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WATER RESOURCES AND THE REGIME OF WATER BODIES

Breaking Walls Towards Fully Open Source Hydrological Modeling[1]

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Abstract—Hydrological models are powerful mathematical tools to address environmental problems and are often used for watershed management and planning. Hydrological models are data driven and the lack of data availability often limits model development. In this paper, we address several challenges in building and running a hydrological model for streamflow simulations based solely on freely available data and open source software. The Soil and Water Assessment Tool (SWAT) hydrological modeling software has been used in the Map Window Geographic Information System (GIS). All spatial and non-spatial data used in this study were obtained from various free of charge online sources. Model calibration and validation represent major challenges following the initial model construction since they involve several trial and error processes to reach acceptable model performances. These critical steps were programmed here as automated scripts in the *R* open source statistical package. The challenges of model building are described step by step through video tutorials. Using a case study in the Mendoza watershed in Argentina, we show that simulated streamflow exhibits sound agreement with the observed streamflow considering daily time steps (NSE = 0.69, $R^2 = 0.72$ and Percent bias = +9%). The workflow demonstrated in this study can be applied for other watersheds, especially in data-sparse regions that may lack key regional or local data sets.

Keywords: SWAT model, open source software, free data, hydrology

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INTRODUCTION

Managing water resources correctly should play a significant role for building a more sustainable world, especially in the face of climate, land cover and demographic changes that we are experiencing at the global scale [19]. Applications of hydrological models for addressing various issues that are linked with water resources are under increasing demand [1, 6, 16–18]. Hydrological models are mostly data driven and there is a growing need for data to address an increasing number of water-related issues (e.g., pollutions, floods, biodiversity and ecosystems conservation, energy production, food security and water scarcity). Encouragingly, there are now various providers of spatial and non-spatial data available online for hydrological research, including NASA, USGS, FAO and others [2–4, 11].

Different kinds of challenges often limit our ability to build and calibrate hydrological models. These mainly include data scarcity, software requirements and availability, and computational capacity. This complexity can be of various levels depending on the objectives of the study. As an example, to model diffuse or heavy metal pollutions, observational data on the pollutants is needed to calibrate the model and evaluate its performance, but this data is rarely available. Another important barrier can be software availability, which may involve choosing free and open source solutions over proprietary packages based on cost considerations (especially in developing countries).

The Soil and Water Assessment Tool (SWAT) [1] (http://swat.tamu.edu/) is an open source hydrological model that is based typically on daily time steps simulations. SWAT models are traditionally built on the ArcGIS proprietary platform [20], but they can

[1] The article is published in the original.

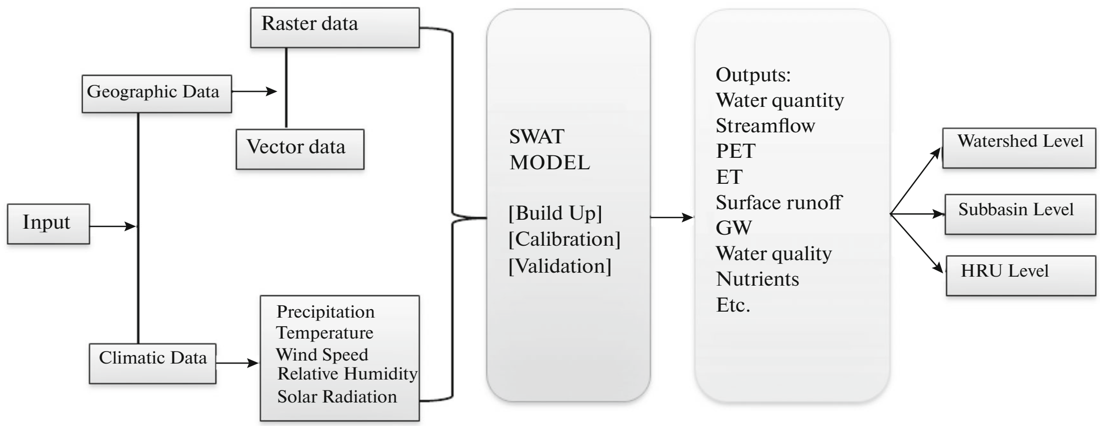

Fig. 1. Flow chart of data and software requirement for SWAT model preparation, calibration and validation.

also be prepared on the Map Window open source GIS interface [7] MWSWAT (http://www.waterbase.org/download_mwswat.html), which is an extension of Map Window. The major processes that SWAT simulates are water, sediment and nutrient flows. SWAT describes the hydrology of the selected catchment by estimating several processes: interception, evapotranspiration, surface runoff (SCS curve number method, USDA Soil Conservation Service, 1972), soil percolation, lateral and groundwater flows, and river routing (variable storage coefficient method, Williams, 1969). SWAT considers the catchment to be divided into sub-basins, river reaches, and further hydrological response units (HRUs). While the sub-basins can be delineated and located spatially, the further subdivision into HRUs is performed in a stochastic manner by considering the observed unique combinations of land use, soil, and slope, without any specified location in each sub-basin [14]; hence, it is considered to be a semi-distributed hydrological model. SWAT has been extensively used in various regions around the world (for a review, see [6]).

The goal of this paper is to propose a methodology for efficiently assembling and preparing the minimum set of required input data to build a SWAT model for any watershed in the world. This methodology is based solely on freely available data and open source software solutions. The proposed methodology is presented in online videos on the technical steps required for data extraction and preparation, and for model calibration and validation. We illustrate our methodology through a case study in the Mendoza River watershed in Argentina. Finally, we discuss the limitations of our methodology and the implications of emerging environmental data sharing in the global context.

DATA AND METHOD

Spatially distributed or semi-distributed hydrological models are data-driven; therefore the availability of data for building a model remains a major issue. Data requirement for building a hydrological model in SWAT can be subdivided into three major categories: geographic, weather and hydrological data (see Fig. 1). These data are typically structured according to several main data models such as tables, GIS raster, GIS vector or multi-dimensional arrays (e.g., NetCDF).

Digital Elevation Model (DEM), Land Use (LU) and soil maps are raster datasets, while river geometry comes typically in vector formats, hydrological and weather data as tables, and climatic data as arrays of points. Raster data are available in various resolutions ranging from several kilometers to a few meters per pixel. Evapotranspiration (ET) data can now also be obtained from global ET and aridity index from the Consultative Group on International Agricultural Research (CGIAR) data portal, with 1 km resolution. Since ET is not an essential input for a SWAT model we did not use it here for the model building phase. Similarly, the vector data are available at very different scales. For the weather data, the minimum requirements are for precipitation and for minimum and maximum daily temperatures. Hydrological data concern essentially water flow, water quality and sediment loads. Both weather and hydrological data are generally made available as simple data tables. Finally, the outputs from global and regional climate models that can be used to predict the impacts of climate changes on the hydrological model are usually stored in NetCDF format. Table 1 presents the data used in the Mendoza catchment case study.

Table 1. Data used for the Mendoza catchment in Argentina

Data Type	Data Sources	Scale/Resolution	Description-Web site
DEM	SRTM	90 m	Elevation http://srtm.csi.cgiar.org
Land use	GlobCover	1000 m	Classified land use such as crop, urban forest water etc. http://ionia1.esrin.esa.int
Soil	FAO	1 : 5000000	Classified soil and physical properties such as sand, silt, clay, bulk density. http://www.fao.org/climatechange/54273/en
Hydrological network	Hydroshed	1 : 25000	River network http://hydrosheds.cr.usgs.gov
River flow	GRDC	–	River discharge http://grdc.bafg.de
Weather	NCDC	–	Precipitation, Temperature, Wind Speed, Solar radiation http://www.ncdc.noaa.gov

Mendoza Watershed Case Study

The Mendoza River watershed covers 19553 km^2 (see Fig. 2). The peak flow occurs during summer due to snow and glacier melt. We focus on the upper portion of the watershed that covers 7291 km^2. The major land covers are vegetation, bare rocks, shrubs, snow and glaciers. Detailed information on the watershed can be obtained from [8]. The flow variations are quite significant ranging from peak flow at 150–200 m^3/s to low flow around 15–20 m^3/s. The river plays an important role for domestic use at the downstream area of Mendoza city.

Spatial Data

DEM was obtained from the shuttle radar topographic mission (SRTM) with a 90 m resolution. The SRTM produced the most complete, highest-resolution digital elevation model of the Earth [5]. The land-use grid comes from the Global Land Cover Characterization with a 1 km resolution (GLCC, Version 2). The soil map was produced by UNESCO and FAO as the Soil Map of the World at a scale of 1 : 5000000 (FAO, 1995). The soil and land-use associated characteristics were obtained from the literature [17, 18]. The Digital global stream network was obtained from the USGS public domain geographic database HYDROSHED.

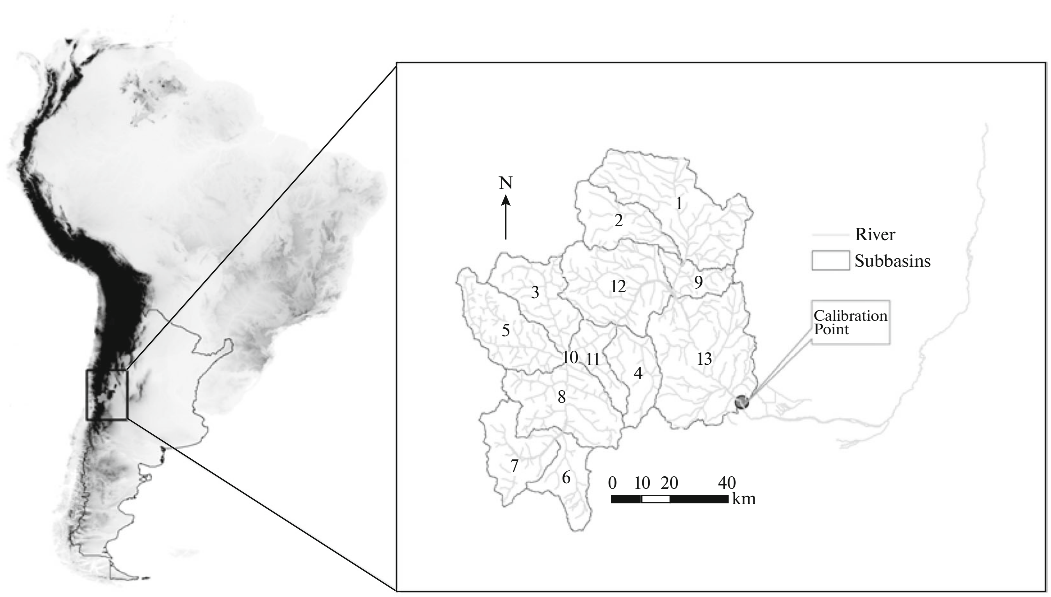

Fig. 2. Study area map showing the calibration point and the delineation of the sub-basins.

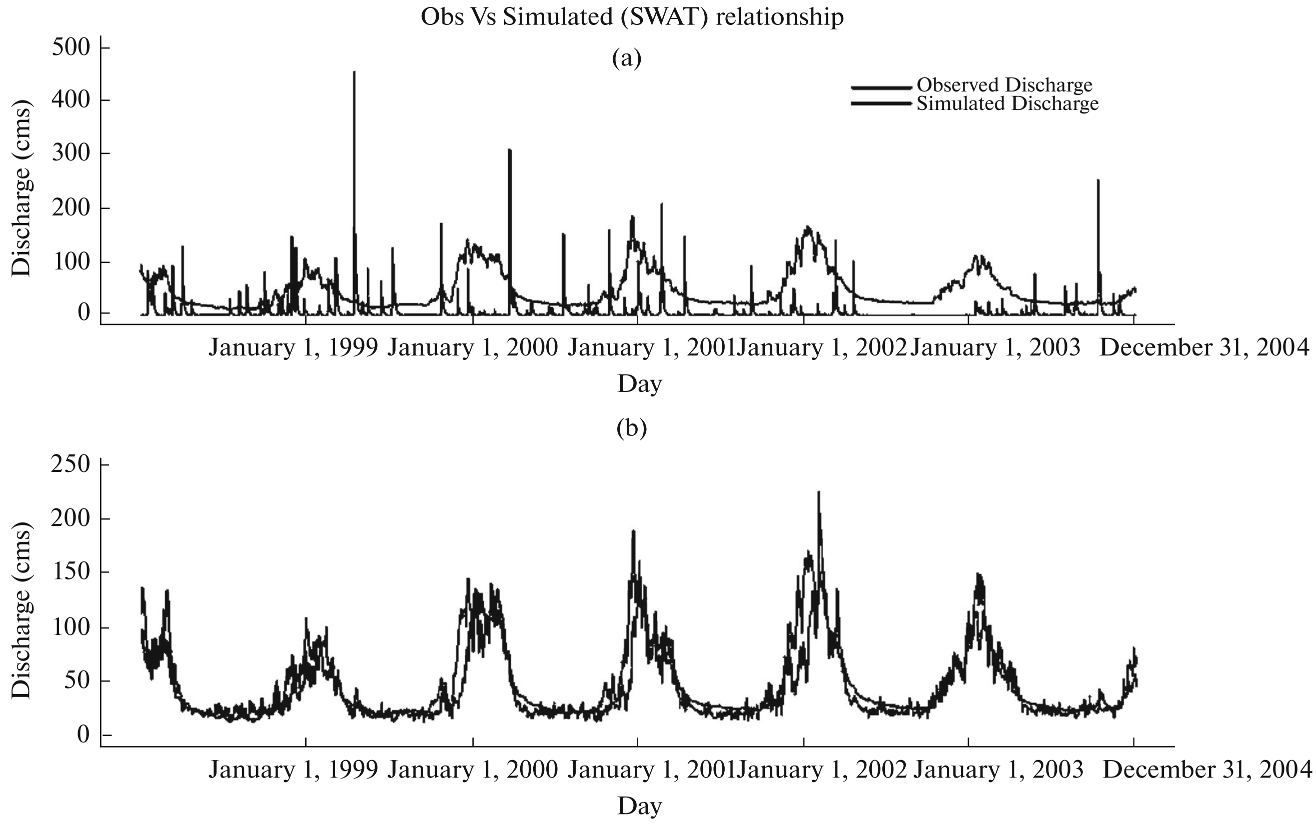

Fig. 3. Mendoza catchment observed vs. simulated discharge before (a) and after (b) calibration.

Weather Data

For this case study we used precipitation and temperature data from National Climatic Data Center of the United States of America and from the World Meteorological Organization. Various spatial and temporal issues arise when building the SWAT model; four major problems are notified here: (1) discontinuity of time series, (2) scale differences, (3) unexpected characters, (4) changes of units, from Fahrenheit to centigrade, or from inches to millimeters. The solution proposed to solve these issues is a set of scripts developed in *R* in order to track and correct all these issues by harmonizing data. These scripts are made available as a supplement to this article.

SWAT Model Building and Calibration

At first, the model simulated with globally available data performed very poorly. In order to optimize the default parameter settings, we run the SWAT executable in *R* interface and optimize the parameters based on climatic characteristics of the study area. The parameters related to snow and glacier melt (TLAPS and PLAPS) are adjusted based on the existing contours of the glacier mass balance studies. This evaluation is based on the following goodness-of-fit statistics: Nash Sutcliffe Efficiency (NSE) [13], R^2 and Percent Bias (PB). The calibration scripts are also provided as supplements.

RESULTS

Before model calibration, three major problems were identified in the simulated discharge, which are (a) a systematic under estimation, (b) high peaks, and (c) low flows highly under-estimated. Most of the problems were solved adjusting the snow and glacier melt related parameters (see Fig. 3). The list of sensitive parameters, their default values, and the calibrated values are presented in Table 2.

The calibrated model resulted in the following evaluation statistics: NSE = 0.69, R^2 = 0.72 and PB = +9% according to the statistical performance criteria described by Moriasi et al. [12].

DISCUSSION

Several open source hydrological models are available on line. However, a GIS is essential to build the hydrological model for sub-basin delineation, flow accumulation and the flow direction process. Typically, the SWAT model source code is provided on its internet website, but the building up of a new hydrological model project needs some GIS analyses. Most

Table 2. List of sensitive parameters and their optimized values

Parameter	Description	Range	Optimized value
TLAPS	Temperature lapse rate, °C/km	0, –10	–2.8
PLAPS	Precipitation lapse rate, mm H_2O/km	0, 100	3.8
SFTMP	Snowfall temperature, °C	–5, +5	1.821
SMTMP	Snow melt base temperature, °C	–5, +5	2.1
SNOEB	Initial snow water content in elevation band, mm	0, 300	148
TIMP	Snow pack temperature lag factor	0.01, 1	1
SMFMN	Melt factor for snow on December 21, mm H_2O/°C–day	0, 10	2.8
SMFMX	Melt factor for snow on June 21, mm H_2O/°C–day	0, 10	3.3
SURLAG	Surface runoff lag time, days	1, 4	1

often, the ArcSWAT [20] interface running in ArcGIS is used for model development. ArcGIS is a proprietary software package with licensing costs that can now be avoided by using the Map Window solution MWSWAT. Using open source solution can be especially useful in developing countries where licensing costs are often a barrier to access some proprietary solutions. Another advantage of using MWSWAT over ArcSWAT is that MWSWAT has a built-in window for the visualization of the hydrological model results through geospatial maps.

The first supplementary code provided for calibration in the open source statistical tool R can be helpful for formatting the meteorological data for multiple stations, especially in large watersheds with scarce data. Similarly, the second *R* code made available is useful for the trial and error process. Note that *R* codes can also run from web-based platforms to build online workflows incorporating all steps of hydrological modeling: from data acquisition, basin delineation, model calibration, to spatial map representations. Moreover, *R*-based automatic calibration codes are now available for SWAT model calibration [9] also [21]. It is important to mention that we did not use automatic calibration because process implementation is essential in mountainous terrains that are affected by factors such as elevation snow and glacier melt and orographic precipitation. We therefore limited our tool for manual calibration with a trial and error method. A relative comparison of the significance of process implementation and auto calibration in mountainous complex terrains is studied in [15].

However, two major limitations must be mentioned. First, the minimum amount of data needed for model calibration and validation are difficult to get from all places around the world. Most countries are not making available hydrological data (e.g. discharge) on the web. But in many countries, especially developed ones, online discharge data are becoming more and more available. For our case study, freely available discharge data was obtained from the GRDC. However, in our case study we used daily data from local authority to improve the model calibration. Data from weather stations provided by NCDC are also less dense in the developing world. Second, computational capabilities can become a major challenge for working with high resolution models, therefore research has been carried out for running SWAT on distributed platforms [10, 22].

CONCLUSIONS

The overall objective of this work was to address the applicability of freely available data and open source software for hydrological research. The conclusions drawn from our case study on the Mendoza catchment are that model generated runoff has a very close match with the measured runoff. Based on visual observations (Fig. 3) and the statistical performance (NSE = 0.69, $R^2 = 0.72$, PB = 9%) the open source model with globally available freely accessible data can be utilized for addressing various environmental issues especially those linked with discharge. Consequently, making freely available data interoperable, as well as the outputs of developed models, would certainly represent an important step towards removing the barriers to data availability, accessibility, and integration. This would greatly facilitate storage, diffusion and exchange of hydrological data, allowing faster and easier updates, fostering new collaboration and cooperation between various scientific disciplines, potentially allowing better understanding and interconnections of water-related processes. This would enable scientists to better compare results, models and methodologies, bringing more reliable information and knowledge, increasing scientific accountability and credibility, and hopefully leading to better decisions by water managers. In this study, we demonstrated that data extraction and hydrological model implementation and calibration could be obtained from freely available data and open source packages. This methodology and its associated workflow will be particularly important and useful in data sparse regions or in large transboundary catchments to address for instance water sharing issues under climate change.

ACKNOWLEDGMENTS

This research was funded by the EU FP7 Project ACQWA (Assessing Climate Change Impact on Water quantity and quality) under Contract no. 212250 (http://www.acqwa.ch) and the EU FP7 Project enviroGRIDS under Contract no. 226740 (http://www.envirogrids.net).

SUPPLEMENT 1. R SCRIPT FOR GLOBAL CLIMATE DATA PROCESSING

```
#————————————————————————#
# Global Climate Data Processing in R          #
# EnviroSPACE Lab,University of Geneva      #
# Contact: kazi.rahman@unige.ch               #
#————————————————————————#
# Read the input data from the NCDC extracted csv file
#1. Make sure that the file is comma delimited
#2. Remove all the succeeding characters present in the PRCP column data <- read.table(“F:\\NCDC.MENDOZA\\InData.csv”, header=T, sep=",")
# Read the station information from a CSV file
stations <- read.table(“F:\\NCDC.MENDOZA\\Stations.csv”, header=T, sep=",")
# Start and end years
StartYear = 1996
EndYear = 2010
# Remove no data points from the data (Precipitation is 99.99 and temperature is 9999.99)
data <- data[data[,"PRCP"] < 90 & data[,"MAX"] < 900 & data[,"MIN"] < 900,c(“STN”,"YEARMODA","PRCP","MAX","MIN")]
# Convert precipitation from inches into mm and temperature from Fahrenheit into Celsius
data$PRCP <- data$PRCP * 25.4
data$MIN <- (data$MIN - 32.0) * 5 / 9
data$MAX <- (data$MAX - 32.0) * 5 / 9
# Create a dummy
allDays = c(31,28,31,30,31,30,31,31,30,31,30,31)
tDay = 0
# Creates a string with all the days between 2000 and 2010
Outdata = NULL
Outdata$dateStr = NULL
for(iYr in StartYear:EndYear){
for(iMn in 1:12){
mZeros = ''
if(iMn < 10){mZeros = '0'}
if(iYr%%4 == 0 && iMn == 2){nDays <- 28} else {nDays <- allDays[iMn]}
for(iDay in 1:nDays){
dZeros = ''
if(iDay < 10){dZeros = '0'}
tDay = tDay + 1
Outdata$dateStr[tDay] <- as.numeric(paste(as.character(iYr),mZeros,as.character(iMn),dZeros,as.character(iDay),collapse = NULL,sep=""))}}}
# Loop through each of the station
for(iStn in 1:length(stations$STN)){
# Extract data for a given station
tdata <- data[data[,"STN"]==stations[iStn, "STNID"],]
# Assign precipitation and temperature data to the Outdata variable
# 1 Assign no data for each of the dates
Outdata$PCP = rep(-99.0,length(Outdata$dateStr))
Outdata$TMIN = rep(-99.0,length(Outdata$dateStr))
Outdata$TMAX = rep(-99.0,length(Outdata$dateStr))
for(tDay in 1:length(tdata$YEARMODA)){
Outdata$PCP[Outdata$dateStr == tdata$YEARMODA[tDay]]= tdata$PRCP[tdata$YEARMODA == tdata$YEARMODA[tDay]]
Outdata$TMIN[Outdata$dateStr == tdata$YEARMODA [tDay]] = tdata$MIN[tdata$ YEARMODA == tdata$YEARMODA[tDay]]
Outdata$TMAX[Outdata$dateStr == tdata$YEARMODA [tDay]] = tdata$MAX[tdata$YEARMODA == tdata$YEARMODA[tDay]]
}
# Write the extracted data into pcp and tmp files to be used as inputs in SWAT
write.table(“20000101",file=paste("pcp”,as.character(stations[iStn,"STNID"]),".txt",sep=""), append=F, quote = FALSE, row.names = FALSE, col.names = FALSE)
write.table(“20000101",file=paste("tmp”,as.character(stations[iStn,"STNID"]),".txt",sep=""), append=F, quote = FALSE, row.names = FALSE, col.names = FALSE)
write.table(sprintf(“%.1f”,Outdata$PCP),file= paste(“pcp”,as.character(stations[iStn,"STNID"]), ".txt",sep=""), append = T, quote = FALSE, row.names = FALSE, col.names = FALSE)
write.table(sprintf(“%.1f,%.1f”,Outdata$TMAX, Outdata$TMIN),file=paste(“tmp”, as.character(stations[iStn,"STNID"]),".txt",sep=""), append=T, quote = FALSE, row.names = FALSE, col.names = FALSE)
```

```
}
```

SUPPLEMENT 2. LIST OF ONLINE VIDEOS

List of online Videos:

www.cas.mcmaster.ca/~cgeorge/Mendoza_Start.zip

www.cas.mcmaster.ca/~cgeorge/Mendoza_AWD.zip

www.cas.mcmaster.ca/~cgeorge/Mendoza_HRU.zip

www.cas.mcmaster.ca/~cgeorge/Mendoza_Run.zip

www.cas.mcmaster.ca/~cgeorge/Mendoza_Visualise.zip

SUPPLEMENT 3. R SCRIPT FOR SWAT MODEL CALIBRATION

```
#————————————————————————#
# SWAT Calibration in R Environment        #
# EnviroSPACE Lab,University of Geneva     #
# Contact: kazi.rahman@unige.ch             #
#————————————————————————#
# Step 1: Execute SWAT2009
system("swat2009.exe")
# Step 2: Read observed and simulated files
Qo<-read.table("obs7.txt")[,3]
Qs1<-read.table("output.rch",skip=9)
Qs<-Qs1[Qs1$V2==7,7]
# Step 3: Calculate Model Performance Statistics
SSR<-sum((Qs-Qo)^2)
NS<-1-(SSR/(sum((Qo-mean(Qo))^2)))
PBIAS<-100*(sum(Qs)-sum(Qo))/sum(Qo)
SSR;NS;PBIAS
# Step 4: Plotting Obs Vs Simulated relationship
Qo1<-Qo[c(1:2191)];
Qs1<-Qs[c(1:2191)];
vectory<-c(0,1.1*max(max(Qs1),max(Qo1)))
vectorx<-c(0,length(Qs1))
dates<-c("1/1/99","1/1/00","1/1/01","1/1/02",
"1/1/03","31/12/04")
date.ticks<-c(365,731,1096,1461,1826,2191)
plot(vectorx,vectory,type="n",xlab="Day",ylab=
"Discharge (cms)",axes=FALSE)
axis(1,at=date.ticks,labels=dates)
axis(2,at=NULL,labels=NULL)
#grid(nx=500,ny=100,col="lightgray",lty="solid")
lines(Qo1,lwd=2)
lines(Qs1,lwd=2,col='blue')
title("Obs Vs Simulated( SWAT) relationship",
cex.main = 1,font.main=1,col.main= "black",)
legend(1500,450,"Observed Discharge", col='black',
lwd=3,lty=1,bty="n")
legend(1500,420,"Simulated Discharge", col='blue',
lwd=3,bty="n")
box(which='plot')
```

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