Transboundary watershed modelling - problems and limitations on the Minho international river (Iberian Peninsula)

João Rocha[a], Peter Roebeling[b], Henrique Alves[c] Pedro Almeida[d]

(a) Dept. Environment and Planning - CESAM - University of Aveiro, Portugal
joaocrocha@ua.pt

(b) Dept. Environment and Planning - CESAM - University of Aveiro, Portugal
peter.roebeling@ua.pt

(c) Dept. Environment and Planning - CESAM - University of Aveiro, Portugal
henriqueteloalves@ua.pt

(d) Dept. Environment and Planning - CESAM - University of Aveiro, Portugal
pedrof.almeida@ua.pt

ABSTRACT

In this paper we discuss the problems encountered in applying the Soil and Water Assessment Tool (SWAT) to international river basins, and propose solutions to overcome these problems. A case study is provided for the application of SWAT2009 model assemblage for the Minho international river basin (Iberian Peninsula).

Three major areas of concern were identified: non harmonized spatial data; non harmonized time series data; and non-normalized input data. First, the SWAT model assemblage data acquisition process was initially a major concern as the input data (climate, hydrology) and the gaps on the daily records reduced the analysis scope from a 20 year to 10 year period. Second, the different types of cartographic data (scale, output cell size, projections and coordinate systems) created several issues on the two countries databases overlay. Finally, the model calibration represented also a challenge due to heterogeneous distribution of temporal and spatial data.

Proposed solutions to these problems included: alternative data sources to fill the gaps on spatial and temporal databases, statistical correlations between different climate stations, and GIS geo-mathematical techniques. The overall SWAT modelling presented several challenges throughout the model data acquisition, assemblage and later calibration and validation processes for the simulated scenarios.

KEY WORDS: *Transboundary watershed modelling, Water quality assessment, Swat Model Inputs*

INTRODUCTION

Worldwide, water resources management has become a major concern in governance and policies strategies – either focused on agricultural land use activities and irrigation systems maintenance, or on floods, droughts and erosion control, and on water quality and drinking water supply.

Over the past decades there has been a growing human occupation of territories, included in the watersheds, often accompanied by scenarios of unsustainable development and unplanned anthropogenic activities. These forms of land use and territory occupation provoked inevitable consequences on water quality, on the maintenance of ecosystems, and on human well-being.

Transboundary water management deals with numerous challenges due to the complexity of policies, social, cultural, historical, and physical relationships (Timmerman & Langaas, 2005). Within the involved countries and institutions, as Botterweg and Rodda (1999) stress, exist complex processes with many actors at different levels that, in turn, are supported by the three pillars of sharing water resources: technical, political, and institutional (Savenije & van der Zaag, 2000).

Effective sustainable and integrated water resources management relies not only on socio-political issues but, also, on the use of environmental data as input for transboundary watershed modelling that may be used as a tool supporting decisions. Environmental data are considered to be a prime component in policy decision-making (Timmerman and Langaas, 2005), although a great deal of the existing environmental data is underestimated and no great attention is given to physical, chemical, biological, and climate data (Timmerman, 2004). Environmental data are considered to be the basis for watershed modelling as they will be used as input parameters for the accurate modelling scenarios and for the model calibration (observed data versus simulated data) and subsequent validation of the model results.

International river basin modelling is often a challenge for hydro-physical modellers due to the quantity of involved data, the different data sources accessed, the gaps in available spatial and temporal data, as well as the different cartographic and alphanumeric databases offset. Regardless of the final objective of the watershed simulation (watershed process models (e.g. rainfall-runoff prediction, flood mitigation, water quality and quantity assessment, land use and irrigation planning, hydropower operations); hydro-economic watershed models; multi-objective decision making models; conflict resolution models (Mirchi *et al.,* 2010)), they can provide a comprehensive and reliable understanding of problems and can be used to simulate different scenarios. Both simulation and optimization model results can support the creation of several alternatives on water management issues linked to legal-political as well as socioeconomic objectives (Heinz *et al.,* 2007) and, therefore, can help to establish several management approaches.

The correct choice of the model depends, as Yang and Wang (2010) stress, on the objective of the study. Hence the different types of available models must be able to create an accurate, precise and realistic representation of both watershed system response and our understanding of reality (Fenicia *et al.,* 2008).

Although the term "transboundary" can be used to address limits between systems, interfaces, and countries, in this paper the transboundary term is used in the sense of administrative or politic limits between two or more countries

– following the Convention on the protection and use of transboundary watercourses and international lakes (Helsinki in 1992) and enforced by the United Nations (UN/ECE, 1992)

This paper discusses the input data gathering and harmonization challenges encountered in the Soil and Water Assessment Tool (SWAT; Neitsch *et al.,* 2005) model assemblage for the Minho international river basin (Iberian Peninsula), that was used to assess Dissolved Inorganic Nitrogen (DIN) water pollution by the major agricultural sectors in the catchment. When addressing transboundary rivers, several difficulties can be linked to the model preparation, to the model calibration and validation. For the case study of the Minho River, three major areas of concern were identified: non-harmonized spatial data; non-harmonized time series data; non-normalized input data.

The present study is focus on the SWAT2009 model (datasets) preparation and application for Minho international catchment in order to assess DIN water pollution deliveries and to determine the costs related to the adoption of Best Agricultural Practices (BAPs) across agricultural sectors. The SWAT model is undertaken to simulate stepwise reductions scenarios in N-fertilizer application rates for the agriculture activities. To asses the corresponding DIN water pollution deliveries several BAPs scenarios were established for water quality improvement by the key agricultural land use categories (Roebeling, 2011; Rocha, 2011). Following Rocha (2011) the SWAT2009 model can be used to perform a wide range of BAP´s and linked environmental (e.g. water quality) and economic (e.g. agricultural production-yield) impacts, and therefore, can result on an accurate approach to assess cost-effectiveness BAP adoption.

The next section provides a background for the SWAT2009 model input data acquisition and normalization. Next, we present the steeps for the model settle as well as the related issues on the several stages, from the watershed delineation throughout the final stages. Next, we debate the creation of management schedules and the linked best agricultural practices scenarios.

SWAT model input data

SWAT is a catchment scale continuous-time model that integrates water quality, hydrology, topography, climate, soil, nutrients, land cover and management, pesticides and vegetation cover parameters (Arnold *et al.,* 1998; Neitsch *et al.,* 2002; Gassman *et al.,* 2007).

The data acquisition and the database construction was a major concern as the different time series for the input data (climate, hydrology, and water quality) and the gaps on the daily values reduced the analysis scope from the theoretical modelling period of 20 years to a set of 10 year simulations. Second, the different types of cartographic data (scale, output cell size, projections and coordinate systems) created several issues on the overlay of the databases of the two countries. The model detail range was affected by

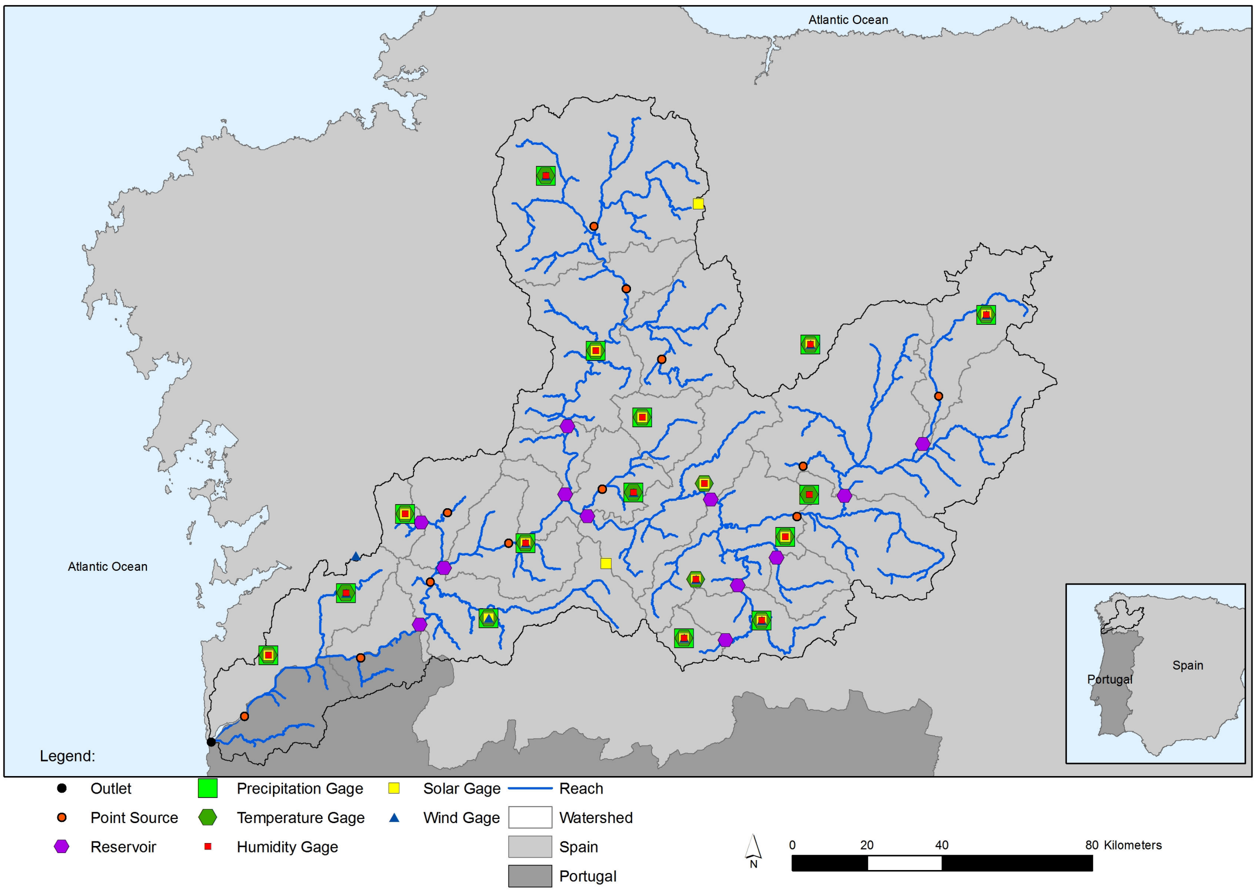

Figure 1. Minho watershed delineation, linked sub-basins and used gages

the lack of harmonized records. Finally, the model calibration represented also a challenge due to heterogeneous distribution of temporal and spatial data, resulting in an erratic hydrologic pattern and also in undesirable calibration options and scenarios. As Srinivasan (*et al.,* 2010) stresses, often the observed data for model calibration are very limited, and the calibration relies on the modellers experience and expertise.

Across the literature (Ouyang *et al.,* 2006; Ndomba *et al.,* 2008; Galván *et al.,* 2009; Girolamo & Porto, 2012; Hoque *et al.,* 2012; Wagner *et al.,* 2012: Anderson *et al.,* 2012) references are found regarding the lack of data, and also to the gaps in data series – either with spatial or with temporal emphasis. The database construction for the weather, flow and quality daily series was initially set for the 1991-2011 period, though later reduced to the 2001-2010 period – hence the major data converging and harmonised records were within this last period.

The weather data definition was based on measured daily precipitation (rain gages), minimum and maximum temperature (from 2001-2010), relative humidity (from 2006-2010), solar radiation (from 2003-2010), and wind speed (from 2003-2010) data. The weather data gap fill was aided with 7 reference stations (weather generators) scattered throughout the catchment area (6 weather stations in Spain (Sp), and 1 in Portugal (Pt)). Although some “no data” records were found, the weather pattern was established with good quality coverage.

In the flow data, no major temporal and spatial parallel was available between the Pt and Sp gauges, as there is only one available Pt gage (with daily flow records for the 1980-2005 period) and for the Sp gauges the records are available only 4 gages. For the latter gages, all but one is located inconveniently for a rational sub basin division of the watershed. Although the model was settle for the 2001-2010, there are several missing records with gaps varying from several days to whole months and, as a result, the model calibration was made with 6 Sp flow gages for the 2007-2010 period.

Watershed delineation

To execute the watershed delineation, the Digital Elevation Model (DEM) was first created on 25 m based topography data, from both Portuguese and Spanish cartographic institutes. The shape files used to create the DEM raster file were, however, in different coordinate and projection systems which, in turn, generated some overlapping gaps that were later reduced. Although those gaps were corrected, the 25 m contour lines had different altitude values (on the shapefile attribute table) for the same location and, as a result, this alphanumeric data was not used. The SRTM 90 raster file was considered to be an option for the DEM support definition, though not used as some reclassification procedures failed to create a reliable cartographic base to join the two countries’ watersheds.

Hence, the watershed was delineated using the MTN25 raster file (http://cnig.es) for the Spanish part and 25m resolution contour altitude lines shapefiles for the Portuguese side. The two DEMs created were then fixed with respect to the differences of coordinate and projection systems. To merge them it was necessary to smooth and equalize the relief, which, as mentioned before, was uneven in the overlapping areas. For this the Mosaic tool of the Spatial Analyst of ArcGis software was used, resulting in a single raster which blends the discrepancies in altitude by using an algorithm that takes into account an average of the blended values as well as the distance from the centre of one pixel to the border of the overlapping pixel. From the initial 25 m resolution data, the used DEM was settled for a 100 m resolution with corresponding losses in detail.

For the stream network definition, similar projection and coordinate system issues were resolved using the 25m resolution shapefiles, and no major gaps were found. As a result a high detail stream network was created. The threshold based stream network definition was created with a 500 ha area.

For outlet and inlet definition the model assemblage faced one of the first nuisances in terms of geographical gauges distribution and pattern concentration, and the different time series for the input data (flow, water quality, and reservoirs). Although the Minho catchment (figure. 1) area covers only 4,8% (825 km^2) of the Portuguese mainland territory, the relative abundance of gauges is quite different – with fewer available monitoring stations than in the Spanish part of the Minho catchment area. On the other hand, the reservoirs are located on the Spanish territory. It was virtually infeasible to delineate independent sub-basins for the Portuguese part due to the stream network positioning relative to the Portuguese-Spanish border. Although the model tries to recreate the watershed as a whole it would be very interesting and of high information value to measure pollutant outputs by country, for example. The option to minimize this problem was to delineate two watersheds downstream of the dam. This way two sub-basins were created which cover the totality of the Portuguese part of the watershed while, at the same time, their areas are roughly divided in half between the two countries, which facilitates further calculations and extrapolations. The watershed delineation process ended with 20 created sub-basins.

The land use definition was done using the Corine Land Cover 2006 (CLC) shapefile data set with a 100m resolution (EEE, 2009). Some misclassified land cover classes were found between the two countries, resulting in a minor difficulty to establish the correct linkage within some CLC categories. For example, as the CLC categories are very generic and doesn’t detail the locations of the agricultural land uses needed to build the model, the solution was to use comprehensive agricultural statistics (REF). The watershed was divided into 6 areas: 5 provinces in Spain and 1 district in Portugal. The statistics were compiled by province/district but taking out the municipalities not included in the watershed. The areas of the different land covers were then allocated to the most likely corresponding CLC classes. The results were agricultural land use classes composed of other cultures within them (sub-cultures), with the same CLC class being occupied by different cultures in different provinces/districts in accordance to the statistics. The same procedure was used to infer forest areas, bush lands and grasslands. The only direct uses of the CLC classes were the cases of urban and industrial areas, and water bodies.

The soil data was created using the European Soil Portal of the Joint Research Centre (ESP/JRC, 2012). A shapefile with the soils of the Iberian Peninsula, containing both the geographic location and the description of the soil types, was coupled with detailed measurements of the soil characteristics (SROA, 1970, FAO-ISRIC-ISSS, 2006).

The groundwater database was established using Spanish sources as these cover the majority of the basin area and because no Pt groundwater data were available. The Confederación Hidrográfica Miño - Sil (Hydrographic Confederation of the Minho-Sil) provided aquifers distribution as well as groundwater parameters (e.g. measured groundwater levels, recharge delay and base flow recession constant). Aquifers loaction data were overlaid with the sub-basins as to assign each sub basin to the proper aquifer and to the corresponding input data.

The water use database was created by overlaying the available data from the Spanish Hydrographic Confederation.

Agricultural management practices

Agricultural management practices are not exactly the same across the considered countries (e.g. different land uses and territory occupation patterns), although they were merged to create standard land management practices and operations scenarios. On the Iberian Peninsula the agriculture land cover is not exclusively defined by one particular land use category (e.g. corn, pasture or vineyard) – there are also complex occupation patterns of small agricultural parcels combining several crops (corn fields bordered by fruit trees;, potatoes and corn on the same parcel; vineyard bordered by fruit trees). The CLC nomenclature defines some agricultural areas sub-divisions (e.g. annual crops associated with permanent crops; complex cultivation patterns) for which no precise crop combinations could be established. As a result the land cover patterns, the management operations and the linked operations schedules were established using the national agriculture inventories and the agriculture statistics from both countries (INE, 2012 a; b). Farmers' expertise was also taken in account to create a more accurate management schedule for the vineyard (based on Rocha *et al.,* 2011, Roebeling *et al.,* 2011).

The SWAT crop database and management operations (corn, vineyard, pine, and eucalyptus) updated and improved from previous works (Rocha *et al.,* 2011, Roebeling *et al.,* 2011, Rial-Rivas *et al.,* 2011, Nunes *et al.,* 2013) was used for the Minho catchment. The operations schedule, set by date, comprehends a wide range of operations, in which the corn, vineyards and pastures crops have meticulousness detail easily comparable with farmers' actual practices.

Considered BAPs for reduced N exportation rates and linked water quality improvement include reductions in fertilizer application rates, with gradual reductions ranging from 100% to 20% (current application rates to reduced application rates) in steps of 10%. For Portugal and Spain these BAPs are described in the Code of Best Agricultural Practices (MADRP, 1997- PT; MAGRAMA, 1998- SP), and are based in the 91/676/CE Directive on the protection of waters against agricultural nitrate pollution (see Roebeling *et al.,* 2012).

To asses various N-fertilizer application BAP scenarios and to establish potential relationships between crop yields, gross margins and DIN exportation levels, three major management practices were considered:

- gradual reduction in single application rates (1 application) corresponding to the current practices-APA;
- gradual reduction in fractionated application rates (2 applications) - BP1 ;
- gradual reduction in slow release application rates (slow release fertilizers) - BP2.

The model was run, on a daily basis for the 2001-2010, and the simulation first year was considered as a warm-up period. Sensitivity analyses were carried out, and showed that: CN2.mgt; GW_DELAY.gw; GWQMN.gw; GW_REVAP.gw; REVAPMN.gw; RCHRG_DP.gw; ESCO.hru; EPCO.hru; SOL_AWC().sol are the most sensitive parameters.

The SWAT model is being automatically calibrated using the Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspour *et al.,* 2004; Abbaspour *et al.,* 2007) within the SWAT Calibration Uncertainty Procedures (SWAT-CUP) programme routines.

CONCLUSIONS

In this study we prepare the SWAT2009 input data for the Minho transboundary catchment (2001-2010 period) using the available datasets for both Portugal and Spain. To this end three major areas of concern were identified: non harmonized spatial data; non harmonized time series data; and non-normalized input data. As a result we created a harmonized database for all the SWAT input with fixed gaps on the daily records (10 year period), with a harmonized cartographic data (scale, output cell size, projections and coordinate systems) and temporal and spatial data distribution.

The approach developed in this paper contributes to the actual implementation and achievement of BAPs using SWAT based-scenarios (stepwise reductions in N-fertilizer application rates) to assess DIN water pollution deliveries across agricultural sectors, estimating the costs associated with achieving specified water quality improvement objectives.

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