Open-source GIS software and components for modelling watershed phenomena

Understanding the soil and water components under different management options with QGIS and the SWAT+.

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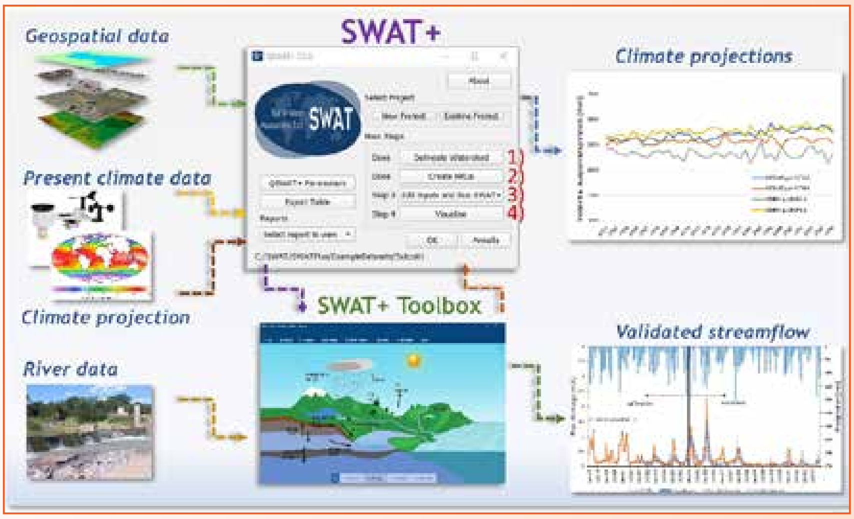

Fig. 1 – Workflow with input and output components for running SWAT+ through the QSWAT plugin for QGIS.

Open source GIS, and in particular QGIS, is a leading free and open source solution for desktop mapping since many years already. Its versatility, ease of use, and analytical power have made it the software of choice for many professionals around the world (see https://analytics.qgis.org). Field data collection a

Modelling the watershed balance

Current and future climate change are expected to increase our challenges in preserving natural resources and ecosystem services. At the watershed scale, the processes taking places relate to interactions between soil and water and are influenced by land use management. Precipitation, infiltration, runoff, evapotranspiration, soil erosion, soil and water pollutions are the main components to be considered whenever for the simulation of the watershed system within the current and future conditions under changing drivers (i.e., human interventions and climate change). One of the most popular watershed modelling tools is the Soil and Water Assessment Tool (SWAT), a public domain model jointly developed by USDA Agricultural Research Service and Texas A&M University (Arnold et al., 1998). SWAT has been used worldwide for different applications (water quality, land use, soil erosion, crop yield, etc.) during the last four decades. As of May 2022, a total of 5154 articles report SWAT applications within different journals according to the SWAT Literature Database (https://www.card.iastate.edu/swat_articles/).
SWAT enables the simulation of watershed and river basin quantity and quality of surface and ground water under the influence of land use, management, and climate change. It can be used to monitor and control soil erosion, non-point source pollution and basin management. An entirely reconstructed version of SWAT, nicknamed SWAT+, was only launched in recent years to improve the capabilities of SWAT code maintenance and future development. Reservoir operation functions have been added to SWAT+ in addition to the new model structure to increase model simulation performance. Now, the physical objects (hydrologic response units (HRUs), aquifers, canals, ponds, reservoirs, point sources, and inlets) are built as separate modules.

QSWAT: the QGIS plugin for the new SWAT+ model

SWAT model was implemented withing the GIS environment with dedicated plugins both for commercial and open-source GIS platforms. The GIS implementations has allowed users to manage more efficiently the watershed modelling process in its natural environment, the GIS, where the spatial component of the various datasets can be handled straightforwardly. QSWAT is the most recent implementation as QGIS plugin, written in Python, of the new version SWAT+. As of 6th April 2022, QSWAT3 v1.5 for QGIS3 was released for 32 and 64bit machines. SWAT+ is written in FORTRAN and is also available as command-line executable file that runs text file inputs without interface (SWAT+ installer 2.1.0 was released on 31 March 2022 for Windows, Linux, and MacOS). QSWAT is increasingly gaining momentum thanks to the spreading and robustness of the open-source GIS platform. QGIS has a huge number of users and a solid reputation. It is utilized in academic and professional settings, and it has been translated into more than 48 languages. Moreover, the release of SWAT code as open source has benefitted the diffusion and improvement of the model by making it more robust and suitable for different applications thanks to the collaboration of several users with various expertise. Different channels are available for users' collaboration such as QSWAT user group, SWAT+ Editor user group and SWAT+ model user group (https://swat.tamu.edu). Other plugins are also available, such as the one developed for the commercial ESRI ARCGIS (ArcSWAT). Beyond the functions provided by QSWAT for setting the watershed to be analysed, SWAT+ is complemented by additional software: SWAT Editor (a user interface for modifying SWAT+ inputs and running the model installed

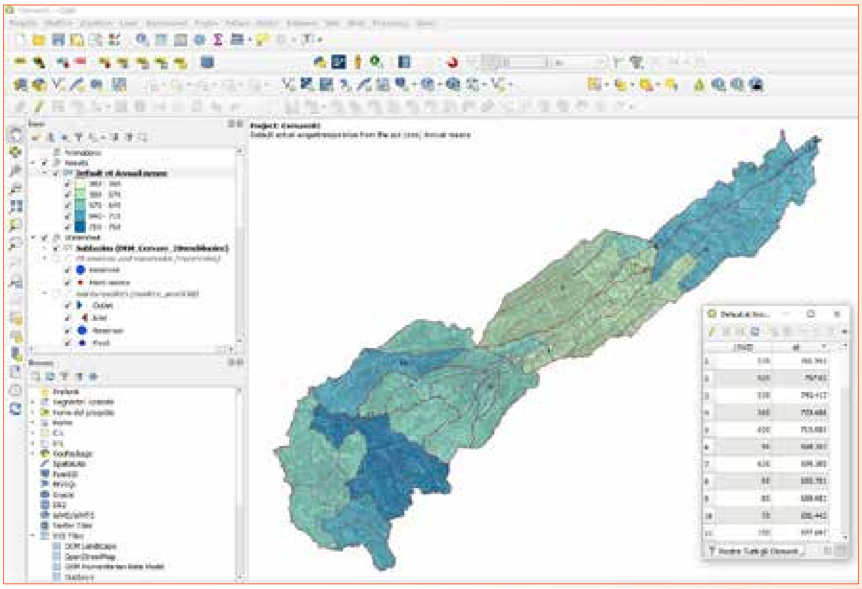

Fig. 2 – Spatial distribution of annual means of the actual evapotranspiration from the soil at subbasin scale for a watershed through QSWAT.

along with QSWAT), SWAT+ Toolbox (a user-friendly tool for SWAT+ for sensitivity analysis, manual and automatic calibration), SWATplus-CUP (the Calibration Uncertainty Program for SWAT+ requiring a license purchase) and SWATplusR (a set of tools taking advantage of the R environment for parameter sensitivity analysis, model calibration and the analysis model results). Moreover, the SWAT website provides datasets for running the model even if specific datasets, with adequate spatial and temporal resolution, are always recommended for the study areas to be analysed. The datasets available have often global coverage and are relative to climate, soil, land use and Digital Elevation Models (DEMs). Look up tables are also supplied with QSWAT to properly match to standard legends the land use and soil codes.

The four-steps process and the minimum set of data for running SWAT+

The following spatial and tabular data are required for running SWAT+: Land use/cover, DEM, Soil data (hydrological group, clay, silt, sand), Climate data (temperature, precipitation, humidity, solar radiation, wind speed) and Hydrology (river discharge).

QSWAT runs SWAT+ by following a four-step procedure: 1) Delineate watersheds, 2) Create Hydrologic Response Units (HRUs), 3) Edit inputs and run SWAT, and 4) Visualize.

The first step deals with the definition of the watershed and its structure by extracting the channels and the watershed boundary by processing the DEM of the study area with the classical Terrain Analysis Using Digital Elevation Models (TauDEM) functions that divide the watershed in subbasins (areas with a principal stream channel). The second step involves the creation of the HRUs, lumped areas with the same combination of soil, topography, and land use, not spatially related to each other (Rathjens et al., 2016). The third step concerns the weather data selection and the set-up of model parameters. For instance, the latter are relative to the potential evapotranspiration method (e.g., Priestley-

Taylor, Penman-Monteith or Hargreaves), curve number method for soil moisture, land use management and conservation practices. The fourth step is dedicated to the visualization of the results at basin and sub-basin scale and to the outputs exploration for a given channel and gauge.
The model can simulate daily, monthly, yearly, and average outputs for different model components (e.g., channel, aquifer, reservoir, etc.), for nutrient balance, water balance, plant weather and losses from the basin, HRUs and landscape units. Results can be printed and exported in different formats such as tabular or text structure.

Calibration and validation

After the SWAT+ run and the production of the outputs, model calibration and validation are strongly recommended.
The model can be calibrated and validated for hydrologic, sediment, nitrogen, and phosphorus components. These last steps guide the user on the fine-tuning process of the model parameters to produce results coherent with the real watershed processes. It requires the collection of data on river discharge that are often missing for several watersheds or available in analogic format, moreover water quality data (e.g., sediments load, dissolved oxygen, nitrate and phosphorous concentrations, etc.) can be used. Alternative approaches for hydrology calibration may involve the use of evapotranspiration data from satellite data to overcome the lack of river discharge data from the gauge stations at the outlets. SWAT+ allows several options for calibrating and validating the simulation under the different parametrizations defined by the users. A sensitivity analysis is quite common approach undertaken to pinpoint the main sensitive parameters and to reduce their redundancy during cal/val process. Literature review is always useful to start listing a set of common parameters affecting streamflow and sediment yield process. SWAT-Calibration and Uncertainty Programs (SWAT-CUP) is by far the most known tool for assessing the sensitivity of parameters by providing several model evaluation techniques based on the relevant statistics (e.g., Pearson's correlation coefficient, root mean square error (RMSE), etc.). Following the identification of the most sensitive parameters the calibration and validation phase are carried out by focussing on specific components (e.g., daily discharge). The time series of the available data (e.g., t0-tn) is divided to provide a reference period for the warm-up (e.g., t0-t5), calibration (e.g., t6-t15) and validation (e.g., t16-tn).
Finally, model performances are assessed by using classical statistic measures (e.g., RMSE).
Calibration and validation can be long and tedious. Therefore, it is always recommended to follow a precise work protocol (Abbaspour et al. 2018).
Extending model simulation capabilities: land use management and climate change
The impact of alternative land uses, and climate change are pressing concerns in different regions of the world. SWAT+ allows modelling diverse land use scenarios to meet sustainability goals (Pulighe et. al., 2020) through a module where alternative land management practices can be defined (e.g., ploughing, seeding, tillage, irrigation, fertilization rates and crop nutrients uptake, etc.), by defining dates or specific land use classes and regions.
Similarly, climate projections from climate models under different representative concentration pathways (RCPs) scenarios of greenhouses emissions can be loaded as weather data to create climate scenarios for the future decades that can be compared to the baseline period covering the historical meteorological data. SWAT+ can ingest these

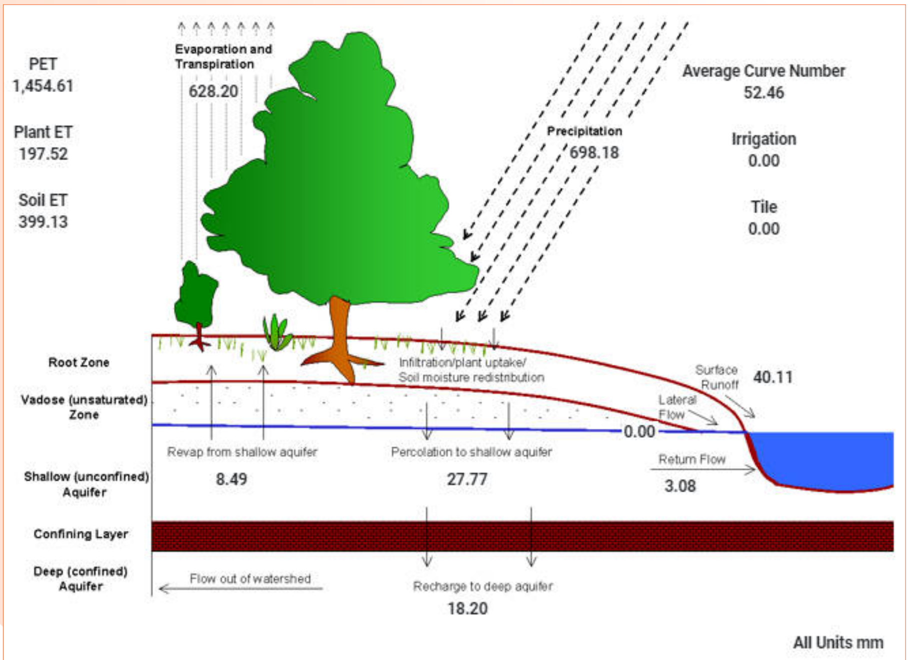

Fig. 3 – Schematic representation of the hydrology outputs at watershed level through QSWAT.

data for simulating seasonal changes in precipitation and temperatures, hydrological extremes, flow regime alterations and river discharge, future water quality (i.e., nitrogen and phosphorus) and soil erosion conditions, and future biomass production. Estimating the mentioned effects on the hydrological regime might have strong impacts also on agricultural activities posing challenges to land use management and irrigation (Pulighe et al., 2021).

Conclusions

Open-source GIS (QGIS) and free to use models such as SWAT+ can be considered effective and strategic tools for monitoring and assessing water and soil interactions at the watershed level. In addition, the growing availability of public domain geospatial datasets can increase the applicability of the simulation of the watershed processes worldwide and for a wide variety of use cases. QSWAT will be a valuable tool for the SWAT scientific community thanks to the full integration with the geospatial functions, the new functionality offered by SWAT+ and the contribution of a wide and growing open-source community. QSWAT could be a powerful tool to assess the effects of climate change and land use management and the impacts on water quality and land degradation. We believe that in the near future, the evaluation of the effectiveness of policy interventions and the deployment of sustainable soil/water management practices will become an interesting arena for experimenting and acknowledging the potentiality of SWAT+.

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METAKEYS

QGIS; QSWAT; WATERSHED; RIVER BASIN; SWAT+; CLIMATE CHANGE

ABSTRACT

The Soil and Water Assessment Tool (SWAT) enables the simulation of watershed and river basin quantity and quality of surface and ground water under the influence of land use, management, and climate change. It can be used to monitor and control soil erosion, non-point source pollution and basin management. The recent version (SWAT+) was implemented by a dedicated QGIS plugin (QSWAT) widening the userbase and the potential modelling application worldwide. QSWAT, along with additional software for preparing the input dataset and for performing the calibration/validation phase, further extends the watershed modelling capabilities. Such tools and the growing diffusion of public open geospatial datasets are expected to increase the range of applications especially with the availability climate projections datasets. The latter will enable users to simulate all the water-soil phenomena at watershed level under future conditions to better understand and plan suitable action for preserving the natural resources.

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