Introducing a new open source GIS user interface for the SWAT model

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ABSTRACT

The Soil and Water Assessment Tool (SWAT) model is a robust watershed modeling tool. It typically uses the ArcSWAT interface to create its inputs. ArcSWAT is public domain software which works in the licensed ArcGIS environment. The aim of this paper was to develop an open source user interface for the SWAT model. The interface, QSWAT, is written in the Python programming language and uses various functionalities of the open source geographic information system, QGIS. The current interface performs similar functions to ArcSWAT, but with additional enhanced features such as merging small subbasins and static and dynamic visualization of outputs. The interface is demonstrated through a case study in the Gumera watershed in the Lake Tana basin of Ethiopia, where it showed a successful performance. QSWAT will be a valuable tool for the SWAT scientific community, with improved availability and functionality compared with other options for creating SWAT models.

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Software availability

Software name: QSWAT
Year first available: 2015
Software required: QGIS
Programming language: Python
Availability: Software (including source code) and documentation can be downloaded from http://swat.tamu.edu/software/qswat/
License: GNU General Public License
Cost: free

1. Introduction

The Soil and Water Assessment Tool (SWAT) model (Arnold and Fohrer, 2005; Arnold et al., 1998) is a physically based, watershed-scale model operating on a daily time step. It is a product of four decades of modeling efforts by USDA-Agricultural Research Service, USDA-Natural Resources Conservation Service, and Texas A&M University. It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields (e.g., fertilizer and pesticides) in large complex watersheds with varying soils, land uses and management conditions over long periods of time.

It has gained international acceptance as an interdisciplinary watershed modeling tool and is currently being used in close to 100 countries. It has been extensively used to investigate water resource and nonpoint-source pollution problems for a range of scales and environmental conditions across the globe (Gassman et al., 2007). It also contributes to understanding complex ecosystems as well as water availability, water quality, climate change, and agricultural production issues across the world (Dile et al., 2016, 2013; Krysanova et al., 2007; Lautenbach et al., 2013; Panagopoulos et al., 2012; Schuol et al., 2008a, 2008b; Srinivasan et al., 2005; Vandenberghe et al., 2007). This is proven with its strong publication track record in scientific journals. As of March 2016, a total of 2772 peer-reviewed SWAT model applications and developments have been published in about 500 different journals (SWATPubDatabase, 2015).

Several tools have been developed to enhance the application and development of the SWAT modeling effort. For example, Geographic Information Systems (GIS) have been successfully integrated with the SWAT model to collect, manipulate, visualize and analyze the inputs and outputs (Srinivasan and Arnold, 1994). A GIS interface is a key tool in driving the widespread adoption of the

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SWAT model (Gassman et al., 2010). Several versions of GIS interfaces starting from GRASS-GIS to the most recent ArcGIS 10.2/10.3 (Krysanova and Srinivasan, 2014) have been used to generate input data needed by the SWAT model. GRASS-SWAT was the first major GIS interface coupled to the SWAT model that generated and integrated topographic, soil and land use inputs. Thereafter, several GIS-coupled SWAT interfaces were developed, with ArcSWAT being the most popular.

ArcSWAT is public domain software which is freely available; however, the code is not open source since it is licensed to ArcGIS software (Winchell et al., 2013). The standard version of ArcGIS for desktop costs $7000 (http://www.esri.com/software/arcgis/arcgis-for-desktop/pricing) and the spatial analyst (single user) costs $2500 (http://www.esri.com/software/arcgis/extensions/spatialanalyst/pricing) as of March 2016. Despite the popularity and remarkable applications of ArcSWAT, the high price tag for ArcGIS restricts legal usage only to those who are able to buy the ArcGIS software. Moreover, the current version of ArcSWAT does not have an integrated capability for visualization of outputs.

Besides the financial benefits of open source software, there is an increasing demand that software used in science should be open source to guarantee reproducibility, reliability, security and fast deployment. For example, an editorial in *Nature* (Ince et al., 2012) discusses that anything less than release the actual source code is an indefensible approach for any scientific results suggesting that making source code available can make results dependent on software reproducible. The journal *Science* requires that all code "involved in the creation or analysis of data" has to be provided by article authors (Hanson et al., 2011). Open source code encourages collaboration and improves quality and thereby advances the science. The code for the SWAT model, for example, is open source and immensely helped its users. Likewise, the SWAT model has significantly benefited from several enhancements by other researchers/modelers around the world, which helped developing the model further and making it suitable for various applications in a short period of time (Krysanova and Srinivasan, 2014).

An open source GIS interface for the SWAT model (MWSWAT, www.waterbase.org) was developed by George and Leon (2008) using the MapWindow GIS (Ames et al., 2008) to reap the benefits of the open source software. MWSWAT showed that a free and open source alternative to ArcSWAT can be successful and provide a much more accessible route to modeling with SWAT. The major limitation of MWSWAT was its reduced capability in larger watersheds. Furthermore, the MapWindow software performs poorly when used with large datasets (Chen et al., 2010).

Chen et al. (2010) compared 31 open source GIS software packages and evaluated them for a wide range of functional aspects. They found that Quantum GIS (QGIS) outperformed other software packages and that its functionalities were adequate for most general applications in water resource management. QGIS is a free and open source desktop GIS application that provides data viewing, editing and analysis capabilities. Most functions in commercial GIS can be performed in QGIS, and it can do advanced functions when integrated with open source GIS packages such as PostGIS, GRASS and MapServer. Furthermore, plugins written in Python or C++ can significantly enhance the capabilities of QGIS. Several plugins exist to geocode, perform geoprocessing, and develop interfaces with PostgreSQL/PostGIS, SpatiaLite and MySQL databases. QGIS can work in multiple operating systems including Mac OS X, Linux, UNIX, and Microsoft Windows. It has a small file size compared to commercial GIS software, requiring less RAM and processing power. QGIS has a wide user base and reputation. It is used in academic and professional environments, and it is translated into more than 48 languages. Given its robustness, there has been a growing demand from SWAT users to develop a QGIS interface for the SWAT model.

Therefore, the objective of this paper is to develop and demonstrate with a case study a new open source interface for SWAT using QGIS. We named the new software QSWAT. Besides all the scientific merits of being open source software, QSWAT has added capabilities of merging small subbasins and has static and dynamic visualizations of outputs.

The structure of the paper will be as follows. Initially, the development of QSWAT including watershed delineation, HRU definition, and linking QSWAT with SWAT Editor will be presented. Thereafter, QSWAT will be demonstrated with a case study. The paper ends with the conclusion. A summary of the format for QSWAT inputs and outputs and a conceptual diagram that shows merging of small subbasins (SI1), and video that animates QSWAT outputs (SI2) are provided as supplementary information.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2016.08.004.

2. QSWAT development

2.1. Design

QSWAT is written in Python (www.python.org), a modern, increasingly popular high-level programming language. Python is intended to support code readability, which is a useful asset for an open source project like QSWAT. QSWAT is installed as a plugin to QGIS, and the conceptual architecture is shown in Fig. 1. For QSWAT to be installed and become functional, QGIS should be installed first. The design of QSWAT is divided into two parts: (1) *QSWAT Control*, which contains all the code that reacts to users' interactive inputs, and (2) *QSWAT Functions*, which contains code for performing certain tasks like merging subbasins or snapping points to the stream network.

QSWAT uses a suite of programs called Terrain Analysis Using Digital Elevation Models (*TauDEM*, http://hydrology.usu.edu/taudem/taudem5) to perform various geoprocessing functions (Tarboton, 1997; Tesfa et al., 2011; Wilson, 2012). It also interacts with QGIS itself, particularly the *Layers Panel* which shows legend information, and the *Map Canvas* where the maps are displayed. QGIS supplies a number of functions used by QSWAT, too many to be listed here; however, the *Geospatial Data Abstraction Library* (*GDAL, www.gdal.org) functions* will be discussed in this paper. Many of these components interact with map files, rasters and shapefiles held in the computer's file system.

QSWAT accepts any raster or vector supported by GDAL (www.gdal.org), the industry standard for raster and vector processing. Currently, GDAL accepts 72 raster file formats, 26 vector formats, and several spatial databases. If the raster supplied by the user is not a GeoTIFF, QSWAT uses GDAL to perform the conversion since TauDEM requires a DEM in GeoTIFF form. QSWAT always makes copies of raster and vector files supplied by the user, placing the copies in the directory tree under the project directory. This means that such files may be modified (as in this case) or deleted without affecting the originals; the project is unaffected if the originals are moved, edited or deleted, and the project may be moved to another location, including another machine, without the links to its input files being lost. This, together with the use of relative paths to files in the project file, and the storing of user-defined parameters in that file, meets the objective of the easy moving, copying and archiving of projects between and within computers.

As a QGIS plugin, QSWAT is discovered and made available by QGIS when the latter is started. QSWAT has the option of creating a new project or opening an existing project. A project consists of a project file (holding the state of QGIS, the loaded layers, user settings, etc) and a project directory (where the project input and output files are stored). The main components of QSWAT are 1)
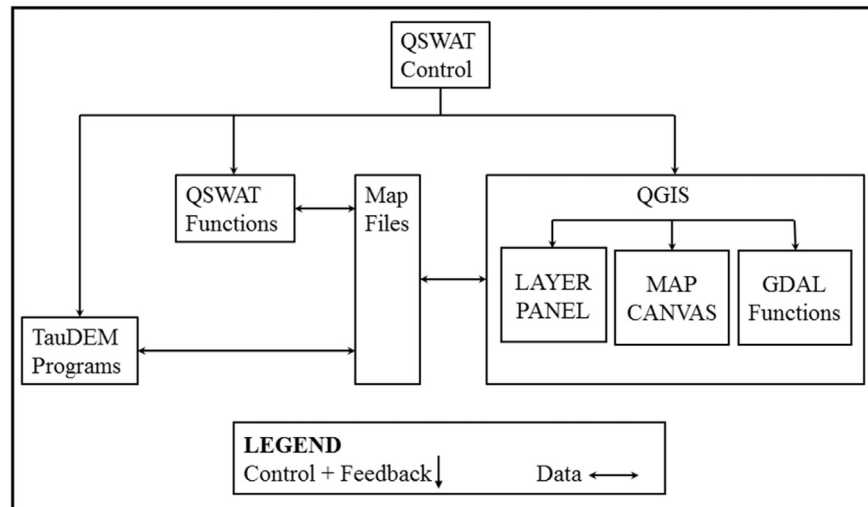
Fig. 1. A conceptual architecture for QSWAT.

watershed delineation, 2) Hydrological Response Units (HRU) creation, 3) opening the SWAT Editor to complete input preparation and execute SWAT, and 4) visualization of results. Fig. 2 shows the main components of QSWAT and the functionalities.

2.2. Watershed delineation

QSWAT uses TauDEM for watershed delineation. TauDEM

provides a suite of programs to perform various geoprocessing functions (Tarboton, 1997; Tesfa et al., 2011; Wilson, 2012). QSWAT uses some of the capabilities of TauDEM such as pit (depression) removal using the flooding approach, calculation of flow paths and slopes, calculation of contributing areas using single and multiple flow direction methods, delineation of stream networks using contributing area threshold, delineation of watersheds and sub-basins, areas draining to stream segments, and the association
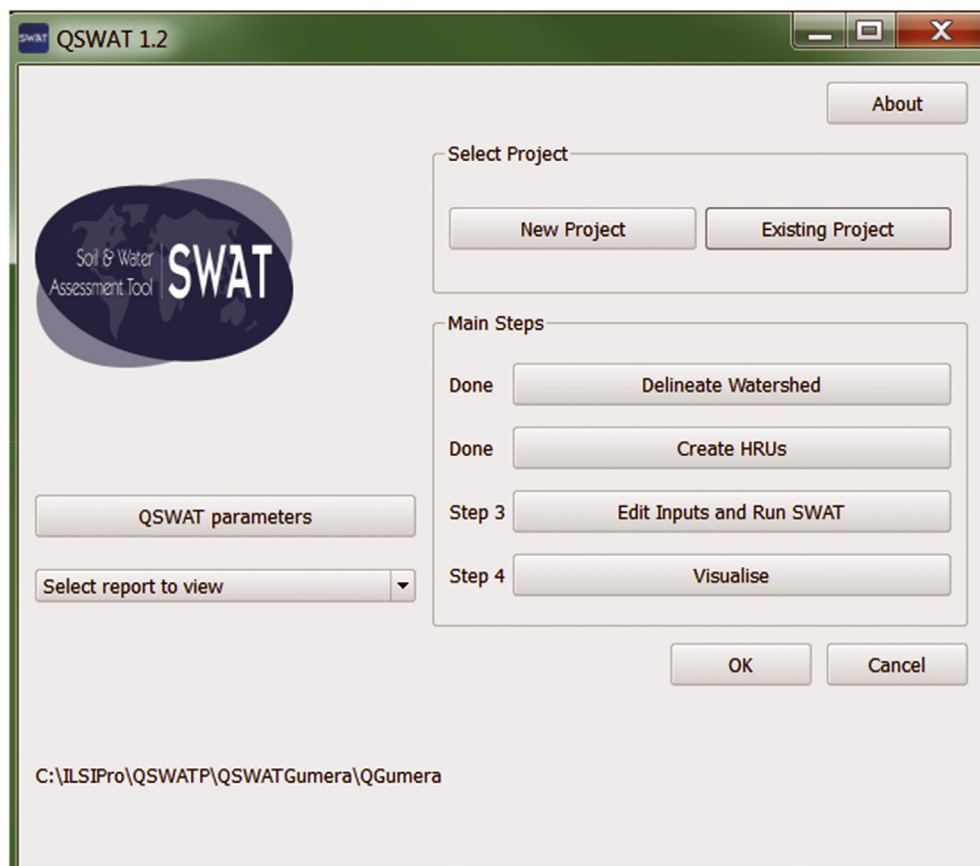

Fig. 2. Main QSWAT form.

between subbasin and stream segment attributes. QSWAT uses the 5.1.2 version of TauDEM, which is designed to work in a multi-processing mode using the standard *Message Passing Interface* (MPI) (Wu et al., 2013). MPI is a specification for a standard library for message passing that was defined by the MPI Forum, a broadly based group of parallel computer vendors, library writers, and applications specialists (Gropp et al., 1996). Investigations for QSWAT suggested that MPI is useful in reducing processing times of DEMs (Digital Elevation Models) with over a million values but makes only a marginal difference for smaller sizes. Thus QSWAT is designed to run with or without MPI installed. The version of MPI used by TauDEM on Windows is supplied by Microsoft, and is free but not open source.

QSWAT has the capability to burn in an existing vector file that defines a stream network. It is a very useful technique if the terrain is fairly level, when delineation is much less likely to identify stream positions accurately. Watershed delineation requires a threshold area (or number of DEM cells) to form a stream. A threshold of 1% of the DEM size is used by QSWAT as default threshold value. However, QSWAT allows the threshold to be adjusted to create more or fewer streams and resulting subbasins.

QSWAT normally requires at least one main outlet (downstream outlet) defined by a point vector file to delineate a watershed. QSWAT can use an existing file or exploit the interactive capability of QGIS to mark internal outlet points on the map canvas (e.g. if intermediate river gauges are available). This is done by creating and displaying the stream network so that the relevant points on streams can be visually identified. It also allows placement of inlets, point sources, and reservoirs. Drawn outlets/inlets/point sources may not fall precisely on a stream reach. In such cases, they are *snapped* to the nearest stream, provided that they fall within a threshold distance from the stream network, which defaults to 300 m. QSWAT reports how many of the added outlets/inlets/point sources have been successfully snapped, and the result of snapping can be reviewed.

TauDEM delineates a watershed by first calculating where streams will flow and then calculating the region (called a subbasin) which drains to each reach of a stream. A reach is the portion of a stream between two points, where points are stream sources (beginning of the stream), stream junctions, inlets, outlets, point sources and reservoirs. Small subbasins may be formed by TauDEM when stream junctions happen to be close together. SWAT is a hydrological model, and the subbasin sizes should be as homogeneous as possible in order to have a better hydrological representation. Small subbasins may distort SWAT model results. In particular, a large basin draining through a small one can result in exaggerated flow velocity and sediment production. In such cases, QSWAT can help to merge small subbasins to downstream subbasins. Subbasins can be merged by selecting subbasins manually and/or by requesting the merging of all subbasins below a certain threshold (e.g., subbasins less than 5% of the mean subbasin size). Merging is achieved by, in effect, removing the boundary between the subbasin to be merged and the subbasin downstream from it. Merging in QSWAT does not involve any change to the drainage network. A conceptual diagram is presented in SI1 (Figure SI1) that shows the watershed configuration before and after merging. This functionality is currently not available in ArcSWAT.

2.3. HRU creation

The SWAT model works by modeling assumedly homogeneous areas called Hydrological Response Units (HRUs). An HRU has a particular subbasin it belongs to and has a particular combination of land use, soil, and slope range. The HRUs in QSWAT are created using land use and soil data layers and associated lookup tables.

These data layers are used to identify land use and soil values for each DEM raster cell, since slopes are already available from watershed delineation. Each HRU will belong to a particular subbasin, and each cell within it will have the same land use, soil, and slope range. Beyond belonging to a subbasin, an HRU is not spatially explicit. All the cells in an HRU, which may in practice occur scattered across the subbasin, are modeled as if they are contiguous and drain directly into the subbasin's stream reach. Apart from its subbasin, land use, soil and slope, the only HRU spatial attribute of interest to SWAT is the area (which will determine, for example, the amount of water it receives in rainfall). The creation of HRUs is therefore based on counting cells, since the count multiplied by the grid cell area gives the HRU area. Initially, the subbasin raster map is generated from watershed delineation. Each cell on the raster gives a subbasin number. For each such cell, the land use value from the land use map, the soil value from the soil map, and the slope range according to the slope value from the slope map is read. For each combination of subbasin, land use, soil and slope, the number of occurrences is counted. Each combination is a potential HRU, and the count gives its area. The cells contributing to each potential HRU can be mapped and displayed as a *FullHRUs* shapefile.

Some HRUs will be much smaller than others, and it is normal practice to remove small ones from the model to reduce processing and simulation time. Their area is redistributed proportionately to the remaining ones. This redistribution ensures that the total area of the watershed is the same as the sum of the areas of its HRUs. QSWAT has two major HRU creation options to reduce the number of HRUs. These are the single HRU option and the multiple HRU option in each subbasin. The single HRU option can be achieved either by choosing the largest HRU or by selecting the largest of each of land use, soil, and slope range. Multiple HRUs can be created by 1) filtering land uses, soils and slope ranges in each subbasin, 2) filtering HRUs according to their sizes, or 3) setting a target number of HRUs across the whole basin. For the Multiple HRUs option (i.e. case 1 and 2), insignificant HRUs can be eliminated by percentage thresholds or area thresholds. Filtering by percentages will tend to preserve variety in each subbasin even when the subbasins vary widely in area. Filtering by area will tend to give more variety in larger subbasins as well as provide HRUs that are more homogeneous in size. QSWAT allows splitting of land uses (e.g., if the original land use is agricultural, and if there is evidence that 50% of the agricultural land is corn and 50% is wheat, the agricultural land can be split accordingly). QSWAT has also the capability of exempting certain land uses from possible elimination during HRU selection.

2.4. Linking with the SWAT Editor

QSWAT creates a number of database tables from the watershed delineation and HRU creation steps. These databases will be used as input to the SWAT Editor. The SWAT Editor thereafter creates SWAT readable text files from the databases. Moreover, it helps to create text files for weather data and edits various databases. It also executes the SWAT model and reads and exports SWAT outputs. The SWAT Editor is also used to manually change model parameters in the model calibration process.

2.5. Visualizing outputs

The current ArcSWAT does not include visualizations of outputs. Visualizations are required for quickly discovering issues of interest in the data that warrant further investigation and analysis. QSWAT has three types of visualizations. The first two are *static* and *dynamic* visualizations. They are designed to show spatially distributed data and use the map canvas and legend panel of QGIS. They

color-code the stream, subbasin, or actual HRUs according to SWAT output data, usually using five categories obtained through the Jenks Natural Breaks Algorithm (George, 1967). For a static visualization, summarized results will be displayed on the map of the watershed for different SWAT run, period of visualization, output variable, and summary functions (e.g., total, annual, monthly or daily mean, maximum, or minimum). For a dynamic visualization, the outputs are displayed for each time step over a period of time via animation. The time step for dynamic animation is similar to the time step of the model simulation. The speed of the animation can be adjusted, and it can be paused and changed manually by dragging the slider or using the keyboard's right and left arrow keys.

The third visualization is the *plot* function that shows graphs of outputs and is mostly intended for comparisons between different subbasins, model simulations, or simulated and observed results. The data is output into a text file and then read by a separate tool called SWATGraph (www.waterbase.org), which is supplied with QSWAT. Plots can also be included from observed data as a comma separated value file. SWATGraph displays the plot data as histograms or line graphs. It also shows the input data, calculates and shows correlation coefficients (R) between all pairs of plots, and calculates Nash-Sutcliffe efficiency (NSE) coefficients between each pair of simulated-observed data.

3. Case study

3.1. Study area

The QSWAT software is demonstrated in a case study watershed called Gumera watershed. The Gumera watershed is located in the Lake Tana basin, which is the source of the Upper Blue Nile basin in Ethiopia (Fig. 3). The Gumera watershed has a catchment area of
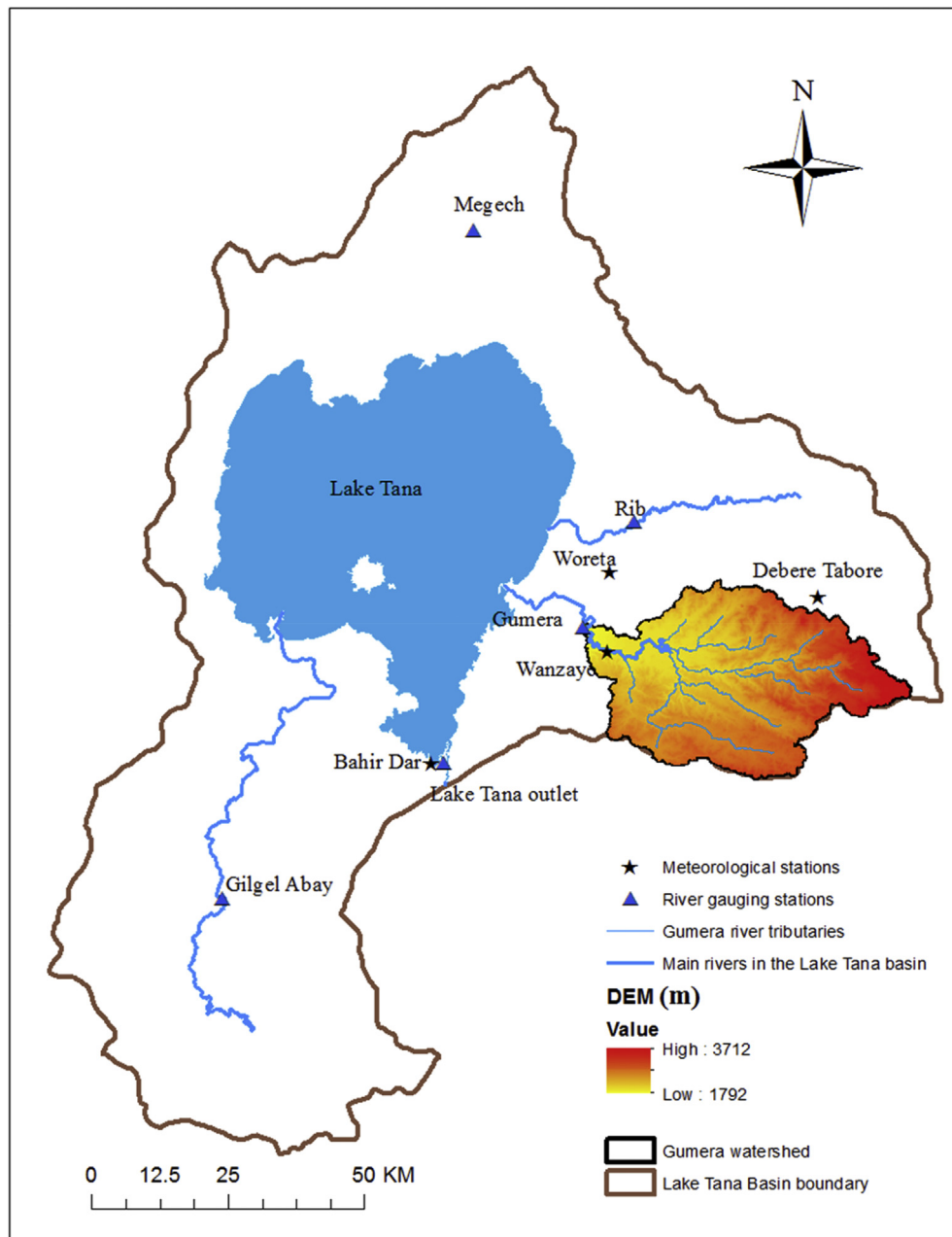

Fig. 3. Location of the Gumera watershed in the Lake Tana basin including river gauging stations and meteorological stations.

Table 1
Calibrated SWAT parameters, their descriptions, range and fitted values (Arnold et al., 2012).

Parameter	Descriptions	Range		Fitted parameter value
		Max	Min	
r_CN2[a]	Curve number	−0.1	0.1	−0.085
v_ALPHA_BF[b]	Base-flow alpha factor (days)	0	1	0.541
a_GW_DELAY[c]	Groundwater delay time (days)	−20	30	−3.25
a_GWQMN	Threshold water depth in the shallow aquifer required for return flow to occur (mm)	0	1000	795
a_GW_REVAP	Groundwater "revap" coefficient	0	0.18	0.00702
v_ESCO	Soil evaporation compensation factor	0.5	0.95	0.82175
r_SOL_AWC	Available water capacity of the soil (mm)	−0.1	0.1	−0.0918
a_REVAPMN	Threshold water depth in the shallow aquifer for "revap" to the deep aquifer to occur (mm)	0	250	55.75

[a] The qualifier (r_) refers that the original parameter value is multiplied by (1 + fitted parameter value).
[b] The qualifier (v_) refers that the original parameter value is to be replaced by the fitted parameter value.
[c] The qualifier (a_) refers that the fitted parameter value is added to the original parameter value.

1893 km² and flows into Lake Tana from the east. The gauged part of the Gumera watershed covers 1278 km², and the elevation ranges from 1792 m to 3712 m (Fig. 3). The climate of the basin is dominated by a tropical highland monsoon with most of the rain (~70—90%) occurring between June and September (Conway and Schipper, 2011; Mohamed et al., 2005).

3.2. Input data

3.2.1. Spatial data

The spatial data used in QSWAT for the case study included a digital elevation model (DEM) as well as soil and land cover data. The DEM data were required for delineating the watershed. The soil and land use data were required for defining the HRUs. DEM data of 30 m resolution were obtained from the Shuttle Radar Topographic Mission (SRTM) (SRTM, 2015). The land use and soil maps of the study area were collected from the Ethiopian Ministry of Water, Irrigation, and Energy (MoWE, 2012). The soils' physical and chemical property parameters required by SWAT were derived from the digital soil map of the world CD-ROM Africa map sheet (FAO, 1995).

A large part (97%) of the Gumera watershed is under cultivation. The two agricultural land use types in the original land use system (dominantly cultivated and moderately cultivated) were reclassified into TEFF and CORN SWAT land use codes. Teff and corn are the most widely cultivated crop types in Ethiopia (CSA, 2012; EIAR, 2007). There are six identified soil types in the Gumera watershed. A large portion of the soil has loam and clay-loam soil texture.

3.2.2. Temporal data

Weather data is a major input to the hydrological processes in SWAT. Rainfall and maximum/minimum temperature data at Debre Tabore, Woreta and Wanzaye meteorological weather stations were used (Fig. 3). The rainfall and maximum/minimum temperature data span the 1990—2011 period. Relative humidity, solar radiation and wind speed data were simulated using SWAT's built-in weather generator (Neitsch et al., 2012) based on the weather data at the Bahir Dar meteorological station (Fig. 3). The weather generator was also used to fill data gaps in the rainfall and maximum/minimum temperature data. The weather data was collected from the Ethiopian National Meteorological Services Agency (ENMSA, 2012).

The performance of the SWAT simulation was evaluated using monthly streamflow data from the Gumera River gauging station (Fig. 3). The hydrological data, which were collected from the Ethiopian Ministry of Water and Energy (MoWE, 2012), span the 1990—2007 period. This limited our evaluation of the model simulation to 1990—2007, even though climate data were available up to 2011.

3.3. Model setup

Watershed discretization, using a threshold area of 2759 ha, created 25 subbasins. QSWAT's merge function was used, and subbasins that had an area less than 25% of the mean subbasin area were merged with the downstream subbasins. This resulted in a total of 22 subbasins in the watershed. Three slope classes were defined in the watershed: 0—5%, 5—15%, and >15%. The HRUs were
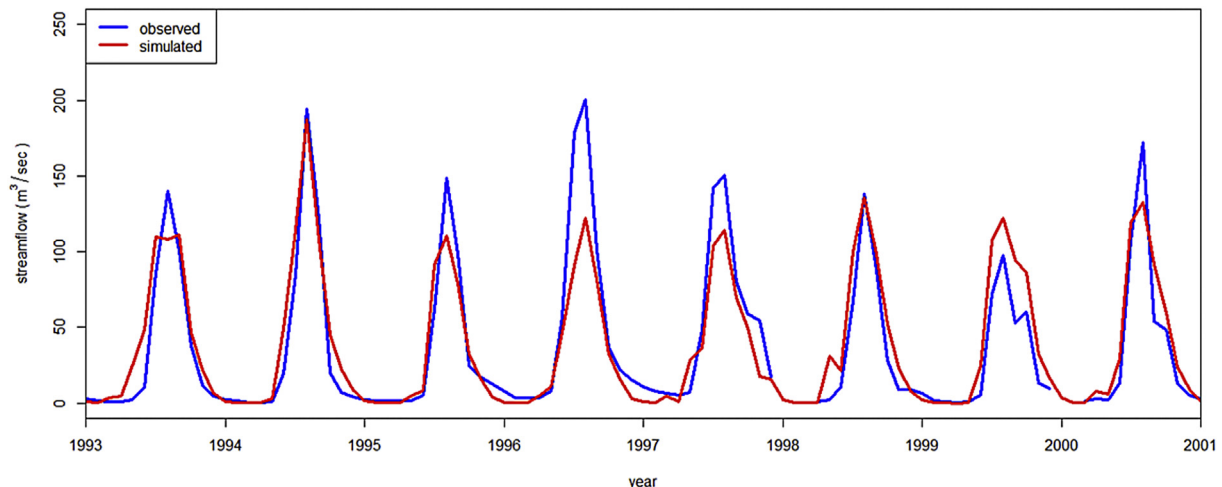

Fig. 4. Observed vs simulated monthly streamflow using default SWAT model parameters at the gauging station at the outlet of the Gumera River.
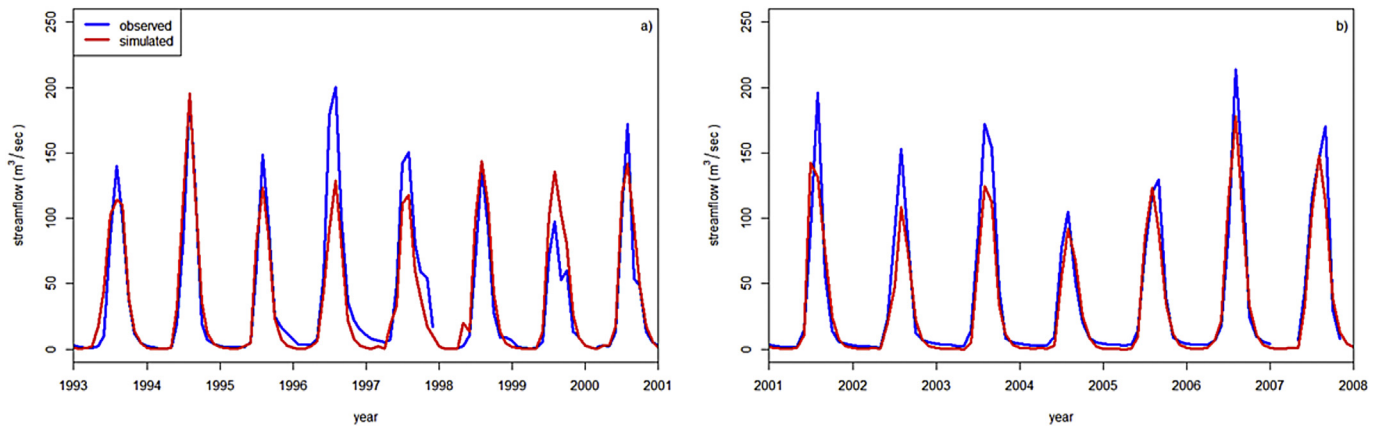
Fig. 5. Observed streamflow vs simulated streamflow using calibrated SWAT model parameters during a) calibration period, and b) validation period.

created using the multiple HRU option of filtering by land use, soil and slope. A 10% threshold area was used to define HRUs — applying a 10% threshold means that land uses, soils and slope ranges whose areas are less than 10% of the subbasin area are eliminated from HRU formation within each subbasin. Since the forest areas were very small, forest land uses were exempted from the 10% threshold rejection criteria. This is to avoid elimination of forest land use types from HRU creation and maintain diversity in the land use types. Altogether, a total of 158 HRUs were created during the HRU definition process.

Incorporating land management practices in the SWAT model significantly improves representation of real world conditions and further improves hydrological budget simulations. Therefore, in this study, land management information for teff and corn crops was implemented based on data from Dile and Srinivasan (2014).

SWAT has different options for calculating the hydrological components in a watershed. In this study, the Penman-Monteith method was used to determine potential evapotranspiration. Surface runoff was estimated using the Soil Conservation Service's curve number method. In SWAT, surface runoff is estimated separately for each HRU and routed to obtain the total runoff for the subbasin. A variable storage routing method was used for routing the flow of water in the channels.

3.4. Model calibration and validation

Calibration of SWAT parameters was based on the Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm (Abbaspour et al., 2004, 2007), using observed monthly streamflow at the Gumera River gauging station for the 1993—2000 period (Fig. 3). Based on
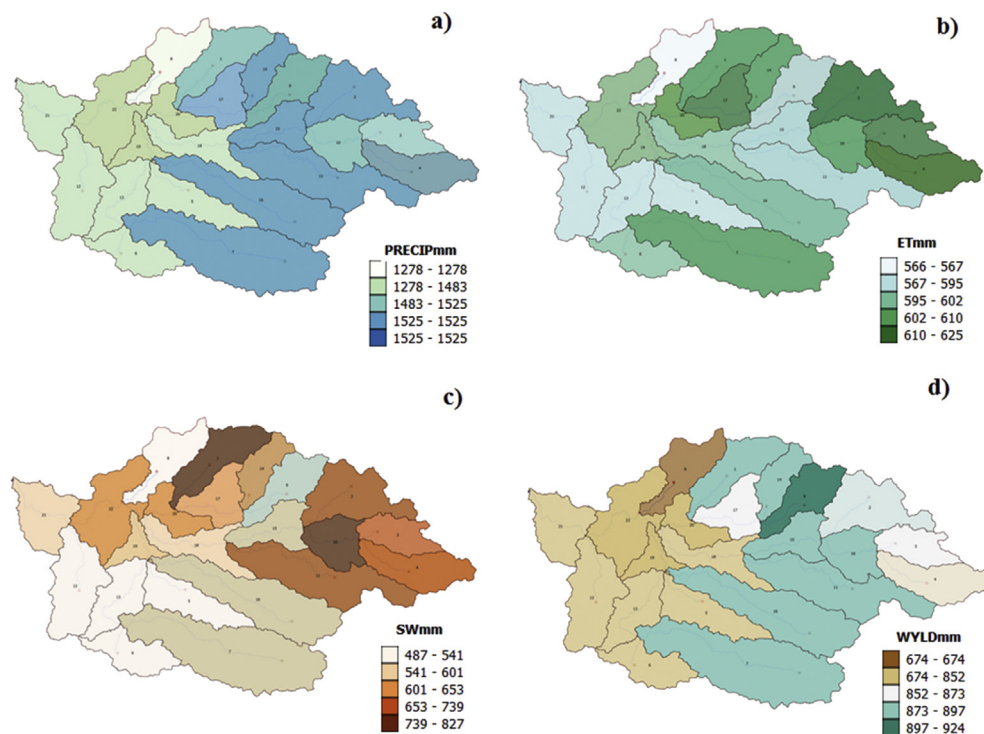

Fig. 6. Mean annual a) precipitation (PRECIPmm, mm), actual evapotranspiration (ETmm, mm), d) soil water (SWmm, mm), and d) water yield (WYLDmm, mm) for the Gumera watershed for the 1992 to 2011 period.

literature recommendation (e.g. Dile et al., 2016; Setegn et al., 2010) eight most sensitive parameters in the watershed were selected and calibrated. Table 1 presents calibrated model parameters, their descriptions, range and final fitted parameter values. The model was validated using the observed monthly streamflow data for the 2001–2007 period. The catchment was simulated with a three-year model warm-up (Daggupati et al., 2015).

The performance of the model was evaluated using Nash-Sutcliffe Efficiency (NSE) and Percent bias (PBIAS). The NSE was also chosen as objective function for calibrating the parameters in SUFI-2. NSE is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Gebremariam et al., 2014; Nash and Sutcliffe, 1970). NSE can range from $-\infty$ to 1. An NSE value of 1 corresponds to a perfect match between observed and simulated streamflow. An NSE value between 0 and 1 is considered an acceptable level of performance, whereas an NSE value ≤ 0 suggests that the observed mean is a better predictor than the model. Percent bias (PBIAS) compares the average tendency of the simulated data to correspond to the observed data (Gupta et al., 1999). The optimal value of PBIAS is 0, positive values of PBIAS indicating model underestimation and negative values indicating model overestimation (Gupta et al., 1999). Moriasi et al. (2007) suggested that PBIAS can easily quantify water balance errors and easily indicate model performance. Moriasi et al. (2007) suggested that model simulations of streamflow are considered satisfactory if NSE > 0.50, and PBIAS < ±25%.

3.5. Results

3.5.1. Model calibration and validation

The performance of the model simulation using inputs generated from the QSWAT interface were evaluated before any model parameter calibration. The NSE and PBIAS were 0.83 and −2.9%, respectively, for monthly simulations. According to Moriasi et al. (2007), the simulation with the default model parameters showed very good model performance. The negative PBIAS value indicates that the model was overestimating the overall simulation during the 1993 to 2000 period. However, a few peaks were underestimated (Fig. 4).

The calibration of SWAT model parameters using SWAT-CUP (Abbaspour et al., 2007) further improved the NSE value. The PBIAS value did not show any improvement. The NSE and PBIAS values after model calibration were 0.86 and +3%, respectively. The calibration of the model improved the agreement between observed and simulated streamflow hydrographs (Fig. 5a). During the validation period, the NSE and PBIAS values were 0.89 and 14.2%, respectively. The NSE values suggest that the model showed a very good performance during the validation period (Moriasi et al., 2007). The PBIAS suggests that the model showed good
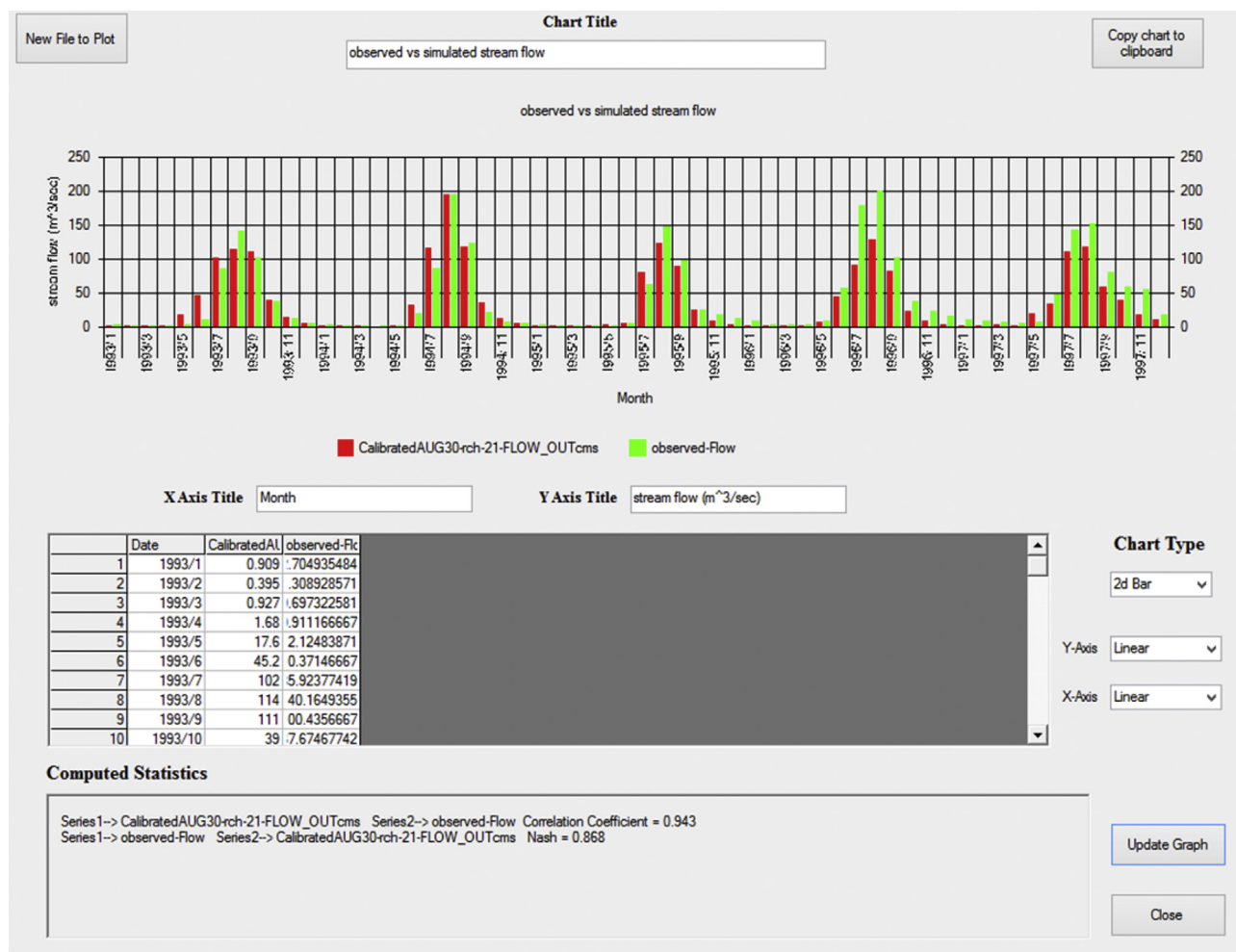

Fig. 7. SWATGraph showing observed and simulated streamflow at the outlet of Gumera watershed for the 01/1990 to 12/2000 period.

performance. Overall, the calibrated model replicated the observed flows for an independent dataset reasonably well (Fig. 5b).

3.5.2. Visualization of results

QSWAT has the capability to visualize results. It can help visualize static data, and it can animate the results at model simulated time steps. For example, Fig. 6a–d show the static annual mean precipitation, actual evapotranspiration, soil water, and surface runoff during the 1993 to 2011 period for each subbasin after model calibration. QSWAT can also show the total, daily, monthly or annual means, maxima and minima for reach and subbasin outputs. Currently, the ranges are calculated using Jenks natural breaks algorithm in QSWAT, which may not provide satisfactory ranges for small values. In such situations, equal breaks or other algorithms may be used in QGIS to calculate the ranges.

QSWAT can also display animations of the SWAT outputs. The results of the 1993 to 2000 monthly water yield (WYLDmm) animations were captured in a video and provided as a supplementary material (SI2).

SWATGraph can display and compare different scenarios. It can also compare observed data with simulated outputs. For example, Fig. 7 plots observed monthly streamflow against simulated monthly streamflow at the outlet of the watershed as histograms. It can also plot data in line graphs. SWATGraph calculates NSE and R^2 if two or more data series are available. SWATGraph provides the option of copying the chart to a clipboard to export the file for publication purposes. It also allows changing of chart and axis titles.

4. Conclusions

QSWAT, an open source GIS interface for the SWAT model, was developed on the QGIS platform. QSWAT prepares inputs for SWAT, followed by the launching of the SWAT Editor for final input preparation and execution of the SWAT model. It also provides the option to visualize the outputs. In this paper, core elements of QSWAT are presented. QSWAT performs all the functions that ArcSWAT does, along with some additional capabilities which include merging of subbasins when the delineated subbasins are small, and visualizations of outputs. Visualization of outputs both statically and dynamically can be helpful for interpreting the large amounts of SWAT outputs.

QSWAT was applied in a case study area and successfully produced inputs for the SWAT model. Model evaluation indicated that the SWAT model showed a satisfactory performance in simulating the observed streamflow. Visualization was helpful to easily analyze the SWAT outputs. QSWAT, therefore, is a credible tool in working with the SWAT model.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2016.08.004.

References

Abbaspour, K.C., Johnson, C.A., van Genuchten, M.T., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. Vadose Zone J. 3, 1340–1352. http://dx.doi.org/10.2113/3.4.1340.

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

Ames, D.P., Michaelis, C., Anselmo, A., Chen, L., Dunsford, H., 2008. MapWindow GIS. In: Encyclopedia of GIS. Springer, US, pp. 633–634.

Arnold, J.G., Fohrer, N., 2005. SWAT2000: current capabilities and research opportunities in applied watershed modelling. Hydrol. Process 19, 563–572. http://dx.doi.org/10.1002/hyp.5611.

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., Neitsch, S.L., 2012. Soil and Water Assessment Tool: Input/output Documentation – Version 2012. Texas Water Resour. Institute. TR-439.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., Ramanarayanan, T.S., Bednarz, S.T., 1998. Large area hydrologic modeling and assessment part II: model application. J. Am. Water Resour. Assoc. 34, 91–101.

Chen, D., Shams, S., Carmona-Moreno, C., Leone, A., 2010. Assessment of open source GIS software for water resources management in developing countries. J. Hydro-environ. Res. 4, 253–264. http://dx.doi.org/10.1016/j.jher.2010.04.017.

Conway, D., Schipper, E.L.F., 2011. Adaptation to climate change in Africa: challenges and opportunities identified from Ethiopia. Glob. Environ. Chang. 21, 227–237. http://dx.doi.org/10.1016/j.gloenvcha.2010.07.013.

CSA, 2012. Central Statistical Authority of Ethiopia. http://www.csa.gov.et/.

Daggupati, P., Pai, N., Ale, S., Douglas-Mankin, K.R., Zeckoski, R., Jeong, J., Parajuli, P., Saraswat, D., Youssef, M., 2015. A recommended calibration and validation strategies for hydrological and water quality models. Trans. ASABE 58 (6), 1705–1719. http://dx.doi.org/10.13031/trans.58.10712.

Dile, Y.T., Berndtsson, R., Setegn, S.G., 2013. Hydrological response to climate change for gilgel abay river, in the Lake Tana Basin – Upper Blue Nile Basin of Ethiopia. PLoS One 8, e79296. http://dx.doi.org/10.1371/journal.pone.0079296.

Dile, Y.T., Karlberg, L., Daggupati, P., Srinivasan, R., Wiberg, D., Rockström, J., 2016. Assessing the implications of water harvesting intensification on upstream–downstream ecosystem services: a case study in the Lake Tana basin. Sci. Total Environ. 542, 22–35. http://dx.doi.org/10.1016/j.scitotenv.2015.10.065.

Dile, Y.T., Srinivasan, R., 2014. Evaluation of CFSR climate data for hydrologic prediction in data-scarce watersheds: an application in the Blue Nile River Basin. JAWRA J. Am. Water Resour. Assoc. 1–16. http://dx.doi.org/10.1111/jawr.12182.

EIAR, 2007. Crop Technologies Usage (In Amharic). Ethiopia, Addis Ababa.

ENMSA, 2012. Metreological Data: the Ethiopian National Metreological Services Agency. Addis Ababa, Ethiopia.

FAO, 1995. World Soil Resources: an Explanatory Note on the FAO (Food and Agriculture Organization) World Soil Resources Map at 1:25 000 00 Scale. Rome, Italy.

Gassman, P.W.P., Reyes, M.R.M., Green, C.H.C.C.H., Arnold, J.G.J.J.G., 2007. The soil and water assessment tool: historical development, applications, and future research directions. Trans. ASABE 50, 901–910.

Gassman, P.W.W.P.W., Arnold, J.G.J.G.G., Srinivasan, R., Reyes, M., 2010. The Worldwide Use of the SWAT Model: Technological Drivers, Networking Impacts, and Simulation Trends, in: ASABE – 21st Century Watershed Technology: Improving Water Quality and Environment 2010, pp. 226–233.

Gebremariam, S.Y., Martin, J.F., DeMarchi, C., Bosch, N.S., Confesor, R., Ludsin, S.A., 2014. A comprehensive approach to evaluating watershed models for predicting river flow regimes critical to downstream ecosystem services. Environ. Model. Softw. 61, 121–134. http://dx.doi.org/10.1016/j.envsoft.2014.07.004.

George, C., Leon, L.F., 2008. WaterBase: SWAT in an open source GIS. Open Hydrol. J. 2.

George, J., 1967. The data model concept in statistical mapping. Int. Yearb. Cartogr. 7, 186–190.

Gropp, W., Lusk, E., Doss, N., Skjellum, A., 1996. A high-performance, portable implementation of the MPI message passing interface standard. Parallel Comput. 22, 789–828. http://dx.doi.org/10.1016/0167-8191(96)00024-5.

Gupta, H., Sorooshian, S., Yapo, P., 1999. Status of automatic calibration for hydrologic models: comparison with multilevel expert calibration. J. Hydrol. Eng. 4, 135–143.

Hanson, B., Sugden, A., Alberts, B., 2011. Making data maximally available. Science 331, 649, 80-.

Ince, L.D.C., Hatton, L., Graham-Cumming, J., 2012. The case for open computer programs. Nature 482, 485–488. http://dx.doi.org/10.1038/nature10836.

Krysanova, V., Hattermann, F., Wechsung, F., 2007. Implications of complexity and uncertainty for integrated modelling and impact assessment in river basins. Environ. Model. Softw. 22, 701–709. http://dx.doi.org/10.1016/j.envsoft.2005.12.029.

Krysanova, V., Srinivasan, R., 2014. Assessment of climate and land use change impacts with SWAT. Reg. Environ. Chang. 15, 431–434. http://dx.doi.org/10.1007/s10113-014-0742-5.

Lautenbach, S., Volk, M., Strauch, M., Whittaker, G., Seppelt, R., 2013. Optimization-based trade-off analysis of biodiesel crop production for managing an agricultural catchment. Environ. Model. Softw. 48, 98–112. http://dx.doi.org/10.1016/j.envsoft.2013.06.006.

Mohamed, Y.A., van den Hurk, B.J.J.M., Savenije, H.H.G., Bastiaanssen, W.G.M., 2005.

Hydroclimatology of the Nile: results from a regional climate model. Hydrol. Earth Syst. Sci. 9, 263–278.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidlines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50, 885–900.

MoWE, 2012. Hydrological Data: the Ethiopian Ministry of Water and Energy (MoWE). Addis Ababa, Ethiopia.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptualmodels: part 1. — A discussion of principles. J. Hydrol. 10, 282–290.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R.R., King, K.W., 2012. Soil and Water Assessment Tool Theoretical Documentation Version 2000, Soil and Water Assessment Tool Theoretical Documentation, Version 2000. Grassland Soil and Water Research Laboratory, Agricultural Research Service, Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas.

Panagopoulos, Y., Makropoulos, C., Mimikou, M., 2012. Decision support for diffuse pollution management. Environ. Model. Softw. 30, 57–70. http://dx.doi.org/10.1016/j.envsoft.2011.11.006.

Schuol, J., Abbaspour, K., Srinivasan, R., Yang, H., 2008a. Estimation of freshwater availability in the West African sub-continent using the SWAT hydrologic model. J. Hydrol. 352, 30–49.

Schuol, J., Abbaspour, K.C., Yang, H., Srinivasan, R., Zehnder, A.J.B., 2008b. Modeling blue and green water availability in Africa. Water Resour. Res. 44, 1–18. http://dx.doi.org/10.1029/2007WR006609.

Setegn, S.G., Srinivasan, R., Melesse, A.M., Dargahi, B., 2010. SWAT model application and prediction uncertainty analysis in the Lake Tana Basin, Ethiopia. Hydrol. Process 367, 357–367.

Srinivasan, M.S., Gérard-Marchant, P., Veith, T.L., Gburek, W.J., Steenhuis, T.S., 2005. Watershed scale modeling of critical source areas of runoff generation and phosphorus transport. J. Am. Water Resour. Assoc. 41.

Srinivasan, R., Arnold, J.G., 1994. Integration of a basin-scale water quality model with GIS. J. Am. Water Resour. Assoc. 30, 453–462. http://dx.doi.org/10.1111/j.1752-1688.1994.tb03304.x.

SRTM, 2015. Source of the 30 M Resolution. http://earthexplorer.usgs.gov/ (accessed 12.10.15.).

SWATPubDatabase, 2015. SWAT Publication Database. http://swat.tamu.edu/publications/ (accessed 8.31.15.).

Tarboton, D.G., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resour. Res. 33, 309. http://dx.doi.org/10.1029/96WR03137.

Tesfa, T.K., Tarboton, D.G., Watson, D.W., Schreuders, K.A.T., Baker, M.E., Wallace, R.M., 2011. Extraction of hydrological proximity measures from DEMs using parallel processing. Environ. Model. Softw. 26, 1696–1709. http://dx.doi.org/10.1016/j.envsoft.2011.07.018.

Vandenberghe, V., Bauwens, W., Vanrolleghem, P.A., 2007. Evaluation of uncertainty propagation into river water quality predictions to guide future monitoring campaigns. Environ. Model. Softw. 22, 725–732. http://dx.doi.org/10.1016/j.envsoft.2005.12.019.

Wilson, J.P., 2012. Digital terrain modeling. Geomorphology 137, 107–121. http://dx.doi.org/10.1016/j.geomorph.2011.03.012.

Winchell, M., Srinivasan, R., Di Luzio, M.J., 2013. ArcSWAT 2.3.4 Interface for SWAT2012. Temple, Texas.

Wu, Y., Li, T., Sun, L., Chen, J., 2013. Parallelization of a hydrological model using the message passing interface. Environ. Model. Softw. 43, 124–132. http://dx.doi.org/10.1016/j.envsoft.2013.02.002.