Journal of Hydrology 524 (2015) 733–752

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model

K.C. Abbaspour [a,*], E. Rouholahnejad [a], S. Vaghefi [a], R. Srinivasan [b], H. Yang [a,c], B. Kløve [d]

[a] Eawag, Swiss Federal Institute of Aquatic Science and Technology, P.O. Box 611, 8600 Dübendorf, Switzerland
[b] Texas A&M University, Texas Agricultural Experimental Station, Spatial Science Lab, College Station, TX 77845, USA
[c] Department of Environmental Science, University of Basel, Switzerland. Petersplatz, 1, 6003 Basel, Switzerland
[d] Univ Oulu, Fac Technol, POB 4300, FIN-90014 Oulu, Finland

ARTICLE INFO

Article history:
Received 18 December 2013
Received in revised form 10 February 2015
Accepted 7 March 2015
Available online 18 March 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Michael Brian Butts, Associate Editor

Keywords:
Water resources
Runoff ratio
Nitrate load
SWAT-CUP
SUFI-2
Blue water

SUMMARY

A combination of driving forces are increasing pressure on local, national, and regional water supplies needed for irrigation, energy production, industrial uses, domestic purposes, and the environment. In many parts of Europe groundwater quantity, and in particular quality, have come under sever degradation and water levels have decreased resulting in negative environmental impacts. Rapid improvements in the economy of the eastern European block of countries and uncertainties with regard to freshwater availability create challenges for water managers. At the same time, climate change adds a new level of uncertainty with regard to freshwater supplies. In this research we build and calibrate an integrated hydrological model of Europe using the Soil and Water Assessment Tool (SWAT) program. Different components of water resources are simulated and crop yield and water quality are considered at the Hydrological Response Unit (HRU) level. The water resources are quantified at subbasin level with monthly time intervals. Leaching of nitrate into groundwater is also simulated at a finer spatial level (HRU). The use of large-scale, high-resolution water resources models enables consistent and comprehensive examination of integrated system behavior through physically-based, data-driven simulation. In this article we discuss issues with data availability, calibration of large-scale distributed models, and outline procedures for model calibration and uncertainty analysis. The calibrated model and results provide information support to the European Water Framework Directive and lay the basis for further assessment of the impact of climate change on water availability and quality. The approach and methods developed are general and can be applied to any large region around the world.

1. Introduction

Higher standards of living, demographic changes, land and water use policies, and other external forces are increasing pressure on local, national and regional water supplies needed for irrigation, energy production, industrial uses, domestic purposes, and the environment. In many parts of Europe groundwater quantity and quality in particular has come under server pressures and water levels have decreased, resulting in negative environmental impacts (Kløve et al., 2014). Rapid, and often, unpredictable changes with regard to freshwater supplies create uncertainties for water managers. At the same time, climate change adds a new level of uncertainty with regard to freshwater supplies and to the main water use sectors such as agriculture and energy, which will in turn exacerbate uncertainties regarding future demands for water. As meeting future water demands becomes more uncertain, and water scarcity is continuously increasing (Yang et al., 2003), societies become more vulnerable to a wide range of risks associated with inadequate water supply in quantity and/or quality (UN Report, 2012).

Hydrological models are important tools for planning sustainable use of water resources to meet various demands.

Abbreviations: REVAMPM.gw, treshold depth of water in the shallow aquifer required for capillary flow into root zone to occur (mm); GW_REVAP.gw, groundwater "revap" coefficient; GWQMN.gw, treshold depth of water in the shallow aquifer required for return flow to occur (mm); SHALLST_N.gw, concentration of nitrate in groundwater contribution to streamflow from subbasin (mg N l^{-1}); CN2.mgt, SCS runoff curve number for moisture condition II; FRT_SURFACE.mgt, fraction of fertilizer applied to top 10 mm of soil; SOL_AWC.sol, Available water capacity of the soil layer (mm mm^{-1}); ESCO.hru, soil evaporation compensation factor; HRU_SLP.hru, average slope steepness (m m^{-1}); OV_N.hru, Manning's "*n*" value for overland flow; SLSUBBSN.hru, average slope length (m); RCN.bsn, concentration of nitrogen in rainfall (mg N l^{-1}); NPERO.bsn, nitrogen percolation coefficient; CMN.bsn, rate factor for humus mineralization of active organic nitrogen; SOL_NO_3.chm, initial NO_3 concentration in the soil layer (mg kg^{-1}).

* Corresponding author at: 133 Ueberlandstr, 8600 Dübendorf, Switzerland.
E-mail address: abbaspour@eawag.ch (K.C. Abbaspour).

http://dx.doi.org/10.1016/j.jhydrol.2015.03.027
0022-1694/

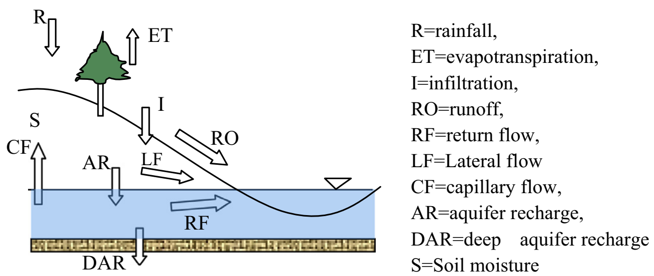

Fig. 1. Schematic illustration of the conceptual water balance model in SWAT.

Some works on the estimation of global water resources are published as early as 1970s by Lvovitch (1973), Korzun et al. (1978), and Baumgarten and Reichel (1975). The country or global-based water resource estimates are performed on: (i) data generalization of the world hydrological network (Shiklomanov, 2000), (ii) general circulation models (GCMs) (TRIP, Oki et al. 2001; HO8, Hanasaki et al., 2013), and (iii) hydrological models (Yates, 1997; WMB, Vörösmarty et al., 2000; Fekete et al., 1999; Macro-PDM, Arnell, 1999; WGHM, Alcamo et al., 2003; Yang and Musiake, 2003; LPJ, Gerten et al., 2004; WASMOD-M, Widén-Nilsson et al., 2007; PCR GLOBWB, van Beek et al., 2011). Global runoff estimates performed with existing global climate models, e.g., Nijssen et al. (2001) and Oki et al. (2001), among others, suffer from low accuracy due to their low spatial resolution, poor representation of soil water processes, and, in most cases, lack of calibration against measured discharge (Döll et al., 2003). More accurate estimations, in terms of the hydrological processes, are based on the global hydrological models mentioned above, which are all raster models with a spatial resolution of 0.5° (55.7 km at the equator) and driven by monthly climatic variables. Probably the most sophisticated of these models is WGHM (Alcamo et al., 2003) that combines a hydrological model with a water use model and calculates surface runoff and groundwater recharge based on a daily water balance of soil and canopy. The global model is calibrated against observed discharge at 724 gauging stations spread globally by adjusting the runoff coefficient and, in case this was not sufficient, by applying up to two correction factors, especially in snow-dominated and semiarid or arid regions. The main shortcomings of the models mentioned above are the weak hydrology, calibration and validated against long-term annual discharge, application of correction factors to the modeled discharges leading to an inconsistent water balance, and lack of quantification of model prediction uncertainty, which could be quite large in distributed models.

The current modeling philosophy requires that models are transparently described; and that calibration, validation, sensitivity and uncertainty analysis are routinely performed as part of modeling work. As calibration is "conditional" (i.e., conditioned on the model structure, model inputs, analyst's assumptions, calibration algorithm, calibration data, etc.) and not uniquely determined, uncertainty analysis is essential to evaluate the strength of a calibrated model.

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) has demonstrated its strengths in the aspects specified above. It is an open source code with a large and growing number of model applications in various studies ranging from catchment to continental scales. In the "Hydrologic Unit Model for the United States" (HUMUS), Arnold et al. (1999) used SWAT to simulate the entire U.S.A. for river discharges at around 6000 gauging stations. This study was then extended within the national assessment of

Table 1
Data description and sources used in the European SWAT project.

Data type	Resolution	Source
Digital Elevation (DEM)	90 m aggregated to 700 m	Shuttle Radar Topography Mission (SRTM) http://www2.jpl.nasa.gov/srtm/
Soil	5 km	FAO–UNESCO global soil map http://www.fao.org/nr/land/soils/digital-soil-map-of-the-world/en/
Landuse	– 300 m	– GlobCover European Space Agency http://due.esrin.esa.int/globcover/
	– 1000 m	– Global Landuse/Land Cover Characterization USGS http://landcover.usgs.gov/glcc/
	– 500 m	– MODIS land cover http://modis-land.gsfc.nasa.gov/
	– 300 m	– GlobCorine provided by European Space Agency http://www.esa.int/About_Us/ESRIN/Express_map_delivery_from_space
River network dataset	≅62 km^2 avg. size catchment	European catchments and Rivers network System (Ecrins) http://projects.eionet.europa.eu/ecrins
Climate	– Observed	– National Climate Data Center (NCDC), http://www.ncdc.noaa.gov/
	– 0.25° grid	– European Climate Assessment Dataset (ECAD), http://www.ecad.eu/
	– 0.5° grid	– Climate Research Unit (CRU), http://www.cru.uea.ac.uk/
	– 1° grid	– Climate Data Guide (NCAR), https://climatedataguide.ucar.edu/
River discharge	326 stations	Global Runoff Data Center (GRDC) http://www.bafg.de/GRDC/EN/Home/homepage_node.html
Nitrate loads	34 stations	ICPDR http://en.wikipedia.org/wiki/International_Commission_for_the_Protection_of_the_Danube_River
Crop yield	Wheat, maize, barley	McGill Univesity http://www.geog.mcgill.ca/landuse/pub/Data/175crops2000/NetCDF/ FAOSTA – Country-based average crop yield
Agricultural management and water resources	Planting, harvesting, fertilization-blue water	FAOSTAT http://faostat.fao.org/site/339/default.aspx – AQUASTAT, FAO http://www.fao.org/nr/water/aquastat/water_res/index.stm
Population		Eurostat http://epp.eurostat.ec.europa.eu/portal/page/portal/population/introduction
Population growth rate		World Bank http://data.worldbank.org/indicator/SP.POP.GROW
Point source pollution		Eurostat for the period of 2000–2009

the USDA Conservation Effects Assessment Project (CEAP). Gosain et al. (2006) modeled twelve large river catchments in India with the purpose of quantifying the climate change impact on hydrology. Schuol et al. (2008) simulated hydrology of the entire Africa with SWAT in a single project and calculated water resources at a subbasin spatial resolution and monthly time intervals. Faramarzi et al. (2009) simulated hydrology and crop yield for Iran with SWAT. In a subsequent work, Faramarzi et al. (2013) used the African model to study the impact of climate change in Africa.