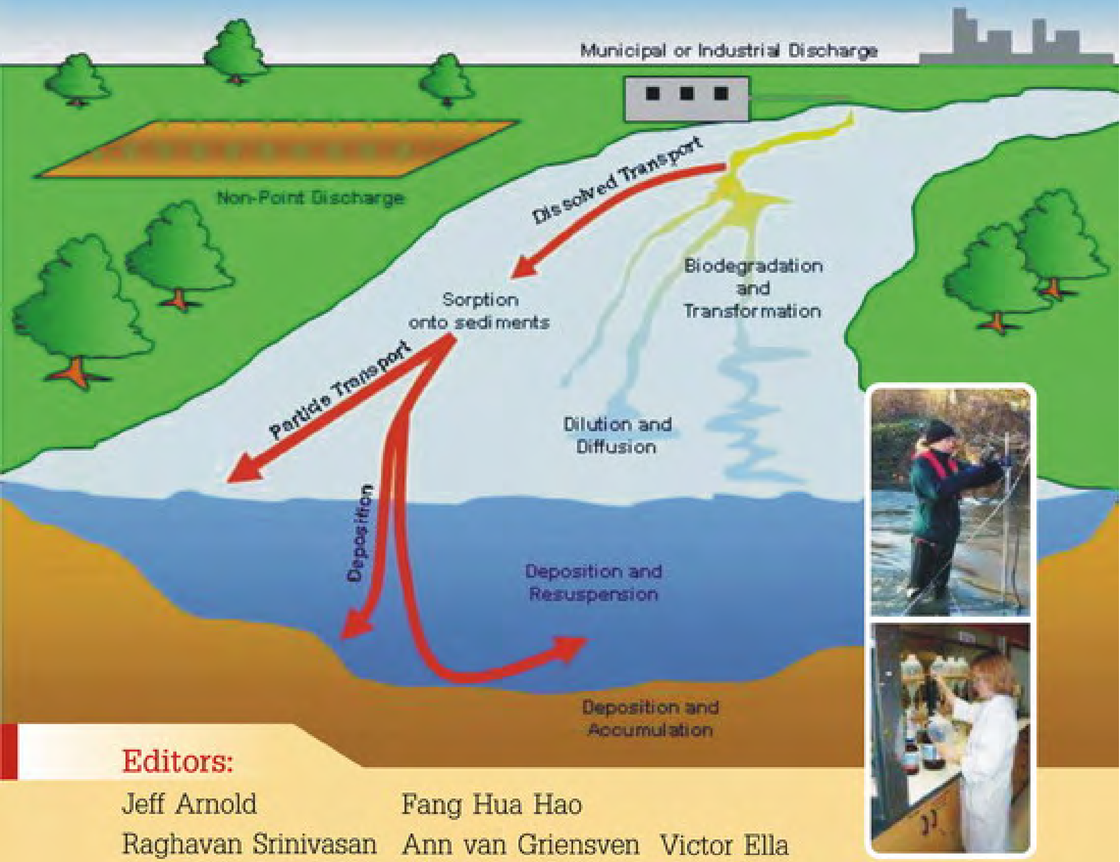
World Association of Soil and Water Conservation
Special Publication No. 4

Soil and Water Assessment Tool (SWAT)
Global Applications



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Following agencies and individual are co-publishers of this book. We highly appreciate their willingness to share their resources and manpower in this promising endeavor of SWAT.

Dr. Shabbir A. Shahid
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(Middle East Region)
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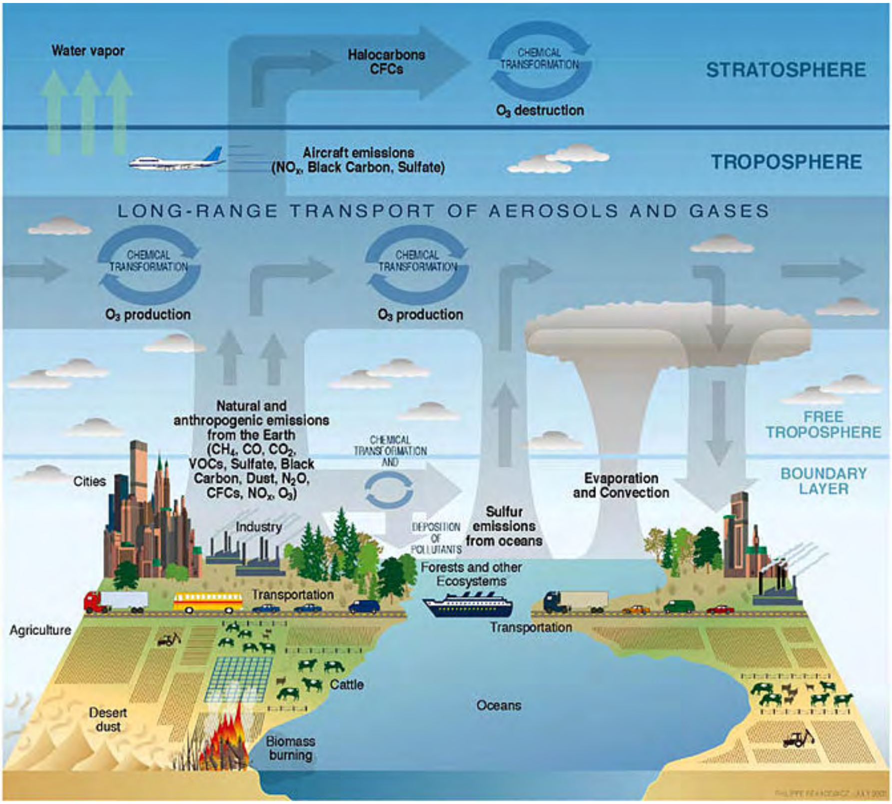
Scientific modeling



Scientific modeling is the process of generating abstract, conceptual, graphical and/or mathematical models. Science offers a growing collection of methods, techniques and theory about all kinds of specialized scientific modeling.

Modeling is an essential and inseparable part of all scientific activity, and many scientific disciplines have their own ideas about specific types of modeling. There is little general theory about scientific modeling, offered by the philosophy of science, systems theory, and new fields like knowledge visualization.

From Wikipedia, the free encyclopedia

http://en.wikipedia.org/wiki/Model_(abstract)

SOIL AND WATER ASSESSMENT TOOL (SWAT): GLOBAL APPLICATIONS

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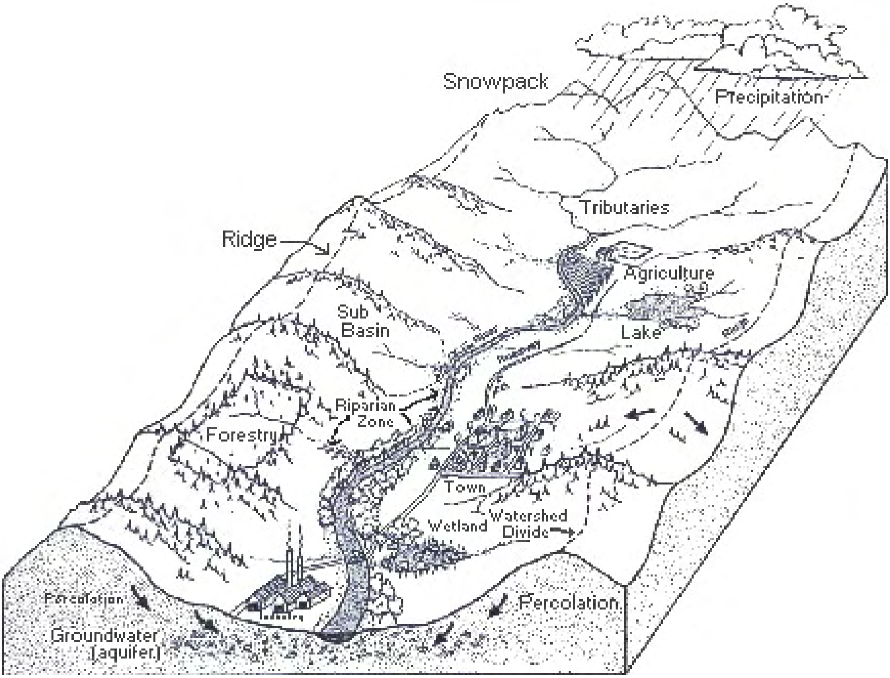
“Assessment efforts should not be concerned about valuing what can be measured but, instead, about measuring that which is valued.”

From: Banta, T.W., Lund, J.P., Black, K.E., and Oblander, F.W. 1996. *Assessment in practice: Putting principles to work on college campuses.* San Francisco: Jossey-Bass. p. 5.



General view of a watershed, catchment or river basin, the main subject of this book

The illustration was produced by the Lane Council of Governments (LCOG), Lane County, Oregon State, U.S.A. (www.lcog.org) and posted on the website of Casper City, Wyoming, U.S.A.
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We thank the LCOG for permitting us to use the drawing in this book.

Foreword

For the past 25 years since WASWC was established, we have been trying to gather information concerning technologies for use in studying soil and water and managing them for agricultural production. Apart from several publications that we worked with our publishing partner, Science Publishers, Inc. U.S.A. (see the end part of this book), we have also been producing Special Publications by stressing on the current subjects of much interest. The first one, *Pioneering Soil Erosion Prediction – USLE Story,* was published in 2003 as a small booklet, to record the history of this attempt, and followed with *Carbon Trading, Agriculture and Poverty,* also a booklet, in 2004.

Lately, we tried to identify subjects that have been studied widely and successfully, so a technical book of conventional length, *No-Till Farming Systems*, has come out in 2008 and proved a success since such practice has been widely known to be useful for crop production in many ways, and, importantly, can help reduce soil loss due to erosion down to only a small fraction of those occurring from normal tillage. The book has been distributed at a low price, thus enabling professionals and academics to have access to such publication that otherwise would be available only from publishers that produce textbooks with relatively high prices. We expect that *No-Till Farming Systems* will be used as a platform where researchers and practitioners may work from, so that some new advancements about the farming system that "park the plow" can be achieved.

SWAT, an acronym for "Soil and Water Assessment Tool", a river basin, or watershed, scale model, has come around for some years, but its origin stemmed from those hydrological models in operation during the 1980s. According to Neitsch et al. (2005), SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemicals yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. Dr. Jeff Arnold of the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) in Temple, Texas, has the credit for being largely responsible for its development.

From a good number of papers on SWAT appearing in the literature world at this time, we are certain there is much information available that when in the book form will make such subject better understood and utilized, thus enhancing more systematic actions to be done for land management and conservation. WASWC therefore has accepted to produce this book by using the same principle as the previous volume, so that it can be distributed to worldwide readers for their immediate use at an affordable price. The book comes with a DVD that contains some computer models that readers may work to learn and experiment with. As a major benefit for being in the digital age, readers at this time are eligible to seek advice from all editors and contributors in any matters that they want to learn more or have problem with. Such privilege is a unique benefit that is always available for WASWC members, as well as other readers of WASWC books.

WASWC will strive to do more works in this line, in order to find the right methods to tackle problems that have occurred to land and soil and help make these resources suitable to sustainably serve humanity with all their functions.

Miodrag Zlatic

President, World Association of Soil and Water Conservation
Faculty of Forestry, Belgrade University
Belgrade, Serbia

Preface and Acknowledgments

The Soil and Water Assessment Tool (SWAT) is an open source watershed model that is continuously developed and refined by the USDA-Agricultural Research Service and scientists at universities and research agencies around the world. It was developed originally to operate with databases available in the United States but has evolved to run with limited data sets now available throughout the world. The model is routinely used in the U.S. by the US-Environmental Protection Agency for developing watershed management strategies to attain water quality standards in impaired water bodies. It is also used for national conservation assessment by the USDA-Natural Resources Conservation Service and in numerous climate change studies. SWAT has been modified and refined by European scientists and used in numerous projects. European development and application was advanced by four international conferences held between 2001 and 2007. In recent years, SWAT has been successfully applied to assess water availability in the African continent, to study the impact of climate change on water resources in India, and to assess water supply and sedimentation issues in the Yellow River and other major rivers in China. Routine application has not occurred in Southeast Asia although SWAT was applied in the Mekong River downstream of China. Dr. Phil Gassman and colleagues recently published an article providing an excellent overview of historical development, applications, and future research directions. There are currently over 400 SWAT related papers in the referred literature.

There are several requirements for successful applications in Southeast Asia including: 1) readily accessible technology – hardware and software, 2) readily available data to input and calibrate the model, 3) the need (i.e. governments requiring assessment of water supply, water quality and climate change), and 4) local support and a critical mass of scientists working in the region. All of these pieces are now in place and the International SWAT Conference held in Chiang Mai in January 2009 is a critical step in the successful application of SWAT and other ecohydrological models in Southeast Asia.

In gathering the works from many years and from many scientists to be in a book, several persons have been involved in it, for which we recognize and appreciate their important role. We thank several specialists who had worked with the models and other accessory programs for allowing us to put in the DVD that accompanies the book. The long and continued service of Katherine Suda of the Biological Engineering Program, North Carolina A&T State University, has been instrumental in acquiring all these essential digital stuffs that are the heart of SWAT - therefore we are very grateful to her for that. Last, but not least, we acknowledge the kind cooperation from various publishers of scientific journals in permitting us to use most papers in this volume that had first appeared in their publications, without which this book would not have been produced. We appreciate the World Association of Soil and Water Conservation for accepting to put various SWAT stuffs together within one cover as WASWC Special Publication No. 4 and within a short time. This is considered an important milestone of the SWAT endeavor, i.e. in distributing the publication as a low-cost part of the assessment tool to be used for managing and conserving land, soil and water in many parts of the world.

Lastly, it would have been hard to accomplish all these things had we not received the grant from the United States Agency for International Development (USAID) for the Sustainable Agriculture and Natural Resources Management Collaborative Research Support Program (SANREM CRSP, with Dr. Theo A. Dillaha as its Director) to Virginia Polytechnic Institute and State University (Virginia Tech), which we have our high appreciation for.

The Editors

December 2008

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PART 3. Using SWAT Software

1.1 Overview of Soil and Water Assessment Tool (SWAT) Model

Susan L. Neitsch, Jeff G. Arnold*, James R. Kiniry and James R. Williams

Preamble

SWAT is the acronym for **S**oil and **W**ater **A**ssessment **T**ool, a river basin, or watershed, scale model developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS). SWAT was developed to predict 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 periods of time. To satisfy this objective, the model

♦ Is physically based. Rather than incorporating regression equations to describe the relationship between input and output variables, SWAT requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modeled by SWAT using this input data.

Benefits of this approach are:
- watersheds with no monitoring data (e.g. stream gage data) can be modeled
- the relative impact of alternative input data (e.g. changes in management practices, climate, vegetation, etc.) on water quality or other variables of interest can be quantified

♦ uses readily available inputs. While SWAT can be used to study more specialized processes such as bacteria transport, the minimum data required to make a run are commonly available from government agencies.

♦ is computationally efficient. Simulation of very large basins or a variety of management strategies can be performed without excessive investment of time or money.

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♦ enables users to study long-term impacts. Many of the problems currently addressed by users involve the gradual buildup of pollutants and the impact on downstream water bodies. To study these types of problems, results are needed from runs with output spanning several decades.

SWAT is a continuous time model, i.e. a long-term yield model. *The model is not designed to simulate detailed, single-event flood routing.*

1. Development of SWAT

SWAT incorporates features of several ARS models and is a direct outgrowth of the SWRRB[1] model (Simulator for Water Resources in Rural Basins) (Williams et al., 1985; Arnold et al., 1990).

Specific models that contributed significantly to the development of SWAT were CREAMS[2] (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS[3] (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al., 1987), and EPIC[4] (Erosion-Productivity Impact Calculator) (Williams et al., 1984).

Development of SWRRB began with modification of the daily rainfall hydrology model from CREAMS. The major changes made to the CREAMS hydrology model were: a) the model was expanded to allow simultaneous computations on several subbasins to predict basin water yield; b) a groundwater or return flow component was added; c) a reservoir storage component was added to calculate the effect of farm ponds and reservoirs on water and sediment yield; d) a weather simulation model incorporating data for rainfall, solar radiation, and temperature was added to facilitate long-term simulations and provide temporally and spatially representative weather; e) the method for predicting the peak runoff rates was improved; f) the EPIC crop growth model was added to account for annual variation in growth; g) a simple flood routing component was added; h) sediment transport components were added to simulate sediment movement through ponds, reservoirs, streams and valleys; and i) calculation of transmission losses was incorporated.

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[1] SWRRB is a continuous time step model that was developed to simulate non-point source loadings from watersheds.

[2] In response to the Clean Water Act, ARS assembled a team of interdisciplinary scientists from across the U.S. to develop a process-based, non-point source simulation model in the early 1970s. From that effort CREAMS was developed. CREAMS is a field-scale model designed to simulate the impact of land management on water, sediment, nutrients and pesticides leaving the edge of the field. A number of other ARS models such as GLEAMS, EPIC, SWRRB and AGNPS trace their origins to the CREAMS model.

[3] GLEAMS is a non-point source model which focuses on pesticide and nutrient groundwater loadings.

[4] EPIC was originally developed to simulate the impact of erosion on crop productivity and has now evolved into a comprehensive agricultural management, field scale, non-point source loading model.

The primary focus of model use in the late 1980s was water quality assessment and development of SWRRB reflected this emphasis. Notable modifications of SWRRB at this time included incorporation of: a) the GLEAMS pesticide fate component; b) optional SCS technology for estimating peak runoff rates; and c) newly developed sediment yield equations. These modifications extended the model's capability to deal with a wide variety of watershed management problems.

In the late 1980s, the Bureau of Indian Affairs needed a model to estimate the downstream impact of water management within Indian reservation lands in Arizona and New Mexico. While SWRRB was easily utilized for watersheds up to a few hundred sq km in size, the Bureau also wanted to simulate streamflow for basins extending over several thousand sq km. For an area this extensive, the watershed under study needed to be divided into several hundred subbasins.

Watershed division in SWRRB was limited to ten subbasins and the model routed water and sediment transported out of the subbasins directly to the watershed outlet. These limitations led to the development of a model called ROTO (Routing Outputs to Outlet) (Arnold et al., 1995), which took output from multiple SWRRB runs and routed the flows through channels and reservoirs. ROTO provided a reach routing approach and overcame the SWRRB subbasin limitation by 'linking' multiple SWRRB runs together. Although this approach was effective, the input and output of multiple SWRRB files was cumbersome and required considerable computer storage. In addition, all SWRRB runs had to be made independently and then input to ROTO for the channel and reservoir routing. To overcome the awkwardness of this arrangement, SWRRB and ROTO were merged into a single model, SWAT. While allowing simulations of very extensive areas, SWAT retained all the features that made SWRRB such a valuable simulation model.

Since SWAT was created in the early 1990s, it has undergone continued review and expansion of capabilities. The most significant improvements of the model between releases include:

♦ SWAT94.2: Multiple hydrologic response units (HRUs) incorporated.

♦ SWAT96.2: Auto-fertilization and auto-irrigation added as management options; canopy storage of water incorporated; a CO_2 component added to crop growth model for climatic change studies; Penman-Monteith potential evapotranspiration equation added; lateral flow of water in the soil based on kinematic storage model incorporated; in-stream nutrient water quality equations from QUAL2E added; in-stream pesticide routing.

♦ SWAT98.1: Snow melt routines improved; in-stream water quality improved; nutrient cycling routines expanded; grazing, manure applications, and tile flow drainage added as management options; model modified for use in Southern Hemisphere.

♦ SWAT99.2: Nutrient cycling routines improved, rice/wetland routines improved, reservoir/pond/wetland nutrient removal by settling added; bank storage of water in reach added; routing of metals through reach added; all year references in model changed from last 2 digits of year to 4-digit year; urban build up/ wash off equations from SWMM added along with regression equations from USGS.

♦ SWAT2000: Bacteria transport routines added; Green & Ampt infiltration added; weather generator improved; allow daily solar radiation, relative humidity, and wind speed to be read in or generated; allow potential ET values for watershed to be read in or calculated; all potential ET methods reviewed; elevation band processes improved; enabled simulation of unlimited number of reservoirs; Muskingum routing method added; modified dormancy calculations for proper simulation in tropical areas.

♦ SWAT2005: Bacteria transport routines improved; weather forecast scenarios added; subdaily precipitation generator added; the retention parameter used in the daily CN calculation may be a function of soil water content or plant evapotranspiration

In addition to the changes listed above, interfaces for the model have been developed in Windows (Visual Basic), GRASS, and ArcView. SWAT has also undergone extensive validation.

2. Overview of SWAT

SWAT allows a number of different physical processes to be simulated in a watershed. These processes will be briefly summarized in this section. For more detailed discussions of the various procedures, please consult the chapter devoted to the topic of interest.

For modeling purposes, a watershed may be partitioned into a number of subwatersheds or subbasins. The use of subbasins in a simulation is particularly beneficial when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology. By partitioning the watershed into subbasins, the user is able to reference different areas of the watershed to one another spatially. Figure 2 shows a subbasin delineation for the watershed shown in Figure 1.

Input information for each subbasin is grouped or organized into the following categories: climate; hydrologic response units or HRUs; ponds/wetlands; groundwater; and the main channel, or reach, draining the subbasin. Hydrologic response units are lumped land areas within the subbasin that are comprised of unique land cover, soil, and management combinations.

No matter what type of problem studied with SWAT, water balance is the driving force behind everything that happens in the watershed. To accurately predict the movement of pesticides, sediments or nutrients, the hydrologic cycle as simulated by the model must conform to what is happening in the watershed.

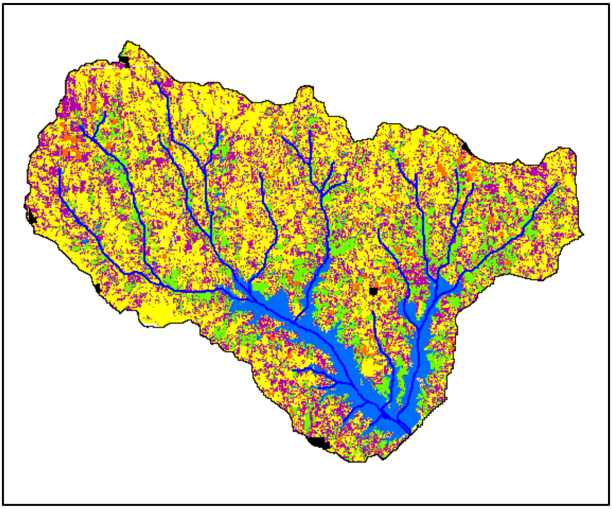

Figure 1. Map of the Lake Fork watershed in northeast Texas showing the land use distribution and stream network.

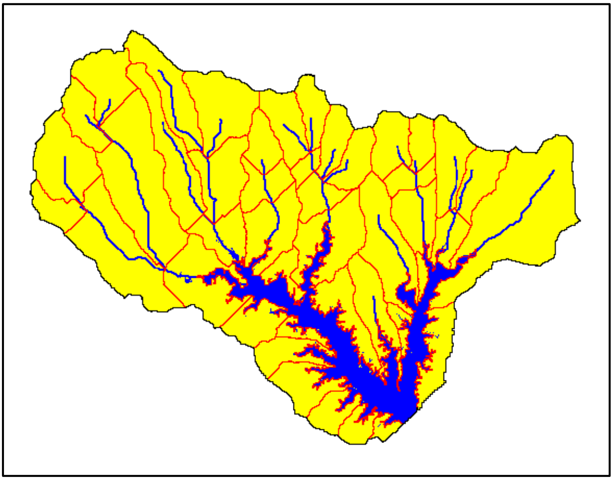

Figure 2. Subbasin delineation of the Lake Fork watershed.

Simulation of the hydrology of a watershed can be separated into two major divisions. The first division is the land phase of the hydrologic cycle, depicted in Figure 3. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subbasin. The second division is the water or routing phase of the hydrologic cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet.

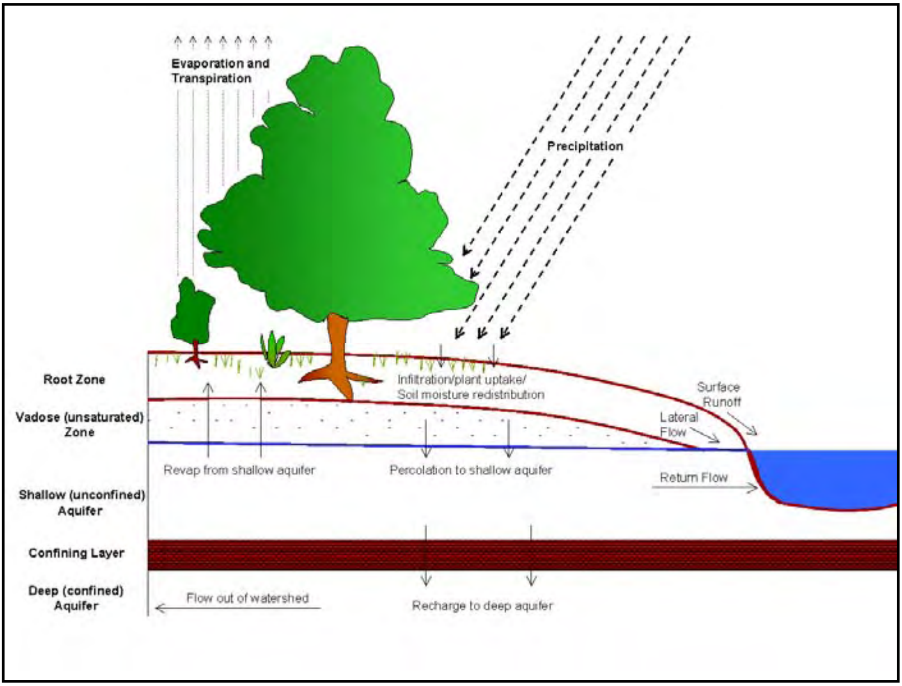

Figure 3. Schematic representation of the hydrologic cycle.

2.1 Land phase of the hydrologic cycle

The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day *i* (mm H_2O), *t* is the time (days), R_{day} is the amount of precipitation on day *i* (mm H_2O), Q_{surf} is the amount of surface runoff on day *i* (mm H_2O), E_a is the amount of evapotranspiration on day *i* (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm H_2O), and Q_{gw} is the amount of return flow on day *i* (mm H_2O).

The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance.

Figure 4 shows the general sequence of processes used by SWAT to model the land phase of the hydrologic cycle. The different inputs and processes involved in this phase of the hydrologic cycle are summarized in the following sections.

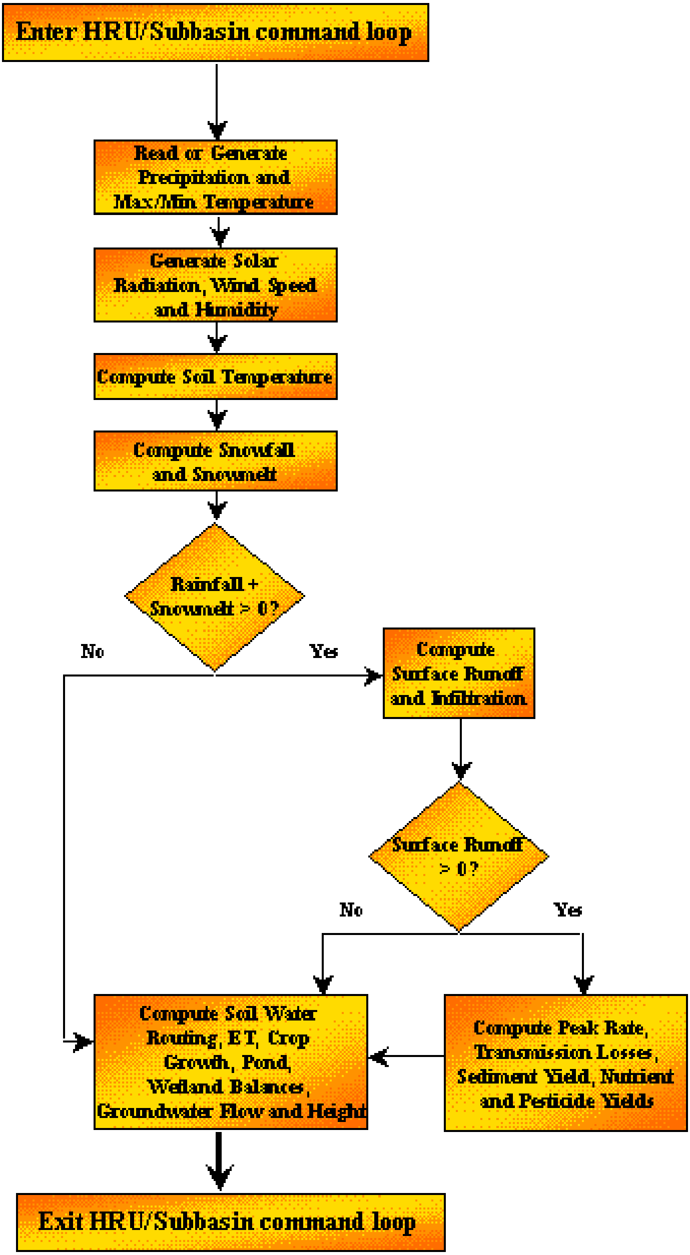

Figure 4. HRU/Subbasin command loop.

2.1.1 Climate

The climate of a watershed provides the moisture and energy inputs that control the water balance and determine the relative importance of the different components of the hydrologic cycle.

The climatic variables required by SWAT consist of daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity. The model allows values for daily precipitation, maximum/minimum air temperatures, solar radiation, wind speed and relative humidity to be input from records of observed data or generated during the simulation.

Weather generator. Daily values for weather are generated from average monthly values. The model generates a set of weather data for each subbasin. The values for any one subbasin will be generated independently and there will be no spatial correlation of generated values between the different subbasins.

> **Generated precipitation.** SWAT uses a model developed by Nicks (1974) to generate daily precipitation for simulations which do not read in measured data. This precipitation model is also used to fill in missing data in the measured records. The precipitation generator uses a first-order Markov chain model to define a day as wet or dry by comparing a random number (0.0-1.0) generated by the model to monthly wet-dry probabilities input by the user. If the day is classified as wet, the amount of precipitation is generated from a skewed distribution or a modified exponential distribution.
>
> **Subdaily rainfall patterns.** If subdaily precipitation values are needed, a double exponential function is used to represent the intensity patterns within a storm. With the double exponential distribution, rainfall intensity exponentially increases with time to a maximum, or peak, intensity. Once the peak intensity is reached, the rainfall intensity exponentially decreases with time until the end of the storm.
>
> **Generated air temperature and solar radiation.** Maximum and minimum air temperatures and solar radiation are generated from a normal distribution. A continuity equation is incorporated into the generator to account for temperature and radiation variations caused by dry vs. rainy conditions. Maximum air temperature and solar radiation are adjusted downward when simulating rainy conditions and upwards when simulating dry conditions. The adjustments are made so that the long-term generated values for the average monthly maximum temperature and monthly solar radiation agree with the input averages.
>
> **Generated wind speed.** A modified exponential equation is used to generate daily mean wind speed given the mean monthly wind speed.
>
> **Generated relative humidity.** The relative humidity model uses a triangular distribution to simulate the daily average relative humidity from the

monthly average. As with temperature and radiation, the mean daily relative humidity is adjusted to account for wet- and dry-day effects.

Snow. SWAT classifies precipitation as rain or freezing rain/snow using the average daily temperature.

Snow cover. The snow cover component of SWAT has been updated from a simple, uniform snow cover model to a more complex model which allows non-uniform cover due to shading, drifting, topography and land cover. The user defines a threshold snow depth above which snow coverage will always extend over 100% of the area. As the snow depth in a subbasin decreases below this value, the snow coverage is allowed to decline non-linearly based on an areal depletion curve.

Snow melt. Snow melt is controlled by the air and snow pack temperature, the melting rate, and the areal coverage of snow. If snow is present, it is melted on days when the maximum temperature exceeds 0°C using a linear function of the difference between the average snow pack-maximum air temperature and the base or threshold temperature for snow melt. Melted snow is treated the same as rainfall for estimating runoff and percolation. For snow melt, rainfall energy is set to zero and the peak runoff rate is estimated assuming uniformly melted snow for a 24 hour duration.

Elevation bands. The model allows the subbasin to be split into a maximum of ten elevation bands. Snow cover and snow melt are simulated separately for each elevation band. By dividing the subbasin into elevation bands, the model is able to assess the differences in snow cover and snow melt caused by orographic variation in precipitation and temperature.

Soil temperature. Soil temperature impacts water movement and the decay rate of residue in the soil. Daily average soil temperature is calculated at the soil surface and the center of each soil layer. The temperature of the soil surface is a function of snow cover, plant cover and residue cover, the bare soil surface temperature, and the previous day’s soil surface temperature. The temperature of a soil layer is a function of the surface temperature, mean annual air temperature and the depth in the soil at which variation in temperature due to changes in climatic conditions no longer occurs. This depth, referred to as the damping depth, is dependent upon the bulk density and the soil water content.

2.1.2 Hydrology

As precipitation descends, it may be intercepted and held in the vegetation canopy or fall to the soil surface. Water on the soil surface will infiltrate into the soil profile or flow overland as runoff. Runoff moves relatively quickly toward a stream channel and contributes to short-term stream response. Infiltrated water may be held in the soil and later evapotranspired or it may slowly make its way to the surface-water system via underground paths. The potential pathways of water movement simulated by SWAT in the HRU are illustrated in Figure 5.

Canopy storage. Canopy storage is the water intercepted by vegetative surfaces (the canopy) where it is held and made available for evaporation. When using the curve number method to compute surface runoff, canopy storage is taken into account in the surface runoff calculations. However, if methods such as Green &

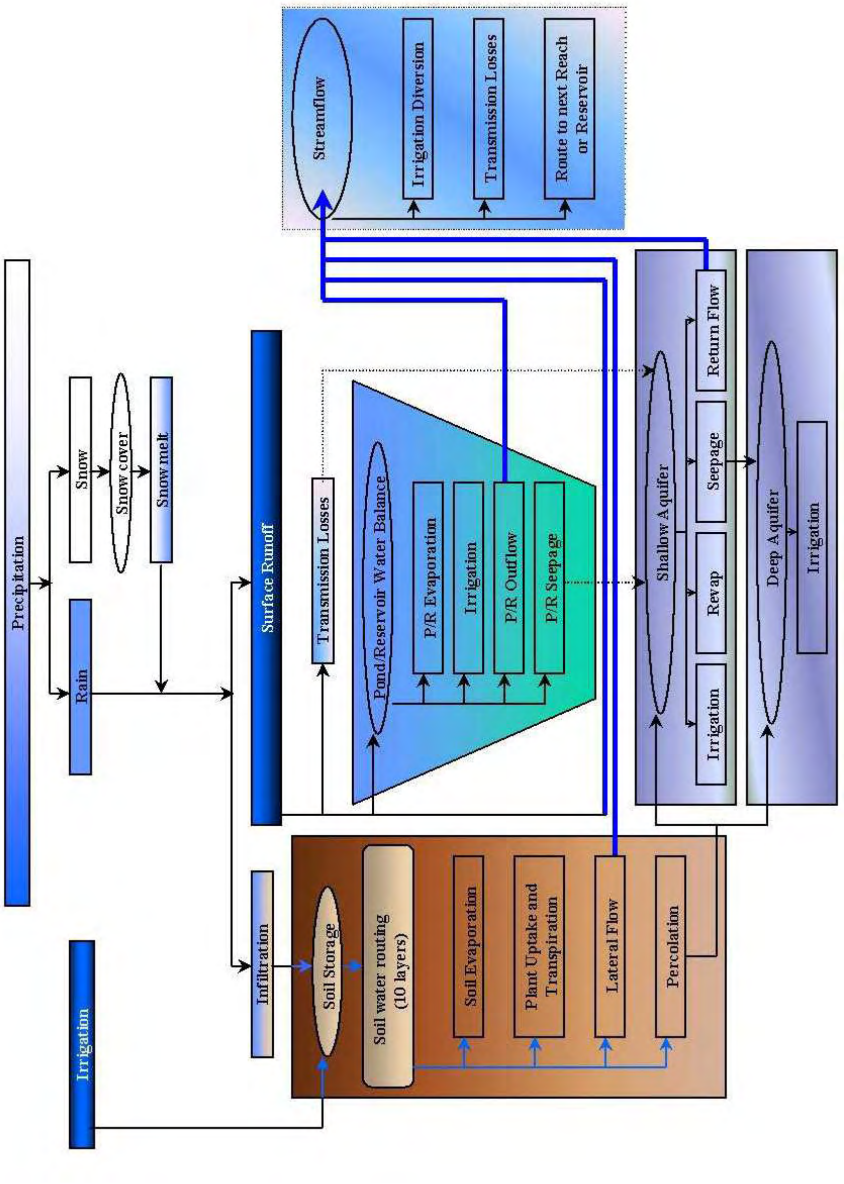

Figure 5. Schematics of pathways available for water movement in SWAT.

Ampt are used to model infiltration and runoff, canopy storage must be modeled separately. SWAT allows the user to input the maximum amount of water that can be stored in the canopy at the maximum leaf area index for the land cover. This value and the leaf area index are used by the model to compute the maximum storage at any time in the growth cycle of the land cover/crop. When evaporation is computed, water is first removed from canopy storage.

Infiltration. Infiltration refers to the entry of water into a soil profile from the soil surface. As infiltration continues, the soil becomes increasingly wet, causing the rate of infiltration to decrease with time until it reaches a steady value. The initial rate of infiltration depends on the moisture content of the soil prior to the introduction of water at the soil surface. The final rate of infiltration is equivalent to the saturated hydraulic conductivity of the soil. Because the curve number method used to calculate surface runoff operates on a daily time-step, it is unable to directly model infiltration. The amount of water entering the soil profile is calculated as the difference between the amount of rainfall and the amount of surface runoff. The Green & Ampt infiltration method does directly model infiltration, but it requires precipitation data in smaller time increments.

Redistribution. Redistribution refers to the continued movement of water through a soil profile after input of water (via precipitation or irrigation) has ceased at the soil surface. Redistribution is caused by differences in water content in the profile. Once the water content throughout the entire profile is uniform, redistribution will cease. The redistribution component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow, or percolation, occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is governed by the saturated conductivity of the soil layer. Redistribution is affected by soil temperature. If the temperature in a particular layer is 0°C or below, no redistribution is allowed from that layer.

Evapotranspiration. Evapotranspiration is a collective term for all processes by which water in the liquid or solid phase at or near the earth's surface becomes atmospheric water vapor. Evapotranspiration includes evaporation from rivers and lakes, bare soil, and vegetative surfaces; evaporation from within the leaves of plants (transpiration); and sublimation from ice and snow surfaces. The model computes evaporation from soils and plants separately as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential evapotranspiration and leaf area index (area of plant leaves relative to the area of the HRU). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant transpiration is simulated as a linear function of potential evapotranspiration and leaf area index.

Potential evapotranspiration. Potential evapotranspiration is the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation that has access to an unlimited supply of soil water. This rate is assumed to be unaffected by microclimatic processes such as advection or heat-storage effects. The model offers three options for estimating potential evapotranspiration: Hargreaves (Hargreaves et al., 1985), Priestley-Taylor (Priestley and Taylor, 1972), and Penman-Monteith (Monteith, 1965).

Lateral subsurface flow. Lateral subsurface flow, or interflow, is streamflow contribution that originates below the surface but above the zone where rocks are saturated with water. Lateral subsurface flow in the soil profile (0-2 m) is calculated simultaneously with redistribution. A kinematic storage model is used to predict lateral flow in each soil layer. The model accounts for variation in conductivity, slope and soil water content.

Surface runoff. Surface runoff, or overland flow, is the flow that occurs along a sloping surface. Using daily or subdaily rainfall amounts, SWAT simulates surface runoff volumes and peak runoff rates for each HRU.

Surface runoff volume is computed using a modification of the SCS curve number method (USDA Soil Conservation Service, 1972) or the Green & Ampt infiltration method (Green and Ampt, 1911). In the curve number method, the curve number varies non-linearly with the moisture content of the soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation. The Green & Ampt method requires subdaily precipitation data and calculates infiltration as a function of the wetting front matric potential and effective hydraulic conductivity. Water that does not infiltrate becomes surface runoff. SWAT includes a provision for estimating runoff from frozen soil where a soil is defined as frozen if the temperature in the first soil layer is less than 0°C. The model increases runoff for frozen soils but still allows significant infiltration when the frozen soils are dry.

Peak runoff rate. Predictions are made with a modification of the rational method. In brief, the rational method is based on the idea that if a rainfall of intensity i begins instantaneously and continues indefinitely, the rate of runoff will increase until the time of concentration, t_c, when all of the subbasin is contributing to flow at the outlet. In the modified Rational Formula, the peak runoff rate is a function of the proportion of daily precipitation that falls during the subbasin t_c, the daily surface runoff volume, and the subbasin time of concentration. The proportion of rainfall occurring during the subbasin t_c is estimated as a function of total daily rainfall using a stochastic technique. The subbasin time of concentration is estimated using Manning's Formula considering both overland and channel flow.

Ponds. Ponds are water storage structures located within a subbasin which intercept surface runoff. The catchment area of a pond is defined as a fraction of the total area of the subbasin. Ponds are assumed to be located off the main channel in a subbasin and will never receive water from upstream subbasins. Pond water storage is a function of pond capacity, daily inflows and outflows, seepage and evaporation. Required inputs are the storage capacity and surface area of the pond when filled to capacity. Surface area below capacity is estimated as a non-linear function of storage.

Tributary channels. Two types of channels are defined within a subbasin: the main channel and tributary channels. Tributary channels are minor or lower order channels branching off the main channel within the subbasin. Each tributary channel within a subbasin drains only a portion of the subbasin and does not receive groundwater contribution to its flow. All flow in the tributary channels is released and routed through the main channel of the subbasin. SWAT uses the attributes of tributary channels to determine the time of concentration for the subbasin.

> **Transmission losses** are losses of surface flow via leaching through the streambed. This type of loss occurs in ephemeral or intermittent streams where groundwater contribution occurs only at certain times of the year, or not at all. SWAT uses Lane's method described in Chapter 19 of the SCS Hydrology Handbook (USDA Soil Conservation Service, 1983) to estimate transmission losses. Water losses from the channel are a function of channel width and length and flow duration. Both runoff volume and peak rate are adjusted when transmission losses occur in tributary channels.

Return flow. Return flow, or base flow, is the volume of streamflow originating from groundwater. SWAT partitions groundwater into two aquifer systems: a shallow, unconfined aquifer that contributes return flow to streams within the watershed and a deep, confined aquifer that contributes return flow to streams outside the watershed (Arnold et al., 1993). Water percolating past the bottom of the root zone is partitioned into two fractions - each fraction becomes recharge for one of the aquifers. In addition to return flow, water stored in the shallow aquifer may replenish moisture in the soil profile in very dry conditions or be directly removed by plant. Water in the shallow or deep aquifer may be removed by pumping.

2.1.3 Land cover/plant growth

SWAT utilizes a single plant growth model to simulate all types of land covers. The model is able to differentiate between annual and perennial plants. Annual plants grow from the planting date to the harvest date or until the accumulated heat units equal the potential heat units for the plant. Perennial plants maintain their root systems throughout the year, becoming dormant in the winter months. They resume growth when the average daily air temperature exceeds the minimum, or base, temperature required. The plant growth model is used to assess removal of water and nutrients from the root zone, transpiration, and biomass/yield production.

Potential growth. The potential increase in plant biomass on a given day is defined as the increase in biomass under ideal growing conditions. The potential increase in biomass for a day is a function of intercepted energy and the plant's efficiency in converting energy to biomass. Energy interception is estimated as a function of solar radiation and the plant’s leaf area index.

Potential and actual transpiration. The process used to calculate potential plant transpiration is described in the section on evapotranspiration. Actual transpiration is a function of potential transpiration and soil water availability.

Nutrient uptake. Plant use of nitrogen and phosphorus are estimated with a supply and demand approach where the daily plant nitrogen and phosphorus demands are calculated as the difference between the actual concentration of the element in the plant and the optimal concentration. The optimal concentration of the elements varies with growth stage as described by Jones (1983).

Growth contraints. Potential plant growth and yield are usually not achieved due to constraints imposed by the environment. The model estimates stresses caused by water, nutrients and temperature.

2.1.4 Erosion

Erosion and sediment yield are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). While the USLE uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield. The substitution results in a number of benefits: the prediction accuracy of the model is increased, the need for a delivery ratio is eliminated, and single storm estimates of sediment yields can be calculated. The hydrology model supplies estimates of runoff volume and peak runoff rate which, with the subbasin area, are used to calculate the runoff erosive energy variable. The crop management factor is recalculated every day that runoff occurs. It is a function of aboveground biomass, residue on the soil surface, and the minimum C factor for the plant. Other factors of the erosion equation are evaluated as described by Wischmeier and Smith (1978).

2.1.5 Nutrients

SWAT tracks the movement and transformation of several forms of nitrogen and phosphorus in the watershed. In the soil, transformation of nitrogen from one form to another is governed by the nitrogen cycle as depicted in Figure 6. The transformation of phosphorus in the soil is controlled by the phosphorus cycle shown in Figure 7. Nutrients may be introduced to the main channel and transported downstream through surface runoff and lateral subsurface flow.

Nitrogen. The different processes modeled by SWAT in the HRUs and the various pools of nitrogen in the soil are depicted in Figure 6. Plant use of nitrogen is estimated using the supply and demand approach described in the section on plant growth. In addition to plant use, nitrate and organic N may be removed from the soil via mass flow of water. Amounts of NO_3-N contained in runoff, lateral flow and percolation are estimated as products of the volume of water and the average

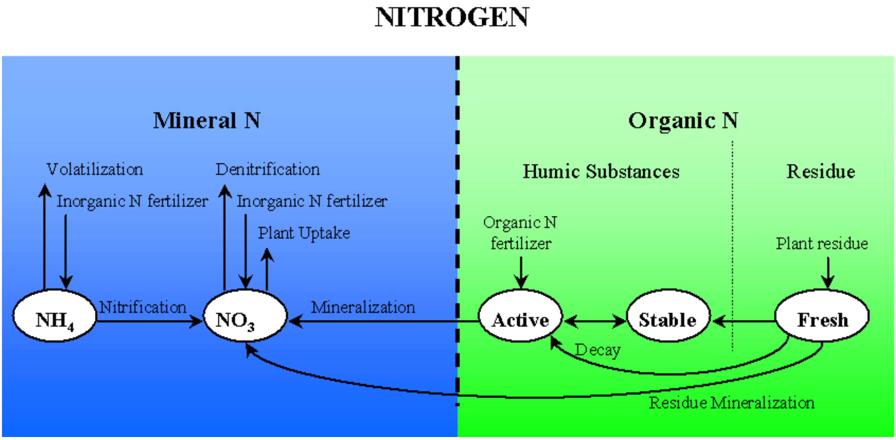

Figure 6. Partitioning of ntrogen in SWAT.

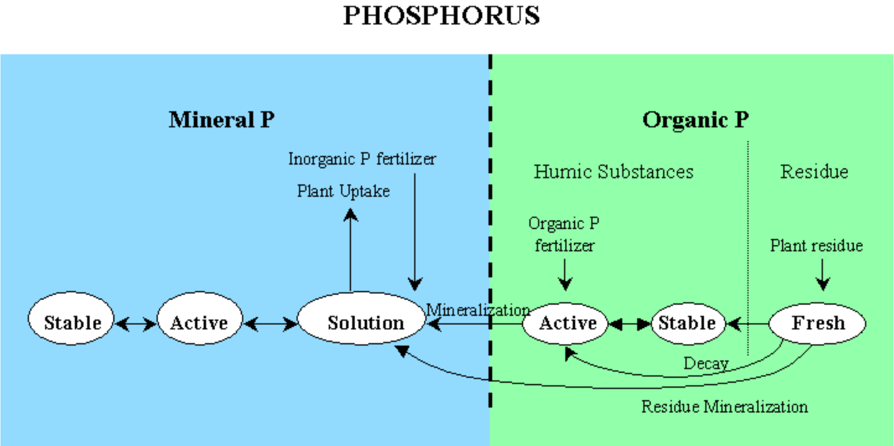

Figure 7. Partitioning of phosphorus in SWAT.

concentration of nitrate in the layer. Organic N transport with sediment is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978) for application to individual runoff events. The loading function estimates the daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield, and the enrichment ratio. The enrichment ratio is the concentration of organic N in the sediment divided by that in the soil.

Phosphorus. The different processes modeled by SWAT in the HRUs and the various pools of phosphorus in the soil are depicted in Figure 7. Plant use of phosphorus is estimated using the supply and demand approach described in the section on plant growth. In addition to plant use, soluble phosphorus and organic P may be removed from the soil via mass flow of water. Phosphorus is not a mobile nutrient and interaction between surface runoff with solution P in the top 10 mm of soil will not be complete. The amount of soluble P removed in runoff is predicted using solution P concentration in the top 10 mm of soil, the runoff volume and a partitioning factor. Sediment transport of P is simulated with a loading function as described in organic N transport.

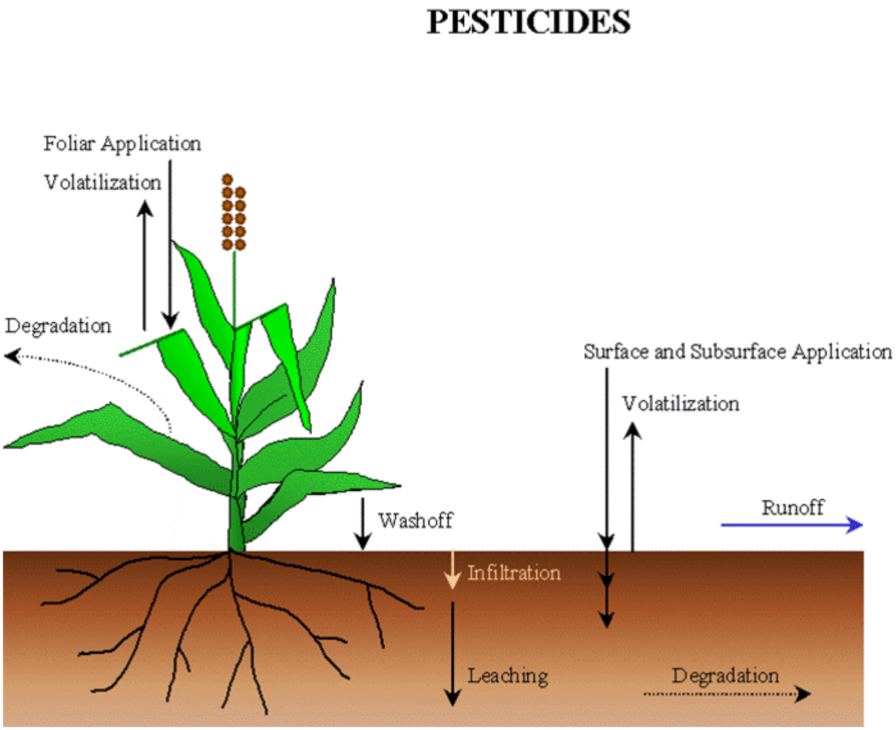

Figure 8. Pesticide fate and transport in SWAT.

2.1.6 Pesticides

Although SWAT does not simulate stress on the growth of a plant due to the presence of weeds, damaging insects, and other pests, pesticides may be applied to an HRU to study the movement of the chemical in the watershed. SWAT simulates pesticide movement into the stream network via surface runoff (in solution and sorbed to sediment transported by the runoff), and into the soil profile and aquifer by percolation (in solution). The equations used to model the movement of pesticide in the land phase of the hydrologic cycle were adopted from GLEAMS (Leonard et al., 1987). The movement of the pesticide is controlled by its solubility, degradation half-life, and soil organic carbon adsorption coefficient. Pesticide on plant foliage and in the soil degrade exponentially according to the appropriate half-life. Pesticide transport by water and sediment is calculated for each runoff event and pesticide leaching is estimated for each soil layer when percolation occurs.

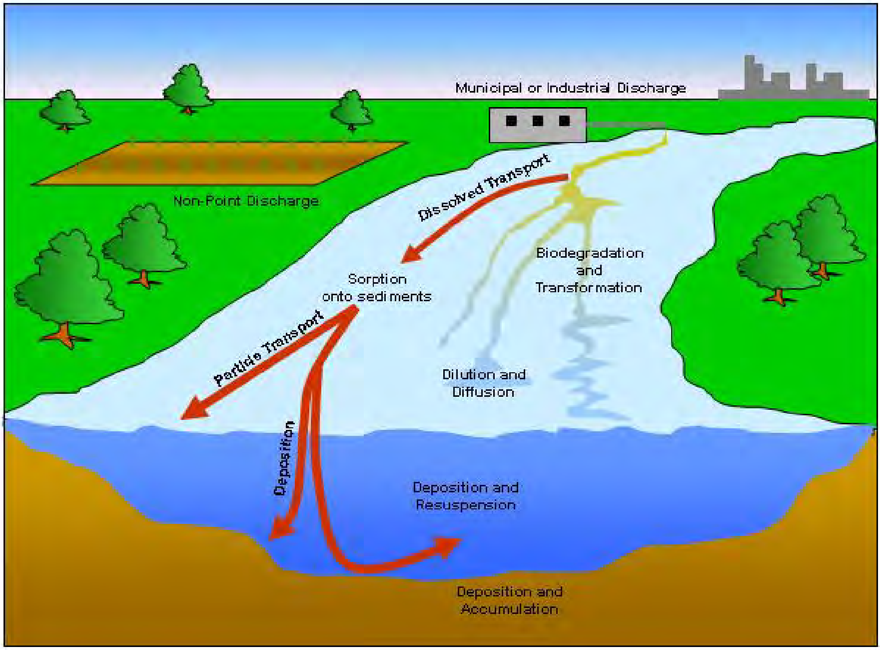

Figure 9. In-stream processes modeled by SWAT.

2.1.7 Management

SWAT allows the user to define management practices taking place in every HRU. The user may define the beginning and the ending of the growing season, specify timing and amounts of fertilizer, pesticide and irrigation applications as well as timing of tillage operations. At the end of the growing season, the biomass may be removed from the HRU as yield or placed on the surface as residue.

In addition to these basic management practices, operations such as grazing, automated fertilizer and water applications, and incorporation of every conceivable management option for water use are available. The latest improvement to land management is the incorporation of routines to calculate sediment and nutrient loadings from urban areas.

Rotations. The dictionary defines a rotation as the growing of different crops in succession in one field, usually in a regular sequence. A rotation in SWAT refers to a change in management practices from one year to the next. There is no limit to the number of years of different management operations specified in a rotation.

SWAT also does not limit the number of land cover/crops grown within one year in the HRU. However, only one land cover can be growing at any one time.

Water use. The two most typical uses of water are for application to agricultural lands or use as a town's water supply. SWAT allows water to be applied on an HRU from any water source within or outside the watershed. Water may also be transferred between reservoirs, reaches and subbasins as well as exported from the watershed.

2.2 Routing phase of the hydrologic cycle

Once SWAT determines the loadings of water, sediment, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed using a command structure similar to that of HYMO (Williams and Hann, 1972). In addition to keeping track of mass flow in the channel, SWAT models the transformation of chemicals in the stream and streambed. Figure 9 illustrates the different in-stream processes modeled by SWAT.

2.2.1 Routing in the main channel or reach

Routing in the main channel can be divided into four components: water, sediment, nutrients and organic chemicals.

Flood routing. As water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another potential loss is removal of water from the channel for agricultural or human use. Flow may be supplemented by the fall of rain directly on the channel and/or addition of water from point source discharges. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method.

Sediment routing. The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. Previous versions of SWAT used stream power to estimate deposition/degradation in the channels (Arnold et al., 1995). Bagnold (1977) defined stream power as the product of water density, flow rate and water surface slope. Williams (1980) used Bagnold's definition of stream power to develop a method for determining degradation as a function of channel slope and velocity. In this version of SWAT, the equations have been simplified and the maximum amount of sediment that can be transported from a reach segment is a function of the peak channel velocity. Available stream power is used to re-entrain loose and deposited material until all of the material is removed. Excess stream power causes bed degradation. Bed degradation is adjusted for stream bed erodibility and cover.

Nutrient routing. Nutrient transformations in the stream are controlled by the in-stream water quality component of the model. The in-stream kinetics used in SWAT for nutrient routing are adapted from QUAL2E (Brown and Barnwell, 1987). The model tracks nutrients dissolved in the stream and nutrients adsorbed to the sediment. Dissolved nutrients are transported with the water while those sorbed to sediments are allowed to be deposited with the sediment on the bed of the channel.

Channel pesticide routing. While an unlimited number of pesticides may be applied to the HRUs, only one pesticide may be routed through the channel network of the watershed due to the complexity of the processes simulated. As with the nutrients, the total pesticide load in the channel is partitioned into dissolved and sediment-attached components. While the dissolved pesticide is transported with water, the pesticide attached to sediment is affected by sediment transport and deposition processes. Pesticide transformations in the dissolved and sorbed phases are governed by first-order decay relationships. The major in-stream processes simulated by the model are settling, burial, re-suspension, volatilization, diffusion and transformation.

2.2.2 Routing in the reservoir

The water balance for reservoirs includes inflow, outflow, rainfall on the surface, evaporation, seepage from the reservoir bottom and diversions.

Reservoir outflow. The model offers three alternatives for estimating outflow from the reservoir. The first option allows the user to input measured outflow. The second option, designed for small, uncontrolled reservoirs, requires the users to specify a water release rate. When the reservoir volume exceeds the principal storage, the extra water is released at the specified rate. Volume exceeding the emergency spillway is released within one day. The third option, designed for larger, managed reservoirs, has the user specify monthly target volumes for the reservoir.

Sediment routing. Sediment inflow may originate from transport through the upstream reaches or from surface runoff within the subbasin. The concentration of sediment in the reservoir is estimated using a simple continuity equation based on volume and concentration of inflow, outflow, and water retained in the reservoir. Settling of sediment in the reservoir is governed by an equilibrium sediment concentration and the median sediment particle size. The amount of sediment in the reservoir outflow is the product of the volume of water flowing out of the reservoir and the suspended sediment concentration in the reservoir at the time of release.

Reservoir nutrients. A simple model for nitrogen and phosphorus mass balance was taken from Chapra (1997). The model assumes: 1) the lake is completely mixed; 2) phosphorus is the limiting nutrient; and, 3) total phosphorus is a measure of the lake trophic status. The first assumption ignores lake stratification and intensification of phytoplankton in the epilimnon. The second assumption is generally valid when non-point sources dominate and the third assumption implies that a relationship exists between total phosphorus and biomass. The phosphorus mass balance equation includes the concentration in the lake, inflow, outflow and overall loss rate.

Reservoir pesticides. The lake pesticide balance model is taken from Chapra (1997) and assumes well mixed conditions. The system is partitioned into a well mixed surface water layer underlain by a well mixed sediment layer. The pesticide is partitioned into dissolved and particulate phases in both the water and sediment layers. The major processes simulated by the model are loading, outflow, transformation, volatilization, settling, diffusion, re-suspension and burial.

References

Arnold, J.G., J.R. Williams, A.D. Nicks, and N.B. Sammons. 1990. SWRRB: A basin scale simulation model for soil and water resources management. Texas A&M Univ. Press, College Station, TX.

Arnold, J.G., P.M. Allen, and G. Bernhardt. 1993. A comprehensive surface-groundwater flow model. J. Hydrol. 142:47-69.

Arnold, J.G., J.R. Williams and D.R. Maidment. 1995. Continuous-time water and sediment-routing model for large basins. Journal of Hydraulic Engineering 121(2):171-183.

Bagnold, R.A. 1977. Bedload transport in natural rivers. Water Resources Res. 13(2):303-312.

Brown, L.C. and T.O. Barnwell, Jr. 1987. The enhanced water quality models QUAL2E and QUAL2E-UNCAS documentation and user manual. EPA document EPA/600/3-87/007. USEPA, Athens, GA.

Chapra, S.C. 1997. Surface water-quality modeling. McGraw-Hill, Boston.

Green, W.H. and G.A. Ampt. 1911. Studies on soil physics, 1. The flow of air and water through soils. Journal of Agricultural Sciences 4:11-24.

Hargreaves, G.L., G.H. Hargreaves, and J.P. Riley. 1985. Agricultural benefits for Senegal River Basin. J. Irrig. and Drain. Engr. 111(2):113-124.

Jones, C.A. 1983. A survey of the variability in tissue nitrogen and phosphorus concentrations in maize and grain sorghum. Field Crops Res. 6:133-147.

Knisel, W.G. 1980. CREAMS, a field scale model for chemicals, runoff and erosion from agricultural management systems. USDA Conservation Research Rept. No. 26.

Leonard, R.A. and R.D. Wauchope. 1980. Chapter 5: The pesticide submodel. p. 88-112. *In* Knisel, W.G. (ed). CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. U.S. Department of Agriculture, Conservation research report no. 26.

Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Groundwater loading effects on agricultural management systems. Trans. ASAE 30(5):1403-1428.

McElroy, A.D., S.Y. Chiu, J.W. Nebgen, A. Aleti, and F.W. Bennett. 1976. Loading functions for assessment of water pollution from nonpoint sources. EPA document EPA 600/2-76-151. USEPA, Athens, GA.

Monteith, J.L. 1965. Evaporation and the environment. p. 205-234. *In* The state and movement of water in living organisms. 19th Symposia of the Society for Experimental Biology. Cambridge Univ. Press, London, U.K.

Nicks, A.D. 1974. Stochastic generation of the occurrence, pattern and location of maximum amount of daily rainfall. p. 154-171. *In* Proc. Symp. Statistical Hydrology, Tucson, AZ. Aug.-Sept. 1971. USDA Misc. Publ. 1275. U.S. Gov. Print. Office, Washington, DC.

Priestley, C.H.B. and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81-92.

Ritchie, J.T. 1972. A model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8:1204-1213.

USDA Soil Conservation Service. 1972. National Engineering Handbook Section 4 Hydrology, Chapters 4-10.

USDA Soil Conservation Service. 1983. National Engineering Handbook Section 4 Hydrology, Chapter 19.

Williams, J.R. 1969. Flood routing with variable travel time or variable storage coefficients. Trans. ASAE 12(1):100-103.

Williams, J.R. 1980. SPNM, a model for predicting sediment, phosphorus, and nitrogen yields from agricultural basins. Water Resour. Bull. 16(5):843-848.

Williams, J.R. 1975. Sediment routing for agricultural watersheds. Water Resour. Bull. 11 (5):965-974.

Williams, J.R. and R.W. Hann. 1978. Optimal operation of large agricultural watersheds with water quality constraints. Texas Water Resources Institute, Texas A&M Univ., Tech. Rept. No. 96.

Williams, J.R. and R.W. Hann. 1972. HYMO, a problem-oriented computer language for building hydrologic models. Water Resour. Res. 8(1):79-85.

Williams, J.R., C.A. Jones and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27(1):129-144.

Williams, J.R., A.D. Nicks, and J.G. Arnold. 1985. Simulator for water resources in rural basins. Journal of Hydraulic Engineering 111(6): 970-986.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall losses: A guide to conservation planning. USDA Agricultural Handbook No. 537. U.S. Gov. Print. Office, Washington, D.C.

2.1 Modeling Blue and Green Water Availability in Africa

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Abstract

Despite the general awareness that in Africa many people and large areas are suffering from insufficient water supply, spatially and temporally detailed information on freshwater availability and water scarcity is so far rather limited. By applying a semidistributed hydrological model SWAT (Soil and Water Assessment Tool), the freshwater components blue water flow (i.e. water yield plus deep aquifer recharge), green water flow (i.e. actual evapotranspiration), and green water storage (i.e. soil water) were estimated at a subbasin level with monthly resolution for the whole of Africa. Using the program SUFI-2 (Sequential Uncertainty Fitting Algorithm), the model was calibrated and validated at 207 discharge stations, and prediction uncertainties were quantified. The presented model and its results could be used in various advanced studies on climate change, water and food security, and virtual water trade, among others. The model results are generally good albeit with large prediction uncertainties in some cases. These uncertainties, however, disclose the actual knowledge about the modeled processes. The effect of considering these model-based uncertainties in advanced studies is shown for the computation of water scarcity indicators.

Keywords: SWAT, SUFI-2, soil water, prediction uncertainty, water scarcity, water balance components

1. Introduction

On a continental and annual basis Africa has abundant water resources but the problem is their high spatial and temporal variability within and between countries and river basins (UN-Water/Africa, 2006). Considering this variability, the continent can be seen as dry with pressing water problems (Falkenmark, 1989;

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Vörösmarty et al., 2005). Though of critical importance, detailed information on water resources and water scarcity is still limited in Africa (Wallace and Gregory, 2002).

Freshwater availability is a prerequisite for food security, public health, ecosystem protection, etc. Thus freshwater is important and relevant for achieving all development goals contained in the United Nations Millennium Declaration (http://www.un.org/millennium/declaration/ares552e.pdf). Two important targets of the Declaration are to halve, by the year 2015, the proportion of people without sustainable access to safe drinking water and to halve the proportion of people who suffer from hunger. These two targets are closely related to freshwater availability.

Up to now, studies of freshwater availability have predominantly focused on the quantification of the 'blue water', while ignoring the 'green water' as part of the water resource and its great importance especially for rainfed agriculture (e.g. in sub-Saharan Africa more than 95% is rainfed (Rockström et al., 2007)). Two of the few studies dealing with green water are Rockström and Gordon (2001) and Gerten et al. (2005). Blue water flow, or the internal renewable water resource (IRWR), is traditionally quantified as the sum of the water yield and the deep aquifer recharge. Green water, on the other hand, originates from the naturally infiltrated water, which is more and more being thought of as a manageable water resource. Falkenmark and Rockström (2006) differentiate between two components of the green water: green water resource (or storage), which equals the moisture in the soil, and green water flow, which equals the sum of the actual evaporation (the non-productive part) and the actual transpiration (the productive part). In some references only the transpiration is regarded as the green water component (e.g. Savenije, 2004). As evaporation and transpiration are closely interlinked processes and evaporated water has the potential to be partly used as productive flow for food production, we prefer to consider the total actual evapotranspiration as the green water flow.

Spatially and temporally detailed assessments of the different components of freshwater availability are essential for locating critical regions, and thus, the basis for rational decision-making in water resources planning and management. There exist already a few global freshwater assessments based on (1) data generalization (e.g. Shiklomanov, 2000; Shiklomanov and Rodda, 2003), (2) general circulation models (GCMs) (e.g. TRIP, Oki et al., 2001; Oki and Kanae, 2006), and (3) hydrological models (e.g. WBM, Vörösmarty et al., 1998, 2000; Fekete et al., 1999; Macro-PDM, Arnell, 1999; WGHM (WaterGAP 2), Alcamo et al., 2003; Döll et al., 2003; LPJ, Gerten et al., 2004; WASMOD-M, Widén-Nilsson et al., 2007). GCMs with their strength on the atmospheric model component perform poorly on the soil water processes (Döll et al., 2003). All the above mentioned hydrological models are raster models with a spatial resolution of 0.5° but show different degrees of complexities. These models either have not been calibrated (e.g. WBM) or only one (e.g. WGHM) or few parameters (e.g. WAS-

MOD-M) have been checked and adjusted against long-term average runoffs. In WGHM, for some basins one or two correction factors have been additionally applied in order to guarantee a maximum of 1% error of the simulated long-term annual average runoff (Döll et al., 2003). Intra-annual runoff differences, which are of key importance in many regions have been included in some studies (e.g. Widén-Nilsson et al., 2007) but not used for calibration.

The existing global and continental freshwater assessment models have been used for climate and socioeconomic change scenarios (Alcamo et al., 2007), water stress computation (Vörösmarty et al., 2005), analysis of seasonal and interannual continental water storage variations (Güntner et al., 2007), global water scarcity analysis taking into account environmental water requirements (Smakhtin et al., 2004), and virtual water trading (Islam et al., 2007) among others. Hence it is important that these models pass through a careful calibration, validation, and uncertainty analysis. Particularly in large-scale (hydrological) models, the expected uncertainties are rather large. For this task, several different procedures have been developed: e.g. Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992), Bayesian inference based on Markov Chain Monte Carlo (MCMC) (Vrugt et al., 2003), Parameter Solution (ParaSol) (van Griensven and Meixner, 2006), and Sequential Uncertainty Fitting (SUFI-2) (Abbaspour et al., 2007).

In this study, we modeled the monthly subcountry-based freshwater availability for Africa and explicitly differentiated between the different freshwater components: blue water flow, green water storage and green water flow. The model of choice was “Soil and Water Assessment Tool” (SWAT) (Arnold et al., 1998) because of two reasons. *First,* SWAT has been already successfully applied for water quantity and quality issues for a wide range of scales and environmental conditions around the globe. A comprehensive SWAT review paper summarizing the findings of more than 250 peer-reviewed articles is written by Gassman et al. (2007). The suitability of SWAT for very large scale applications has been shown in the “Hydrologic Unit Model for the United States” (HUMUS) project (Arnold et al., 1999; Srinivasan et al., 1998). SWAT was also recently applied in the national and watershed assessments of the U.S. Department of Agriculture (USDA) Conservation Effects Assessment Program (CEAP, http://www.nrcs.usda.gov/Technical/nri/ceap/index.html). The *second* reason for choosing SWAT for this exclusive water quantity study was its ability to perform plant growth and water quality modeling, a topic we plan to study in the future. An advantage of SWAT is its modular implementation where processes can be selected or not. As processes are represented by parameters in the model, in data scarce regions SWAT can run with a minimum number of parameters. As more is known about a region, more processes can be invoked for by updating and running the model again.

The African model was calibrated and validated at 207 discharge stations across the continent. Uncertainties were quantified using SUFI-2 program

(Abbaspour et al., 2007). Yang et al. (2008) compared different uncertainty analysis techniques in connection to SWAT and found that SUFI-2 needed the smallest number of model runs to achieve a similarly good solution and prediction uncertainty. This efficiency issue is of great importance when dealing with computationally intensive, complex, and large-scale models. In addition, SUFI-2 is linked to SWAT (in the SWAT-CUP software) (Abbaspour et al., 2008) through an interface that includes also the programs GLUE, ParaSol, and MCMC.

2. Materials and Methods

2.1 SWAT2005 model and ArcSWAT interface

To simulate the water resources availability in Africa, the latest version of the semiphysically based, semidistributed, basin-scale model SWAT (Arnold et al., 1998) was selected (SWAT2005) (Neitsch et al., 2005). SWAT is a continuous time model and operates on a daily time step. Only the hydrologic component of the model was used in this study. In SWAT the modeled area is divided into multiple subbasins by overlaying elevation, land cover, soil, and slope classes. In this study the subbasins were characterized by dominant land use, soil, and slope classes. This choice was essential for keeping the size of the model at a practical limit. For each of the subunits, water balance was simulated for four storage volumes: snow, soil profile, shallow aquifer, and deep aquifer. In our case, potential evapotranspiration was computed using the Hargreaves method which requires the climatic input of daily precipitation, and minimum and maximum temperature. Surface runoff was simulated using a modification of the SCS Curve Number (CN) method. Despite the empirical nature, this approach has been proven to be successful for many applications and a wide variety of hydrologic conditions (Gassman et al., 2007). The runoff from each subbasin was routed through the river network to the main basin outlet using, in our case, the variable storage method. Further technical model details are given by Arnold et al. (1998) and Neitsch et al. (2005).

The preprocessing of the SWAT model input (e.g. watershed delineation, manipulation of the spatial and tabular data) was performed within ESRI ArcGIS 9.1 using the ArcSWAT interface (Winchell et al., 2007). In comparison to the ArcView GIS interface AVSWAT2000 (Di Luzio et al., 2001), ArcSWAT has no apparent limitation concerning the size and complexity of the simulated area as it was able to model the entire African continent.

2.2 The calibration and uncertainty analysis procedure-SUFI-2

The program SUFI-2 (Abbaspour et al., 2007) was used for a combined calibration and uncertainty analysis. In any (hydrological) modeling work there are uncertainties in input (e.g. rainfall), in conceptual model (e.g. by process simplification or by ignoring important processes), in model parameters (non-uniqueness) and in the measured data (e.g. discharge used for calibration). SUFI-2 maps the aggregated uncertainties to the parameters and aims to obtain the smallest parameter uncertainty (ranges). The parameter uncertainty leads to uncertainty in the output which is quantified by the 95% prediction uncertainty (95PPU) calculated at the 2.5% (L95PPU) and the 97.5% (U95PPU) levels of the cumulative distribution obtained through Latin hypercube sampling. Starting with large but physically meaningful parameter ranges that bracket ‘most’ of the measured data within the 95PPU, SUFI-2 decreases the parameter uncertainties iteratively. After each iteration, new and narrower parameter uncertainties are calculated (see Abbaspour et al., 2007) where the more sensitive parameters find a larger uncertainty reduction than the less sensitive parameters. In deterministic simulations, output (i.e. river discharge) is a signal and can be compared to a measured signal using indices such as R2, root mean square error, or Nash-Sutcliffe. In stochastic simulations where predicted output is given by a prediction uncertainty band instead of a signal, we devised two different indices to compare measurement to simulation: the P-factor and the R-factor (Abbaspour et al., 2007). These indices were used to gauge the strength of calibration and uncertainty measures. The P-factor is the percentage of measured data bracketed by the 95PPU. As all correct processes and model inputs are reflected in the observations, the degree to which they are bracketed in the 95PPU indicates the degree to which the model uncertainties are being accounted for. The maximum value for the P-factor is 100%, and ideally we would like to bracket all measured data, except the outliers, in the 95PPU band. The R-factor is calculated as the ratio between the average thickness of the 95PPU band and the standard deviation of the measured data. It represents the width of the uncertainty interval and should be as small as possible. R-factor indicates the strength of the calibration and should be close to or smaller than a practical value of 1. As a larger P-factor can be found at the expense of a larger R-factor, often a trade off between the two must be sought.

2.3 Database

The model for the continent of Africa was constructed using in most cases freely available global information. The collection of the data was followed by an accurate compilation and analysis of the quality and integrity. The basic input maps included the digital elevation model (DEM) GTOPO30, the digital stream network HYDRO1k (http://edc.usgs.gov/products/elevation/gtopo30/hydro/index.html), and the land cover map Global Land Cover Characterization (GLCC) (http://edcsns17.cr.usgs.gov/glcc/) both at a resolution of 1 km from U.S. Geological Survey (USGS). The soil map was produced by the Food and Agriculture Organization of the United Nations (FAO, 1995) at a resolution of 10 km, including almost 5,000 soil types and two soil layers. Because of the few and unevenly distributed weather stations in Africa with often only short and erroneous time series, the daily weather input (precipitation, minimum and maximum temperature) was generated for each subbasin based on the 0.5_ grids monthly statistics from Climatic Research Unit (CRU TS 1.0 and 2.0, http://www.cru.uea.ac.uk/cru/data/hrg.htm). We developed a semiautomated weather generator, dGen, for this purpose (Schuol and Abbaspour, 2007). Information on lakes, wetlands and reservoirs was extracted from the Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004). River discharge data, which is essential for calibration and validation, were obtained from the Global Runoff Data Centre (GRDC, http://grdc.bafg.de). More details on the databases are discussed by Schuol et al. (2008).

2.4 Model setup

The ArcSWAT interface was used for the setup and parameterization of the model. On the basis of the DEM and the stream network, a minimum drainage area of 10,000 km^2 was chosen to discretize the continent into 1,496 subbasins. The geomorphology, stream parameterization, and overlay of soil and land cover were automatically done within the interface. To mitigate the effect of land cover change over time, and to decrease the computational time of the very large-scale model, the dominant soil and land cover were used in each subbasin. The simulation period was from 1968 to 1995 and for these years we provided daily generated weather input. The first 3 years were used as warm-up period to mitigate the unknown initial conditions and were excluded from the analysis. Lakes, wetlands, and reservoirs, which affect the river discharge to a great extent, were also included in the model. As detail information was lacking, only 64 reservoirs with storage volumes larger than 1 km^3 were included (Fig. 1). In this study, wetlands on the main channel networks as well as lakes were treated as reservoirs. The parameterization was mostly based on information from GLWD-1 (Lehner and Döll, 2004).

2.5 Model calibration procedures

Model calibration and validation is a necessary, challenging but also to a certain degree subjective step in the development of any complex hydrological model. The African model was calibrated using monthly river discharges from 207 stations. These stations were unevenly distributed throughout the continent (Fig. 1) and covered, in most cases, only parts of the whole analysis period from 1971 to 1995. For this reason it was inevitable to include different time lengths (minimum of 3 years) and time periods at the different stations in the calibration procedure. Consistently at all stations, using a split-sample procedure, the more recent half of the discharge data were used for calibration and the prior half were used for validation. In order to compare the monthly measured and simulated discharges, Φ, a weighted version of the coefficient of determination (slightly modified; Krause et al., 2005) was selected as efficiency criteria:

$$\Phi = \begin{cases} |b|\ R^2 & \text{if } |b| \le 1 \\ |b|^{-1}\ R^2 & \text{if } |b| > 1 \end{cases} \qquad (1)$$

where the coefficient of determination R^2 represents the discharge dynamics, and b is the slope of the regression line between the monthly observed and simulated runoff. Including b guarantees that runoff under- or over-predictions are also reflected.

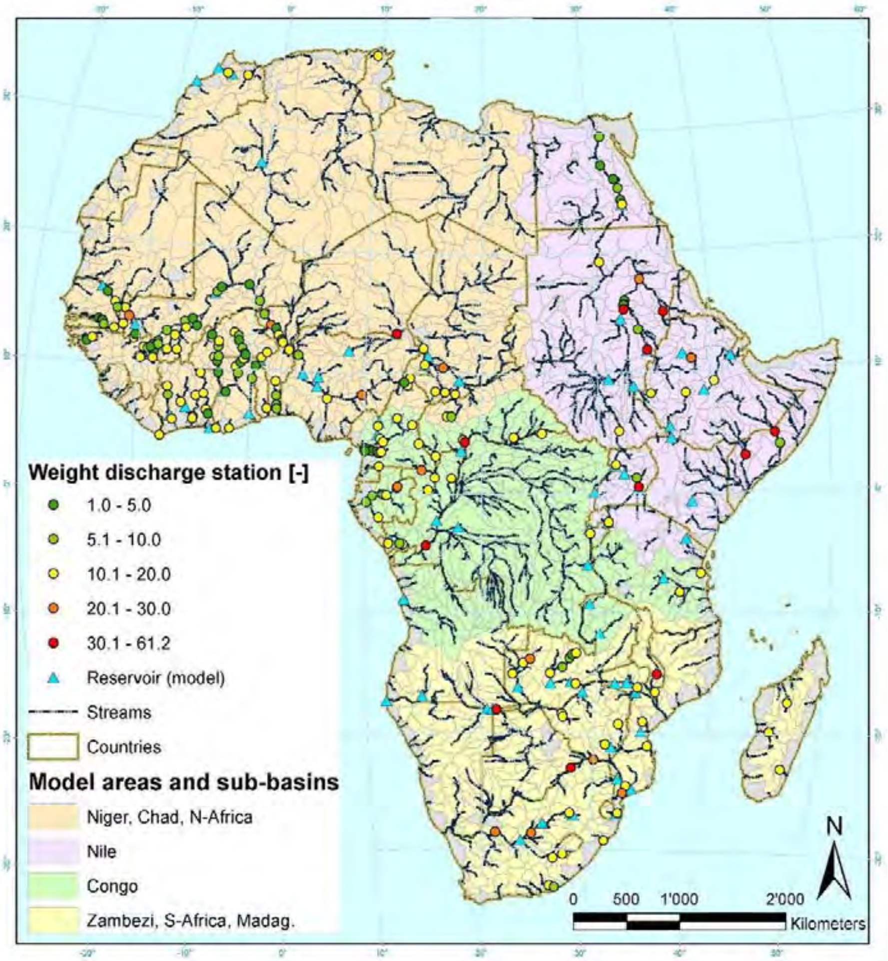


Figure 1. Location of the reservoirs included in the model and the four model areas used in the third calibration procedure. Also shown are the discharge stations and their associated weights in the calibration.

A major advantage of this efficiency criterion is that it ranges from 0 to 1, which compared to Nash-Sutcliff coefficient with a range of $-\infty$ to 1, ensures that in a multisite calibration the objective function is not governed by a single or a few badly simulated stations.

In order to obtain some knowledge of the uncertainty associated with the selected calibration method, three independent calibrations were performed, each having a different objective function. In the first procedure the objective function was formulated as the *n*-station-sum of Φ:

$$g = \sum_{i=1}^{n} \Phi_i \qquad (2)$$

In the second procedure, each station was weighted (*w*) depending on the contributing area *A* in km^2 and the number of monthly observations *s* used for calibration at a certain station *i* and the upstream stations *j*:

$$g = \sum_{i=1}^{n} \left(w_i \cdot \Phi_i \right) \qquad (3)$$

where

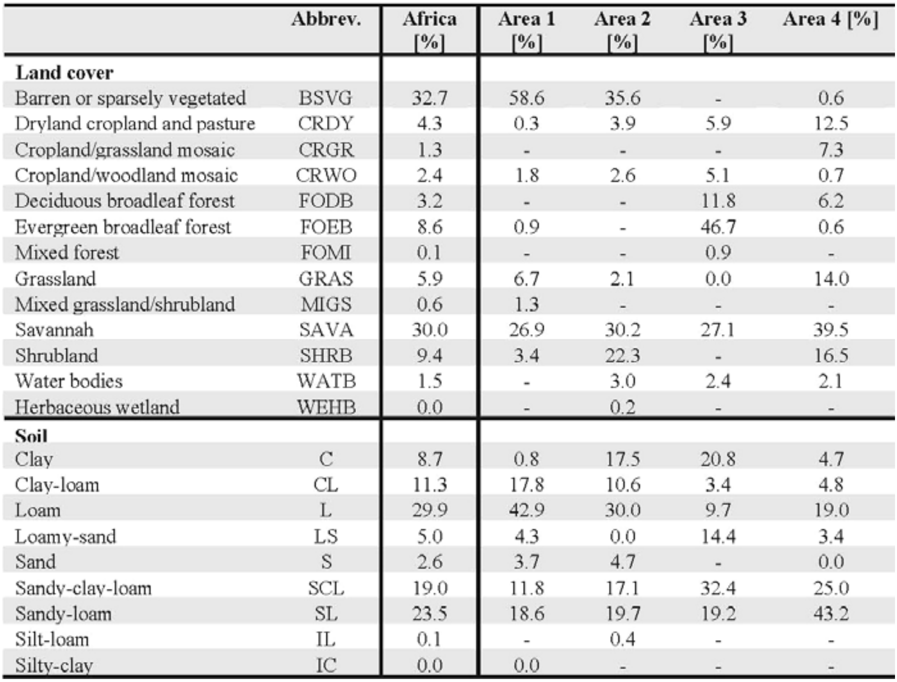
$$w_i = \sqrt{\frac{\left(A_i - \sum_{j=1}^{n} A_j \right) \cdot s_i}{s_i + \sum_{j=1}^{n} s_j}} \qquad (4)$$

The idea behind this weighting is that a runoff station with a long data series and a large watershed without further stations upstream provides more information for calibration and should have a larger weight than a station in a densely gaged area or a station with a short time series. The weights ranged from 1 to 61 for the furthest downstream station on Congo River at Kinshasa (Fig. 1).

In the third calibration procedure the region was divided into four modeling zones and each zone was calibrated independently. The four model areas basically delineated the large river basins in the continent (Fig. 1) and included: Area 1, Niger, Chad, and North Africa with an area of 11.8 million km^2 and 106 stations; Area 2, Nile with an area of 6.1 million km^2 and 27 stations; Area 3, Congo with an area of 4.8 million km^2 and 38 stations; and Area 4, Zambezi, South Africa, and Madagascar with an area of 5.1 million km^2 and 36 stations. The zoning was based on the intra-continental variations in the climate as well as the dominant land covers and soil types.

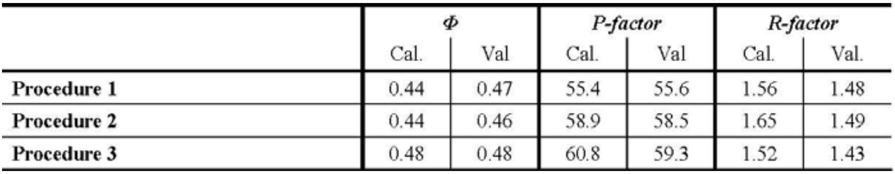
The choice of the parameters initially included in the calibration procedures was based on the experience gained in modeling West Africa (Schuol et al., 2008) for which a detailed literature-based pre-selection as well as a sensitivity analysis has been performed. Some of the selected SWAT parameters (e.g. curve number) are closely related to land cover, while some others (e.g. available water capacity, bulk density) are related to soil texture. For these parameters a separate value for each land cover/soil texture was selected, which increased the number of calibrated parameters substantially. The percentage of land cover and soil texture distribution within Africa and the four sub-regions is listed in Table 1. In the course of the iterative SUFI-2 calibration, not only the parameter ranges were narrowed, but also the number of parameters was decreased by excluding those that turned out to be insensitive.

Table 1. Soil texture and land cover distribution within the modeled African basin and the four subareas.



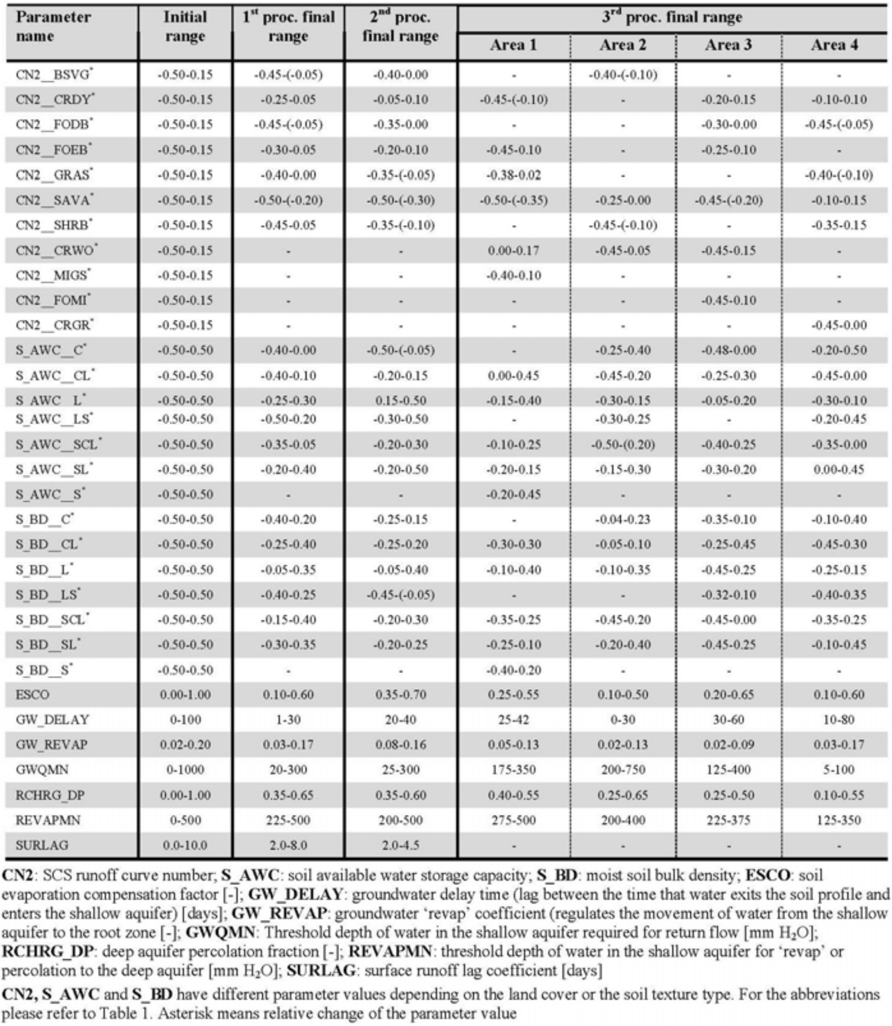
	Abbrev.	Africa [%]	Area 1 [%]	Area 2 [%]	Area 3 [%]	Area 4 [%]
Land cover						
Barren or sparsely vegetated	BSVG	32.7	58.6	35.6	-	0.6
Dryland cropland and pasture	CRDY	4.3	0.3	3.9	5.9	12.5
Cropland/grassland mosaic	CRGR	1.3	-	-	-	7.3
Cropland/woodland mosaic	CRWO	2.4	1.8	2.6	5.1	0.7
Deciduous broadleaf forest	FODB	3.2	-	-	11.8	6.2
Evergreen broadleaf forest	FOEB	8.6	0.9	-	46.7	0.6
Mixed forest	FOMI	0.1	-	-	0.9	-
Grassland	GRAS	5.9	6.7	2.1	0.0	14.0
Mixed grassland/shrubland	MIGS	0.6	1.3	-	-	-
Savannah	SAVA	30.0	26.9	30.2	27.1	39.5
Shrubland	SHRB	9.4	3.4	22.3	-	16.5
Water bodies	WATB	1.5	-	3.0	2.4	2.1
Herbaceous wetland	WEHB	0.0	-	0.2	-	-
Soil						
Clay	C	8.7	0.8	17.5	20.8	4.7
Clay-loam	CL	11.3	17.8	10.6	3.4	4.8
Loam	L	29.9	42.9	30.0	9.7	19.0
Loamy-sand	LS	5.0	4.3	0.0	14.4	3.4
Sand	S	2.6	3.7	4.7	-	0.0
Sandy-clay-loam	SCL	19.0	11.8	17.1	32.4	25.0
Sandy-loam	SL	23.5	18.6	19.7	19.2	43.2
Silt-loam	IL	0.1	-	0.4	-	-
Silty-clay	IC	0.0	0.0	-	-	-

Table 2. Final statistics for the three calibration procedures.



	Φ		*P-factor*		*R-factor*	
	Cal.	Val	Cal.	Val	Cal.	Val.
Procedure 1	0.44	0.47	55.4	55.6	1.56	1.48
Procedure 2	0.44	0.46	58.9	58.5	1.65	1.49
Procedure 3	0.48	0.48	60.8	59.3	1.52	1.43

Table 3. The SWAT model parameters included in the final calibration procedures and their initial and final ranges.



Parameter name	Initial range	1st proc. final range	2nd proc. final range	3rd proc. final range			
				Area 1	Area 2	Area 3	Area 4
CN2__BSVG*	-0.50-0.15	-0.45-(-0.05)	-0.40-0.00	-	-0.40-(-0.10)	-	-
CN2__CRDY*	-0.50-0.15	-0.25-0.05	-0.05-0.10	-0.45-(-0.10)	-	-0.20-0.15	-0.10-0.10
CN2__FODB*	-0.50-0.15	-0.45-(-0.05)	-0.35-0.00	-	-	-0.30-0.00	-0.45-(-0.05)
CN2__FOEB*	-0.50-0.15	-0.30-0.05	-0.20-0.10	-0.45-0.10	-	-0.25-0.10	-
CN2__GRAS*	-0.50-0.15	-0.40-0.00	-0.35-(-0.05)	-0.38-0.02	-	-	-0.40-(-0.10)
CN2__SAVA*	-0.50-0.15	-0.50-(-0.20)	-0.50-(-0.30)	-0.50-(-0.35)	-0.25-0.00	-0.45-(-0.20)	-0.10-0.15
CN2__SHRB*	-0.50-0.15	-0.45-0.05	-0.35-(-0.10)	-	-0.45-(-0.10)	-	-0.35-0.15
CN2__CRWO*	-0.50-0.15	-	-	0.00-0.17	-0.45-0.05	-0.45-0.15	-
CN2__MIGS*	-0.50-0.15	-	-	-0.40-0.10	-	-	-
CN2__FOMI*	-0.50-0.15	-	-	-	-	-0.45-0.10	-
CN2__CRGR*	-0.50-0.15	-	-	-	-	-	-0.45-0.00
S_AWC__C*	-0.50-0.50	-0.40-0.00	-0.50-(-0.05)	-	-0.25-0.40	-0.48-0.00	-0.20-0.50
S_AWC__CL*	-0.50-0.50	-0.40-0.10	-0.20-0.15	0.00-0.45	-0.45-0.20	-0.25-0.30	-0.45-0.00
S AWC L*	-0.50-0.50	-0.25-0.30	0.15-0.50	-0.15-0.40	-0.30-0.15	-0.05-0.20	-0.30-0.10
S_AWC__LS*	-0.50-0.50	-0.50-0.20	-0.30-0.50	-	-0.30-0.25	-	-0.20-0.45
S_AWC__SCL*	-0.50-0.50	-0.35-0.05	-0.20-0.30	-0.10-0.25	-0.50-(0.20)	-0.40-0.25	-0.35-0.00
S_AWC__SL*	-0.50-0.50	-0.20-0.40	-0.20-0.50	-0.20-0.15	-0.15-0.30	-0.30-0.20	0.00-0.45
S_AWC__S*	-0.50-0.50	-	-	-0.20-0.45	-	-	-
S_BD__C*	-0.50-0.50	-0.40-0.20	-0.25-0.15	-	-0.04-0.23	-0.35-0.10	-0.10-0.40
S_BD__CL*	-0.50-0.50	-0.25-0.40	-0.25-0.20	-0.30-0.30	-0.05-0.10	-0.25-0.45	-0.45-0.30
S_BD__L*	-0.50-0.50	-0.05-0.35	-0.05-0.40	-0.10-0.40	-0.10-0.35	-0.45-0.25	-0.25-0.15
S_BD__LS*	-0.50-0.50	-0.40-0.25	-0.45-(-0.05)	-	-	-0.32-0.10	-0.40-0.35
S_BD__SCL*	-0.50-0.50	-0.15-0.40	-0.20-0.30	-0.35-0.25	-0.45-0.20	-0.45-0.00	-0.35-0.25
S_BD__SL*	-0.50-0.50	-0.30-0.35	-0.20-0.25	-0.25-0.10	-0.20-0.40	-0.45-0.25	-0.10-0.45
S_BD__S*	-0.50-0.50	-	-	-0.40-0.20	-	-	-
ESCO	0.00-1.00	0.10-0.60	0.35-0.70	0.25-0.55	0.10-0.50	0.20-0.65	0.10-0.60
GW_DELAY	0-100	1-30	20-40	25-42	0-30	30-60	10-80
GW_REVAP	0.02-0.20	0.03-0.17	0.08-0.16	0.05-0.13	0.02-0.13	0.02-0.09	0.03-0.17
GWQMN	0-1000	20-300	25-300	175-350	200-750	125-400	5-100
RCHRG_DP	0.00-1.00	0.35-0.65	0.35-0.60	0.40-0.55	0.25-0.65	0.25-0.50	0.10-0.55
REVAPMN	0-500	225-500	200-500	275-500	200-400	225-375	125-350
SURLAG	0.0-10.0	2.0-8.0	2.0-4.5	-	-	-	-

CN2: SCS runoff curve number; **S_AWC**: soil available water storage capacity; **S_BD**: moist soil bulk density; **ESCO**: soil evaporation compensation factor [-]; **GW_DELAY**: groundwater delay time (lag between the time that water exits the soil profile and enters the shallow aquifer) [days]; **GW_REVAP**: groundwater 'revap' coefficient (regulates the movement of water from the shallow aquifer to the root zone [-]; **GWQMN**: Threshold depth of water in the shallow aquifer required for return flow [mm H_2O]; **RCHRG_DP**: deep aquifer percolation fraction [-]; **REVAPMN**: threshold depth of water in the shallow aquifer for 'revap' or percolation to the deep aquifer [mm H_2O]; **SURLAG**: surface runoff lag coefficient [days]

CN2, S_AWC and **S_BD** have different parameter values depending on the land cover or the soil texture type. For the abbreviations please refer to Table 1. Asterisk means relative change of the parameter value

To account for the uncertainty in the measured discharge data, a relative error of 10% (Butts et al., 2004) and an absolute measured discharge uncertainty of 0.1 $m^3 s^{-1}$ were included when calculating the *P-factor*. The absolute uncertainty was included in order to capture the dry periods of the many intermittent streams.

3. Results and Analysis

3.1 Model calibration

The three calibration procedures produced more or less similar results for the whole of Africa in terms of the values of the objective function F, the *P-factor*, and the *R-factor* (Table 2). The final parameter ranges in the three procedures, although different, were clustered around the same regions of the parameter space as shown in Table 3. This is typical of a non-uniqueness problem in the calibration of hydrologic models. In other words, if there is a single model that fits the measurements there will be many of them (Abbaspour, 2005; Abbaspour et al., 2007). Yang et al. (2008) used four different calibration procedures, namely GLUE, MCMC, ParaSol, and SUFI-2, for a watershed in China. All four produced very similar final results in terms of R^2, Nash-Sutcliffe (*NS*), *P-factor* and *R-factor* while converging to quite different final parameter ranges. In this study also, where only SUFI-2 was used with three different objective functions, all three methods resulted in different final parameter values.

In the following, we used the results of the third approach, because dividing Africa into four different hydrologic regions accounted for more of the spatial variability and resulted in a slightly better objective function value.

In order to provide an overview of the model performance in different regions, the *P-factor* (percent data bracketed) and the *R-factor* (a measure of the thickness of the 95PPU band) at all the stations across Africa are shown for both calibration and validation in Figure 2. In addition, the efficiency criteria, F, calculated based on the observed and the ‘best’ simulation (i.e. simulation with the largest value of the objective function), and also the *NS* coefficient are shown at each station. Overall, in calibration (validation), at 61% (55%) of the stations over 60% of the observed data were bracketed by the 95PPU and at 69% (70%) of the stations the R-factor was below 1.5. The F value was at 38% (37%) of the stations higher than 0.6 and the *NS* was at 23% (21%) of the stations higher than 0.7. In general, the model performance criteria were quite satisfactory for such a large-scale application. Some areas of poorly simulated runoffs were the Upper Volta, the East African Lakes region, and the Zambezi and Orange basin in the South of Africa. The reasons for this might be manifold and are not always clearly attributable. Of great importance are (1) over- or under-estimation in precipitation; (2) difficulties in simulating the outflow from lakes and wetlands; (3) insufficient data on the management of the reservoirs; (4) the effect of smaller lakes, reservoirs, wetlands, and irrigation projects that were not included; (5) simplifications by using dominant soil types and land cover classes in the subbasins; and (6) various water use abstractions, which were not included.

3.2 Quantification of blue and green water resources and their uncertainty ranges

Using the calibrated model, the annual and monthly blue water flow (water yield plus deep aquifer recharge), green water flow (actual evapotranspiration), and green water storage (soil water) were calculated for each subbasin and summed up for different countries or regions and also the whole continent. We compared our model results with other studies for blue water flow only, as to the best of our knowledge, the green water flow and storage were not explicitly quantified in the other models.

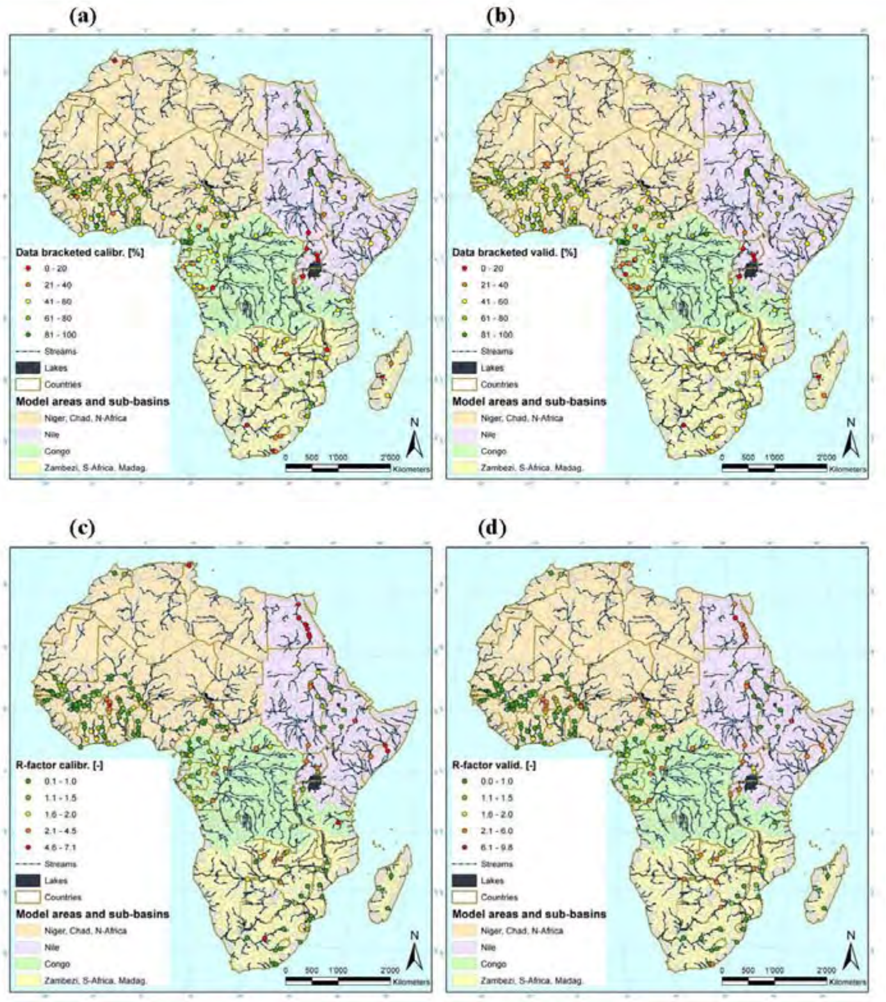


Figure 2 (this page and next page). The *P-factor* (a,b), the *R-factor* (c,d), the weighted coefficient of determination *Φ* (e,f), and the Nash-Sutcliff coefficient (g,h) of the calibration (a,c,e,g) and validation (b,d,f,h) at all 207 stations.

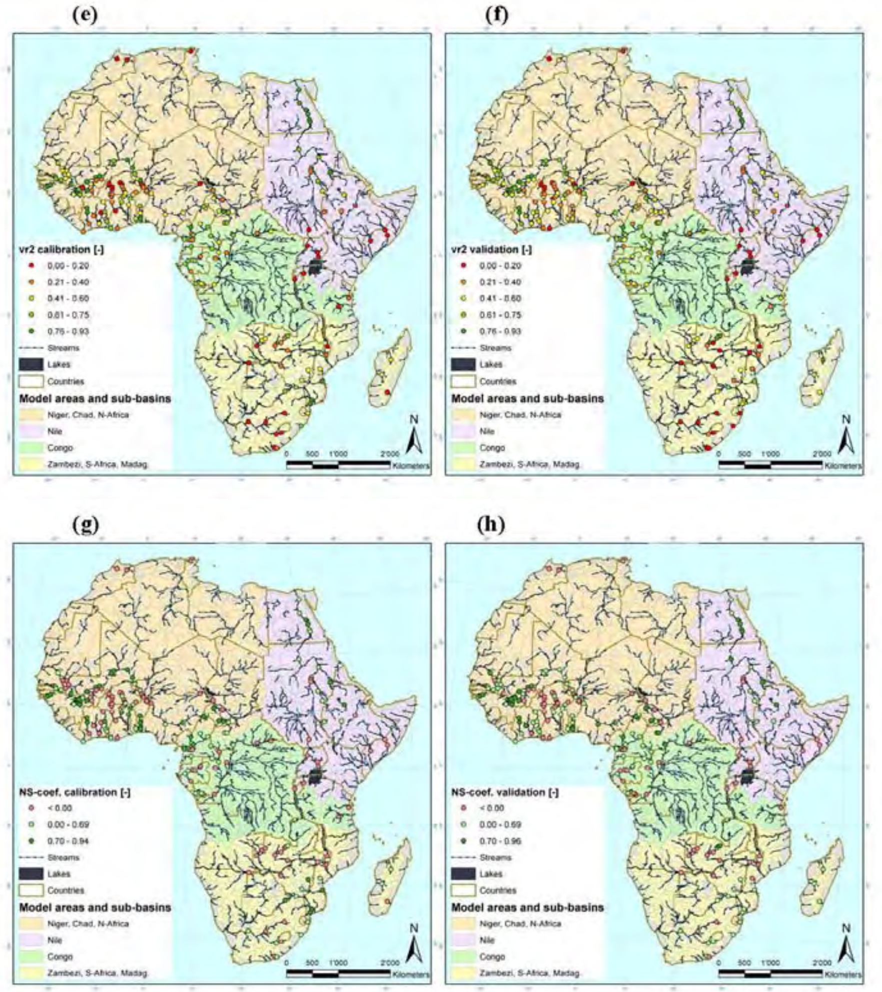


Figure 3 shows the estimated annual blue water for the whole African continent averaged over the period 1971-1995 and the results of ten other existing data-based (DB) or model-based (M) assessments. A direct one-to-one comparison of these values is not possible due to the different time periods and study-specific assumptions. The intent of this comparison is to give an overview of the differences in the existing numbers that are used in various advanced studies. The variation in different estimates indicates the uncertainty associated in such calculations, which is captured almost entirely in our prediction uncertainty as shown in Figure 3.

On the country basis, the simulated long-term annual (averaged over 1971-1995) blue water flow availability in mm a^{-1} was compared with two other global assessments: the FAO estimates (FAO, 2003) and the annual (averaged over 1961-1995) simulation from WaterGAP 2.1e model (Fig. 4). The latter has been produced for the

2005 Environmental Sustainability Index calculation (Esty et al., 2005). For the sake of clarity in illustration, the very high FAO values for Liberia (2,077 mm a^{-1}) and Sierra Leone (2,206 mm a^{-1}) were not included in the figure (limited y axis range).

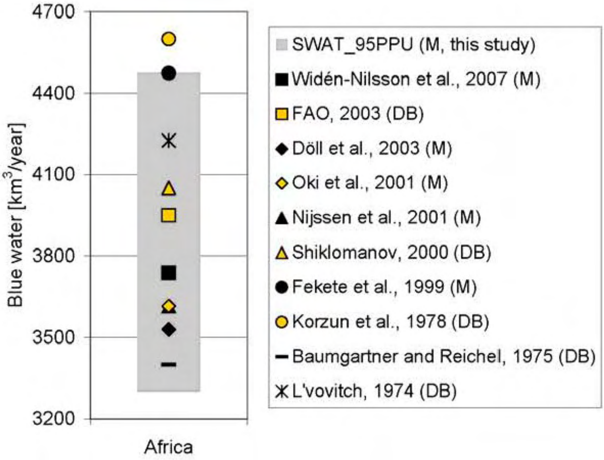


Figure 3. The SWAT 95PPU range of the 1971 to 1995 annual average blue water flow availability for the African continent compared with ten other existing assessments.

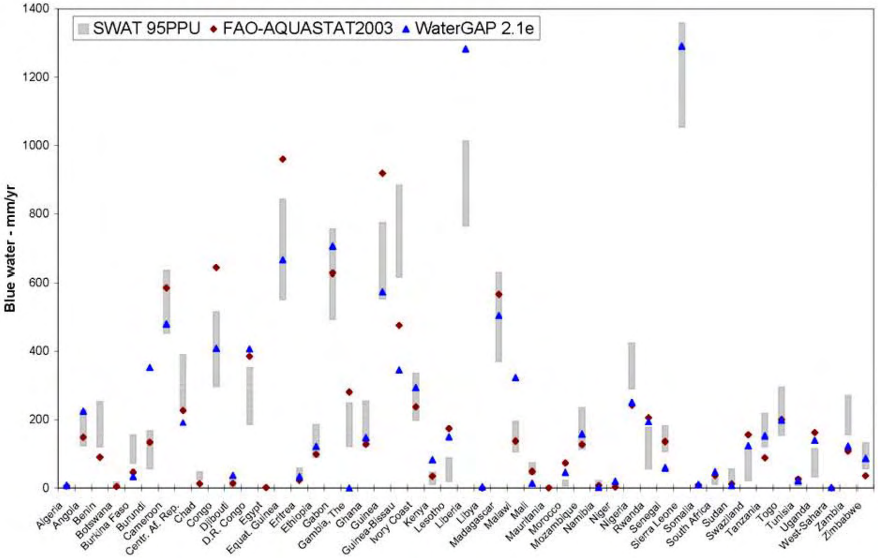
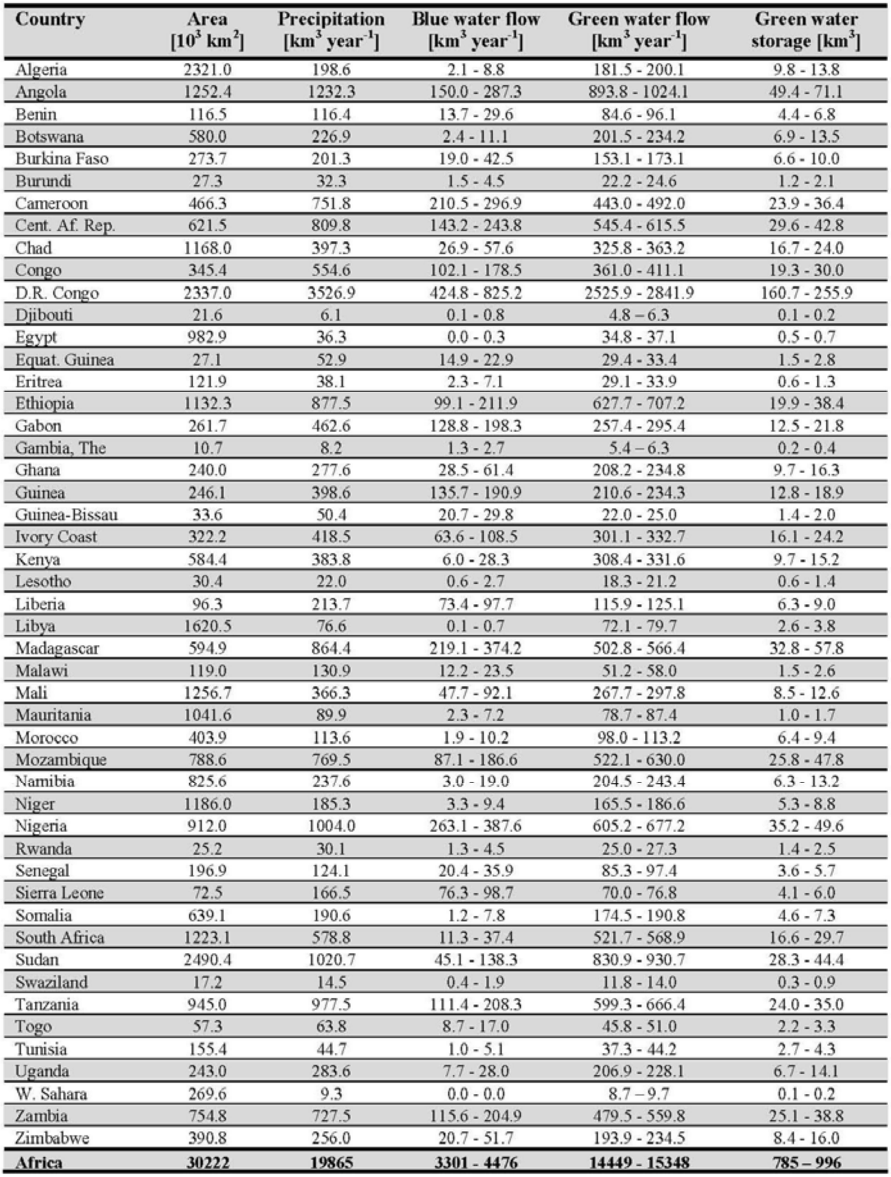


Figure 4. Comparison of the SWAT 95PPU ranges of the annual average (1971-1995) blue water flow availability in the African countries with the results from the FAO assessment and the WaterGAP model.

Table 4. The average precipitation (model input) and the 95PPU ranges for the components of freshwater availability in the African countries.



Country	**Area [10^3 km^2]**	**Precipitation [km^3 year^{-1}]**	**Blue water flow [km^3 year^{-1}]**	**Green water flow [km^3 year^{-1}]**	**Green water storage [km^3]**
Algeria	2321.0	198.6	2.1 - 8.8	181.5 - 200.1	9.8 - 13.8
Angola	1252.4	1232.3	150.0 - 287.3	893.8 - 1024.1	49.4 - 71.1
Benin	116.5	116.4	13.7 - 29.6	84.6 - 96.1	4.4 - 6.8
Botswana	580.0	226.9	2.4 - 11.1	201.5 - 234.2	6.9 - 13.5
Burkina Faso	273.7	201.3	19.0 - 42.5	153.1 - 173.1	6.6 - 10.0
Burundi	27.3	32.3	1.5 - 4.5	22.2 - 24.6	1.2 - 2.1
Cameroon	466.3	751.8	210.5 - 296.9	443.0 - 492.0	23.9 - 36.4
Cent. Af. Rep.	621.5	809.8	143.2 - 243.8	545.4 - 615.5	29.6 - 42.8
Chad	1168.0	397.3	26.9 - 57.6	325.8 - 363.2	16.7 - 24.0
Congo	345.4	554.6	102.1 - 178.5	361.0 - 411.1	19.3 - 30.0
D.R. Congo	2337.0	3526.9	424.8 - 825.2	2525.9 - 2841.9	160.7 - 255.9
Djibouti	21.6	6.1	0.1 - 0.8	4.8 – 6.3	0.1 - 0.2
Egypt	982.9	36.3	0.0 - 0.3	34.8 - 37.1	0.5 - 0.7
Equat. Guinea	27.1	52.9	14.9 - 22.9	29.4 - 33.4	1.5 - 2.8
Eritrea	121.9	38.1	2.3 - 7.1	29.1 - 33.9	0.6 - 1.3
Ethiopia	1132.3	877.5	99.1 - 211.9	627.7 - 707.2	19.9 - 38.4
Gabon	261.7	462.6	128.8 - 198.3	257.4 - 295.4	12.5 - 21.8
Gambia, The	10.7	8.2	1.3 - 2.7	5.4 – 6.3	0.2 - 0.4
Ghana	240.0	277.6	28.5 - 61.4	208.2 - 234.8	9.7 - 16.3
Guinea	246.1	398.6	135.7 - 190.9	210.6 - 234.3	12.8 - 18.9
Guinea-Bissau	33.6	50.4	20.7 - 29.8	22.0 - 25.0	1.4 - 2.0
Ivory Coast	322.2	418.5	63.6 - 108.5	301.1 - 332.7	16.1 - 24.2
Kenya	584.4	383.8	6.0 - 28.3	308.4 - 331.6	9.7 - 15.2
Lesotho	30.4	22.0	0.6 - 2.7	18.3 - 21.2	0.6 - 1.4
Liberia	96.3	213.7	73.4 - 97.7	115.9 - 125.1	6.3 - 9.0
Libya	1620.5	76.6	0.1 - 0.7	72.1 - 79.7	2.6 - 3.8
Madagascar	594.9	864.4	219.1 - 374.2	502.8 - 566.4	32.8 - 57.8
Malawi	119.0	130.9	12.2 - 23.5	51.2 - 58.0	1.5 - 2.6
Mali	1256.7	366.3	47.7 - 92.1	267.7 - 297.8	8.5 - 12.6
Mauritania	1041.6	89.9	2.3 - 7.2	78.7 - 87.4	1.0 - 1.7
Morocco	403.9	113.6	1.9 - 10.2	98.0 - 113.2	6.4 - 9.4
Mozambique	788.6	769.5	87.1 - 186.6	522.1 - 630.0	25.8 - 47.8
Namibia	825.6	237.6	3.0 - 19.0	204.5 - 243.4	6.3 - 13.2
Niger	1186.0	185.3	3.3 - 9.4	165.5 - 186.6	5.3 - 8.8
Nigeria	912.0	1004.0	263.1 - 387.6	605.2 - 677.2	35.2 - 49.6
Rwanda	25.2	30.1	1.3 - 4.5	25.0 - 27.3	1.4 - 2.5
Senegal	196.9	124.1	20.4 - 35.9	85.3 - 97.4	3.6 - 5.7
Sierra Leone	72.5	166.5	76.3 - 98.7	70.0 - 76.8	4.1 - 6.0
Somalia	639.1	190.6	1.2 - 7.8	174.5 - 190.8	4.6 - 7.3
South Africa	1223.1	578.8	11.3 - 37.4	521.7 - 568.9	16.6 - 29.7
Sudan	2490.4	1020.7	45.1 - 138.3	830.9 - 930.7	28.3 - 44.4
Swaziland	17.2	14.5	0.4 - 1.9	11.8 - 14.0	0.3 - 0.9
Tanzania	945.0	977.5	111.4 - 208.3	599.3 - 666.4	24.0 - 35.0
Togo	57.3	63.8	8.7 - 17.0	45.8 - 51.0	2.2 - 3.3
Tunisia	155.4	44.7	1.0 - 5.1	37.3 - 44.2	2.7 - 4.3
Uganda	243.0	283.6	7.7 - 28.0	206.9 - 228.1	6.7 - 14.1
W. Sahara	269.6	9.3	0.0 - 0.0	8.7 – 9.7	0.1 - 0.2
Zambia	754.8	727.5	115.6 - 204.9	479.5 - 559.8	25.1 - 38.8
Zimbabwe	390.8	256.0	20.7 - 51.7	193.9 - 234.5	8.4 - 16.0
Africa	**30222**	**19865**	**3301 - 4476**	**14449 - 15348**	**785 – 996**

Also not shown in the figure are the values for six African countries for which WaterGAP produced negative values (as it considers evaporation losses from lakes and wetlands even though they depend on inflow from other countries). In general, the large differences between FAO and WaterGAP estimates indicate the uncertainty in the country-based blue water estimates. Overall, a large number of these estimates fell within our prediction uncertainties. Although the calculated uncertainties may appear large, we maintain that the actual uncertainty may indeed be even larger because the coverage of the measured data in the 95PPU was in some areas relatively small (small *P-factor*). To decrease model uncertainty, a better description of the climate data, reservoir management, and water use would be essential.

In Table 4 the annual average water availability in each country is shown in $km^3 a^{-1}$. The subbasin-based precipitation and the 95PPU ranges for the blue water flow, green water flow, and the green water storage were aggregated to obtain country- and then continental-based values. The uncertainties (95PPU) in green water flow estimates were generally smaller than those of the blue water flow or green water storage because of its sensitivity to fewer parameters. It should be noted that the modeled green water storage was solely calibrated indirectly as there were no soil moisture observations. This study explored the possibility of using data from remote sensing satellites, but so far only found monitored surface soil moisture (top few centimeters) in areas without forest or sand dunes. The relationship between these values and that of the root zone soil moisture is still unclear (Wagner et al., 2003, 2007).

Next to the above annual continental and country-based estimates, this study also provides monthly time series of freshwater components for each subbasin with valuable information on both spatial and temporal distributions. Such information has not been available at this detail for the whole continent. In Figures 5a-5c the long-term average annual freshwater components are shown in each subbasin. These figures show the local (sub-country) differences especially in large countries with partly (semi-)arid climate. In areas like North Africa, the south of Chad (Chari basin), or the Limpopo basin in the southeast of Africa, with scarce blue water availability, there are considerable green water resources sustaining ecosystems, rainfed agriculture and ultimately people's lives.

Despite the spatial distribution, the intra- and inter-annual variability of the freshwater availability is of great importance. Figure 6 shows the coefficient of variation (CV) of the 1971-1995 annual values in each subbasin for the blue water flow, the green water flow and the green water storage. In general the CV, which is an indicator for the reliability of a freshwater source, varied noticeably within the continent and was the lowest for the green water flow, while it was the largest for the blue water flow. The reason for this is that the supply of water for evapotranspiration is limited by soil's capacity to deliver water to the roots. This capacity is within a narrow range between soil's field capacity and wilting point. The inter-annual variability of the blue water flow is especially large in the Sahel, at the Horn of Africa, and in the southern part of Africa, areas which are known for recurring severe droughts.

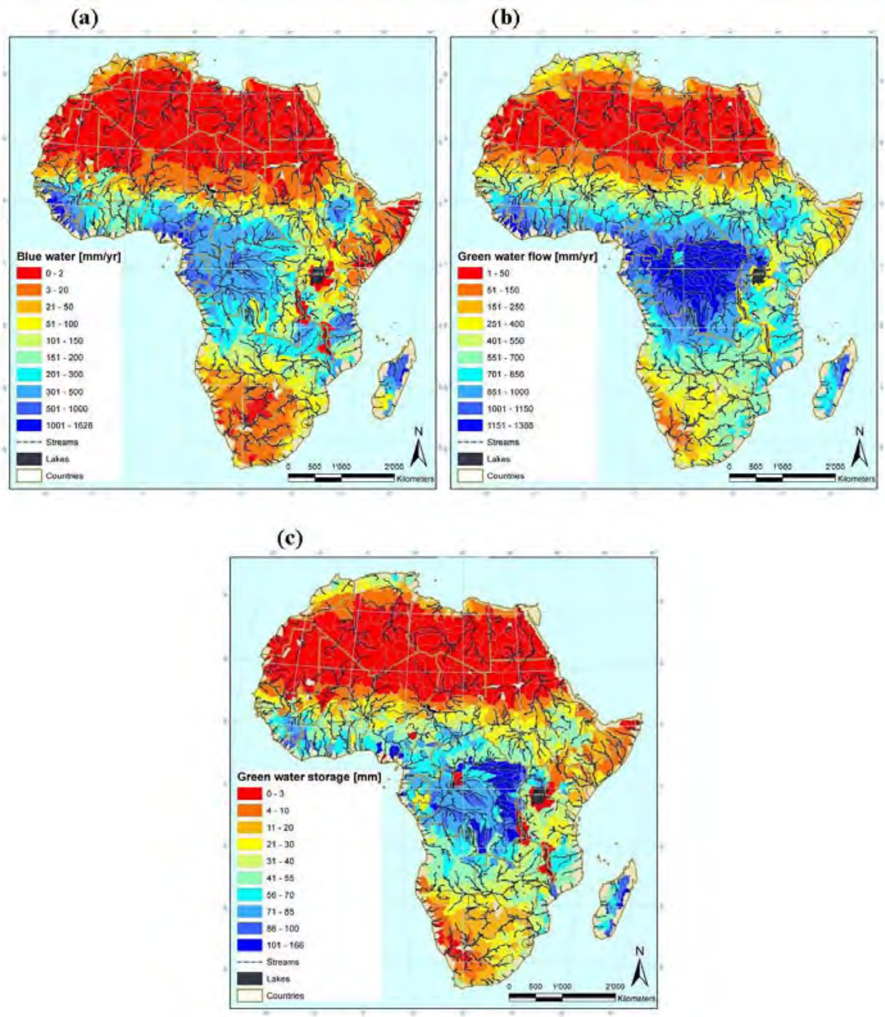


Figure 5. The 1971 to 1995 annual average (a) blue water flow, (b) green water flow, and (c) green water storage in all 1,496 modeled subbasins in Africa.

The intra-annual variability, presented by the 1971-1995 average monthly 95PPU bands of the blue water flow, the green water flow and the green water storage is shown in Figure 7 for three countries as an example. These countries, all with different climatic conditions, are Niger in Western Africa, Zimbabwe in the Southern Africa, and Gabon in Central Africa with an annual average precipitation of 185 mm, 256 mm, and 463 mm, respectively. In order to see the relation between the freshwater components and the water input, the figures also include the average monthly precipitation. All values are shown in mm or mm month^{-1}

and thus can be directly compared. The trends in blue water flow in different countries become clearly apparent. Niger and Zimbabwe, in particular, show large uncertainties for the wet months. It should be noted that the reported uncertainties in the average monthly values combine both modeling uncertainties as well as natural variability. Hence the reliability of the water resources decreases as the uncertainties increase. The green water storage can potentially benefit the agriculture in months with little or without precipitation.

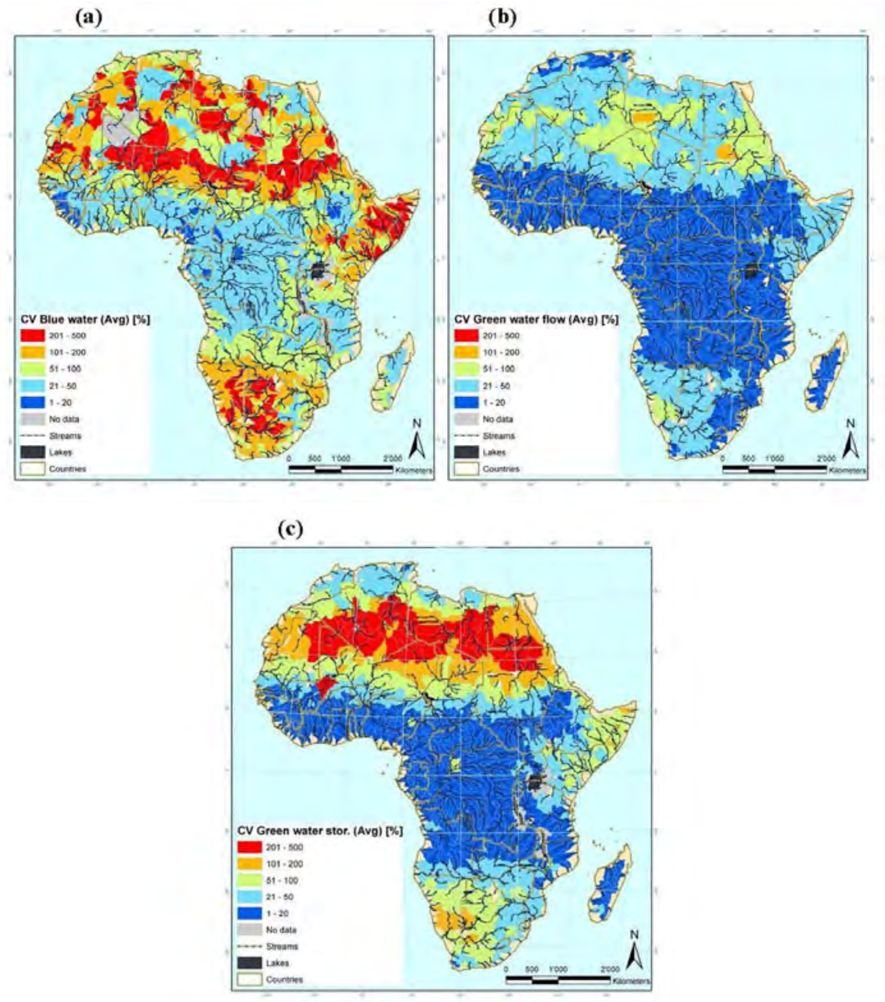


Figure 6. The coefficient of variation (CV) of the average of the 95PPU ranges (Avg) of the 1971 to 1995 modeled annual values of the (a) blue water flow, (b) green water flow, and (c) green water storage in each subbasin.

In Niger the soil water storage is depleted for about half of the year, while in Gabon this volume persists much longer within the (much shorter) dry period. This information is quite helpful in planning cropping season and helps to model scenarios of changing cropping seasons and patterns and its impacts on green and blue water flow and storage.

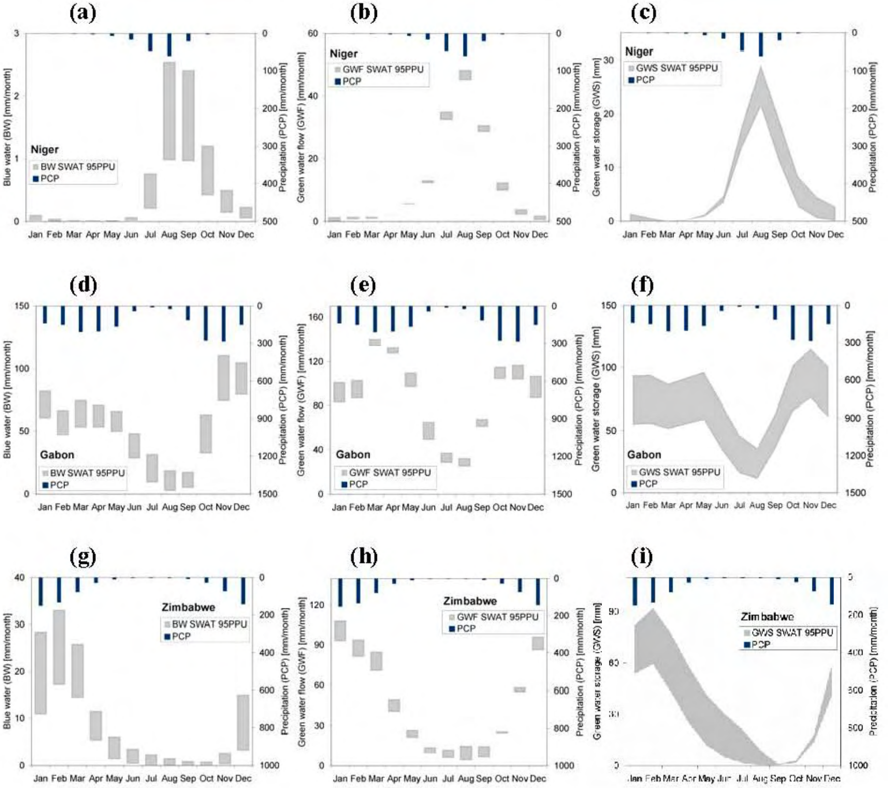


Figure 7. Average (1971-1995) monthly 95PPU ranges of the blue water flow (a,d,g), the green water flow (b,e,h), and the green water storage (c,f,i) in the countries Niger (a-c), Gabon (d-f), and Zimbabwe (g-i).

It should be pointed out that for large countries, variations can be substantial across subbasins. For example, in Niger the country-based annual average blue water flow availability is 3 to 8 mm a^{-1} but some subbasins in the south of the country provide about 10 times more. While not shown in further detail, the model can provide monthly information of the freshwater components for each of the 1,496 subbasins in Africa and they will be published in a special report.

4. Implications of the Model Results

4.1 Blue water scarcity indicators considering uncertainty

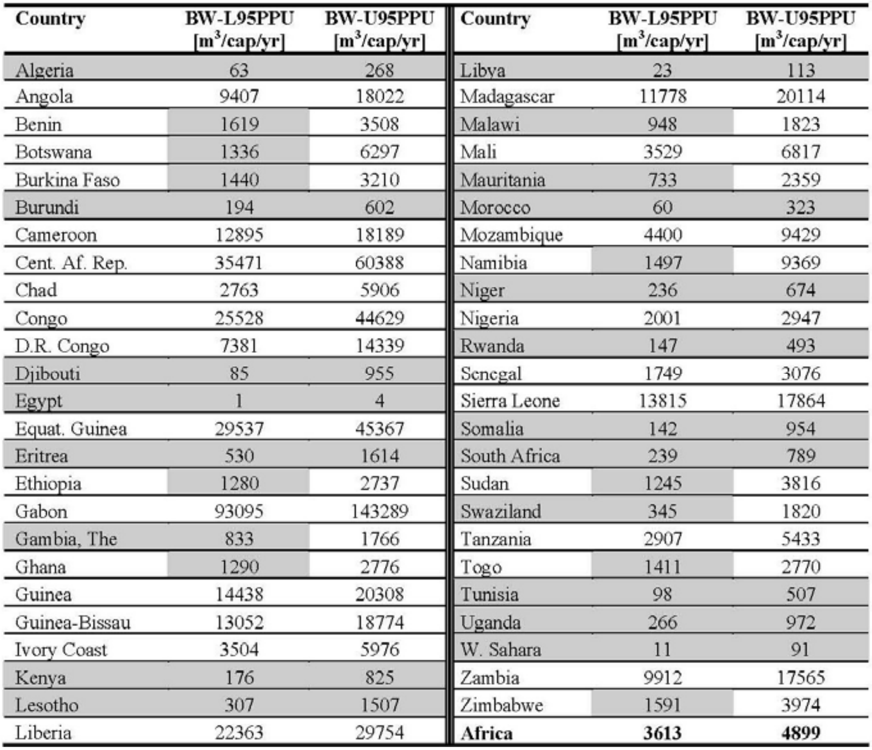
The model results of the temporal and spatial variations of the freshwater availability components and their uncertainty bands can be used in global and national water planning and management, in advanced studies concerning the water and food security, virtual water flow, and effects of land use and climate change (UNESCO, 2006). This study briefly presents the use of the model results for water scarcity analysis. While there exist a large number of water scarcity indicators, one of the most widely used and accepted is the water stress threshold, defined as 1,700 m^3 $capita^{-1}$ a^{-1} (Falkenmark and Widstrand, 1992). This scarcity index does not indicate that water is scarce for domestic purposes, but rather for irrigation and thus for food production (Rijsberman, 2006). Yang et al. (2003) have found that below a threshold of about 1,500 m^3 $capita^{-1}$ a^{-1} the cereal import in a country inversely correlates to its renewable water resources. Below this value different degrees of water stresses (extreme stress: <500 m^3 $capita^{-1}$ a^{-1}, high stress: <1,000 m^3 $capita^{-1}$ a^{-1}) can be defined (Falkenmark et al., 1989). A value between 1,700 and 4,000 m^3 $capita^{-1}$ a^{-1} is considered as just adequate (Revenga et al., 2000). Vörösmarty et al. (2000) have found in a global study that the number of people exposed to high water stress (defined as withdrawal-to-availability-ratio larger than 0.4) is three times larger if the analysis is based on geospatial data at a resolution of 50 km instead of using national estimates. According to Rijsberman (2006) one of the limitations of water scarcity indicators are the annual, national averages that hide important scarcity at monthly and regional scales.

We computed the water availability per capita and water stress indicators not only for each country but also for each of the 1,496 subbasins. The population estimates were taken from the Center for International Earth Science Information Network's (CIESIN) Gridded Population of the World (GPW, version 3, http://sedac.ciesin.columbia.edu/gpw). The data are for the year 2005 and has a spatial resolution of 2.5 arcminute, which we aggregated for each subbasin. In order to address uncertainty of future water stress estimates, Alcamo et al. (2007) computed and compared globally three different indicators of water stress (withdrawals-to availability ratio greater than 0.4, water availability per capita less than 1,000 m^3 a^{-1}, and consumption to-Q90 ratio greater than 1). Although there was a large overlap in the estimated areas with severe water stress, in many regions the three indicators disagreed. Overall, using the water availability per capita indicator resulted in the lowest values of affected area and number of people with severe water stress. In this study we address uncertainty by calculating the per capita water availability by using the lower (L95PPU), the upper (U95PPU) and the average (Avg) 95PPU values of the blue water flow during the simulation time period.

Looking at the water scarcity on a country basis, the use of the L95PPU blue water flow values led to 29 countries with water stress (<1,700 m^3 $capita^{-1}$ a^{-1}), while the use of the U95PPU values led to merely 16 affected countries (Table 5).

Taking the average of the 95PPU range resulted in 20 vulnerable countries. In countries where both L95PPU and U95PPU result in the same conclusion, the risk situation is quite clear. However, in countries such as Burkina Faso, Ethiopia, Ghana, Sudan, and Zimbabwe where only the use of the L95PPU blue water flow values signalizes water scarcity, the situation demands more detailed studies. One can conclude that in many of these countries, and in fact in larger countries in general, it might be of great importance to analyze the water scarcity in a spatially distributed manner on a sub-country level rather than consider the country as a whole.

Table 5. The country-based per capita blue water flow (BW) availability considering the L95PPU and the U95PPU value of the annual average (1971-1995) BW and the population in the year 2005. Gray shaded cells indicate water stress (< 1,700 $m^3cap^{-1}yr^{-1}$). The shading of the country name cells correspond to the estimated water stress based on the average 95PPU value of the blue water flow availability.



Country	BW-L95PPU [m^3/cap/yr]	BW-U95PPU [m^3/cap/yr]	Country	BW-L95PPU [m^3/cap/yr]	BW-U95PPU [m^3/cap/yr]
Algeria	63	268	Libya	23	113
Angola	9407	18022	Madagascar	11778	20114
Benin	1619	3508	Malawi	948	1823
Botswana	1336	6297	Mali	3529	6817
Burkina Faso	1440	3210	Mauritania	733	2359
Burundi	194	602	Morocco	60	323
Cameroon	12895	18189	Mozambique	4400	9429
Cent. Af. Rep.	35471	60388	Namibia	1497	9369
Chad	2763	5906	Niger	236	674
Congo	25528	44629	Nigeria	2001	2947
D.R. Congo	7381	14339	Rwanda	147	493
Djibouti	85	955	Senegal	1749	3076
Egypt	1	4	Sierra Leone	13815	17864
Equat. Guinea	29537	45367	Somalia	142	954
Eritrea	530	1614	South Africa	239	789
Ethiopia	1280	2737	Sudan	1245	3816
Gabon	93095	143289	Swaziland	345	1820
Gambia, The	833	1766	Tanzania	2907	5433
Ghana	1290	2776	Togo	1411	2770
Guinea	14438	20308	Tunisia	98	507
Guinea-Bissau	13052	18774	Uganda	266	972
Ivory Coast	3504	5976	W. Sahara	11	91
Kenya	176	825	Zambia	9912	17565
Lesotho	307	1507	Zimbabwe	1591	3974
Liberia	22363	29754	**Africa**	**3613**	**4899**

The computed blue water flow availability per capita in each of the 1,496 sub-basins considering the extremities of the 95PPU range is shown in Figure 8. In critical regions like the Sahel, the South and the East of Africa, the use of the L95PPU and the U95PPU, respectively, lead to quite different assessments of the water scarcity-affected regions and ultimately to the number of the affected people living there.

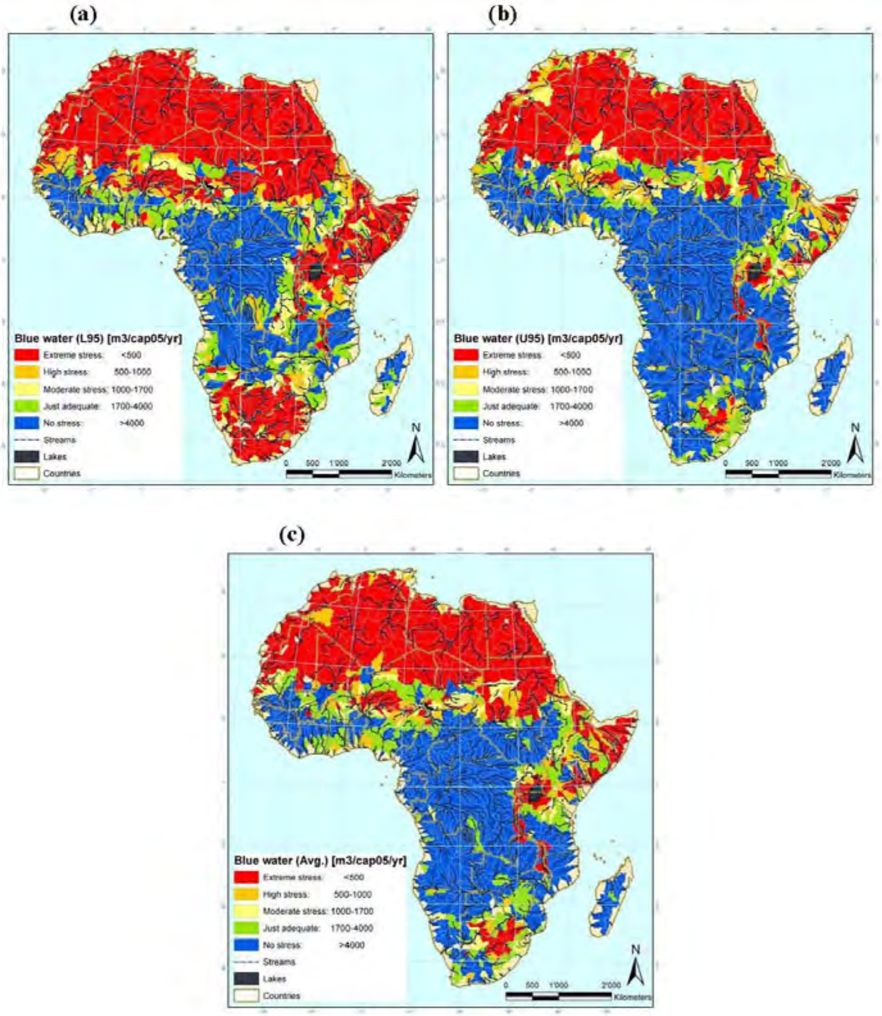


Figure 8. The water scarcity in each modeled African subbasin represented by the modeled 1971 to 1995 annual average blue water flow availability per capita (using population of 2005) using (a) the lower (L95), (b) the upper (U95), and (c) the average (Avg) value of the 95PPU range.

4.2 Model-based uncertainty and natural variation in green water storage

Irrigation, water transfer, and virtual water transfer on a regional, national, and international level are common measures to deal with regional blue water scarcity.

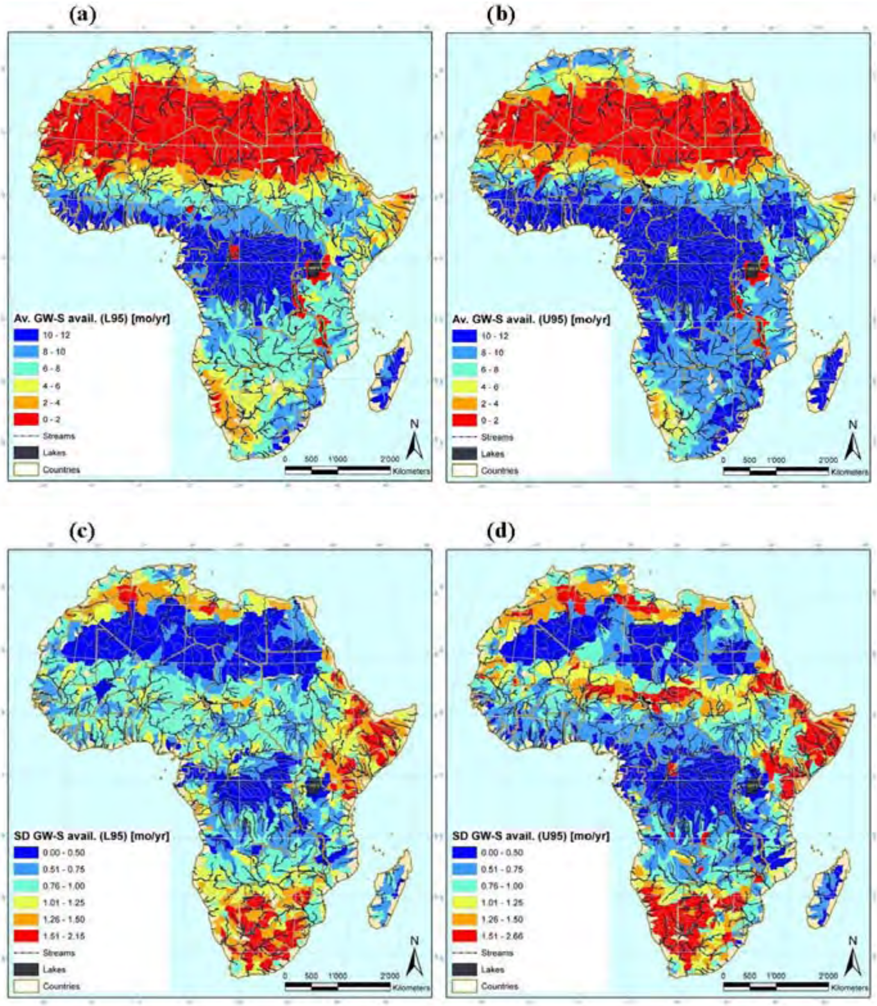


Figure 9. The 1971-1995 average (Avg) (a,b) and standard deviation (SD) (c,d) of the number of months per year where the green water storage (GW-S) is not depleted using the lower (L95) and the upper (U95) value of the 95PPU range.

A better use of the green water, through a more efficient rainfed production, can also partially overcome regional water short falls in countries like Nigeria or South Africa. For the rainfed agriculture, the average (1971-1995) number of months per year where soil water is available (defined as >1 mm m^{-1}) is of utmost importance. This is presented on a subbasin level in Figures 9a and 9b.

Because of the model-inherent uncertainties and natural variability, the border of the areas where rainfed agriculture can be realized can shift remarkably. The standard deviation (SD) of the months per year without depleted green water storage is shown for the 1971-1995 period in Figures 9c and 9d. The areas with a high SD (e.g. the Sahel regions in Chad and Niger, Horn of Africa, South of Africa) indicate unreliable green water storage availability that often leads to reduced crop yield and thus potentially to frequent famines. These areas must develop irrigation systems or alternative cropping practices for a sustainable agriculture.

5. Summary and Conclusion

In this study the well-established semi-distributed model SWAT, in combination with the GIS interface ArcSWAT and SUFI-2 calibration procedure, was successfully applied to quantify the freshwater availability for the whole African continent at a detailed subbasin level and monthly basis with uncertainty analysis. Only globally readily available data sets and information were used for the model setup as well as the model calibration and validation. Within the multisite and multivariable SUFI-2 parameter optimization and uncertainty analysis procedure, three different approaches were performed, which provided valuable insight into the effect of the calibration procedure on model results. The final model results for the freshwater availability components, blue water flow, green water flow, and green water storage were presented at different spatial (continent, countries, and subbasins) and temporal (annual and monthly) resolutions. Particular attention was paid to clearly quantify and display the 95% prediction uncertainty of the outputs, which turned out to be quite large in some cases. The effect of considering these uncertainty estimates in advanced studies was shown for the computation of water scarcity indicators for each of the 1,496 subbasins.

Many of the difficulties and limitations within this continental modeling study were data related and resulted from, among others, (1) limited and unevenly distributed rain gages and discharge stations with varying time series lengths, (2) limited globally available knowledge of the attributes and especially the management of the reservoirs, and (3) lack of data on soil moisture and/or deep aquifer percolation, which made a desirable calibration/validation of these components impossible. Technical modeling problems in need of further research and improvement were related to the inclusion of the lakes and their outflow to rivers. These resulted in poorer model results in the area of the great lakes of East Africa. This study did not include water use and especially irrigation in the model. Compared to other continents like Asia, this was thought to be of lesser importance in this study.

Some interesting further development would be to (1) make use of the model results in advanced studies on climate change, water and food security, as well as virtual water trade, which, as it has been pointed out by Yang and Zehnder (2007), are in great need of the estimates of spatially and temporally differentiated freshwater components; (2) further improve the African model as new data becomes available (e.g. remote sensing data); and (3) model the freshwater availability in the other continents, in order to finally obtain a global picture.

Overall, this study provided significant insights into continental freshwater availability on a subbasin level and with a monthly time step. This information was very useful for developing an overview of the actual water resources status and helped to spot regions where an in-depth analysis may be necessary. As shown, the inherent uncertainties need to be considered, before general conclusions are drawn.

Acknowledgment

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References

Abbaspour, K.C. 2005. Calibration of hydrologic models: When is a model calibrated?, MODSIM 2005 International Congress on Modelling and Simulation Proceedings, 2449-2455.

Abbaspour, K.C., J. Yang, I. Maximov, R. Siber, K. Bogner, J. Mieleitner, J. Zobrist, and R. Srinivasan. 2007a. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT, *J. Hydrol.*, *333*, 413-430.

Abbaspour, K.C., J. Yang, M. Vejdani, and S. Haghighat. 2007b. SWAT-CUP: calibration and uncertainty programs for SWAT, 4th International SWAT Conference Proceedings, in press.

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rosch, and S. Siebert (2003). Development and testing of the WaterGAP 2 global model of water use and availability, *Hydrol. Sci. J.-J. Sci. Hydrol.*, *48*(3), 317-337.

Alcamo, J., M. Flörke, and M. Märker. 2007. Future long-term changes in global water resources driven by socio-economic and climatic changes, *Hydrol. Sci. J.-J. Sci. Hydrol.*, *52*(2), 247-275.

Arnell, N.W. (1999). Climate change and global water resources, *Glob. Environ. Change - Human Policy Dimens.*, *9*, S31-S49.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modeling and assessment - Part 1: Model development, *J. Am. Water Resour. Assoc.*, *34*(1), 73-89.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and P.M. Allen. 1999. Continental scale simulation of the hydrologic balance, *J. Am. Water Resour. Assoc.*, *35*(5), 1037-1051.

Baumgartner, A., and E. Reichel. 1975. *The world water balance*, 182pp., Elsevier, Amsterdam.

Beven, K, and A. Binley. 1992. The future of distributed models - model calibration and uncertainty prediction, *Hydrol. Process.*, *6*(3), 279-298.

Butts, M.B., J.T. Payne, M. Kristensen, and H. Madsen. 2004. An evaluation of the impact of model structure on hydrological modelling uncertainty for streamflow simulation, *J. Hydrol.*, *298*(1-4), 242-266.

Di Luzio, M., R. Srinivasan, and J.G. Arnold. 2001. *ArcView Interface for SWAT2000 - User's Guide*, Blackland Research Center, Texas Agricultural Experiment Station and Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, Temple, Texas.

Döll, P., F. Kaspar, and B. Lehner. 2003. A global hydrological model for deriving water availability indicators: Model tuning and validation, *J. Hydrol.*, *270*(1-2), 105-134.

Esty, D.C., M. Levy, T. Srebotnjak, and A. de Sherbinin. 2005. *2005 Environmental Sustainability Index: Benchmarking National Environmental Stewardship*, Yale Center for Environmental Law & Policy, New Haven.

Falkenmark, M. 1989. The massive water scarcity now threatening Africe - Why isn't it being addressed?, *AMBIO*, *18*(2), 112-118.

Falkenmark, M., and J. Rockström. 2006. The new blue and green water paradigm: Breaking new ground for water resources planning and management, *J. Water Resour. Plan. Manage.-ASCE*, *132*(3), 129-132.

Falkenmark, M., and C. Widstrand. 1992. Population and water resources: A delicate balance, *Popul. Bull.*, *47*(3), 1-36.

Falkenmark, M., J. Lundquist, and C. Widstrand. 1989. Macro-scale water scarcity requires micro-scale approaches: Aspects of vulnerability in semi-arid development, *Nat. Resour. Forum*, *13*, 258-267.

FAO (Food and Agriculture Organization). 1995. The digital soil map of the world and derived soil properties, (CD-ROM), Version 3.5, Rome.

FAO (Food and Agriculture Organization). 2003. Review of the world water resources by country, *Water Report Nr. 23*, Rome.

Fekete, B.M., C.J. Vörösmarty, and W. Grabs. 1999. Global composite runoff fields of observed river discharge and simulated water balances, *Report No. 22*, Global Runoff Data Centre, Koblenz, Germany.

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

Gerten, D., S. Schaphoff, U. Haberlandt, W. Lucht, and S. Sitch. 2004. Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model, *J. Hydrol.*, *286*, 249-270.

Gerten, D., H. Hoff, A. Bondeau, W. Lucht, P. Smith, and S. Zaehle. 2005. Contemporary "green" water flows: Simulations with a dynamic global vegetation and water balance model, *Phys. Chem. Earth*, *30*, 334-338.

Güntner A., J. Stuck, S. Werth, P. Döll, K. Verzano, and B. Merz. 2007. A global analysis of temporal and spatial variations in continental water storage, *Water Resour. Res.*, *43(5)*, W05416.

Islam, M.S., T. Oki, S. Kanae, N. Hanasaki, Y. Agata, and K. Yoshimura. 2007. A grid-based assessment of global water scarcity including virtual water trading, *Water Resour. Manage.*, *21*, 19-33.

Korzun, V.I., A.A. Sokolow, M.I. Budyko, K.P. Voskresensky, G.P. Kalinin, A.A. Konoplyanstev, E.S. Korotkevich, P.S. Kuzin, and M.I. L'vovich (Eds.). 1978. *World water balance and water resources of the earth*, UNESCO, Paris.

Krause, P., D.P. Boyle, and F. Bäse. 2005. Comparison of different efficiency criteria for hydrological model assessment, *Adv. Geosci.*, *5*, 89-97.

Lehner, B., and P. Döll. 2004. Development and validation of a global database of lakes, reservoirs and wetlands, *J. Hydrol.*, *296*(1-4), 1-22.

L'vovitch, M.I. 1974. *The water resources and their future* (in Russian), Mysl' P. H. Moscow; trans. ed. by R. Nace, American Geophysical Union, Washington, D.C., 1979.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2005. *Soil and Water Assessment Tool - Theoretical Documentation - Version 2005*, Grassland, Soil and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas.

Nijssen, B., G.M. O'Donnell, D.P. Lettenmaier, D. Lohmann, and E.F. Wood. 2001. Predicting the discharge of global rivers, *J. Clim.*, *14*(15), 3307-3323.

Oki, T., and S. Kanae. 2006. Global hydrological cycles and world water resources, *Science*, *313*, 1068-1072.

Oki, T., Y. Agata, S. Kanae, T. Saruhashi, D.W. Yang, and K. Musiake. 2001. Global assessment of current water resources using total runoff integrating pathways, *Hydrol. Sci. J.-J. Sci. Hydrol.*, *46*(6), 983-995.

Revenga, C., J. Brunner, N. Henninger, K. Kassem, and R. Payne. 2000. Pilot analysis of global ecosystems: Freshwater systems, World Resources Institute, Washington DC, USA.

Rijsberman, F.R. 2006. Water scarcity: Fact or fiction?, *Agricult. Water Manag.*, *80,* 5-22.

Rockström, J., and L. Gordon. 2001. Assessment of green water flows to sustain major biomes of the world: Implications for future ecohydrological landscape management, *Phys. Chem. Earth (B)*, *26*(11-12), 843-851.

Rockström, J., M. Lannerstad, and M. Falkenmark. 2007. Assessing the water challenge of a new green revolution in developing countries, *PNAS*, *104*(15), 6253-6260.

Savenije, H.H.G. 2004. The importance of interception and why we should delete the term evapotranspiration from our vocabulary, *Hydrol. Process.*, *18*, 1507-1511.

Schuol, J., and K.C. Abbaspour. 2007. Using monthly weather statistics to generate daily data in a SWAT model application to West Africa, *Ecol. Model.*, *201*, 301-311.

Schuol, J., K.C. Abbaspour, R. Srinivasan, and H. Yang. 2007. Estimation of freshwater availability in the West African sub-continent using the SWAT hydrologic model, *J. Hydrol.*, in press.

Shiklomanov, I.A. (2000). Appraisal and assessment of world water resources, *Water Int.*, *25*(1), 11-32.

Shiklomanov, I.A., and J. Rodda (Eds.). 2003. *World water resources at the beginning of the 21st century*, Cambridge Univ. Press, New York.

Smakhtin, V., C. Revenga, and P. Döll. 2004. Taking into account environmental water requirements in global-scale water resources assessments, *Comprehensive Assessment Research Report 2*, Colombo, Sri Lanka.

Srinivasan, R., T.S. Ramanarayanan, J.G. Arnold, and S.T. Bednarz. 1998. Large area hydrologic modeling and assessment - Part II: Model application, *J. Am. Water Resour. Assoc.*, *34*(1), 91-101.

UNESCO. 2006. Water a shared responsibility, *The United Nations World Water Development Report 2*, UNESCO-WWAP.

UN-Water/Africa. 2006. African water development report 2006, Economic Commission for Africa, Addis Ababa, Ethiopia.

van Griensven, A., and T. Meixner. 2006. Methods to quantify and identify the sources of uncertainty for river basin water quality models, *Water Sci. Technol.*, *53*(1), 51-59.

Vörösmarty, C.J., C.A. Federer, and A.L. Schloss. 1998. Evaporation functions compared on US watersheds: Possible implications for global-scale water balance and terrestrial ecosystem modeling, *J. Hydrol.*, *207*(3-4), 147-169.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers. 2000. Global water resources: Vulnerability from climate change and population growth, *Science*, *289*, 284-288.

Vörösmarty, C.J., E.M. Douglas, P.A. Green, and C. Revenga. 2005. Geospatial indicators of emerging water stress: an application to Africa, *Ambio*, *34*(3), 230-236.

Vrugt, J.A., H.V. Gupta, W. Bouten, and S. Sorooshian. 2003. A Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters, *Water Resour. Res.*, *39*(8), 1201.

Wagner, W., K. Scipal, C. Pathe, D. Gerten, W. Lucht, and B. Rudolf. 2003. Evaluation of the agreement between the first global remotely sensed soil moisture data with model and precipitation data, *J. Geophys. Res.*, *108*(D19), 4611.

Wagner, W., G. Blöschl, P. Pampaloni, J.-C. Calvet, B. Bizzarri, J.-P. Wigneron, and Y. Kerr. 2007. Operational readiness of microwave remote sensing of soil moisture for hydrologic applications, *Nord. Hydrol.*, *38*(1), 1-20.

Wallace J.S., and P.J. Gregory. 2002. Water resources and their use in food production systems, *Aquat. Sci.*, *64,* 363-375.

Widén-Nilsson, E., S. Halldin, and C.-Y. Xu. 2007. Global water-balance modelling with WASMOD-M: Parameter estimation and regionalisation, *J. Hydrol.*, *340*, 105-118.

Winchell, M., R. Srinivasan, M. Di Luzio, and J.G. Arnold. 2007. *ArcSWAT interface for SWAT2005 - User's Guide*, Blackland Research Center, Texas Agricultural Experiment Station and Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, Temple, Texas.

Yang, H., and A.J.B. Zehnder. 2007. 'Virtual water' - an unfolding concept in integrated water resources management, *Water Resour. Res.*, *43*(12), W12301.

Yang, H., P. Reichert, K.C. Abbaspour, and A.J.B. Zehnder. 2003. A water resources threshold and its implications for food security, *Environ. Sci. Technol.*, *37*(14), 3048-3054.

Yang, J., P. Reichert, K.C. Abbaspour, H. Yang, and J. Xia. 2007. Comparing uncertainty analysis techniques for a SWAT application to the Chaohe basin in China, *J. Hydrol.*, submitted.

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^{o}C to 28^{o}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.

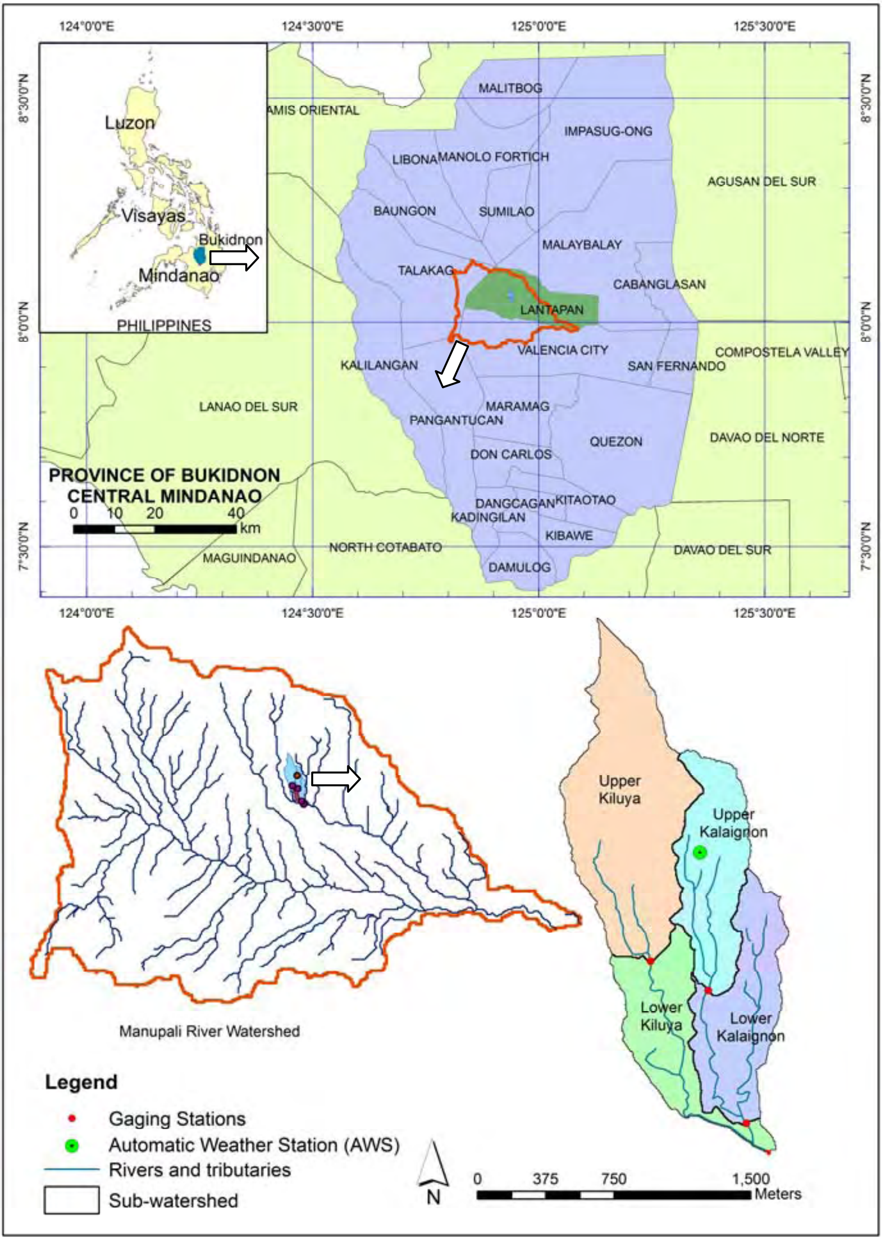


Figure 1. The Manupali River watershed and test sub-watersheds showing the locations of gaging stations and automatic weather station (AWS) and its location in the province of Bukidnon, Philippines.

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 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.

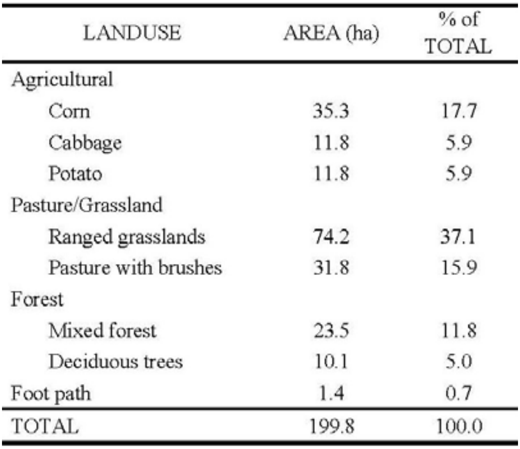
2.5 Data analysis

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.

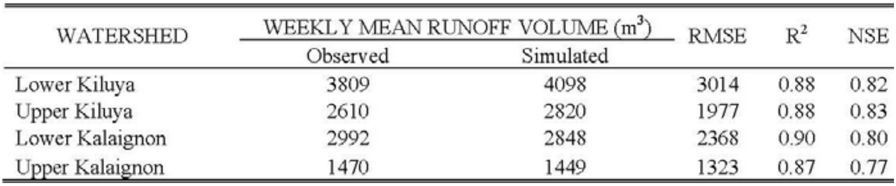


LANDUSE	AREA (ha)	% of TOTAL
Agricultural		
Corn	35.3	17.7
Cabbage	11.8	5.9
Potato	11.8	5.9
Pasture/Grassland		
Ranged grasslands	74.2	37.1
Pasture with brushes	31.8	15.9
Forest		
Mixed forest	23.5	11.8
Deciduous trees	10.1	5.0
Foot path	1.4	0.7
TOTAL	199.8	100.0

Table 2. Slope classification of the study area.

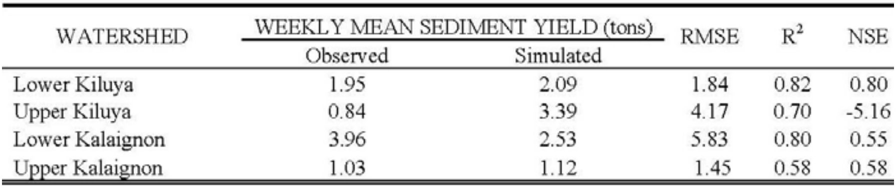
Slope (%)	Area (ha)	% of Total
0-8	45.4	22.71
8-18	0.1	0.03
18-30	57.6	28.82
Above 30	96.7	48.44
TOTAL	199.8	100.0

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.

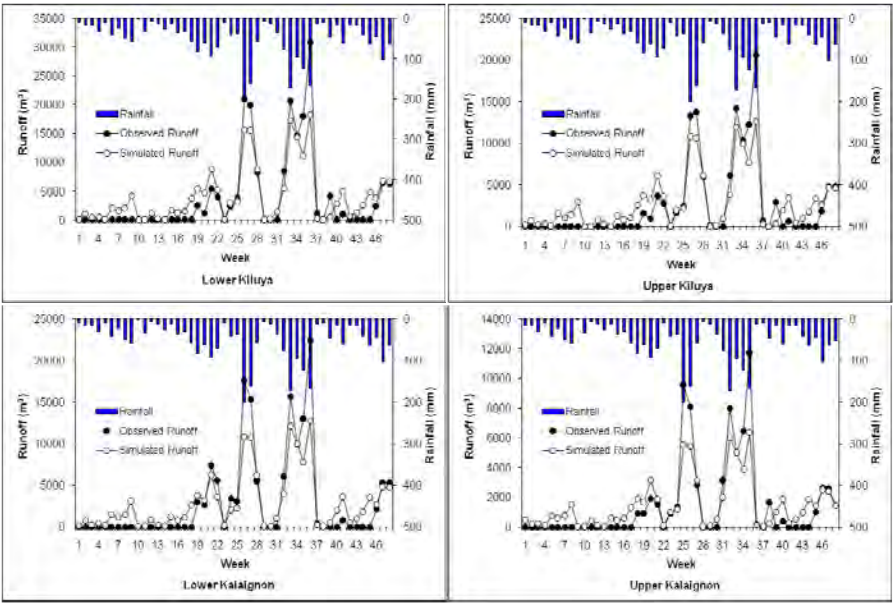


Figure 2. Observed and calibrated simulated runoff volumes at the four sub-watersheds superimposed with the weekly rainfall amount in the study area.

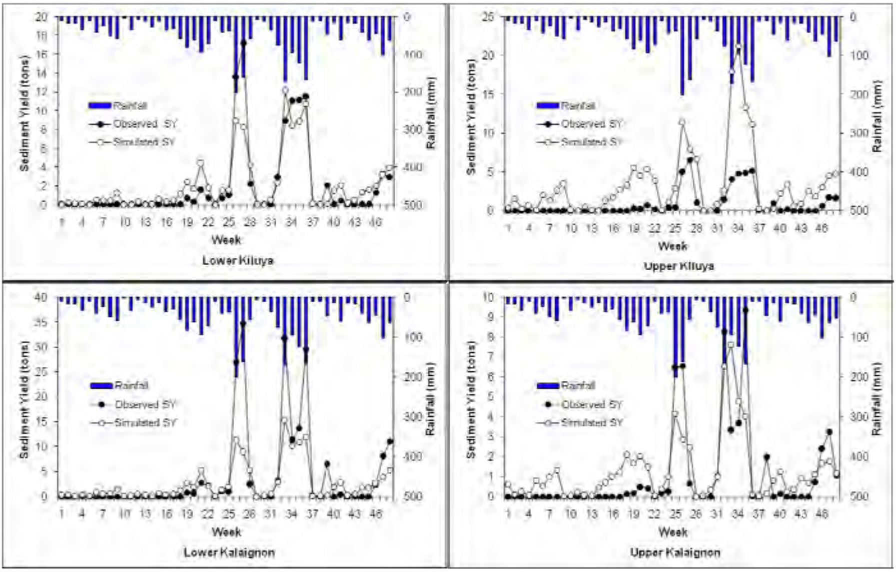


Figure 3. Observed and simulated sediment yields at the four sub-watersheds superimposed with the weekly rainfall amount in the study area during calibration period.

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.

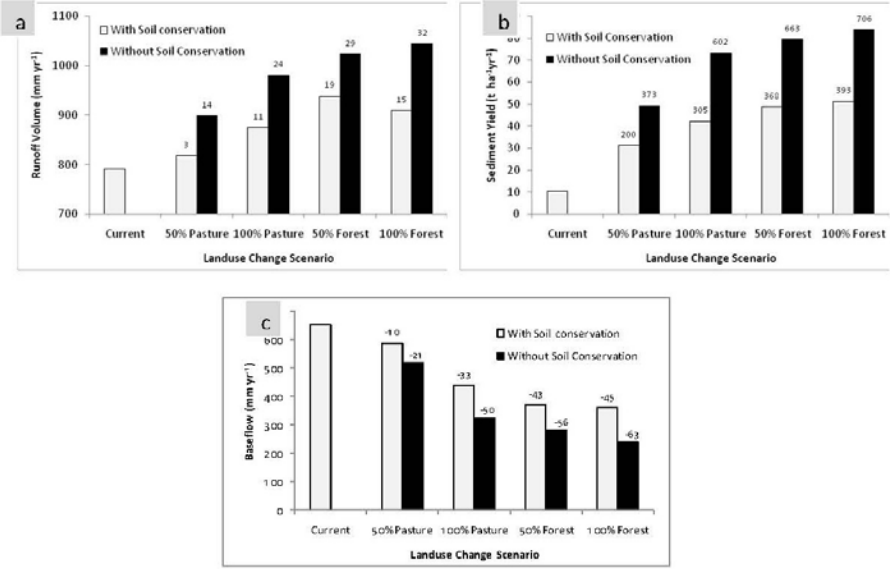


Figure 4. Simulated runoff volume (mm yr^{-1}), sediment yield (t ha^{-1} yr^{-1}), baseflow (mm yr^{-1}) in the study area as affected by percentage pasture and forest areas converted to agricultural land. The numbers on top of the bars indicate the percentage change from its current value.

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

This project was made possible through support provided by the United States Agency for International Development (USAID) and the generous support of the American people for the Sustainable Agriculture and Natural Resources Management Collaborative Research Support Program (SANREM CRSP) under terms of Cooperative Agreement Award No. EPP-A-00-04-00013-00 to the Office of International Research and Development (OIRED) at Virginia Polytechnic Institute and State University (Virginia Tech); and terms of sub-agreement 19070A-425632 between Virginia Tech and North Carolina Agricultural and Technical State University (NCA&T). The authors also thank Dr. David J. Midmore and Engr. Edward R. Lapong for providing the data used in the calibration of the model.

References

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. *J. American Water Res. Assoc.* 34(1):73-89.

Bureau of Soils and Water Management, Department of Agriculture (BSWM). 1985. Land resources evaluation report for Bukidnon province: the physical land resources volume 1. BSWM-DA, Manila, Philippines.

Daño, A.M., and D.J. Midmore. 2002. Analyses of soil and water conservation technologies in vegetable based upland production system of Manupali Watershed. 12th ISCO Conference, Beijing.

Ella, V.B. 2005. Simulating soil erosion and sediment yield in small upland watersheds using the WEPP model. In: I. Coxhead and G.E. Shively, eds., Land use change in tropical watersheds: Evidence, causes and remedies. CABI publishing. Wallingford, Oxfordshire, UK. pp 109-125.

Hudson, N. 1995. Soil conservation. BT Batsford Limited, London. 391 pp.

Lapong, E.R. 2005. Effect of land use patterns on runoff, sediment yield, and pesticide loading in selected microcatchments in Manupali Watershed, Lantapan, Bukidnon, Philippines. Unpublished Master's thesis, University of the Philippines at Los Baños, College, Laguna, Philippines. 178 pp.

National Water Resources Board (NWRB). 2004. Water for food: Aiming for self-sufficiency and rural development. In: Ella, V.B. 2005. Simulating soil erosion and sediment yield in small upland watersheds using the WEPP model. In: I. Coxhead and G.E. Shively, eds., Land use change in tropical watersheds: Evidence, causes and remedies. CABI publishing. Wallingford, Oxfordshire, UK. pp 109-125.

Nash, J.E., and J.E. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I. A discussion of principles. *J. Hydrol*. 10:282-200.

Paningbatan, Jr. E.P. 2005. Identifying soil erosion hotspots in the Manupali River watershed. In: I. Coxhead and G.E. Shively, eds., Land use change in tropical watersheds: Evidence, causes and remedies. CABI publishing. Wallingford, Oxfordshire, UK. pp 126-132.

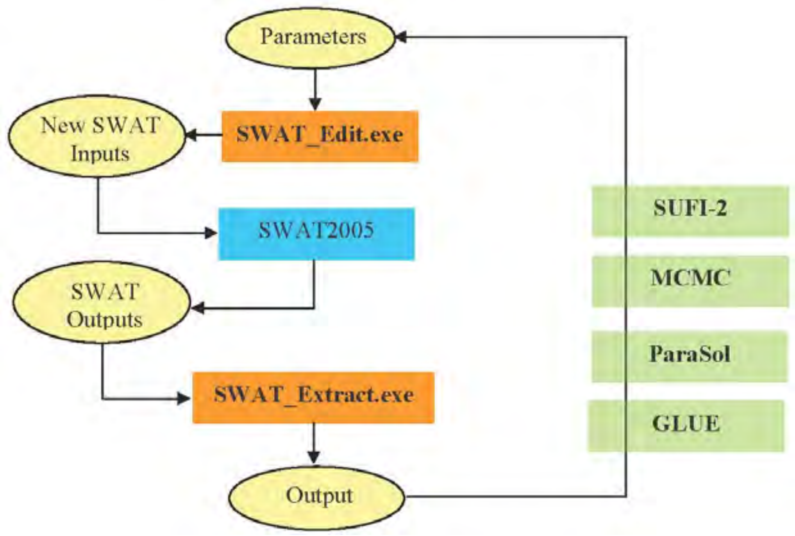
Santhi, C., R. Srinivasan, J.G. Arnold, and J.R. Williams. 2006. A modeling approach to evaluate the impacts of water quality management plans implemented in Texas. Environmental Modeling and Software. 21:1141-1157.

Williams, J.R., and H.D. Berndt. 1977. Sediment yield prediction based on watershed hydrology. *Trans. ASAE*. 20(6): 1100-1104.

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)

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

II. Software
- A. MapWindow GIS
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  - 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
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Index for Models, Abbreviations and Acronyms

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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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1992-1997: Hans Hurni, Switzerland

1997-2001: David W. Sanders, UK
2002-2004: Samran Sombatpanit, Thailand
January-March 2005: Martin Haigh, UK
April 2005-June 2006: Samran Sombatpanit, Thailand (Acting)
July 2006-December 2007: Miodrag Zlatic, Serbia

WASWC Secretariat and Websites: See p. vi, this volume.

WASWC Publications

– Published in association with other institutions or publishers –

1988

- *Conservation Farming on Steep Lands.* Edited by W.C. Moldenhauer and N.W. Hudson, ISBN 0935734198

1989

- *Land Husbandry – A Framework for Soil and Water Conservation.* by T.F. Shaxson, N.W. Hudson, D.W. Sanders, E. Roose and W.C. Moldenhauer, ISBN 0935734201

1990

- *Soil Erosion on Agricultural Land.* Edited by J. Boardman, I.D.L. Foster and J.A. Dearing, ISBN 0471906027 (From a meeting co-sponsored by WASWC)

1991

- *Development of Conservation Farming on Hillslopes.* Edited by W.C. Moldenhauer, N.W. Hudson, T.C. Sheng and San-Wei Lee, ISBN 0935734244
- *Soil Management for Sustainability.* Edited by R. Lal and F.J. Pierce, ISBN 0935734236

1992

- *Conservation Policies for Sustainable Hillslope Farming.* Edited by S. Arsyad, I. Amien, Ted Sheng and W.C. Moldenhauer, ISBN 0935734287
- *Soil Conservation for Survival.* Edited by K. Tato and H. Hurni, ISBN 0935734279
- *Erosion, Conservation and Small-Scale Farming.* Edited by H. Hurni and K. Tato, ISBN 3906290700
- Environmental Regeneration in Headwaters. Edited by J. Krecek and M.J. Haigh

1993

- *Working with Farmers for Better Land Husbandry.* Edited by N. Hudson and R.J. Cheatle, ISBN 1853391220

1995

- *Adopting Conservation on the Farm: An International Perspective on the Socio-economics of SWC.* Edited by T.L. Napier, S.M. Camboni and S.A. El-Swaify, ISBN 0935734317

1996

- *Hydrological Problems and Environmental Management in Highlands and Headwaters.* Edited by J. Krecek, G.S. Rajwar and M.J. Haigh, ISBN 8120410483

1997

- *Soil Conservation Extension: From Concepts to Adoption.* Edited by S. Sombatpanit, M. Zoebisch, D. Sanders and M.G. Cook, ISBN 8120411897

1999

- *Multiple Objective Decision Making for Land, Water and Environmental Management.* Edited by S.A. El-Swaify and D.S. Yakowitz, ISBN 1-57444-091-8
- *Incentives in Soil Conservation: From Theory to Practice.* Edited by D.W. Sanders, P. Huszar, S. Sombatpanit and T. Enters, ISBN 1-57808-061-4

2000

- *Reclaimed Land: Erosion Control, Soils and Ecology.* Edited by M.J. Haigh, ISBN 90 5410 793 6

2001

- *Response to Land Degradation.* Edited by E.M. Bridges, I.D. Hannam, L.R. Oldeman, F. Penning de Vries, S.J. Scherr and S. Sombatpanit, ISBN 812041942

2004

- *Ground and Water Bioengineering for Erosion Control and Slope Stabilization.* Edited by D.H. Barker, A.J. Watson, S. Sombatpanit, B. Northcutt and A.R. Maglinao, ISBN 1-57808-209-9

2007

- *Monitoring and Evaluation of Soil Conservation and Watershed Development Projects.* Edited by J. de Graaff, J. Cameron, S. Sombatpanit, C. Pieri and J. Woodhill. ISBN 978-1-57808-349-7

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)
2008: No. 3. *No-Till Farming Systems.* Edited by Tom Goddard, Michael A. Zoebisch, Yantai Gan, Wyn Ellis, Alex Watson and Samran Sombatpanit, ISBN 978-974-8391-60-1, 544 pp. (With one CD)
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 stuff that include free software and the WASWC e-LIBRARY)

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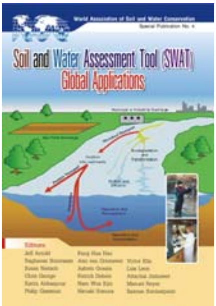

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