Integration of MOHID Model and Tools with SWAT Model

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Abstract

MOHID Water Modelling System is an integrated state of the art modular system, composed by a series of models that simulate surface water bodies, streams and watersheds. MOHID's code development follows a methodology which improves its robustness related to programming errors. MOHID is written in ANSI FORTRAN 95, profiting from all its new features, including the ability to produce object oriented code, although it is not an object oriented language. It includes object oriented features. This results in a series of object oriented models for simulating the water cycle which integrates several different scales and processes.

SWAT source code was partially modified, namely in the inputs and outputs of the model, using MOHID's code and programming philosophy. These changes maintained the integrity of the original model, thus guarantying that results remain equal to the original version of SWAT. This allowed to output results in MOHID format, thus making it possible to immediately process it with MOHID visualization and data analysis tools.

MOHID River Network is a river model developed in European funded project (TempQSim). A link between SWAT and MOHID River Network was developed. Presently, two modified versions exist, based on the two SWAT releases (SWAT2000 and SWAT2005).

The inclusion of output result files in HDF5 format is currently under development. This allows the visualization of watershed properties (modeled by SWAT) in animated maps using MOHID GIS and animation tools. These tools allow the production of animated files showing the spatial and time evolution of the modeled properties.

The modified version of SWAT described here has been applied to various national and European projects. Results of the application of this modified version of SWAT to estimate diffuse nutrients loads to estuaries and water bodies will be shown.

MOHID source code and its support tools are freely available under the GNU Public License.

KEYWORDS: SWAT-MOHID, Hydrological, Statistics, Mondego

Introduction

SWAT has demonstrated its potential in analyzing the water cycle and the related hydrologic fluxes at the catchment scale and the associated nutrient transport in study sites all around the world (Arnold & Fohrer, 2005). The release of the source code is surely one of the reasons of SWAT success. The free access to the code allowed also the many modified versions of SWAT allowing its adaptation to users needs.

Like SWAT, MOHID is an open source code model under the GNU Public License, and has users all around the world. MOHID is written in ANSI FORTRAN 95, profiting from all its new features, including the ability to produce object oriented code with it, although it is not an object oriented language. It includes object oriented features like those described in Decyk et al (1997). This development strategy resulted in a series of object oriented models for simulating the water cycle which integrates several different scales and processes. This type of programming allowed a straightforward integration of SWAT and MOHID models and tools.

Two modified versions of SWAT were developed, based on the two SWAT releases (SWAT2000 and SWAT2005). The functionalities described herein are equal in both versions. So we refer to this modified versions in this paper has SWAT-MOHID. However, all the results showed here were obtained with SWAT2005 version. The aim of these developments is not to replace the use of SWAT graphical user interfaces for input or output, but to complement it. This also means that the developed outputs do not include all the SWAT variables but instead, they were developed on a need basis either for easier exploring, results analysis, model coupling, etc. This development benefits from many current developments and improvements of MOHID tools made by its users and will continue to benefit in the future. To make this development sustainable two important aspects were taken into account: i) the use of a source code version control software to keep track of changes made by many users in the code ii) the use of online discussion forum and wiki (using Wikipedia technology) that together allow s the users to help each other and to participate in the documentation of the models and tools.

One of the reasons to develop SWAT-MOHID was to compute nutrient loads onto surface water bodies (e.g. reservoirs, estuaries), using them has boundary conditions for models like MOHID Water and CeQualW2.

So far the coupled version of MOHID and SWAT has been used to study the dynamics of eutrophication in several Portuguese reservoirs and estuaries.

This paper shows the developments made in SWAT using Mohid tools and presents the results of the application of SWAT-MOHID to the Portuguese Mondego Watershed. The application of the model was made in the framework of HARP-NUT Guidelines, which allows making an annual comparison between the load oriented approach to the source oriented approach(Borgvang & Selvik, 2000; Schoumans & Silgram, 2003). Only the hydrodyamic calibration for Mondego is shown in this paper.

SWAT-MOHID

SWAT source code was partially modified, namely in the inputs and outputs of the model, using MOHID's code and programming philosophy. These changes maintained the integrity of the original model, thus guarantying that results are equal to the original version of SWAT. A first modification was the implementation of time series outputs. The modified SWAT source code enables the user to output time series for two geometric entities found in SWAT: (i) hydrological response units (HRU) and (ii) or sub-basins/reaches.. The output of the time series is done with a frequency which is independent of the "normal" SWAT output and the format of the time series is done in MOHID format.

Time series written for selected HRU's are organized in four categoiries: (i) meteorological information, (ii) plant growth, (iii) nutrient concentration and (iv) erosion. Time series written fro selected sub-basins/reaches are nutrient concentration, sediments concentrations and the water flows into the reaches.

Since the time series are written in MOHID format, the user has two new possibilities: (i) use MOHID tools to analyze them or (ii) use them as boundary conditions for a detail river network model (MOHID River Network). These features are described in more detail later in this paper.

MOHID time series are stored as ASCII files, with syntax very similar to XML files. Figure 1 shows an example of a MOHID time series. The header section contains general information (reference date, time units used and the identification of each column), followed by a block which contains columns with the actual data. The first column represents the time passed since the reference date.

Figure 1. Example file of a MOHID Time series.

MOHID Time Series editor

MOHID Time Series Editor is a graphical user interface written in VB.NET which allows the user to visualize in a straightforward way MOHID time series required or produced by the MOHID numerical programs.

In each time series graphic window it is possible to change the features of the graphic using the available buttons in the menu located above the graph, namely: 1) Chart Type: opens a Command and Options window allowing the selection of several actions: General, Border/Fill, Data Sheet, Type, Series Groups, Show/Hide; 2) Show/Hide Legend: selecting the button causes the appearance of the legend, clicking on it again makes the legend disappear; 3) Commands and Options: opens a Command and Options window allowing the selection of several actions: General, Border/Fill, Data Sheet, Type, Series Groups, Show/Hide; 4) Chart Wizard: opens a Command and Options window allowing the selection of actions concerning Data Source, Data Sheet and Type; 5) CheckBox1: checking it allows the selection in Window Width [days] the number of days to appear in the graph and in the ruler the location in the time interval of that number of days; 6) Save Image: saves the graph as a GIF or JPEG file in the path provided by the user. This sample representation of a time series file shows.

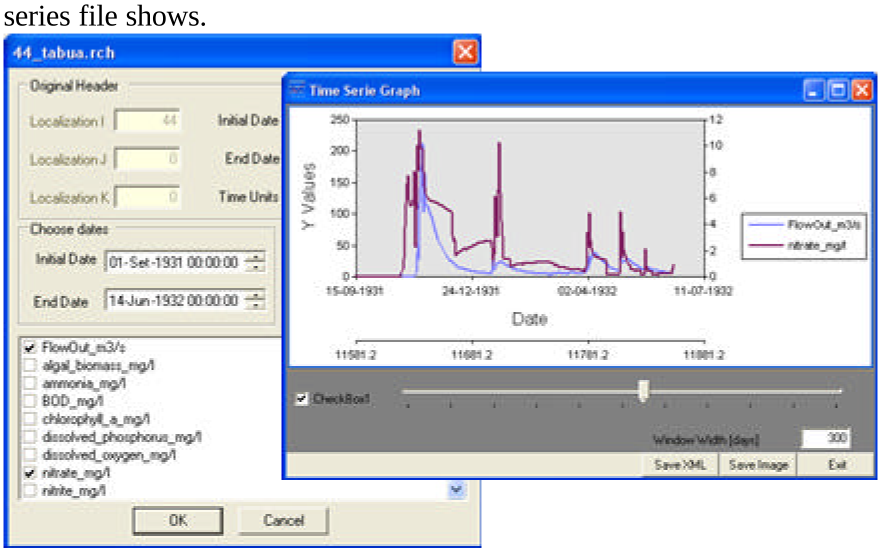

Figure 2. Example of the visualization of two reach SWAT results: flow and nitrate concentration.

MOHID Time Series Analyzer

The MOHID Time Series Analyzer application calculates statistics and obtains graphs of comparison between two time series data. Running options for this application are specified in a graphical interface. For model validation or model comparison studies it is useful to calculate comparison statistics and graphs. The MOHID Time Series Analyzer allows the computation of such information for one or more properties with two site specific time series files in a user-friendly way.

The information is obtained based on data located on a time window. That time window is defined as the time period for which data in both time series exists and any further constrain indicated by the user in the interface. If time instants in the two time series are different then the second time series data is linearly interpolated for the first time series data time instants.

The MOHID Time Series Analyzer statistics output is organized in the Statistic (All), Statistic (Daily) and Statistic (Monthly) tabs, for statistics considering all data, daily averages and monthly averages, respectively.

This output is only produced after the data input by the user in the General tab and the successful data processing. In each of the statistics tabs the information content is similar: 1) Observed Average (average of the first time series); 2) Modeled Average (average of the second time series); 3) Bias; 4) RMSE (root mean square error); 5) R2 (Pearson product-moment correlation coefficient); 6) Model Efficiency (Nash-Sutcliffe coefficient). These parameters are proposed by Evans et al. (2003) to evaluate model efficiency.

MOHID HDF

MOHID's HDF class is a class on the top of the Hierarchical Data Format (HDF library). HDF is a general purpose library and file format for storing scientific data, developed and maintained by the United States National Center for Supercomputing Applications. The main functionality of this library is to store matrix data in a structured way (Braunschweig et al., 2004).

The inclusion of output result files in HDF5 format is currently under development. This allows the visualization of watershed properties (modeled by SWAT) in animated maps using MOHID animation tools like MOHID-GIS (Figure 3). These tools allow the production of animated graphic files showing the spatial and time evolution of the modeled properties. The user decides on the time step output. For each output a vector with the values of soil water content of each sub-basin is stored.

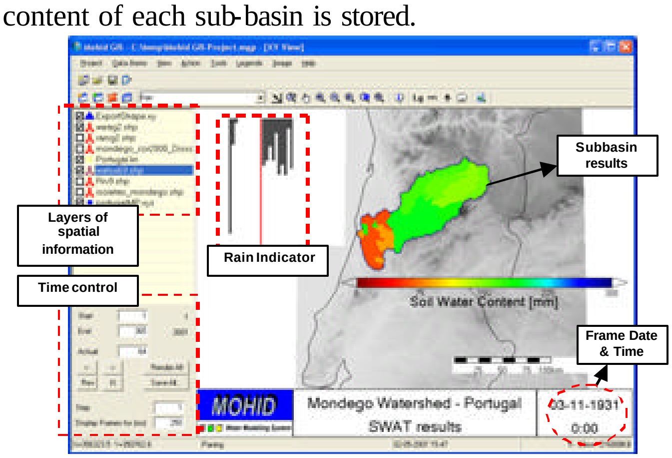

Figure 3. SWAT Soil Water content results and visualization in MOHID-GIS using the HDF result files produced by SWAT-MOHID (see complete animation in: http://www.mohid.com/Gallery/Swat_HDF_view.gif)

Coupling SWAT with Mohid River Network

Common problems for the application of basin models in the temporary catchments are related to: i) Periods without runoff (which results in numerical problems for most models) ii) Extreme first flush effects with the beginning of the rain period (sub-hourly time steps required in simulations) iii) Quality of the water (sediments, solutes) is frequently poor described in the models and highly variable in time.

In order to respond to such demands a physical based model, the TempQsim STREAM model, was developed (Galvão et al., 2005). This model is currently maintained by MOHID group under the name MOHID River Network (MRN). MRN computes water, sediments and properties transport in a river network. The model is written in FORTRAN 95 and follows an object oriented programming philosophy with a finite volume approach (Braunschweig et al, 2004). The different processes occurring in the river are programmed in different modules. This model has been calibrated for Vène watershed (France) with a special focus on the transport of particulates for the first significant flood events (Obermann, 2007).

Fluid flow in this model is governed by conservation equations for mass, momentum, energy and any additional constituents and the numerical algorithm is based on the finite volume approach. Following this strategy it is easier to build conservative transport models and coupling between modules is also simpler because it is based on fluxes. Object oriented programming was also used, which facilitates model coupling. An interface between this model and SWAT was also developed in order to simulate agriculture in the catchment using MOHID for simulating the river network and the corresponding sediment transport and biochemistry (Chambel-Leitão et al, 2006) (Figure 4). SWAT source code was slightly changed so time series of flow / properties are produced for each sub-basin. A "watsub" theme with the location of the outlets of each sub-basin (created by SWAT ESRI ® ArcView extension) is read by MOHID GIS and dynamically construct links between the time series locations of SWAT and discharge nodes of the MRN. MRN runs using surface runoff, lateral flow and groundwater flow from SWAT as input discharges. Property concentrations can be considered constant (user supplied) or can be an output of modified SWAT.

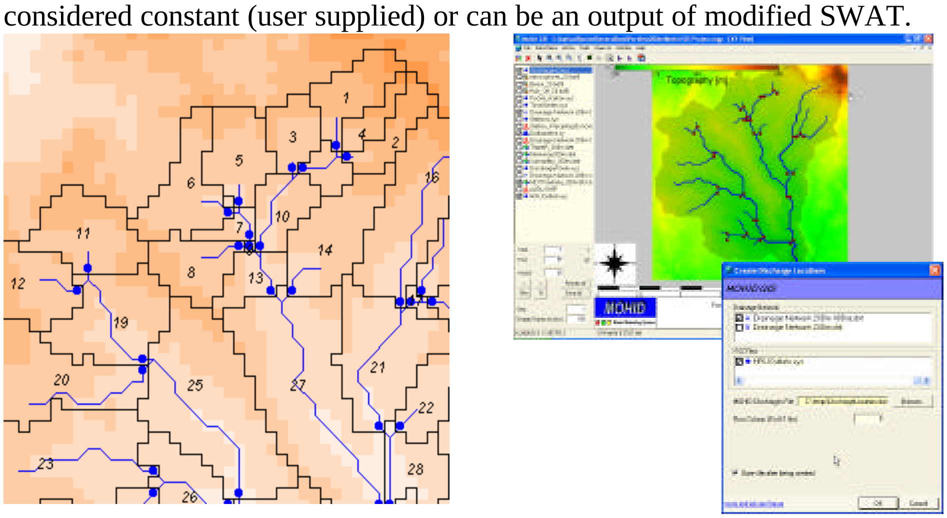

Figure 4. Connection of SWAT and MOHID River Network using MOHID-GIS interface.

In the framework of the TempQsim project (www.tempqsim.net) the problem of temporary waters and the role of rainy events for the total river budgetwas addressed. Rainy events are the major challenge of catchment models and specifically of SWAT. For this reason MOHID Land (www.mohid.com) was developed allowing to the use of variable fine grids and a dynamic time step determined by the iterative procedure.

SWAT-MOHID coupling was tested for Pardiela Basin. Pardiela is a temporary river located in the south Mediterranean part of Portugal called Alentejo covered by undulating plains ranging from 50 m to 400 m elevation. A first run was made with SWAT model and MOHID coupled with SWAT, for similar river networks, to see if they were producing the same results. For similar channel manning's N coefficient, flow results were the same (Figure 5). In both models the Kinematic wave equation was used (Neitsch et al., 2000).

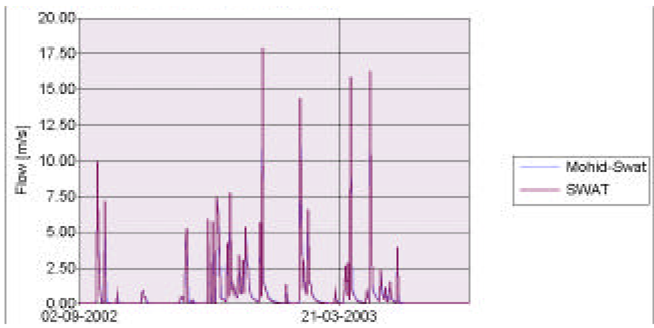

Figure 5. River flow in Swat compared with flow in Mohid coupled with Swat .

SWAT-MOHID application

The modified version of SWAT described here, SWAT-MOHID, has been applied to various national and European projects. Results of SWAT-MOHID will be shown for the Mondego watershed Mondego River is located in the central region of Portugal drains to the Atlantic Ocean a basin with an area of about 6700 km^2. This river basin has an elongated shape with the longest axis orientated NE–SW and the maximum altitude is nearly 2000 meters. The Mondego itself is the largest entirely Portuguese river with a length of 234 km and is located in a region of transition between Atlantic to Mediterranean climate. In the early 90's the estuary was object of important geomorphologic modifications in order to improve navigability and the upper communication between the two arms was closed. In the late 90's symptoms of eutrophication have been identified. However comparing land use from CORINE land cover from 1990 and 2000 the agriculture area has decreased. In order to simulate the nutrient dynamics of the watershed and its effects on the estuary, data was gathered to setup SWAT-MOHID model.

The digital elevation model (DEM) is in a raster format with a grid resolution of 70 m, which has been clipped from the Shuttle Radar Topography Mission (SRTM) DEM data (Hounam & Werner, 1999).

The land use map (Figure 6) has been clipped from the CORINE (released in 2000 obtained in http://dataservice.eea.europa.eu/dataservice/) whose legend is based on the CORINE level 3 legend. The original legend entries were reclassified and, in some cases, aggregated to conform to the land use database present in the SWAT model (the watershed results included 15 land use classes). For simplicity of representation Figure 6 shows only four classes composed from level 1 classes of CORINE.

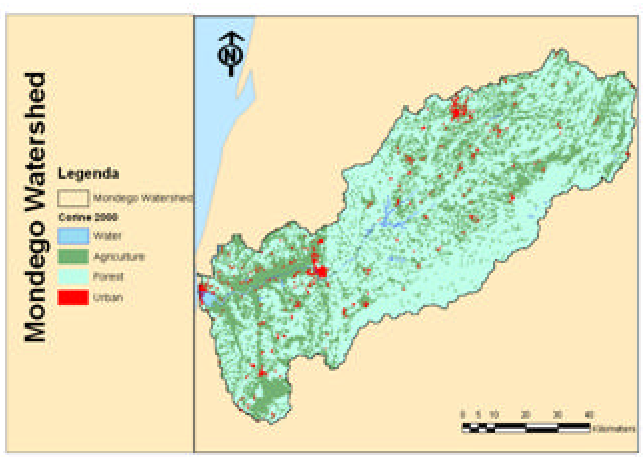

Figure 6. Simplified land use map. LU/LC in the Mondego watershed area (Corine 2000). i) Water - Wetlands + Water bodies; ii) Agriculture - Agricultural areas; iii) Forest - Forest and semi natural areas; iv) Urban - Artificial surfaces

The soil map 1:1 000 000 was gathered from EEA data center in vector form covering the entire Mondego Watershed. This data set was first digitalized by Platou et al (1989) and further improved by Vossen & Meyer-Roux (1995) [1]. The physical-chemical parameters needed to fill the SWAT soil database were produced using pedotransfer functions based on texture (Saxton et al., 1986). Daily precipitation data were obtained for several stations in the area; only those having long near-complete time series were retained. Daily precipitation values from 1931 to 2002 were obtained for seven stations (http://snirh.pt). Monthly values of maximum and minimum temperature, solar radiation, wind speed, and relative humidity were available for four meteorological stations for a period of 30 years (ISA, 2004): Caramulo, Penhas Douradas and Viseu. Several daily flow stations were available for model calibration. Three of them were chosen (Tábua, Mucela & Coimbra) because they had long near-complete time series (thirty to fourthly year data), which were included in the time period of precipitation data selected (http://snirh.pt).

Flow results were evaluated using MOHID Time Series Analyzer and the results are shown in Figure 7, Figure 8 for Coimbra gauge station and in Table 1 for the three gauge stations the obtained statistic parameters. To obtain these results the changes made in relation to SWAT defaults were: GW_DELAY=10, ALPHA_BF=0.5 and distribution of the precipitation stations in the sub-basins according with Isohyets.

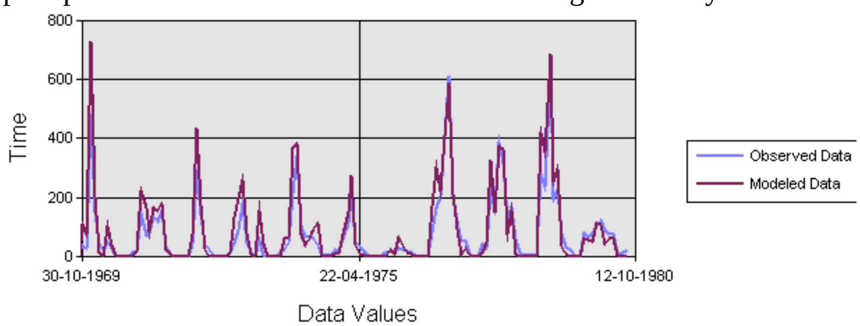

Figure 7. Monthly values of observed and modeled data in Coimbra gage station. Graph produced with MOHID Time Series Analyzer

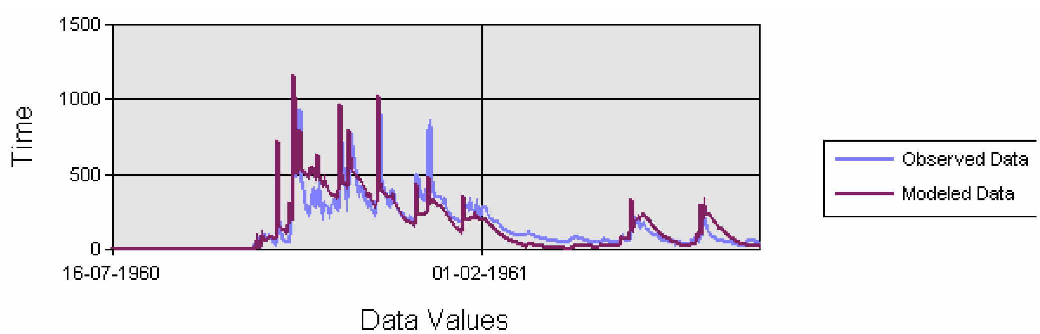

Figure 8. Daily values of observed and modeled data in Coimbra gage station. Graph produced with MOHID Time Series Analyzer.

Flows simulated show a correlation (R2) always higher than 0.69 with 30 year measurements of the three gauge stations (Table 1). This means that the general dynamics of the watershed is satisfactory. However in the case of the Tábua gauge station the model efficiency is low, basically due to an underestimation of flows. This tendency also happens in Mucela and Coimbra but the differences are smaller (Figure 7 for the case of Coimbra). The excess simulated flow can be related either to an underestimation of evapotranspiration or it can be related with the underestimation of water lost to the deep aquifer. This last value is

[1] http://dataservice.eea.europa.eu/dataservice/metadetails.asp?id=196

difficult to estimate. However, the evapotranspiration estimation can be significantly improved if the soil depth is known (as well as other soil parameters). In this simulation a constant soil depth in all watershed of 1 meter was assumed.

Table 1. Evaluation of flow results after calibration for a thirty years period. Values produced with MOHID Time Series Analyzer.

Flow gage station	Coimbra		Tabua		Mucela	
	Daily	Monthly	Daily	Monthly	Daily	Monthly
RMSE - Root Mean Squared Error [m3/s]	88	51	37	25	15	9
R2 - Pearson Product -Moment Correlation Coefficient [-]	0.78	0.91	0.76	0.9	0.69	0.83
E - Model eficiency (Nash-Sutcliffe) [-]	0.69	0.82	0.05	0.27	0.52	0.68

Figure 8 shows that it is possible that base flow is being underestimated. This could also be related with an underestimation of soil retention of water or with a wrong parameterization of the aquifer in SWAT.

A wrong estimation of evapotranspiration could be a reason for wrong flow results. This could be related with a wrong input to the SWAT weather generator or with wrong estimations of this model. To analyze this, a search was made to find a long period of historical values of some climatic parameter (temperature, relative humidity, wind or radiation). A period of daily temperature between 1982 and 1990 was obtained for meteorological station of A lagoa (reference 12G_05) which is situated in the center of the watershed. These values were compared with the output of average temperature of SWAT-MOHID of the subbaisin where Alagoa meteorological station was located (Figure 9). The model efficiency for the daily values of temperature was 0.54 while for monthly values the efficiency increased to 0.8. These are considered good results taking in consideration that they were obtained from a meteorological station different from the ones used as input for SWAT weather generators.

No values of relative humidity, wind or radiation were found for long periods of historical measurements for this area.

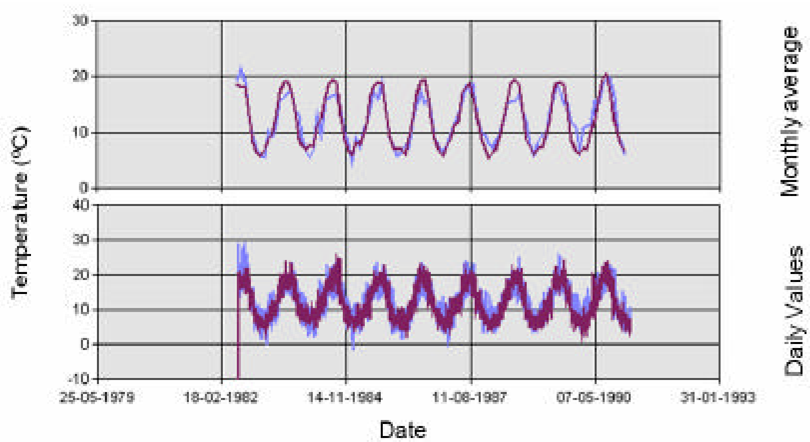

Figure 9. Monthly and Daily values of observed (blue) and modeled (reddish) data in Alagoa meteorological station. Graphs produced with MOHID Time Series Analyzer.

The next step in the application of SWAT will be to find a better soil map for the area, because the present one, though it allowed reasonable results of hydrodynamic, it is surely not enough to estimate the nutrient transport. For example, a constant value of 0.8 % of organic carbon content was assumed. Though this is a typical value in Portuguese soils, it is surely not adequate to estimate the nutrient dynamics in the soil. A second step will be to compile the most frequent agricultural practices in the area and introduce them in to the model.

In November 2006 European Soil Database V2[2] was made available with the associated maps at a scale of 1:1.000.000. This will allow producing a comprehensive map of soil parameters to make a more realistic simulation of nutrients. National soil specialists are also be contacted, to try to find better soil data. In Portugal there is very few soil maps published, and mainly in the South of Portugal (Gonçalves et al., 2005).

With a new soil map it will be possible to obtain HARP-NUT results (loads of total nitrogen and phosphorus per year) originated on anthropogenic diffuse sources and Background sources of nutrients. To estimate Background loads of nutrients the model will be run assuming that the all watershed is covered with oak tree forest.

Conclusions

MOHID and SWAT have free access source code. This has allowed the integration of some aspects of both models. This allowed the use of the advantages of each model. Current version of SWAT-MOHID allows: i) the output of time series and allows them to be compared statistically using MOHID Time Series Analyzer ii) a link between SWAT and MOHID River Network iii) storing of subbabsin and reach results in HDF format which, associated with MOHID-GIS, allows to produce animated graphic files showing the spatial and time evolution of the modeled properties.

The advantage of application of SWAT-MOHID is mainly the improved capabilities to analyze results. The aim of these developments is not to replace the use of SWAT graphical user interfaces for input or output, but to complement it. This also means that the developed outputs do not include all the SWAT variables but instead, they were developed on a need basis either for easier results exploring, results analysis, model coupling, etc. This development benefits from many current developments and improvements of MOHID tools made by its users and will continue to benefit in the future.

Flows simulated in Mondego watershed (considering both daily and monthly averages) show a correlation (R2) always higher than 0.69 with 30 year measurements of the three gage stations. However the model seems to be underestimation flows, though the simulation results in the most downstream station (Coimbra) has an monthly Efficiency of 0.82 and of 0.69 for daily results.

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[2] http://eusoils.jrc.it/ESDB_Archive/ESDBv2/index.htm

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