, ***temporary\soil***.
- Close **MapWindow**. Do NOT save project data.
- **Add Layer**  and select: ***temporary\soil\ na_soil_3.tif***. Also add the layer for the clip box (***SJ_Maps\sj_clip_box_ll.shp***).
- Select *GIS Tools\Raster\Clip Grid With Polygon*. Select the soil layer and the box to clip with from the ones just loaded into the view.
- Check the Clip to Extents (**Fast**) option and select the shape (clip box), press Done when the box is highlighted. Note that the output file name is

created for you. Rename this default name to *temporary\soil\sj_soil_ll_clip.tif*. Click OK to clip.



- Remove the layer ***na_soil_3***. With Add Layer  reload the watershed layer (***SJ_Maps\sj_washd_ll.shp***) to verify the extents. This ***sj_soil_ll_clip.tif*** is the final soil product that, when projected to UTM (see below) will be used in MWSWAT.



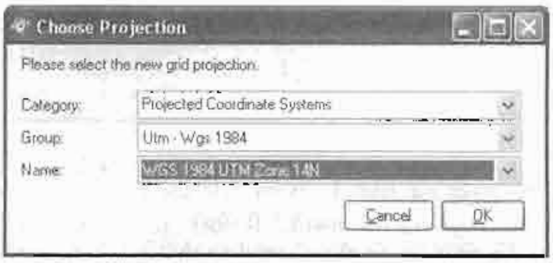
2.3.2 Re-project Soil to UTM

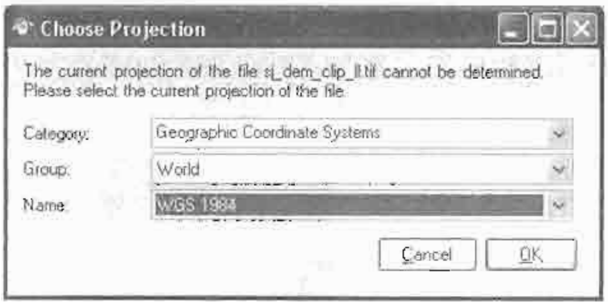
Objective: Re-project the clipped soil file to UTM and re-clip for the area of interest

Due to the fact that MWSWAT needs meter units and a projection that is close to equal area to perform area calculations, the clipped soil file need to be re-projected to UTM coordinates. In this example, there is an additional dataset for the San Juan River watershed already projected in UTM. (additional shapefile: ***sj_washd_utm***: Zone 14N).

Re-Project Soil and re-clip for Area of Interest:

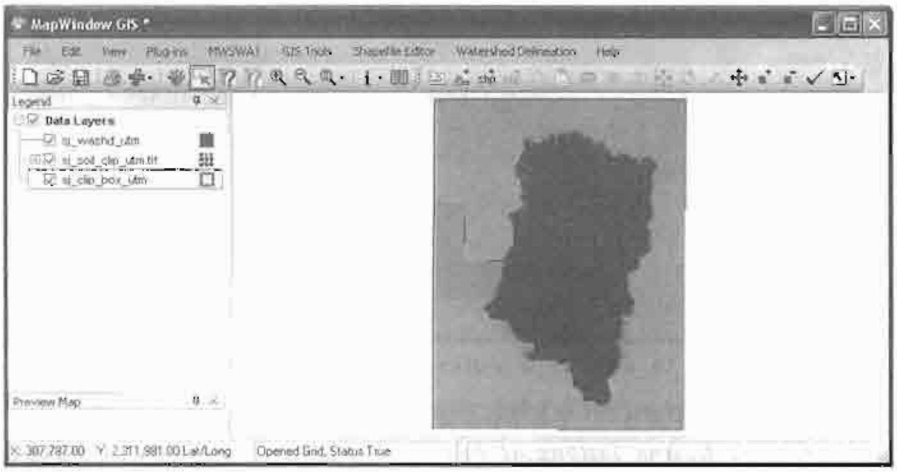
- Remove all the layers and select *GIS Tools\Raster\Reproject Grids*.
- Open the clipped soil file in lat/long (***temporary\soil\ sj_soil_ll_clip.tif***), when loaded click OK to re-project.
- Choose projection details: Projected Coordinate System, Datum WGS 1984 and Zone 14N and the current projection values if MapWindow couldn't determine them (Geographic Coordinate, World Projections, Datum: WGS 1984).





- A new file will be created (***temporary\soil\sj_soil_clip_ll_Reprojected.tif***). Do not add the layer when asked, as it has a different projection, but clear all layers and then add it. Also add the watershed in UTM (***SJ_Maps\sj_washd_utm.shp***).
- Load the clipping box in UTM view (SJ_Maps\sj_clip_box_utm.shp) to re-clip and remove all the missing values generated with the rotation of the grid when re-projected.
- Clip the re-projected soil with the UTM clip box. Select *GIS Tools\Raster\Clip Grid With Polygon* and rename the output file as *sj_soil_clip_utm.tif*. OK to clip. When done, close MapWindow (do not

save project changes) and copy the file *sj_soil_clip_utm.tif* to the project folder as this is going to be the soil file to be used with MWSWAT.



3. Setup for Malawi: Linthipe Watershed

3.1 Elevation Data (DEMs)

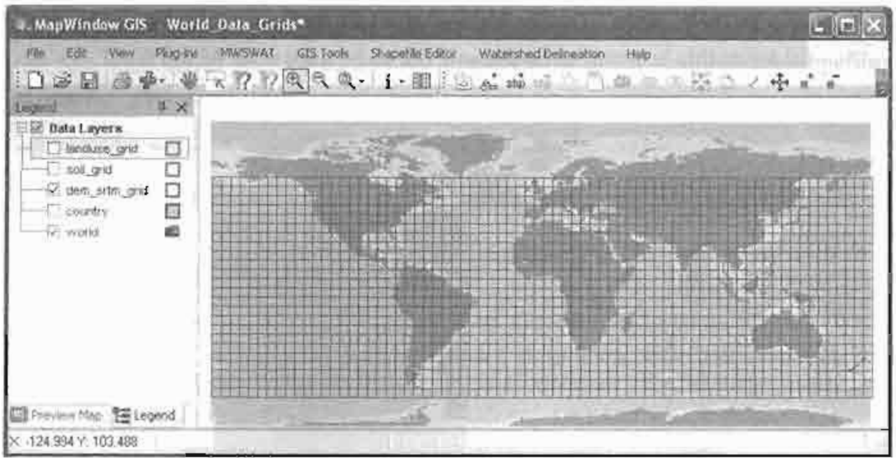
3.1.1 Pre-Process of DEM Data

Objective. Clip the SRTM file for the area of interest.

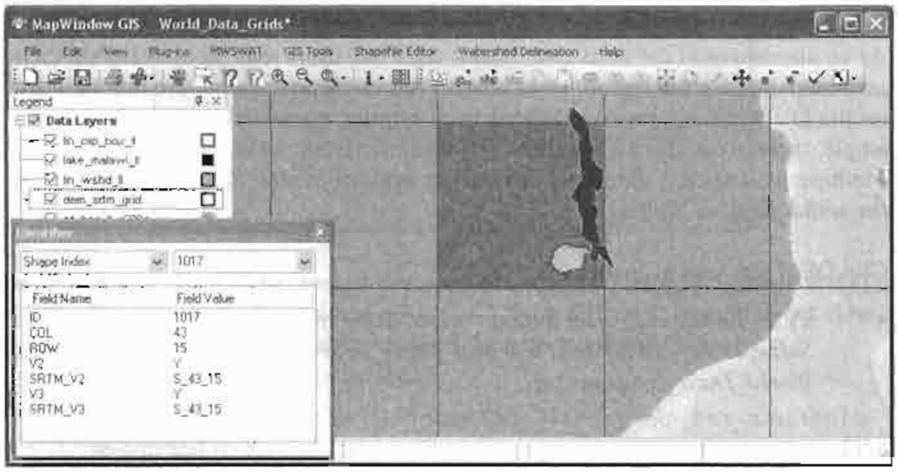
As an alternative to the derivative basins files, the users may have available their own map data for the region. Data sets for the Linthipe example are not included on the DVD but can be downloaded from http://www.waterbase.org. In this example, there are additional datasets for: Malawi rivers, Lake Malawi and for the Linthipe watershed. (additional shapefiles: ***malawi_rivers_ll, lake_malawi_ll*** & ***lin_wshd_ll***; all in lat/long).

Clip DEM for Area of Interest:

- Click the *Open Project* button on the MapWindow toolbar and navigate to *Software\MWSWAT\DATA\World_Data_Grids* Open the project file, *World_Data_Grids.mwprj*.

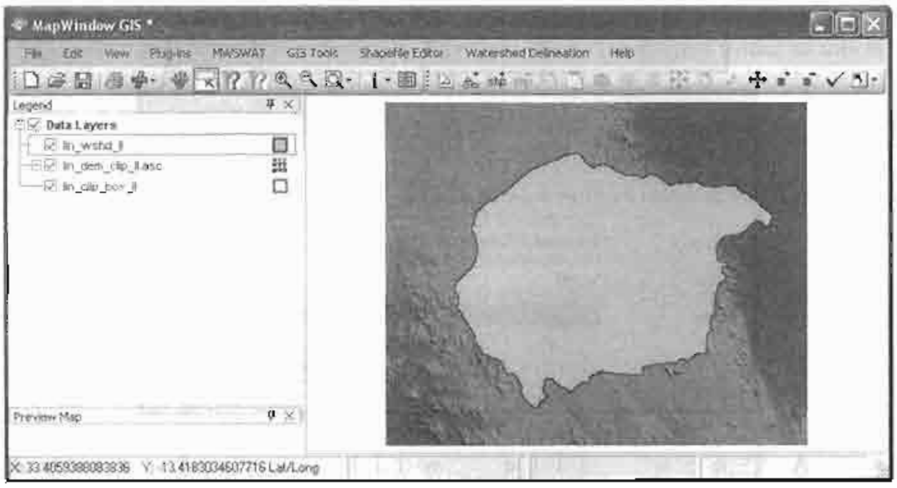


- Add the following layers . *Global_Basins_latlong\af_bas_ll_r500m.shp* (lat/long basins), *Lin_Maps\lin_wshd_ll.shp and Lin_Maps\lake_malawi_ll.shp* (user watershed file and Lake Malawi, just for reference purpose).
- Zoom in to the required level and create a shape file with a rectangle around the area of interest (namely the shape file *Lin_Maps\lin_clip_box_ll.shp*).



- For this watershed only one dem tile is required (*srtm_43_15*), easily identified , so the only process left to do is clipping for the area of interest.

- Close MapWindow: Do NOT save the changes to the project.
- Unzip *srtm_43_15.zip* to extract *srtm_43_15.ASC*, storing it in **temporary\dems** and add it is a layer (being patient – it takes a few minutes). Also add the shapefile ***Lin_Maps\lin_clip_box_ll.shp***.
- Make sure that *GIS Tools* is selected as a Plug-in, and select *GIS Tools\Raster\Clip Grid With Polygon*. Select the dem grid to clip and the shapefile to clip with..
- Check the Clip to Extents (Fast) option and select the shape (clip box), press Done when the box is highlighted. Note that the output file name is created for you (rename this file: ***temporary\dems\lin_dem_clip_ll.asc***). Click OK to clip.
- This ***lin_dem_clip_ll.asc*** is the final DEM product that, when projected to UTM (see the projection section) will be used in MWSWAT. When the clipping is done, remove the large DEM layer (*srtm_43_15.ASC*).
- Reload the watershed (***Lin_Maps\lin_wshd_ll.shp***) to verify the extents.



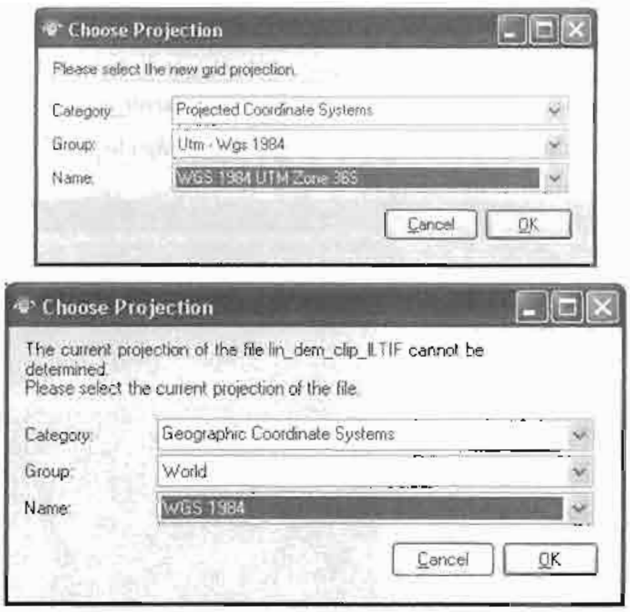
3.1.2 Re-project DEM to UTM

Objective: Re-project the clipped DEM files to UTM and re-clip for the area of interest.

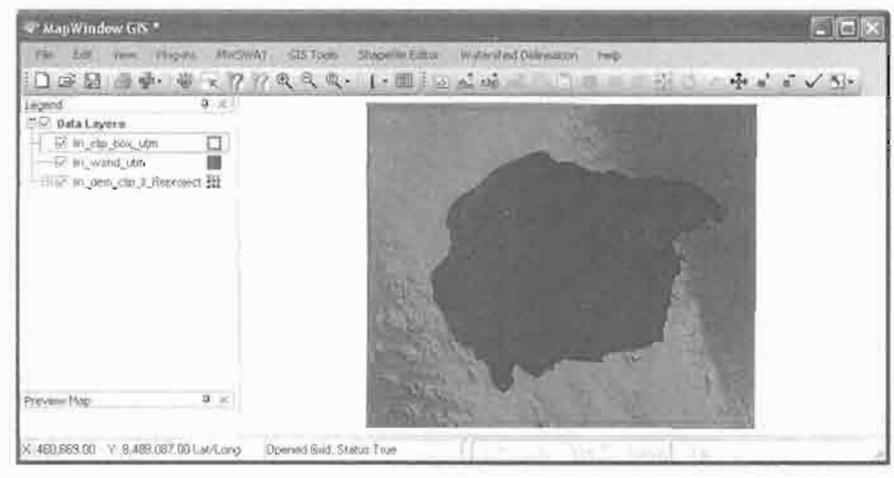
Due to the fact that MWSWAT needs meter units and an equal area projection to perform slope and area calculations, the clipped DEM needs to be re-projected to UTM coordinates (which is close enough to an equal area projection for our purposes). In this example, there is an additional dataset for the Linthipe watershed already projected in UTM. (additional shapefile: ***lin_wshd_utm***: Zone 36S).

Re-Project DEM and re-clip for Area of Interest:

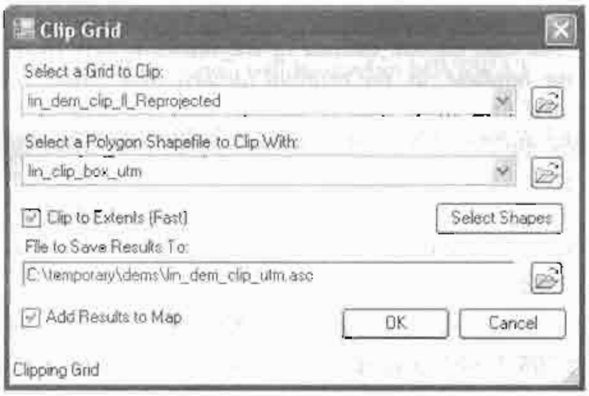
- Select *GIS Tools\Raster\Reproject Grids.*
- Open the clipped DEM in lat/long (***temporary\dems\lin_dem_clip_ll.ASC***), when loaded click OK to re-project.
- Choose projection details: Projected Coordinate System, Datum WGS 1984 and Zone 36S and the current projection values if MapWindow couldn't determine them (Geographic Coordinate, World Projections, Datum: WGS 1984).



- A new file will be created (***temporary\dems\lin_dem_clip_ll_Reprojected.asc***). Do not add this layer when asked, as it has a different projection. Clear all layers, then add the reprojected DEM and and the watershed in UTM (***Lin_Maps\lin_wshd_utm.shp***).
- Create a new clipping box in this UTM view (this will remove all the missing values generated with the rotation of the grid when re-projected).



- Clip the re-projected DEM with the UTM clip box. Select *GIS Tools\Raster\Clip Grid With Polygon* and rename the output file as ***lin_dem_clip_utm.asc***. OK to clip. When done, close MapWindow (do not save project changes) and copy this final file to the project folder as this is going to be the DEM to be used with MWSWAT.



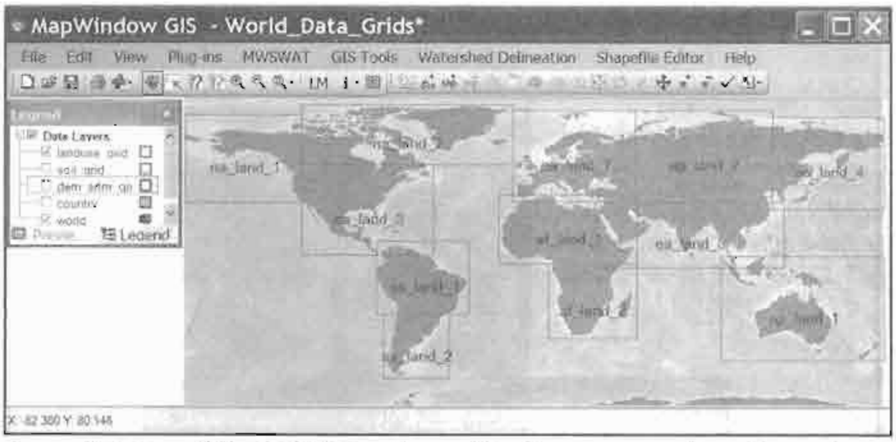
3.2 Landuse Data

3.2.1 Pre-Process of Landuse Data

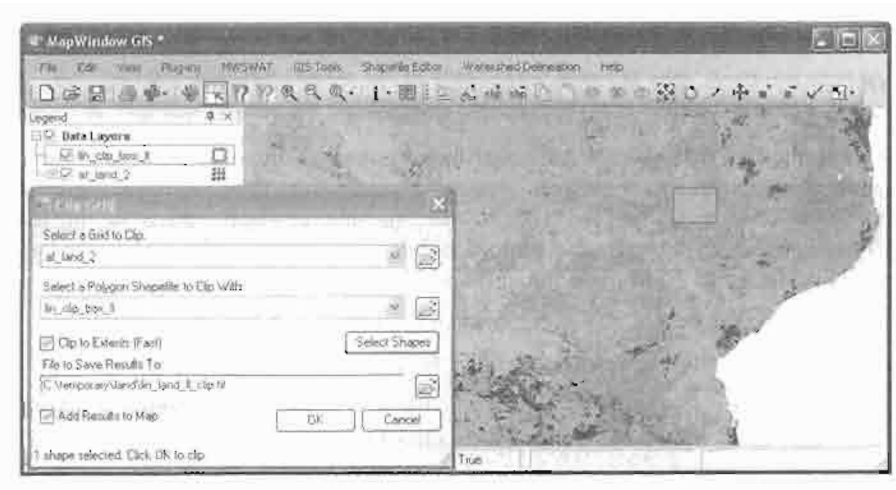
Objective: Merge and clip the Landuse files for the area of interest.

Clip Landuse for Area of Interest:

- Close MapWindow, and open the project ***World_Data_Grids.mwprj*** again. This shows that the tile we need for our area of interest is ***af_land_2***.

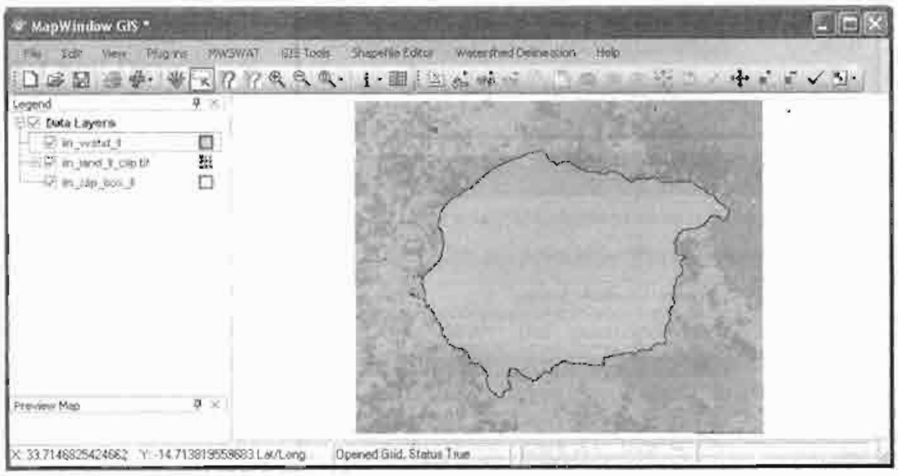


- Extract ***af_land_2.tif*** together with the corresponding .bmp, .bpw, and .mwleg files from ***af_landuse_newres.zip*** (found in the DVD in the folder ***Global_Landuse_Data***). Store them in, say, ***temporary\land***.
- Close MapWindow. Do NOT save the project data.
- Add Layer and select: ***temporary\land\ af_land_2.tif*** (note: be patient! MapWindow takes a few minutes to load the file).
- *Hint: you can choose instead of **na_landuse_newres.zip** to use the tile from **na_landuse.zip**, the original landuse files. These tiles are large are large and take some time to display, and are also slow to react to any changes in the display. So as soon as such a tile is loaded, remove the tick from its legend, i.e. change to*
  This removes the display of the map. You can still proceed with the following steps of loading a clip box and clipping, but you can't see so clearly what is happening.
- Add the layer for the clip box (***Lin_Maps\lin_clip_box_ll.shp***).
- Select *GIS Tools\Raster\Clip Grid With Polygon*. Select the landuse layer and the box to clip with from the ones just loaded into the view.
- Check the Clip to Extents (Fast) option and select the shape (clip box), press Done when the box is highlighted. Note that the output file name is created for you. Rename this default name: ***temporary\land\lin_land_ll_clip.tif***. Click OK to clip.



- Remove the layer ***af_land_2***.

- Use  to zoom to the layer of ***lin_clip_box_ll*** and with Add Layer  reload the watershed layer (***Lin_Maps\lin_wshd_ll.shp***) to verify the extents. This ***lin_land_ll_clip.tif*** is the final landuse product that, when projected to UTM (see below) will be used in MWSWAT.



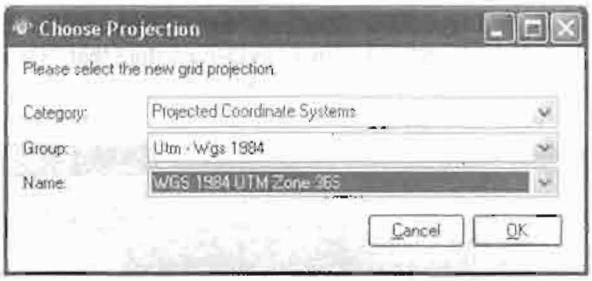
3.2.2 Re-project Landuse to UTM

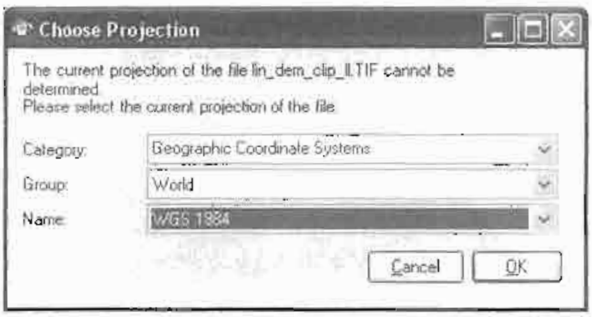
Objective: Re-project the clipped landuse file to UTM and re-clip for the area of interest.

Due to the fact that MWSWAT needs meter units and an equal area (or close to equal area) projection to perform area calculations, the clipped landuse file need to be re-projected to UTM coordinates. In this example, there is, in file downloaded from WaterBase, an additional dataset for the Linthipe watershed already projected to UTM. (additional shape file: ***lin_wshd_utm***: Zone 36S).

Re-Project Landuse and re-clip for Area of Interest:

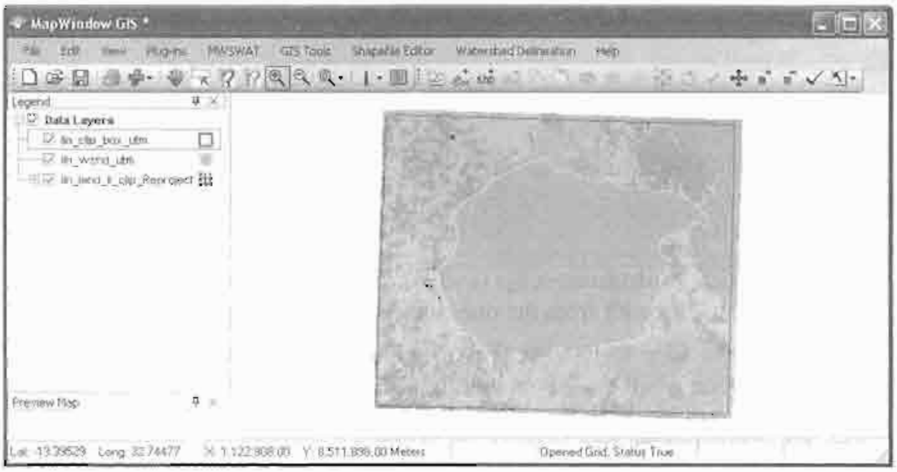
- Clear all the layers and select *GIS Tools\Raster\Reproject Grids*.
- Open the clipped landuse file in lat/long (***temporary\land\lin_land_ll_clip.tif***), when loaded click OK to re-project.
- Choose projection details: Projected Coordinate System, Datum WGS 1984 and Zone 36S and the current projection values if MapWindow couldn't determine them (Geographic Coordinate, World Projections, Datum: WGS 1984).





- A new file will be created (***temporary\land\Lin_land_clip_ll_Reprojected.tif***). Do not add the layer when asked, as it has a different projection, but clear all layers and then add it. Also add the watershed in UTM (*Lin_Maps\lin_wshd_utm.shp*).

- Load the clipping box in UTM view (*Lin_Maps\sj_clip_box_utm.shp*) to re-clip and remove all the missing values generated with the rotation of the grid when re-projected.



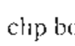
- Clip the re-projected landuse with the UTM clip box. Select *GIS Tools\Raster\Clip Grid With Polygon* and rename the output file as ***lin_land_clip_utm.tif***. OK to clip. When done, close MapWindow (do not save project changes) and copy the file *lin_land_clip_utm.tif* to the project folder as this is going to be the landuse file to be used with MWSWAT

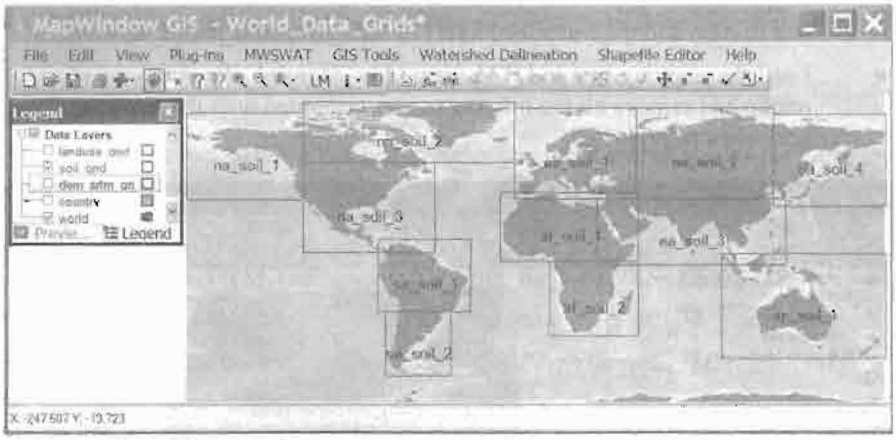
3.3 Soil Data

3.3.1 Pre-Process of Soil Data

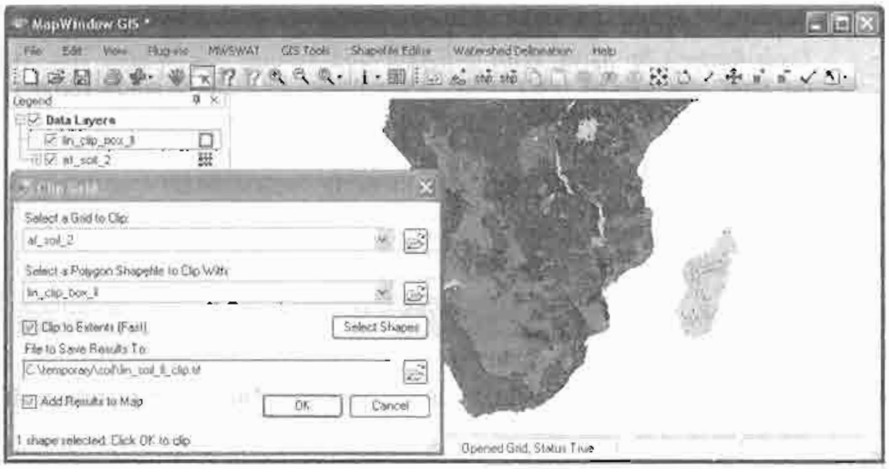
Objective: Clip the soil file for the area of interest.

Clip Soil for Area of Interest:

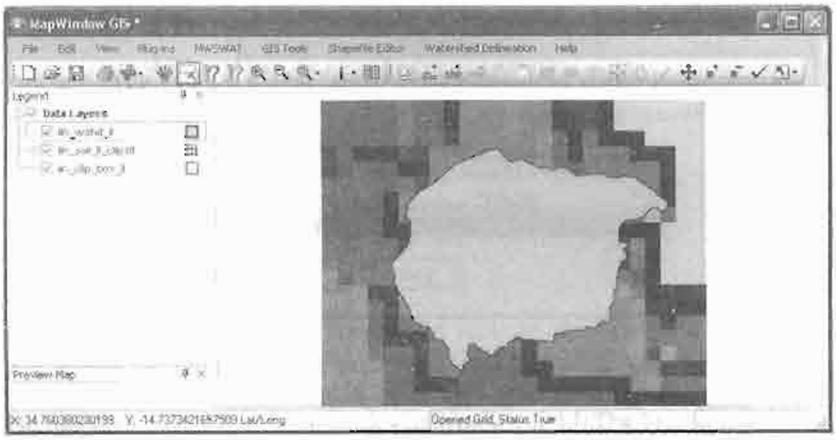
- Open the project ***World_Data_Grids.mwprj*** again. This shows that the soil tile we need is ***af_soil_2***.
- Extract ***af_soil_2.tif*** together with the corresponding .bmp, .bpw and .mwleg files from af_soil.zip (found in the DVD in the folder ***Software\MWSWAT\DATA\Global_Soil_Data***). Store them in, say, ***temporary\soil***.
- Close MapWindow. Do NOT save project data.
- Add Layer  and select: ***temporary\soil\ af_soil_2.tif***. Also add the layer for the clip box (***Lin_Maps\lin_clip_box_ll.shp***).



- Select *GIS Tools\Raster\Clip Grid With Polygon*. Select the soil layer and the box to clip with from the ones just loaded into the view.
- Check the Clip to Extents (Fast) option and select the shape (clip box), press Done when the box is highlighted. Note that the output file name is created for you. Rename this default name: ***temporary\soil\lin_soil_ll_clip.tif***. Click OK to clip.



- Remove the layer *af_soil_2*.
- Zoom out and with Add Layer  reload the watershed layer (***Lin_Maps\lin_wshd_ll.shp***) to verify the extents. This ***lin_land_ll_clip.tif*** is the final landuse product that, when projected to UTM (see below) will be used in MWSWAT.



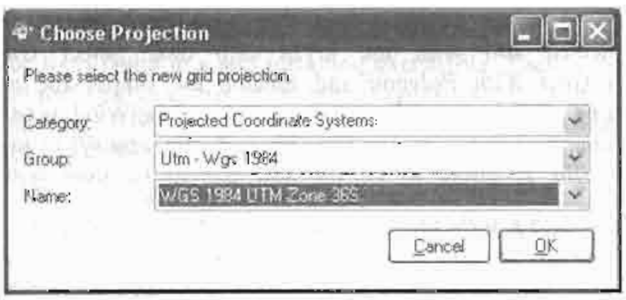
3.3.2 Re-project Soil to UTM

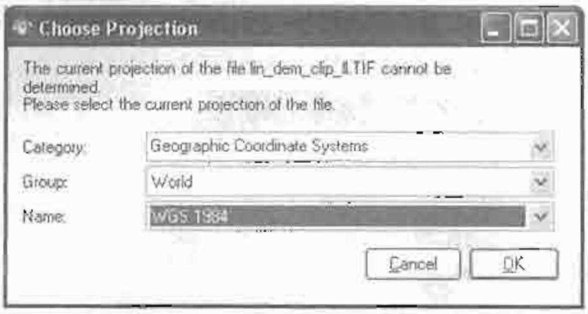
Objective: Re-project the clipped soil file to UTM and re-clip for the area of interest.

Due to the fact that MWSWAT needs meter units and an equal area (or nearly equal area) projection to perform area calculations, the clipped soil file need to be re-projected to UTM coordinates. In this example, there is an additional dataset for the Linthipe watershed already projected in UTM. (additional shapefile: ***lin_wshd_utm***: Zone 36S).

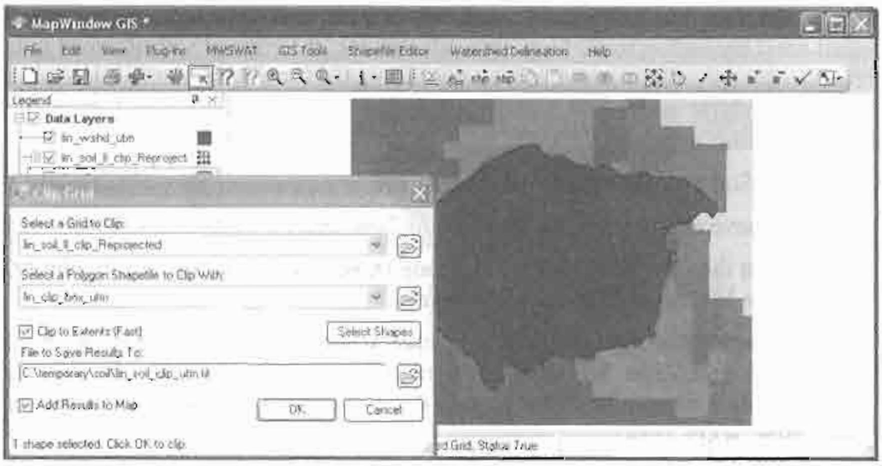
Re-Project Soil and re-clip for Area of Interest:

- Remove all the layers and select *GIS Tools\Raster\Reproject Grids*.
- Open the clipped soil file in lat/long (***temporary\soil\ lin_soil_ll_clip.tif***), when loaded click OK to re-project.
- Choose projection details: Projected Coordinate System, Datum WGS 1984 and Zone 36S and the current projection values if MapWindow couldn't determine them (Geographic Coordinate, World Projections, Datum: WGS 1984).





- A new file will be created (*temporary\soil\lin_soil_clip_ll_Reprojected.tif*). Do not add the layer when asked, as it has a different projection, but clear all layers and then add it. Also add the watershed in UTM (*Lin_Maps\lin_wshd_utm.shp*).
- Load the clipping box in UTM view (*Lin_Maps\sj_clip_box_utm.shp*) to re-clip and remove all the missing values generated with the rotation of the grid when re-projected.



- Clip the re-projected soil with the UTM clip box. Select *GIS Tools\Raster\Clip Grid With Polygon* and rename the output file as *lin_soil_clip_utm.tif*. OK to clip. When done, exit from MapWindow (do not save project changes) and copy the file (*lin_soil_clip_utm.tif*) in the project folder as this is going to be the soil file to be used with MWSWAT.

3.3 SWAT Output Plotting and Graphing Tools (SWATPlot and SWATGraph)

Chris George

Version 1.1 June 2008

1. Introduction

SWATPlot and SWATGraph are companion tools to the MWSWAT tool that generates inputs for and runs the SWAT watershed modelling tool. SWATPlot is a tool designed to make it easy to select SWAT output values from the files output.rch, output.sub, output.hru, output.rsv and output.wtr. (The last two only include output values if you have reservoirs and ponds respectively in your SWAT model.) The normal way to plot such values is to import the SWAT output file into Excel, use an Excel filter to select the reach, subbasin, hru, reservoir or hru, respectively, and then use Excel graphing facilities to draw graphs or histograms. This is a relatively tedious process, especially if you want to use outputs from different runs to compare them. SWATPlot makes this process much simpler. It also allows you to include a file of observed results if you have them.

SWATPlot generates a comma-separated (.csv) file of the results of which you want to draw a graph or histogram. It automatically invokes the second tool SWATGraph to display the graph or histogram. However, if you wish to do some further processing, or use Excel's graphing or calculational capabilities, you can import this intermediate .csv file into Excel, or any other tool you may have.

The design philosophy of both tools is maximum simplicity, to keep the interface clean and easy to use. They are not intended to replace all the features of tools like Excel, but to make the normal display of comparative results simple and fast.

Like MWSWAT, SWATPlot and SWATGraph are free, open source tools produced by the WaterBase project http://www.waterbase.org.

2. Installation

The tools come in a self installing executable. They use two files, mschrt20.ocx and msflxgrd.ocx, that are if necessary installed in your C:\WINDOWS\system32 folder and registered. This means that if you don't already have these files you will need administrator privileges to do the installation.

The installer suggests the folder
C:\Program Files\MapWindow\Plugins\MWSWAT as the installation folder, but you may choose somewhere else if you wish. A shortcut to SWATPlot will appear on your desktop.

3. Running SWATPlot

When you start SWATPlot you see the view in Figure 1.

Figure 1: Initial screen

The first thing to do is to select the Scenarios folder, which is contained in the SWAT project folder. You can find it using the folder search button. The tool keeps a list of up to 10 Scenarios folders, so you can later select one you worked with previously. You select one from the drop-down list as in Figure 2.

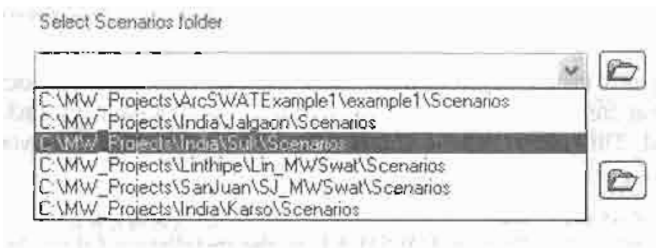


Figure 2: Selecting a previously used scenario

Selecting the Scenarios folder of a SWAT project allows you to input data from any scenarios you have produced with SWAT in that project. The latest one is always called Default, but you may have saved earlier runs as part of the same project, and you can combine data from any of them. We will see later how compatible these runs need to be (in terms of how you have divided the watershed into subbasins and HRUs, and the periods and reporting intervals of the runs).

There is also an option to include a file of observed outputs. We will deal with this later in Section 5.

When you have selected the scenarios folder you are ready to choose your data for the first plot. Click *Add plot* and an empty line appears in the table. Now click the arrow in the leftmost of the pull-down boxes above the table, the one above the heading *Scenario*, and you will see something like Figure 3. Here, as well as the *Default* scenario we have saved two earlier ones, called *adjusted* and *unadjusted*. We are going to compare the flows out of the watershed for these two runs.

We select *unadjusted* for the first plot. We now proceed from left to right choosing the next value from each pull-down box in turn. The second one, *Source*, offers a choice of *reach*, *subbasin*, and *hru*. In addition, if there are ponds (water impoundments) in your model you will see the possible source *water*, and if there are reservoirs you will see the possible source *reservoir*. These sources refer to the SWAT output files output.rch, output.sub, output.hru, output.wtr, and output.rsv respectively. We choose *reach*.

Now in the Subbasin pull-down box we have a choice of all the subbasins in the watershed. We would have the same choice here if we had chosen *subbasin* or *hru* as the source. If we had chosen *water* or *reservoir* we would only see the numbers of the subbasins containing ponds or reservoirs respectively. We want to compare the final flows from the watershed, so we choose subbasin 1, which (for SWAT runs prepared with MWSWAT) is always the most downstream subbasin[1].

[1]This was true until MapWindow version 4.5, when the subbasin with the highest number became the outlet subbasin.

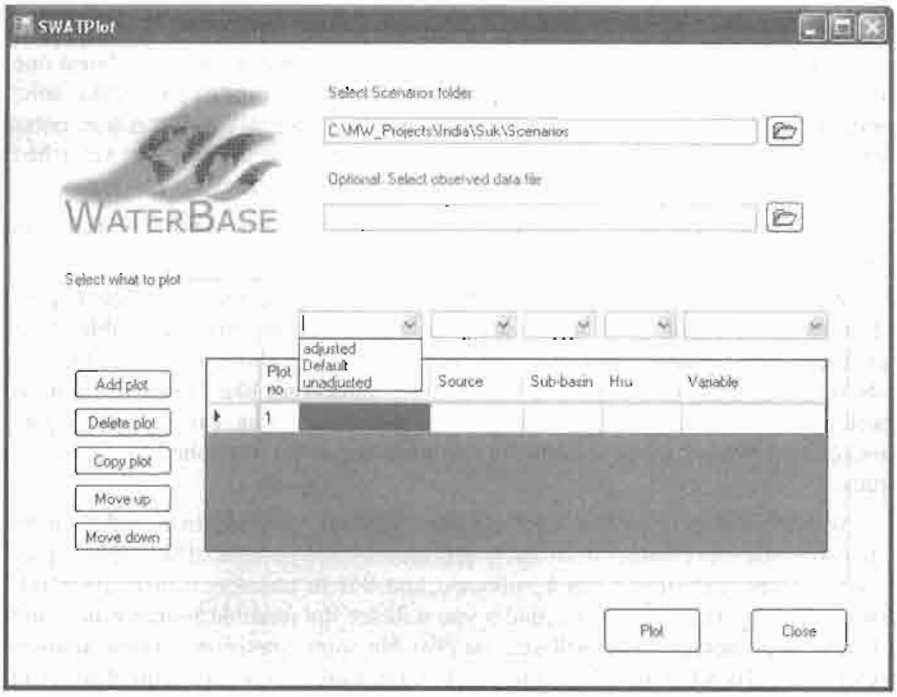


Figure 3: Ready to choose the scenario

Sources *reach*, *subbasin*, and *reservoir* are based on subbasins, so the *Hru* box is not needed – it is marked by "-". If we had chosen *hru* or *water* we would choose from the Hru pull-down box one of the hrus within the chosen subbasin.

Finally we choose which variable we want to plot. The Variable pull-down box gives us a choice of all the variables in the output file selected by our choice of Source. We select *FLOW OUT cms* and we see something like Figure 4.

Our first plot definition is complete. Now we want to add the second. We could use *Add plot* and continue as before. But since the second will be mostly like the first, instead we click *Copy Plot*. This makes a copy of the selected plot (shown by ►), and we then just use the Scenario pull-down box to change the scenario for this one to *adjusted*. We get Figure 5.

We can now add more plots, change the selections we have made, or delete ones we decide we don't need. We can also change the order using the *Move up* and *Move down* buttons: the horizontal ordering of histograms in the graph display will be plots numbered 1 2 etc left to right.

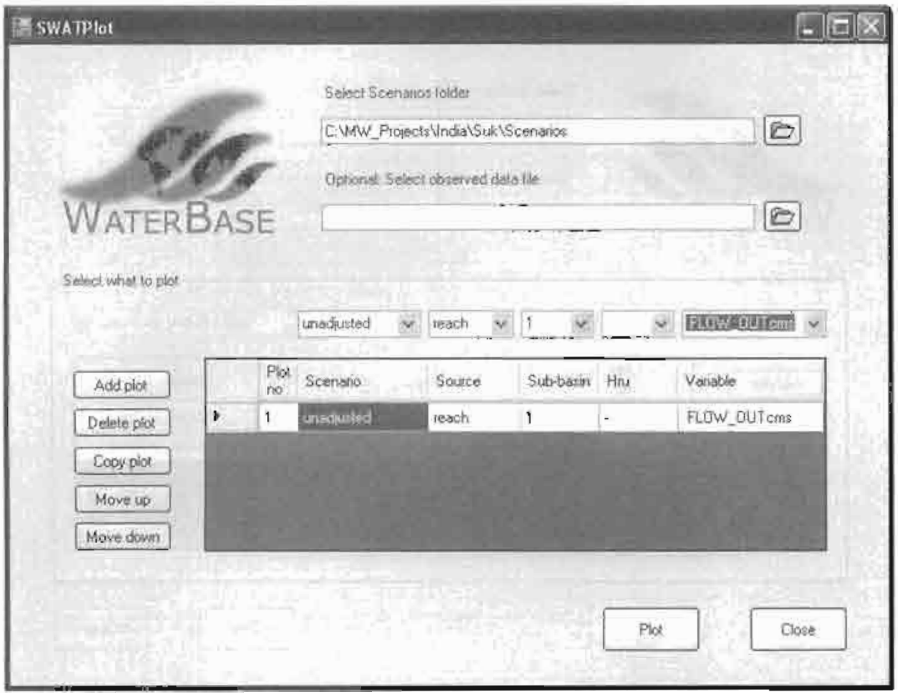


Figure 4: First plot completed

When we have completed the plot selections we click *Plot*. This invites us first to choose a .csv file to save the data. We can if we wish later import this into, for example, Excel if we wish to do further manipulations or use Excel's graphing tools.

Once the data is written to the .csv file SWATGraph is automatically started to display the data graphically: see Figure 6. The data has been displayed as histograms, labelled by months as that was the time interval of our SWAT output. We can change the display to lines using the *Chart Type* pull-down box and clicking *Update Graph*.

Other options include importing another (similarly created) .csv file, using *New File to Plot*, and saving the graph to the clipboard, using *Copy chart to clipboard*, so we can then for example paste it into the Paint tool to make an image file.

The data from the .csv file is also displayed. The column headings, also shown in the graph legend, take the form *Scenario-Source-Number-Variable*, where *Number* is the subbasin number if the source is reach, subbasin or reservoir, and the hru number if the source is hru or water.

You can fill in the *Chart Title* and *Y Axis Titles* if you wish, and change the *X Axis Title*.

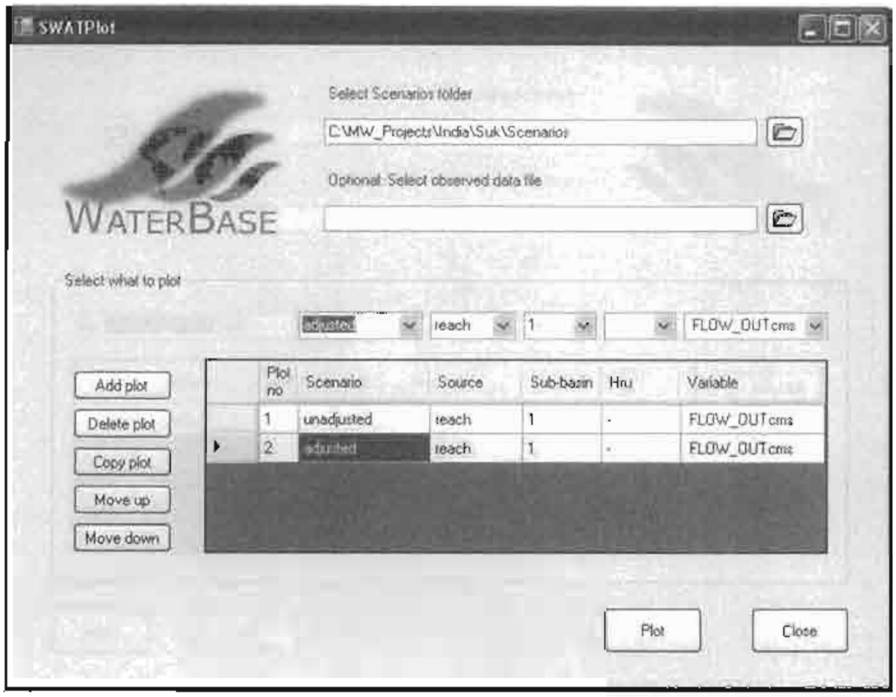


Figure 5: Second plot completed

At the bottom of the screen some statistics are displayed. These are correlation and Nash coefficients for each pair of plots. Some of these may be meaningless, of course, if for example you choose to plot four things that are really two pairs, but it is quicker as well as simpler to calculate them all than it is to ask the users what they want.

4. How compatible do different scenarios need to be?

Obviously, they need to use the same time period, and the same time interval (monthly, daily or yearly). In fact, the number of records in the data is determined by the first plot, so if necessary this can be shorter. Start dates are assumed to be the same; they are not checked.

You also need to be reasonably confident that the things you want to compare are indeed comparable, so if you are comparing hrus, for example, they should be the same hru in each scenario. But if you are comparing reach 1 in each scenario, which (for MWSWAT) gives figures for the whole watershed[2], it doesn't matter how the subbasins and hrus in each were selected.

[2]For MapWindow version 4.5 and above it is the subbasin with the maximum number that gives the watershed outlet

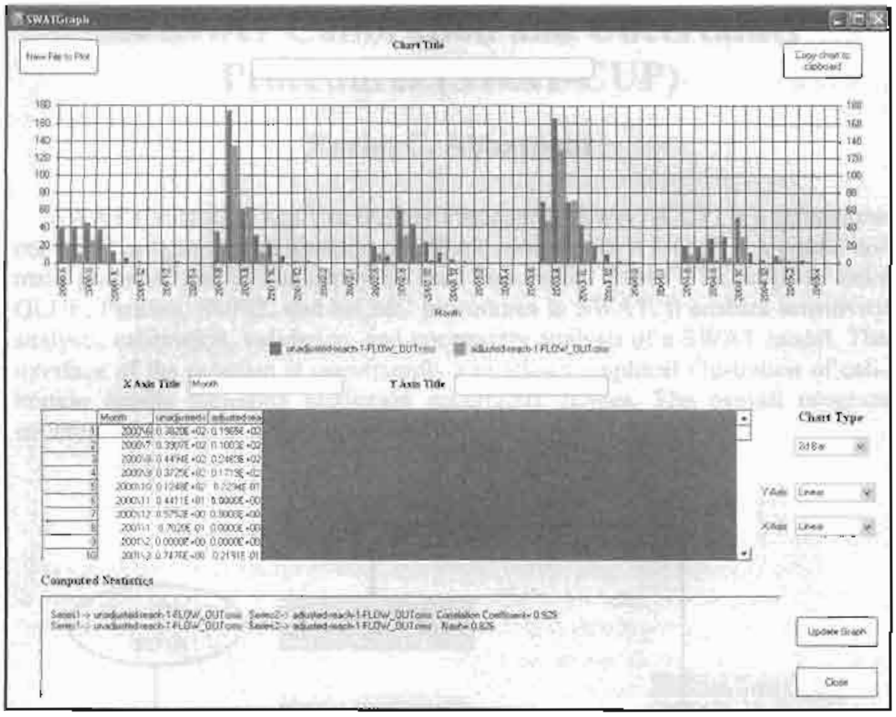


Figure 6: SWATGraph

5. Including observed data

To include observed data you need to prepare a .csv file, i.e. a text file where each line consists of the same number of items (one or more), separated by commas.

The first line should be comma-separated text strings, which will be used as the labels in the graph. If the first string is DATE, or Date, or indeed these four letters in any case, it and the data in the first column are ignored. The dates are assumed to be the same as in the SWAT output plots; they are not checked.

The data on lines two to the end should be numeric.

If you include such an observed data file in SWATPlot then *observed* will appear as an additional Scenario in its pull-down box. (You will be asked to rename one of your SWAT scenarios and start again if it is also called *observed*.) Source, Subbasin and Hru boxes will then be unavailable, but you need to choose a Variable. The choices in the Variable pull-down box will be the labels in the first line of the .csv file.

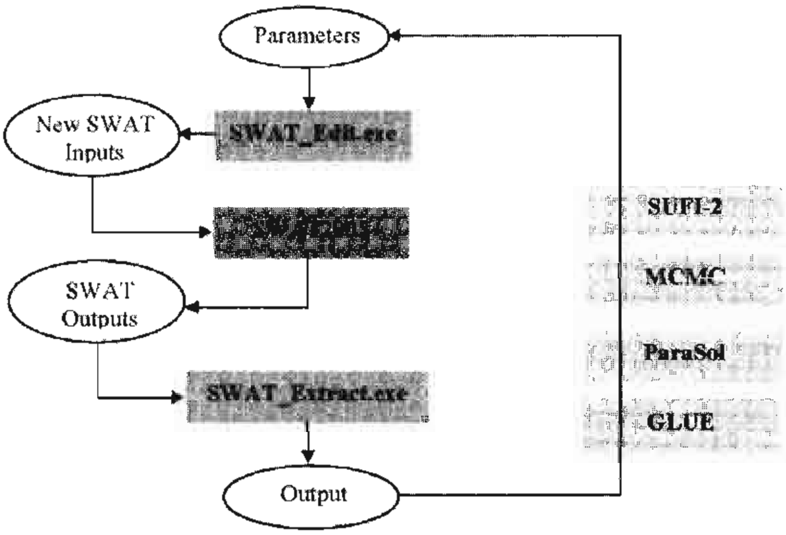
6. Reporting problems

If you have problems or suggestions send them to waterbase.contact@waterbase.org.

3.4 SWAT Calibration and Uncertainty Procedures (SWAT-CUP)

Karim C. Abbaspour

SWAT Calibration and Uncertainty Procedures (SWAT-CUP) is a standalone computer program for calibration of SWAT models. SWAT-CUP is a public domain program, and as such may be used and copied freely. The program links GLUE, ParaSol, SUFI2, and MCMC procedures to SWAT. It enables sensitivity analysis, calibration, validation, and uncertainty analysis of a SWAT model. The interface of the program is user-friendly and allows graphical illustration of calibration results including prediction uncertainty ranges. The overall program structure is as shown in the Figure below.



The program and its manual may be downloaded from:
http://www.eawag.ch/organisation/abteilungen/siam/software/swat/index_EN

Questions and comments should be forwarded to Dr Karim C. Abbaspour at:
abbaspour@eawag.ch

Users are encouraged to visit the above site regularly for new updates.

Last minute update from Dr. Karim Abbaspour, January 6, 2009:

A new version of SWAT-CUP can be downloaded from:
http://www.eawag.ch/organisation/abteilungen/siam/software/swat/index_EN

New Implementations

The differences between the present version and the previous version is that swEdit_2005.exe has been replaced with the same SWAT_Edit.exe program, which works in the same manner for all four algorithms. SWAT_Edit has improved capabilities including:

1- Parameters of all soil layers can now be calibrated (see pages 32-34)
2- Next to landuse, texture, subbasin, and hydrologic unit, slope can also be accounted for
3- Management parameters can all be calibrated including each rotation and operation
4- All crop parameters can be explicitly calibrated
5- Rainfall in the file pcp.pcp can be calibrated for input uncertainty
6- At the end of the file *.gw, 20 auxiliary parameters can be specified as R1, R2, ..., R20, which can be used by other programs linked to SWAT. This was done at the request of some users that had linked their own routines to SWAT and wanted to calibrate those parameters as well along with SWAT parameters.
- Validation can now be explicitly done for GLUE and ParaSol.
- Sensitivity is also done for all algorithms.
- Small changes have been made to files:
- par_inf.sf2 and the way parameters are specified (see pages 32-34 of this manual),
- SUFI2_extract_rch.def, where the number of total columns in the SWAT output.rch must now be specified
- and SUFI2_swEdit.def file
- Swat_EditLog.txt file lists the actual value of all the parameters that have been changes.
- GLUE, ParaSol, and MCMC now use the same *_extract_rch.def file as SUFI2 and can all accept missing observation data.
- Other small changes to GLUE, ParaSol, and MCMC files can be found in the examples provided by the SWAT-CUP program.

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3.5 Contents of SWAT DVD Version 1 (January 2009)

I. SWAT Theoretical Documentation

A. SWAT Theoretical Documentation. Version 2005.pdf
B. SWAT Input-Output File Documentation. Version 2005.pdf

II. Software

A. MapWindow GIS
- 1. MapWindow46SR.exe
- 2. MapWindow User Guides
  - a. Quick_Guide_to_MapWindow_GIS.pdf
  - b. Introduction_to_MapWindow_GIS_Ver_4_3.pdf

B. MWSWAT
- 1. MWSWAT.exe Version 1.4.0.0
- 2. MWSWAT Manual
  - a. Geo-Process.pdf
  - b. MWSWAT Setup.pdf
- 3. DATA
  - a) DEMs
    - a. Global_Basins_latlong
    - b. Global_Landuse_Data
    - c. Global_Soil_Data
    - d. Global_Weather_Data
    - e. SJ_Maps
    - f. World_Data_Grids

C. SWAT Editor
- 1. SwatEditor_Install_2.1.2bRelease.zip
  - a) README.txt
  - b) Setup.Exe
  - c) Setup.Ini
  - d) SwatEditorInstall.msi
- 2. SWATEditor_Documentation.pdf
  - a) ArcSWAT_Documentation.pdf (See Chapt. 9-15)

D. SWAT Plot_and_SWAT Graph
- 1. SWATPlot.exe
- 2. SWATPlot and SWATGraph.pdf

(Continued on next page)

E. SWAT-CUP

1. SWAT-CUP User Manual
   a) SWAT_CUP_Description.pdf
   b) Usermanual_Swat_Cup.pdf
2. SWAT-CUP Setup
   a) ExternalData
      a. Example_projects
      b. SourceData
      c. References

F. ACROBAT Reader

Index for Models, Abbreviations and Acronyms

Geographical INDEX

Subject INDEX

ADDENDUM

WASWC: Its History and Operations

By Bill Moldenhauer and David Sanders (2003)

Updated by Samran Sombatpanit (2007, 2008)

WASWC was established in 1983 with the help and support of the Soil and Water Conservation Society (SWCS) of the U.S.A. The original purpose was to support international activities of both SWCS and the International Soil Conservation Organization (ISCO). The world was divided into nine regions with at least one Vice President from each region. Since there was little contact among ISCO participants from one biennial conference to the next, our first priority was to publish a quarterly newsletter with meeting announcements, international conservation news, book reviews, member news, etc. From the beginning, we tried to give recognition to, and a forum for, workers in the international field who had published mainly in the "gray literature" (company, Government (GO) and non-governmental (NGO) agency and organization reports that had had very small circulation).

This continues to be one of our most vital functions. By 1986 there was great interest in the Food and Agriculture Organization (FAO) of the United Nations and many GOs and NGOs in just how effective their international programs were in solving problems in developing countries. WASWC and SWCS organized a workshop in Puerto Rico with the help of several donor organizations and invited speakers to address the success (or failure) of donor sponsored soil and water conservation and land husbandry programs in developing countries worldwide.

This was a very successful conference and resulted in two publications published by SWCS, *Conservation Farming on Steep Lands* and *Land Husbandry: A Framework for Soil and Water Conservation.* Since our Puerto Rico workshop we have held a workshop in Taiwan in 1989, one in Solo, Central Java, Indonesia, in 1991, and one in Tanzania and Kenya in 1993. These have all been published and were circulated by SWCS.

Our Vice President for Europe, Dr. Martin Haigh, has initiated a series of meetings on Environmental Regeneration in Headwaters in various parts of the globe. Our Vice President for the Pacific Region, Dr. Samir El-Swaify, has initiated a series on "Multiple Objective Decision Making for Land, Water and Environmental Management." Four of our members—Samran Sombatpanit, Michael Zoebisch, David W. Sanders, and Maurice Cook have edited a book titled, *Soil Conservation Extension: From Concepts to Adoption.* David Sanders, Paul

Huszar, Samran Sombatpanit and Thomas Enters have edited a book titled, *Incentives in Soil Conservation: From Theory to Practice.* Lately, Samran Sombatpanit has edited a voluminous book, *Response to Land Degradation,* with five other editors in 2001 and *Ground and Water Bioengineering for Erosion Control and Slope Stabilization*, with four other editors in 2004. Besides the above publications, past WASWC President Hans Hurni initiated a long-term program, "World Overview of Conservation Approaches and Technologies (WOCAT)," based in Berne, Switzerland in 1992 and had a landmark WOCAT Global Overview book *"where the land is greener"* published in 2006. WASWC has supported Jim Cheatle's "Organic Matter Management Network" based in Nairobi, Kenya. WASWC is also closely allied with Reseau Erosion, a project of Vice President Eric Roose, based in Montpellier, France, and operating mainly in Africa. WASWC is closely allied to ISCO and cooperates fully with planning and conducting its biennial conferences. WASWC is requested and very willing to co-sponsor conferences, symposia and workshops it feels will further its philosophy and objectives.

The WASWC Philosophy: WASWC philosophy is that the conservation and enhancement of the quality of soil and water are a common concern of all humanity. We strive to promote policies, approaches and technologies that will improve the care of soil and water resources and eliminate unsustainable land use practices.

WASWC Vision: A world in which all soil and water resources are used in a productive, sustainable and ecologically sound manner.

WASWC Mission: To promote worldwide the application of wise soil and water management practices that will improve and safeguard the quality of land and water resources so that they continue to meet the needs of agriculture, society and nature.

WASWC Slogan: Conserving soil and water worldwide – join WASWC

The Objectives of WASWC: The basic objective of WASWC is to promote the wise use of our soil and water resources. In doing so WASWC aims to:
• Facilitate interaction, cooperation and links among its members.
• Provide a forum for the discussion and dissemination of good soil and water conservation practices.
• Convene and hold conferences and meetings and conduct field studies connected with the development of better soil and water conservation.

• Assist in developing the objectives and themes for ISCO conferences and collaborate in their running.
• Produce, publish and distribute policies, guidelines, books, papers and other information that promote better soil and water conservation.
• Encourage and develop awareness, discussion and consideration of good conservation practices among associated organizations.
• Liaise, consult and work in conjunction with environmental organizations on the development and promulgation of global environmental and conservation policies, strategies and standards.

Recent Developments: The WASWC has had to face some serious problems in recent years and, as a result, some important changes have taken place. The cost of running WASWC has increased over the years and, at the same time, membership numbers dropped to below 400. The drop in numbers was partly because a membership fee of even US$10 per year is a considerable amount of money for many members from developing countries. Added to this, is the problem of paying in dollars and transferring relatively small sums of money internationally. To overcome these problems, a number of important steps have been taken. *First,* a concerted effort has been made to recruit new members. As part of this campaign, an effort has been made to improve the services provided to members. This has included improving the quality and length of the quarterly newsletter and distributing it by e-mail. *Second,* a flexible system of membership fees has been introduced which means that members can join for as little as US$5 and US$10 per year for respectively developing and developed countries. *Third,* a program of decentralization has also been launched with the appointment of several more Vice Presidents and the establishment of National Representatives, now covering approximately 100 countries. This program is not only bringing our association closer to members but has also provided other advantages including a system whereby it is now possible for local organizations to collect membership fees in local currencies and to pay the secretariat in bulk. *Fourth,* the WASWC council has become more actively involved in encouraging regional and local meetings, conferences and other useful activities. *Fifth,* the WASWC council offers 1-year Guest membership to persons who have participated at any technical meeting worldwide, if they wish so. As a result of these measures, membership has risen to several thousands in 2007.
Another major change has been the move of the WASWC secretariat from the SWCS in the U.S.A. to Beijing in China, on April 1, 2003. It is now hosted by the Ministry of Water Resources. The WASWC appreciates the generous help that it received from the SWCS over the 20 years that the SWCS ran its secretariat and intends to maintain a close association with it in the future. However, the Council believes that this move will have a number of advantages. Our Chinese hosts have offered very generous terms for the running of the secretariat; we will have the opportunity to work in a country where running costs are relatively low and where there is considerable technical expertise available and of interest to many

of our members. The most recent development is the establishment of our main website at the Guangdong Institute of Eco-Environmental and Soil Sciences in Guangzhou, in the southern part of China, to offer services to our members along with the other one in Tokyo, Japan, supported by ERECON.

WASWC Council

(For the period up to December 2010)

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2. Deputy President: Machito Mihara, Japan m-mihara@nodai.ac.jp
3. Treasurer: John Laflen, U.S.A. laflen@wctatel.net
4. Executive Secretary: Henry Lu Shunguang, China sglu@mwr.gov.cn
5. Imm. Past President: Samran Sombatpanit, Thailand (& Coordinator General) sombatpanit@yahoo.com, samran_sombatpanit@yahoo.com
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WASWC Publications

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Special Publications, published by WASWC

2003: No. 1. *Pioneering Soil Erosion Prediction – The USLE Story.* By John Laflen and Bill Moldenhauer, ISBN 974 91310 3 7, 54 pp. (available on the website)
2004: No. 2. *Carbon Trading, Agriculture and Poverty.* By Mike Robbins, ISBN 974 92226 7 9, 48 pp. (available on the website)
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2009: No. 4. *Soil and Water Assessment Tool (SWAT): Global Applications.* Edited by J. Arnold, R. Srinivasan, S. Neitsch, C. George, K.C. Abbaspour, P. Gassman, Fang H.H., A. van Griensven, A. Gosain, P. Debels, N.W. Kim, H. Somura, V. Ella, L. Leon, A. Jintrawet, M.R. Reyes, and S. Sombatpanit. Special Publication No. 4., ISBN 978-974-613-722-5, 415 pp. (With one DVD for SWAT stuffs that include free software, plus the WASWC e-LIBRARY)

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www.sontek.com/news/UltraLowFlow.pdf

ACOUSTIC DOPPLER TECHNOLOGY ENABLES FAST ASSESSMENT OF POST-QUAKE HYDRAULIC CONDITIONS

SICHUAN PROVINCE, China.

A 7.9 magnitude earthquake in China left millions homeless and susceptible to thirst and water-borne disease as it ravaged the country's hydrology monitoring stations. SonTek/YSI immediately responded with assistance and hydroacoustic equipment — allowing hydrologists to gauge the speed and strength of water flow, as well as monitor drinking water distribution. The advanced RiverSurveyor® provided fast assessment of flood conditions and did in minutes what had taken hours for a field crew with conventional instruments.

www.sontek.com/news/ChinaQuake.pdf

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KUALA LUMPUR, Malaysia.

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