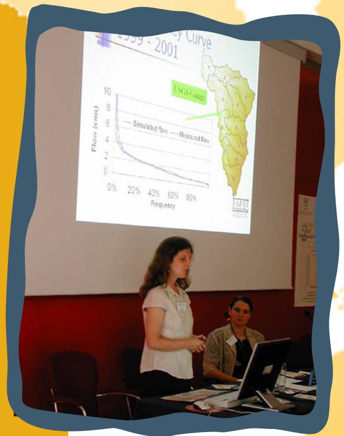
SWAT2003

2nd International SWAT Conference

Proceedings

July 1-4, 2003

Bari, Italy



TWRI Technical Report 266

2003 International SWAT Conference

Edited by

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TWRI Technical Report 266

Foreword

This book of proceedings presents papers that were given at the 2nd International SWAT Conference, SWAT 2003, that convened in 2003 in Bari, Italy.

The focus of this conference was to allow an international community of researchers and scholars to discuss the latest advances in the use of the SWAT (Soil Water Assessment Tool) model to assess water quality trends.

The SWAT model was developed by researchers Jeff Arnold of the United States Department of Agriculture Research Service (USDA-ARS) in Temple, Texas and Raghavan Srinivasan at the Texas Agricultural Experiment Station (TAES), who is the Director of the Texas A&M University Spatial Sciences Laboratory.

SWAT is a comprehensive computer simulation tool that can be used to simulate the effects of point and nonpoint source pollution from watersheds, in the streams, and rivers. SWAT is integrated with several readily available databases and Geographic Information Systems (GIS).

Because of the versatility of SWAT, the model has been utilized to study a wide range of phenomena throughout the world. At the same time, the research community is actively engaged in developing new improvements to SWAT for site-specific needs and linking SWAT results to other simulation models.

This conference provided an opportunity for the international research community to gather and share information about the latest innovations developed for SWAT and to discuss challenges that still need to be resolved.

This proceedings includes papers covering a variety of themes, including new developments associated with SWAT, applications of the SWAT model, the use of related modeling tools, how SWAT can be calibrated or compared to other models, the use of other simulation models and tools, and integrating SWAT with other models. In addition to papers presented at SWAT 2003, posters shown at the conference are also included in this proceeding.

The organizers of the conference--- Antonio Lo Porto (IRSA-CNR), Arnold and Srinivasan —want to express thanks to organizations and individuals who made this conference successful. Organizations that played a key role in this conference include USDA-ARS, TAES, Texas A&M University, the Water Research Institute of Italy (IRSA), the National Research Council of Italy (CNR), the EU Project EuroHarp (an effort to evaluate quantitative tools at European scale for the assessment of nutrients in water resources), the EU

TEMPQSIM project (which is improving water quality models to adapt them to intermittent streams in southern Europe), and the municipality and province of Bari, Italy (where the conference was held). Companies that assisted in the conference include SIT and s.r.l. GIS technologies of Italy, ESRI Italia.

Individuals that should be acknowledged in this proceedings include Ric Jensen of the Texas Water Resources Institute and Jennifer Jacobs of SSL, who helped to edit the proceedings, and Kellie Potucek of TWRI, who assembled the papers into an online technical report.

These proceedings can be referenced as TWRI technical report 266.

The 3rd International SWAT conference is scheduled for July 11-15, 2005, in Zurich, Switzerland. To learn more about SWAT, go on the web to http://www.brc.tamus.edu/swat/ or contact Srinivasan at r-srinivasan@tamu.edu

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A Network of Pilot River Basins as Test Sites for Guidelines and Research

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Issues such as agriculture, land degradation and desertification, water availability, and urban growth are key elements of environmental strategies for sustainable development, which requires appropriate integration of land use, soil and water protection legislative frameworks. To this end, watersheds form meaningful landscape units where actions can be taken, because of the shared functional relationships that exist within their boundaries.

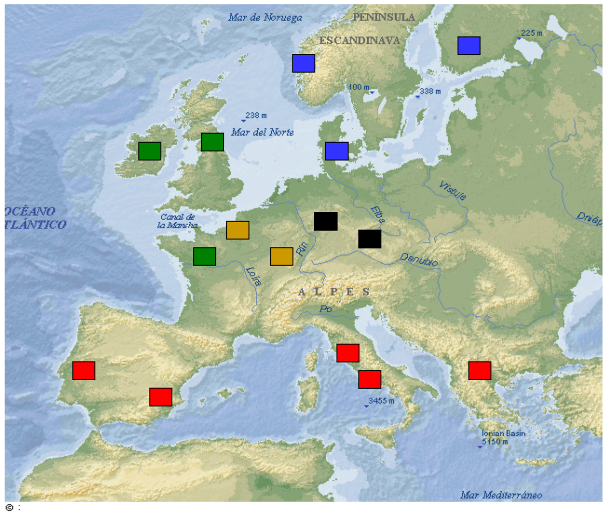
Many national action programmes developed in the context of the United Nations (UN) Convention to Combat Desertification mention among their priorities the protection of watersheds as core measures for achieving their objectives. Watersheds are also the basic territorial units for many monitoring and information system initiatives, and are embedded in the concept of the River Basin Management Plans (RBMP) being introduced by the European Union (EU) Water Framework Directive (WFD). The Observational Network of Watersheds developed at the Joint Research Centre (JRC) will be discussed, together with European Commission initiatives in this context that by linking policy and research aspects aim at the protection of soil and water resources.

The uses made of all major European watersheds have long-term and wide-ranging impacts not only on soil and freshwater resources, but also on the quality and quantity of water runoff to coastal areas. Although the management of water systems has often followed river basin approaches to environmental planning and regulation, until now they have not been developed in a uniform manner across the EU, and have led to large variations in resulting application. In order to overcome this deficiency, one of the underpinning principles of the Water Framework Directive is to place river basin management in a comprehensive and statutory context. To facilitate the development of such an integrated approach, a pilot project for testing guidance documents developed under the Common Implementation Strategy (CIS) of the WFD has been launched.

For this purpose, member states and candidate countries have set up a network of Pilot River Basins (PRBs) covering a wide range of climatic, environmental and socio-economic conditions. The network has been established using strict selection criteria, including the commitment and availability of resources, the implication of the PRBs in on-going research projects, and the strong involvement of non-governmental organizations, practitioners and stakeholders.

At present, the network is made up of 15 river basins from different countries. A multi-phase approach has been proposed to conduct the integrated testing to take into consideration the legal requirements of the member states to comply with reporting obligations under the WFD, but also the need to develop, in the near term, programmes of measures and river basin management plans.

This network serves the purpose of feeding practitioners experience into the policy making process. Since direct feedback is also needed from the research side in order to improve the science-basis of the policy support, the JRC has complemented the PRB network with an additional number of river catchments in Europe, with case-study areas in Finland, France, Greece, Italy, Spain, the UK, and other nations. Activities at each node of the network aim at establishing relationships between anthropogenic activities and the loads of chemicals to soils, inland and coastal waters, and to assess the impact of preventive and remedial measures on these loads.



Location of the Pilot River Basins identified in the CIS pilot project: Cecina (Italy), Júcar (Spain), Guadiana (Portugal), Marne (France), Moselle-Sarre (France, Germany, Luxembourg), Neisse (Germany, Czech Republic, Poland), Odense (Denmark), Oulujoki (Finland), Pinios (Greece), Ribble (UK), Scheldt (Belgium, Netherlands, France), Shannon (Ireland), Somos (Romania, Hungary), Suldal (Norway), and Tevere (Italy).

Fecal Coliform Fate and Transport Simulation with SWAT

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Introduction

The use of animal manure as a fertilizer on cropland and pastures is a practice that can turn what is often considered a waste into an asset. However, trends in animal production have favoured the expansion of confined animal feeding operations and increased the concentration of animal manure in some areas. A key strategy to develop sound manure management practices is to use a model to simulate the potential bacterial and nutrient contamination of streams from manure spreading and grazing animals. Through scenario analysis, the potential benefits of various alternative practices can be assessed. In this study, the bacteria fate and transport of the Soil and Water Assessment Tool is tested on the Shoal Creek watershed, a 366-km^2 watershed located in Barry and Newton County in southwest Missouri.

Because Shoal Creek is designated for swimming and canoeing, the Missouri Water Quality Standards state that the fecal coliform count shall not exceed 200 fecal coliform colonies per 100 milliliters of water as an average during the recreational season (April 1-October 31). Federal guidelines also suggest rating waters as impaired if more than 10 percent of all samples exceed 400 colonies /100 ml. Starting in May 2001, weekly samples have been collected and analyzed for fecal coliform. These concentrations vary tremendously with flow and from sample to sample. The geometric mean of the fecal coliform concentrations and the number of samples with concentrations greater than 400 colonies /100 ml show that the bacteria criteria for swimming waters was violated during the 2001 and 2002 recreation seasons.

Methodology

The environmental model used for the development of this TMDL is the Soil and Water Assessment Tool or SWAT (Arnold et al., 1998) with new equations to describe the fate and transport of bacteria on land, in the soil, and in the streams. The local steering committee helped determine the area specific inputs to this model. Additional watershed inputs came from state and federal agencies, mainly the Natural Resources Conservation Service (NRCS), the Barry County Soil and Water Conservation District (BCSWCD), the Missouri Agricultural Statistics Service (MASS), and the Missouri Climate Center at the University of Missouri Department of Atmospheric Science.

The watershed consists of grassland that is hay and pastures (89%) with some wooded areas (11%). Grassland is fertilized with poultry litter and/or commercial nitrogen. The pastures are in fescue grass over-seeded with red clover. All the soils are characterized by a very high rock content of 30% or more in the surface layer and higher contents (40% or more) for bottom layers. This contributes to low water content of these soils. In addition, existing karst features increase the amount of water that bypasses the soil profile and rapidly reaches the aquifer.

The parameters required to define each hydrologic resource unit (HRU) were defined on the basis of the soil, land use, and topographic characteristics. Main and secondary channel characteristics were defined by the AVSWAT interface, ground-proofed, and adjusted as needed. Manning coefficients were visually estimated. Hydraulic conductivities were estimated based on the soil characteristics in the channel.

The representative grass growing in the watershed is fescue. Half of the fescue pastures are over-seeded with red clover. To represent this scenario in spite of the fact that the SWAT model does not allow two different plants growing at the same time in the same field, we built an imaginary plant that is an average between fescue and red clover, a legume that fixes nitrogen at half the rate that clover normally would.

Pasture acres are fertilized every other year with poultry litter. Once every four years, pastures are fertilized with non-organic nitrogen, harvested for seeds and hay, and then grazed. Once every four years, no fertilizer is added. Pastures are grazed year round for six weeks at a time, except in the spring preceding the hay harvest. Grazing intensities are therefore 5 acres per cow/calf pair once hay is harvested and slightly less than 3 acres per cow/calf pair before. In the winter months, from November through April, cattle are left in the pastures and supplemented with hay. This results in no biomass uptake from the pasture, grass being trampled, and manure deposited on the soil.

Pollutant sources

There are many potential non-point sources due to the agricultural and rural nature of this watershed: livestock, poultry litter spread on pastures, failing septic tanks, wildlife, and other domestic animals including horses, dogs, and pigs. Percentage contributions from each source were determined using DNA source tracking methodologies (Table 1). Four sources of fecal coliform are considered in the model: grazing cattle, cattle standing in the streams, poultry litter, and failing or absent septic tanks. Wildlife (deer, raccoon, wild turkeys, and geese) are not currently considered since DNA tracking showed that wildlife would be responsible for a very small fraction of the total bacteria load during the recreation season.

Table 1. Percentages of isolates identified in each host class during different seasons.

Host class	Cattle	Domestic animals	Poultry	Human	Wildlife
Winter 2001-2002	24%	25%	6%	27%	19%
2002 recreation season	40%	28%	18%	11%	3%
Winter 2002-2003	11%	30%	23%	23%	12%

Fecal coliform loads that are directly deposited by cattle in the streams are treated as direct nonpoint source loadings in the model. For cattle standing in the stream, the percentage of the herds that have access to a stream (25% of them) was determined using GIS and validated with the steering committee. The length of time that cattle stand in a stream and therefore the amount of waste directly deposited are allowed to vary monthly to account for the seasonal changes of temperature. The results are presented in Table 2.

Table 2. Percentage of waste directly deposited in the stream in pastures with stream access.

Month	Percentage of daily waste directly deposited	Month	Percentage of daily waste directly deposited
January	3%	July	10%
February	3%	August	10%
March	3%	September	7%
April	4%	October	4%
May	4%	November	3%
June	7%	December	3%

To estimate the contributions from septic tanks, we treated all the sewage from houses within 250 feet of a stream as direct nonpoint source loadings as well. Direct nonpoint source loadings are added to the stream reach in the appropriate subbasin.

The nonpoint source bacteria loadings come from poultry litter spread on pastures or from grazing animals; surface runoff may transport this bacteria load to the stream during rainfall events. The fecal coliform loads are calculated proportionally to the litter or the manure applied or deposited. Litter application rates vary with each subbasin depending on the number of poultry houses and the available litter. The inputs required by the model are the bacteria content of each type of manure, which were estimated from values found in the literature or from field sampling for poultry litter. For beef, we used the value of 5.4e9 colonies/g/day (Metcalf & Eddy, 1991). For poultry litter, a mix of animal waste and another material, usually wood shavings or rice hulls, the value has been fixed to 10^7 counts/g as a worst-case scenario. Hartel et al. (2000) report fecal coliform concentrations ranging from 10^3 to 10^7 counts per gram (dry weight) of fresh poultry litter. Fecal coliform and E. *coli* concentrations were found to range from 17,000 to 47,000 counts/g in broiler and turkey litter being spread on fields in the Shoal Creek watershed.

Modeling bacteria fate and transport

Fecal coliform die-off is modeled in SWAT using an exponential first order decay process given by the following equation:

$$C_t = C_0 e^{-KtC_{adjT}^{(T-20)}} \qquad [1]$$

where: C_t = concentration at time t, C_0 = initial concentration, K = decay rate (day^{-1}), t = time (days), C_{adjT} = temperate adjustment factor, and T = temperature (^oC). SWAT divides bacteria in two classes of organisms that correspond to two decay rates on the land, in the soil, and in the water. The decay rates are considered to be the same for all animals; only the amounts of slow- and fast-decaying bacteria change between animal species. A review of literature (Crane et al., 1980; Reddy et al., 1981) provided estimates of land and soil decay rates for manures and litter. For bacteria on land, a half-life of three days was chosen as an average between the values found in the literature for cattle and poultry waste. The corresponding decay rate is 0.23 days^{-1}. A tenth of this value, 0.023 days^{-1} was used for bacteria adsorbed to soil particles.

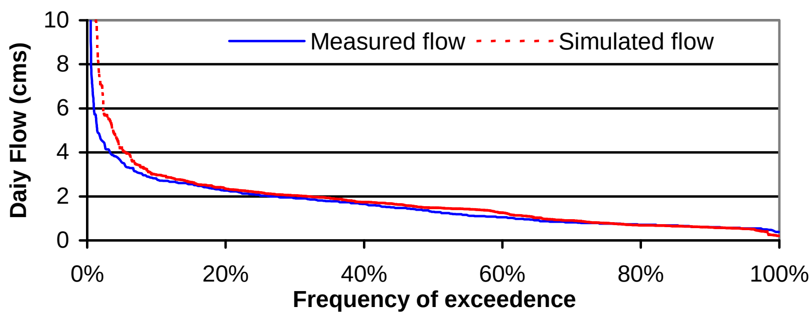
The same equation is used to simulate bacteria decay in the stream. The decay of bacteria during the time it takes for a volume of water to be transported through a stream reach is calculated for each stream reach. The flow rate and the channel characteristics are used to estimate the routing time. Only one rate is used for all types of bacteria and it was determined from data collected by USGS (John Schumacher, personal communication) during a dye test in July 2001. The average decay rate for fecal coliform and E. Coli was 0.084 $hour^{-1}$ or a half-life of 8.3 hours. This value (2.01 $days^{-1}$) was used in the model. In addition, the decay rate on land and in the water is allowed to vary with the air or water temperature. The SWAT default adjustment factor of 1.07 is used in the model.

Results

The model depicting the current condition of the watershed accounts for the physical properties of the watershed and the current farming practices. It was calibrated using the Barry and Newton County hay yields reported to USDA, the daily flow values at the USGS stream gage stations, and the water quality data.

The correct representation of the crop yields ensures that the correct amounts of moisture and nutrients are taken up by the vegetation and get out of the hydrologic system. The average simulated crop yield from 1990 to 2001 is 1.9 tons per acre (t/a) where the average reported yield for Barry and Newton County for the same period is 2.0 t/a, a 5% difference.

The model was calibrated using almost two years of measured daily values. The monitoring periods span from May 17, 1999 until June 20, 2000 and from January 12, 2001 until the end of 2001. There is no specific precipitation data collected in the watershed, which makes calibration of the flow data by comparison of measured and predicted daily values more uncertain, especially during the summer when thunderstorms can be very localized. To insure that the overall statistical characteristics of the flow values are well reproduced, we can compare flow frequency curves (Figure 1). While many peak flow



values are overestimated the fit between the two curves is satisfactory for 90-95% of the time.

Figure 1. Frequency curve of daily flow values from 1999 to 2001.

The comparison of measured and simulated bacteria concentrations can also be calculated on the basis of frequency curves. The concentration frequency curve that results from non-point source loadings and from non-point source direct inputs is shown on Figure 2. It represents the average concentration frequency curve for one recreation season obtained from a 30-year long simulation and those that correspond to one standard deviation on either side of the average. To do an accurate comparison, an arbitrary "sampling" day was chosen to select weekly values from the daily results. The resulting curve is therefore built from a weekly subset of the simulated daily values.

By using the average plus or minus one standard deviation, we insure that the results will be valid for close to 70% of the years. On Figure 2 is also shown the water quality standard of 200 colonies/100ml and the concentration frequency curve obtained from the data collected during the 2001 and 2002 recreation seasons.

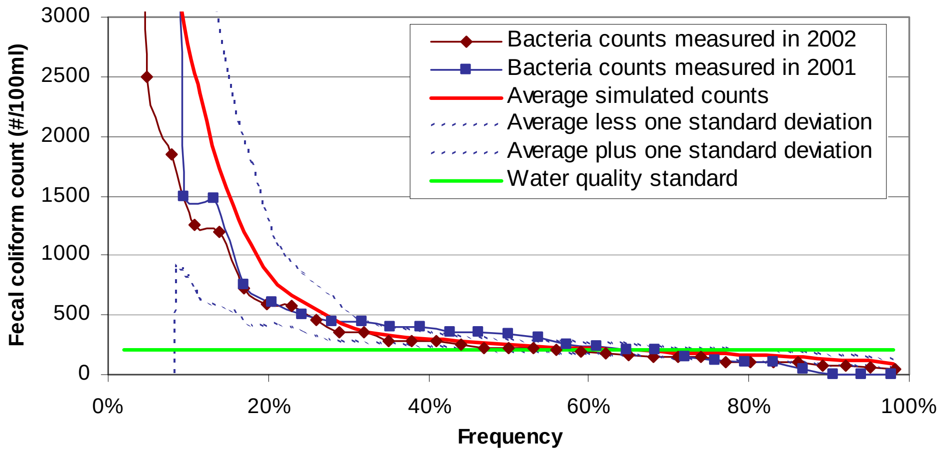


Figure 2. Comparison of average 1-year simulated and measured concentration frequency curves.

Conclusion

The bacteria module of the SWAT model was applied to the Shoal Creek Watershed in Southwest Missouri, taking into account surface applications of fecal coliform due to grazing and poultry litter applications, and direct non-point sources inputs due to cattle standing in the streams and illegal discharges of sanitary sewage. After calibration of the flows, the model was calibrated using two seasons (April1 to October 31) of weekly fecal coliform concentrations measured in grab samples.

The model represents well the variations of fecal coliform measured in the stream: both baseflow and storm events concentrations are in the correct range of values and frequencies.

The confidence interval due to weather variability is quite large. Given that 2001 and 2002 were dry years in Southwest Missouri, the comparison between average model results and these measurements gives credibility to the model. The monitoring program will end in November 2003, providing one more full year of recreational water quality data against which the model results will be compared. In addition, the 2002 and 2003 flow values will be available.

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Enhancement of Tile and Pothole Flow Components in SWAT: Application to the Walnut Creek Watershed, Iowa

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Introduction

Nitrate (NO_3) contaminated drainage water through subsurface drains or "tiles" from the many artificially-drained watersheds in the "Corn Belt" is the primary source of NO_3 to surface waters. Therefore, the tile drain and pothole components of the SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998) model were modified (Arnold et al., 1999 and 2003) to develop a tool that better accounts for flow and nitrate nitrogen (NO_3-N) from tiles and potholes. The modified SWAT (SWAT-M) was evaluated using 9 years of measured flow and NO_3-N data from the Walnut Creek watershed (WCW) in central Iowa. The model was calibrated using measured data from 1992 to 1995 and validated for the period of 1996 to 1999. Due to space limitation only the calibration results are presented here. A scenario adapted by local farmers to reduce in NO_3-N with the late spring nitrate test within a subwatershed (site 220) was evaluated using SWAT-M and the results are presented.

Watershed Description

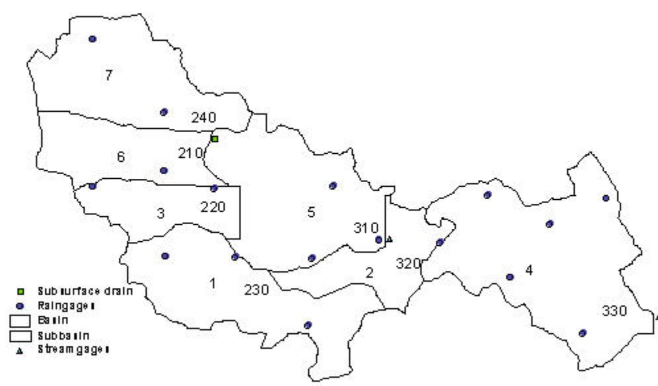


Figure 1. Subbasins, sites and measurement gages in WCW, IA, used by SWAT

The 5130 ha WCW, located in Story county, central Iowa (Figure 1), is typical of the poorly drained, gently rolling landscapes of central Iowa row cropping areas. This landscape contains numerous closed depressions or potholes as a result of a poorly developed surface drainage network on glacial till. These potholes often fill with water, especially during snowmelt and after heavy rainfall, which can result in a reduction in crop yields. Corn and soybeans occupied 87% of the total area while other crops, roads, and forest occupied 13% of the area. Continuous corn production occurred on 15% of the total farmland while 85% of the area was in a corn-soybean rotation (Hatfield et al., 1999). It was assumed that about 66% of the total watershed area is tile drained and 57% of the total surface runoff directly flowed into potholes. Total pothole area occupied 10% of the total land use.

The annual rates of averaged nitrogen fertilizer application are shown in Table 1. Phosphorous fertilizer with an annual rate of 24 kg/ha was applied at all sites during corn production.

Table 1. Nitrogen fertilizer application rates (kg/ha) proposed by farmer collaborators (for all sites with corn crop and site 220 bases on LSNT management practice during 1997-2000).

	YEAR									
Sites	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
All	162	149	153	148	164	164	164	164	187	182
220	162	149	153	148	164	164	168*	118*	174*	109*

* Split application based on LSNT (Late Spring Nitrogen Test) treatment (56 kg/ha applied before planting and the rest was applied during June application) (Hatfield et al., 1999; Jaynes et al., 2003).

Precipitation data measured at 17 sites, the daily maximum and minimum temperature data measured at 2 sites, and solar radiation data at 1 site within the watershed by Jaynes et al. (1999) were used for SWAT simulations. SWAT-M and SWAT 2000 were calibrated using data from 1992-95 and validated using data from 1996-99.

The digital elevation, land use, and soils maps, and measured daily precipitation, temperature and solar radiation for the watershed were provided to the ArcView interface for SWAT2000 (AVSWAT) (DiLuzio et al., 2001) to develop input data files for SWAT.

Subsurface flow and NO_3-N measurements from site 220 were used to evaluate the SWAT models' subsurface flow and NO_3-N load predictions. To compare the model output values to measured values, the average, standard deviation, and the Nash-Sutcliffe model efficiency (E) (Nash and Sutcliffe, 1970) were used. The E values are calculated as follows:

$$E = 1 - \frac{\sum_{i=1}^{n} (X_{mi} - X_{ci})^2}{\sum_{i=1}^{n} (X_{mi} - \overline{X}_m)^2}$$

where E = the efficiency (goodness of fit) of the model, X_{mi} = measured values, X_{ci} = predicted values, $\overline{X}_m$ = average measured values, and n = the number of predicted/measured values. The same input data were used for both SWAT-M and SWAT2000 for comparison purpose.

Scenario

Beginning in 1997, the LSNT (Late Spring Nitrogen Test) N-fertilizer management program was simulated as described by Jaynes et al. (2003) on the 16 fields within sub-basin 220 (Fig. 1). Fourteen of the fields had been in a corn and soybean rotation with N fertilizer applied before corn only. Two of the fields had been in continuous corn prior to the start of the N treatment. The LSNT program consisted of applying an initial 56 kg/ha application of N at or shortly before planting. After the corn plants had grown to a height of 15- to 30-cm (typically mid-June), soil samples were taken and analyzed for NO_3 content to determine the required rate of N to apply by side-dressing (Table 1).

The impacts on surface water quality were determined by comparing NO_3 loads before (from 1992 to 1996) and after treatment (from 1997 to 2000) from the treated sub-basin 220 with LSNT program. During the second simulation, N was applied at a rate similar to other fields. The results from these runs were compared to evaluate the effect of LSNT management practice.

Results and Discussions

Water Balance Calibration

The annual average stream discharge (305.3 mm) at the outlet of WCW and annual average ET (478.7 mm) simulated by SWAT-M for the period of 1992 to 1995 were close to measured values of 345.8 mm and 435.0 mm, respectively (Table 2).

Table 2 shows that improvement of the hydrological routine involving tile and pothole components in SWAT-M resulted in better prediction of annual stream discharge and ET compared to SWAT2000.

Table 2. Comparisons of measured and simulated water balances between SWAT-M and SWAT2000 for WCW

	ET			stream discharge		
	mm					
Year	SWAT-M	SWAT2000	Measured	SWAT-M	SWAT2000	measured
1992	430.4	550.6	500.0	277.5	127.4	271.0
1993	507.9	535.6	370.0	636.1	442.4	865.0
1994	497.3	572.8	440.0	129.4	98.3	69.0
1995	479.3	545.1	430.0	178.3	101.9	178.0
average	478.7	551.0	435.0	305.3	192.5	345.8

Also, similar to actual field measurements, there were more tile and groundwater flows and less surface runoff in SWAT-M than in SWAT2000.

Surface and Tile Flow and NO_3

Table 3 shows the average and standard deviation of daily flow and monthly NO3 at different sites within WCW. The average daily flow predicted by SWAT-M is closer to measured values than those predicted by SWAT2000 during calibration period at the outlet of the watershed (sites 310 and 330).

Table 3. Average and standard deviation (in parenthesis) of daily flow and monthly NO_3-N during calibration

	Flow (m^3/s)			NO_3-N (kg)		
Site	***SWAT2000***	***Measured***	***SWAT-M***	***SWAT2000***	***Measured***	***SWAT-M***
210	0.04 (0.05)*	0.04 (0.06)	0.06 (0.07)	13.8 (42.6)	543.3 (1,178.3)	1,370.3 (2,300.4)
220	0.03 (0.03)	0.03 (0.04)	0.04 (0.04)	18.5 (66.3)	557.3 (997.8)	652.0 (1,003.5)
310	0.16 (0.20)	0.27 (0.43)	0.25 (0.29)	71.0 (130.7)	4,143.3 (7,298.5)	6,291.9 (9,951.0)
330	0.34 (0.41)	0.56 (0.87)	0.49 (0.57)	316.7 (1,046.4)	8,675.4 (15,524.0)	10,187.1 (15,823.9)

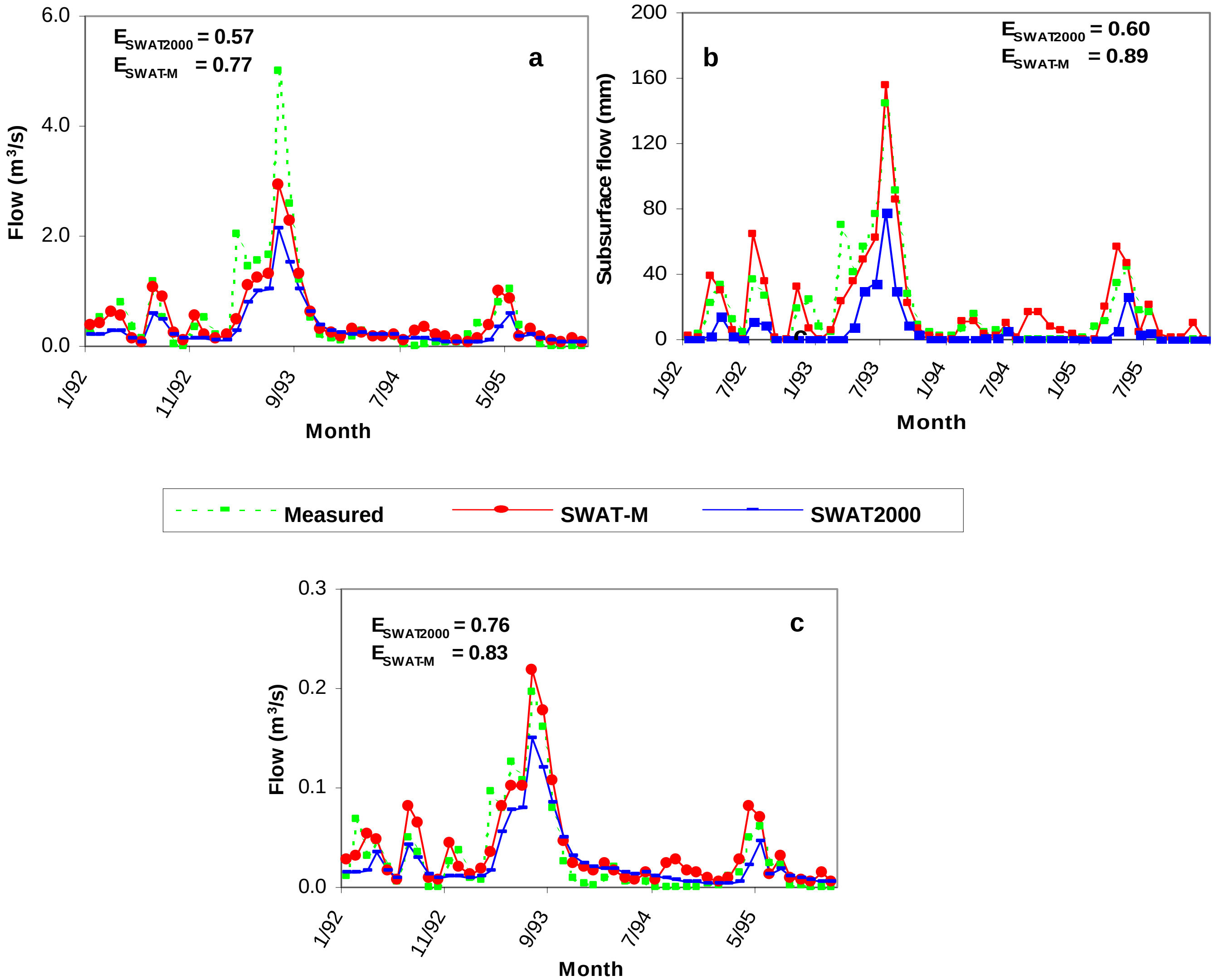


Figure 2. Measured and predicted (a) total flow at site 330 (outlet of watershed), (b) subsurface flow (tile) at site 220, and (c) total flow at site 220 by SWAT-M and SWAT2000.

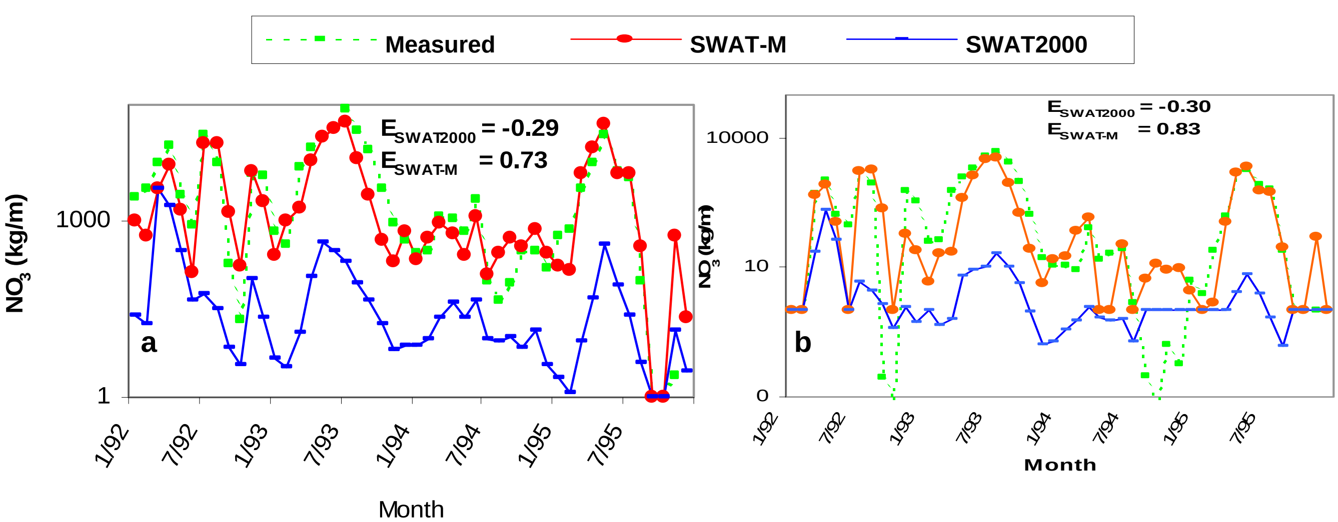


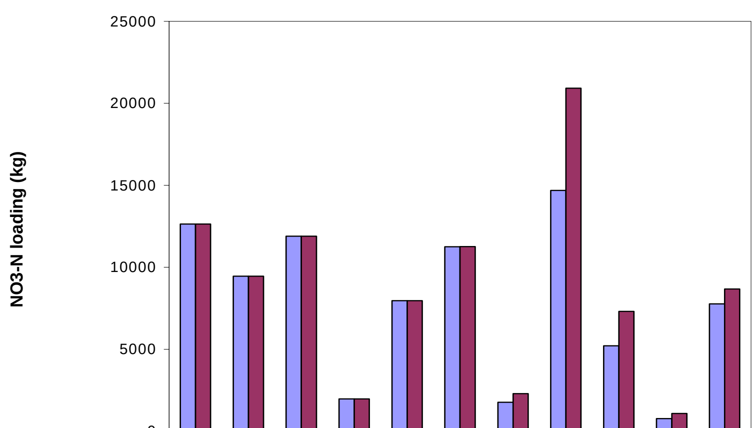
Figure 3. Measured and predicted NO_3-N by SWAT-M and SWAT2000 (a) at site 330 and (b) at site 220.

NO_3-N loads:

Although SWAT-M over-predicted the average NO_3-N, SWAT2000 significantly under-estimated the NO_3-N (Table 3). This is probably due to under-estimation of tile-flow by SWAT2000. The pattern of monthly predicted NO_3-N by SWAT-M at site 330 is much closer to that of measured than SWAT2000 (E = 0.73 for SWAT-M as compared to –0.29 for SWAT2000; Figure 4a). Figure 4b shows a similar pattern to that of site 330 for site 220 which is heavily tiled (E = 0.83 for SWAT-M as compared to –0.30 for SWAT2000).

Scenario

As it was observed in the field study of Jaynes et al. (2003), the LSNT method resulted in lower N fertilizer rates compared to the farmers' standard program (about 30%) from 1997 to 2000. Similar to the field study, the predicted NO_{3-}-N loading by SWAT-M into the stream was reduced by about 29% after the treatment (Figure 4).



	1991	1992	1993	1995	1996	1997	1998	2000	Avera
LSNT Traetment	12640	9459	11900	7964	11250	1776	14690	774	7764
Not Treatment	12640	9459	11900	7964	11270	2302	20930	1084	8684

Year

Figure 4. Simulated NO3-N reduction under LSNT treatment at site 220.

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Satellite Driven Modeling of Snow Runoff in a Small Semi-Arid Mountainous Watershed in Morocco

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Introduction

The "SudMed project" aims at characterizing the surface fluxes on the Tensift watershed, situated in Morocco. The goal of this study is to use satellite data to monitor the snow contribution to runoff in a small semi-arid mountainous sub-watershed: the Rehraya watershed.

In the center of Morocco, the Tensift watershed covers 204,50km². This watershed is composed of three different units :the "Jbilet" (hills situated north of the region and oriented west-east), the Haouz plain and the northern side of the high Atlas range [1]. The Tensift River flows from west to east and is supplied mainly from the basin's south bank: the Atlas north hillside's [2]. The Atlas range is indeed the region's water tower supplying several big irrigated perimeters in the plain. The "Rehraya" is one of the south side Tensift tributary rivers.

The Rehraya watershed is a 228km² Atlasic watershed with altitudes ranging from 1068 to 4167m (the "Jbel Toubkal" highest point of the zone and of the whole Atlas range). An important snow reservoir and several springs supply the river, which is used for human and agricultural needs.

This watershed is the one whose relative snow cover is the most important [1]. Its mean size, its characteristics -representatives of the Atlas range watersheds (vegetation, orientation, and climate) and its quiet steady riverbed make the hydrological processes involved easier to understand in this Atlasic arid mountainous context.

Once the hydrological processes have been analyzed and modeled with the help of climatic measurements, ground data, and remote sensing information, our goal is the analysis of this system's behavior when climate and/or land use changes occur. It is of crucial importance in the present context (global warming, deforestation, and urbanization) to understand the impact of modifications of the Atlasic watershed hydrological regime. They could lead to significant consequences on the whole region's agricultural production. To quantify these changes is useful to help the decision makers.

In this paper are presented the modeling results obtained using only the available data and the methodology adopted to use satellite derived information.

Available data

Very few data are available in this region. The Rehraya watershed is poorly instrumented: one rain gauge and stream gauge are located at the Tahanaoute basin outlet. The data for 31 years (1971-2002) and 40 (1962-2002) years, respectively, are available.

The analysis of the hydrograph underlines two important features of the studied watershed :Extreme variability of the precipitation (see Figure 1) and runoff which characterize mountainous arid areas [2] and temporary storage effect in which we note a dephasing (Figure 1) between the precipitation and runoff signals that are due to snow and groundwater storage. Temperature gages are not available in the watershed. The closest one is next to Marrakech at 412m above sea level. We considered an elevation gradient of –7°C/1000m :the daily maximum and minimum temperature we get for Tahanaoute are presented on Figure 2 (below).

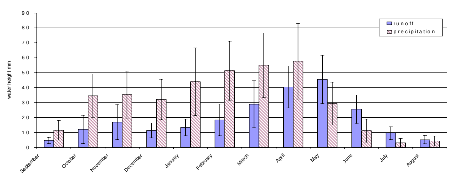

Figure 1. Mean monthly runoff (1962-2002) and precipitation and standard deviation at Tahanaoute (1971-2002).

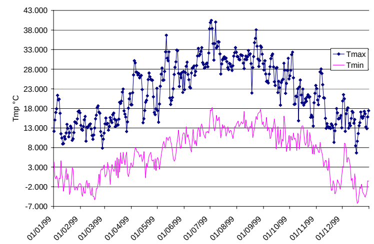

Figure 2 :maximum and minimum daily temperature at Tahanaoute (1999).

Thirty-six Spot vegetation images have been acquired on the zone between October 1998 and June 1999.

The Soil and Water Assessment Tool

The watershed hydrological regime is simulated using the Soil and Water Assessment Tool or SWAT model [3]. Our goal is the understanding of each compartment contribution to the water balance: namely, the water volumes generated by snowmelt, taken by evaporation and evapotranspiration, contained in runoff and stored in groundwater. In this work we focus on the snow compartment and we present snow water equivalents (SWE) in mm simulated by SWAT and averaged for each elevation band on the whole basin, which makes it comparable to the result we get with remote sensing observations.

In SWAT, the snow module uses a degree day method. This method is very dependant on the quality of the input temperature.

Methodology For the Integration of Remote Sensing Information

The watershed snow cover has been monitored using Spot Vegetation images. For the four channels of the vegetation sensor (Blue “B0”, Red “B2”, Near Infrared “B3”, Shortwave Infrared “SWIR”), these images are available daily at a kilometric resolution. Using clear sky condition and low observation angles as quality criteria, we selected weekly time series of vegetation and atmosphere acquisition.

Using known snow optical properties (high visible and low infrared reflectance (Figure 3) we assume the snow cover of each pixel as proportional to a snow index, which takes this spectral characteristics into account.

The snow index we used (IBN = [B0+B2])/2 – SWIR) was evaluated in a previous work [6] in which the comparison with a high resolution derived snow map was satisfying.

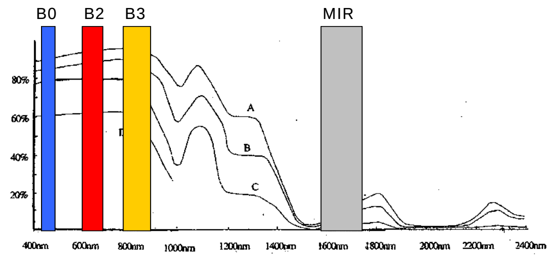

Figure 3. Snow albedo for different snow :recent snow dry (A) and humid (B), snow covered by ice (C), and wet snow (D).

The snow extends for each elevation band from October 1998 to July 1999 obtained by this method (Figure 4) is realistic, the important snow coverage of the basin has been previously reported [1].

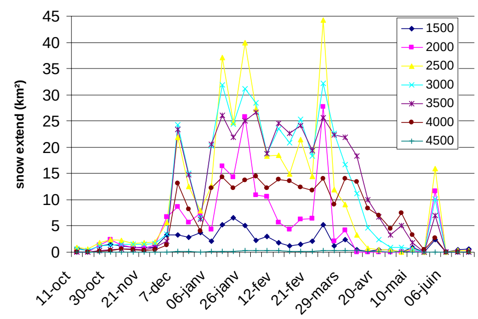

Figure 4. Temporal distribution of snow extend (km²) for each elevation band.

The comparison of these profiles with those obtained from the modeling shows that the simulation presents different problems. At low elevation, it underestimates the snow cover :snow melts too quickly (e.g. at 1500m, fig 5 left). At high elevation, the snow remains too long at the end of the season (e.g. at 3500m) as shown in Figure 5 (right).

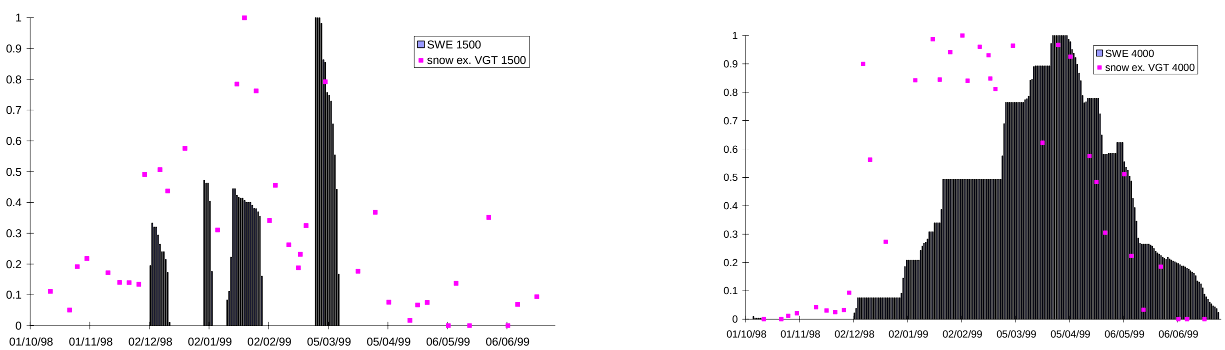

Figure 5. Simulated snow water equivalent and observed snow extend (a-dimensional) for elevation band of 1500m and 4000m.

These results show that an altitudinal gradient applied to daily temperature measured in the plain is not representative of the real basin temperature conditions. Presence or absence of snow, detected via remote sensing image analysis, give interesting and more reliable information.

Considering the snow surface differences between two images, we know if either snow melt or snow fall or neither fall nor melt occurred, and this is directly transferable in terms of temperature conditions (on mean or maximum daily air temperatures) for the model. We implemented a correction routine of this type to the temperature file.

Comparing the results, one should be aware of important considerations. SWE and snow surface are not comparable: the goal is a better restitution of the global dynamic. The precipitations considered are the one measured at the basin outlet. These precipitations are not representative of the whole area and some snowfall events cannot be reproduced if they did not occur as a rainfall event downstream. By remote sensing methods we can only analyze surface differences: if a snow melt snowfall event occurs with no change in surface but just in snow depth, it will be neglected. Because there is no daily image acquisition, we neglect variations that could take place between two images: only the resulting variation is considered leading to a single process (snowfall or snowmelt).

Nevertheless, this method ameliorates the simulated snow dynamic. At low altitudes (Figure 6) we maintain a snow stock seen by the satellite but that was not reproduced with the given temperature.

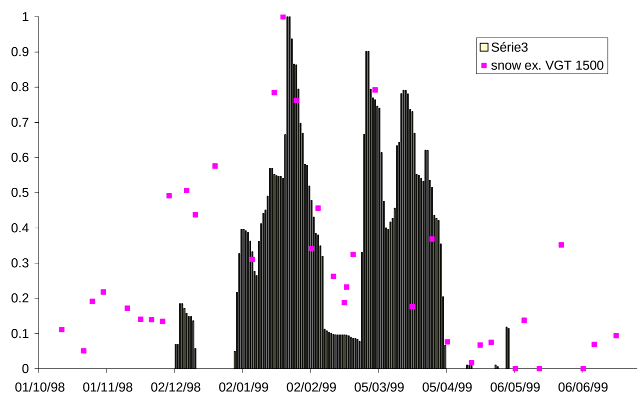

Figure 6. Simulated SWE and remotely sensed snow surface (a-dimensional) at 1500m after correction

Conclusion

A small semi-arid watershed with an important snow coverage and poor instrumentation is simulated with SWAT. The goal is a good simulation of the snow stock dynamic. This dynamic is extracted from Spot vegetation images which have been snow classified.

The consideration of a temperature elevation gradient leads to an underestimation of snow coverage at low elevations and a delay in snow melt at high elevations.

We tested the amelioration we obtained on the snow extend dynamic by correcting the temperatures that are considered. This correction is made via the remote sensing information that was extracted. It leads to an amelioration.

Acknowledgment

This work was supported by the Institut de Recherche et Développement (France) and the Centre d’Etudes Spatiales de la Biosphère (France) through the SudMed project. We wish to thank the “Agence de Bassin Hydraulique du Tensift” (Morocco) for having provided data.

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Applying AVS2000 to Predict Runoff and Phosphorus Movement from an Agricultural Catchment to Support the Modelling of Chlorophyll A Production

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Abstract

The Soil and Water Assessment Tool (SWAT) model was developed as a river basin scale model to quantify and predict effects from different land management practices in large, complex catchments. The AVS2000 is a graphical georeferenced interface version from SWAT to use in ArcView software. The model was applied to a small catchment of 1.8 hectares at Darnum in West Gippsland, Victoria, Australia. The catchment is in a typical rural area for dairy production which Agriculture Victoria Ellinbank has been monitoring since 1994 to investigate phosphorus transfer from grazed pastures. The main objective of applying the AVS2000 was to assess the total phosphorus (dissolved and particulate) concentration in overland flow, or runoff, from farmland to a water body, and its implication for chlorophyll a production. . A chlorophyll a model (CHLOA) was then developed to simulate algae biomass growth related to total phosphorus (TP) movement in runoff generated by AVS2000 and its consequences to accelerate the eutrophication process.

Introduction

Over the last decades, water resources have suffered under the pressure of expanding human activity that may threaten supplies for public potable water and irrigation. Today, diffuse source pollution has become a major factor contributing to water quality degradation. In this case, agricultural activities are the major agent for nutrient and sediment exports, which accelerate the eutrophication process in surface waters.

Eutrophication is a natural process in which water is enriched by inorganic plant nutrients. Eutrophication occurs in many areas around the world but is more common in lentic than lotic habitats. There are different natural pathways to increase nutrient concentrations in waters, including a) forest fires; b) rock weathering; c) soil erosion; and d) rainfall (transport of P).

Victoria is a highly productive state in Australia with significant industrial and agricultural production. Nutrient movement is not unusual in Victoria where water quality in many catchments is deeply degraded (Mitchell, 1990). The environmental condition of Victorian streams was evaluated by Mitchell (1990). Mitchell concluded that some streams in the Gippsland region were in very poor condition, with poor bank vegetation (willows or pasture), severe erosion, eutrophication, and sedimentation problems.

Mathematical models have become widespread tools to aid management due to the high costs of monitoring discharges into water bodies. The Soil and Water Assessment Tool (SWAT) for Geographical Information System (GIS) is a model developed to predict the effect of different land management scenarios on water quality, pollutant loadings and sediment yield in rural catchments (Srinivasan and

Arnold, 1994). The chlorophyll a model (CHLOA) was developed based on a local data to express the eutrophication process related to P concentrations in runoff from a Victorian rural catchment.

The aim of this paper was to develop a sub-routine chlorophyll a model capable to predict eutrophication in the Darnum catchment, Australia, using GIS-linked modelling based on runoff volume and P concentrations simulated by AVS2000 from farmland. This may help avoid accelerating the eutrophication process in West Gippsland.

Materials and Methods

Catchment description

The Darnum site (146^{o} 03’ S, 38^{o} 10’ E) is on a tributary of the Moe River in West Gippsland, Victoria, Australia (Figure 1). A paddock with 3.6 hectares was used in this research, which is a rotational grazing area that is connected to an intensive dairy farm with 120 ha where approximately 350 dairy cows graze. Roughly a half of the paddock (1.8 ha) is called Darnum and drains to a natural depression on the southern boundary where the runoff was concentrated to a monitoring point by a galvanized iron wall buried 75 mm into the soil.

The climate of the Darnum site is described as temperate with a mean annual temperature of 18.4^{o} C. Summers (December to March) are relatively warm with a monthly average maximum temperature of 23.3^{o} C, while winters (June to September) have a monthly average minimum temperature of 5.5^{o} C. Annual average precipitation is approximately 1094 mm, concentrated between May and October.

Pasture is the predominant vegetation, covering roughly 95% of the catchment, with most of the remainder occupied by small areas of Eucalyptus trees forming a boundary between different pasture areas. A small wetland occupies a part of the area located near the water channel in the catchment. The catchment is dominated by Dermosols (Isbell, 1996), which are soils with structured B2 horizons more developed than weak throughout the major part of the horizon, and lacking a strong texture contrast between the A and B horizons. The soil profile is well-drained.

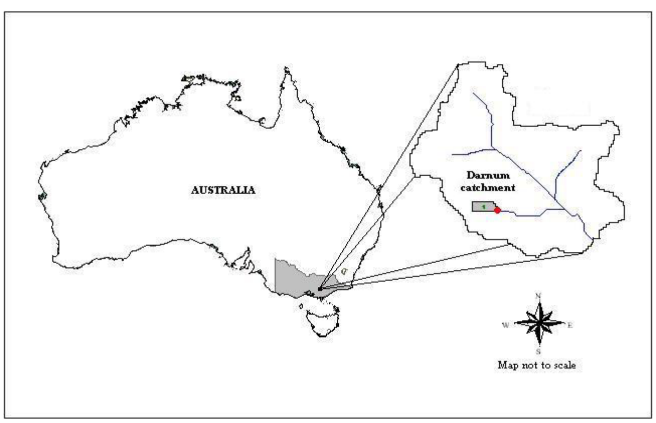

Figure 1. Location of the Darnum site.

The AVS2000 interface for SWAT 2000

SWAT is a river basin, or catchment scale model, developed for the Agricultural Research Service in the United States. It is used to predict the impact of land management practices on water, sediment, and agricultural chemical yields over long periods of time in large, complex catchments with varying soils, land use, and management conditions (Di Luzio et al., 2001). Useful results from a non-georeferenced SWAT have been reported for medium and large catchments by different authors such as Peterson and Hamlett (1998). However, the utility of SWAT is markedly increased by linking it to GIS, which is capable of handling large amounts of attribute data in a spatially reference format. The SWAT ArcView extension is a georeferenced graphical user interface for the SWAT model called AVS2000 (Arnold et al., 1998). The GIS interface requires the designation of land use, soil, weather, groundwater, water use, management, soil chemistry, pond, and stream water quality data, as well as the simulation period to run (Di Luzio et. al., 2001).

Tests of AVS2000 performance

The Nash-Sutcliffe coefficient (R^2) and the Deviation of runoff volumes (D_v) were applied to the runoff as a basic test of goodness-of-fit recommended by the World Meteorological Organization (WMO) for hydrological model performance (ASCE, 1993). The Pearson correlation coefficient (r) and its squared value (r^2) were used to analyse the total P concentration exported in the runoff.

Modelling Chlorophyll a – CHLOA

Chlorophyll is the major light-absorbing pigment in green plants that absorbs sunlight and uses its energy to synthesise carbohydrates from CO2 and water in a process known as photosynthesis. Chlorophyll a is a measure of the portion of the pigment that is still active, which is used to indicate the amount of phytoplankton present in water bodies. Chlorophyll a is considered the principal factor to use as a trophic state indicator in water. There is generally a good relation between planktonic primary production and algal biomass that is an excellent trophic state indicator.
The mathematic model was developed based on the average of TP concentration (µg/L) in summer and the average of annual chlorophyll a (µg/L), which represent the better correlation between the two factors for the assessed area where $R^2 = 0.96$. The equation was defined as:

$$[Chl] = \frac{7.3 * \left(p^{1.45}\right)}{100} \quad (1)$$

Where (p) is the average TP concentration in µg/L; 1.45 is the slope of the regression curve; and 7.3 is the intercept value for the regression.

Results and Discussion

Runoff

Runoff generated by the AVS2000 model is based on the Soil Conservation Service (SCS) runoff equation, which was developed in the 1950s for estimating the runoff yield from rainfall for a variety of soil types and land use conditions of a catchment in U.S. The SCS curve number (CN) is a function of a soil's permeability, land use and antecedent soil water conditions for dry soils. The SCS defines three antecedent moisture conditions: 1 – dry (wilting point), 2 – average moisture, and 3 –

wet (field capacity) conditions (Neitsch et al., 2000). Outcomes from model simulations from 1994 to 2000 were not accurate when compared with the measured data, when the hydrologic soil group and pasture defined the CN2 curve as 86. The model over-predicted runoff, and gave an $R^2 = 0.48$ and $D_v = -61.8\%$. The CN2 curve number was then adjusted to 51 due to the slope differences and the model performance was much better than in all previous simulations. However, some adjustments in the soil water capacity value (SOL_AWC) were necessary to refine the model's achievement. The improvement in accuracy of the model after the CN2 and SOL_AWC input adjustments was confirmed by the statistical analyses ($R^2 = 0.99$ and $D_v = 5.78\%$).

Total Phosphorus

Many model variables in agricultural areas such as nutrient concentrations in the soil, fertilizer applications, tillage operations and biological mixing efficiency can affect the model's simulations when using the calibrated runoff. The initial outcomes showed that the model was under-predicting TP concentrations from the Darnum site where $r^2 = 0.69$. In relation to P concentrations in runoff, the SWAT model has some parameters that can be changed to get better outputs, of which the biological mixing efficiency (BIOMIX) is considered the primary one by the model developers (Neitsch et al. 2001). Adjustments were made to increase the BIOMIX parameter from 0.20, the default value for previous simulations, to 0.60 on the final running. The new BIOMIX value produced a more accurate and acceptable output when compared with the measured data at the Darnum site, where $r^2 = 0.99$.

Chlorophyll a

The outcomes generated by CHLOA showed that if the current management measures were continued at Darnum, the chlorophyll a production would vary between 31.2 µg/L to 271.7 µg/L with an average of 107.9 µg/L (Figure 2). Those values of chlorophyll a can classify the water body between mesotrophic and hypertrophic based on the trophic system proposed by Ryding and Rast (1989). The chlorophyll a average from 2003 to 2010 was 107.9 µg/L), which has classified the aquatic system as hypertrophic.

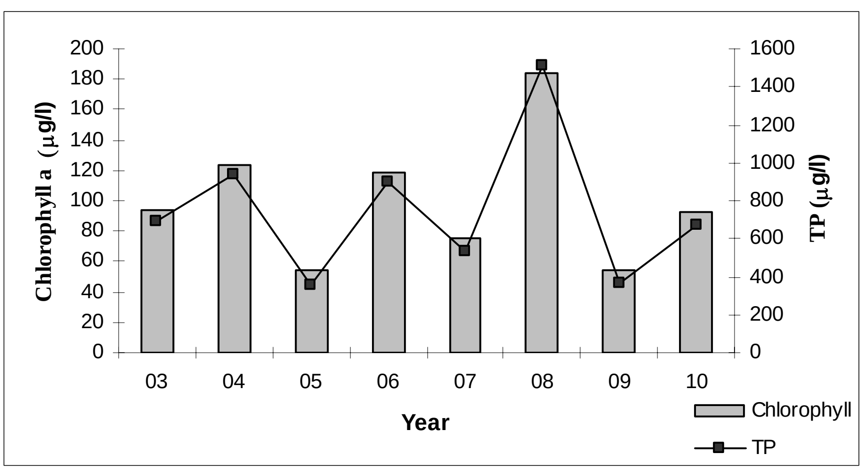

Figure 2. Simulated chlorophyll a production and TP concentration for Darnum.

Conclusions

In this study the GIS version of SWAT 2000–AVS2000 – was successfully applied to a small catchment in Victoria, Australia. The Nash-Sutcliffe coefficient for the final run was $R^2 = 0.99$, while the deviation of the runoff volumes (D_v) was 5.78% after adjustments had been made. The total phosphorus (TP) concentration predictions needed fewer adjustments than the runoff simulations, but some adjustments were made to the BIOMIX parameter to improve the AVS2000 execution. The coefficient of determination substantiated the model's performance where the outcomes achieved an $r^2 = 0.99$ after the adjustments.

The initial poor predictions by the AVS2000 that required adjustment of the CN2 curve value, the SOL_AWC value and the BIOMIX value could be related to the default values, based on current U.S. characteristics, that were likely to be different that those found in Australia. However, it is also possible that the differences were related to the size of the catchment, which was much smaller than those for which the model had been calibrated in the U.S. Nevertheless, the final predictions by the model showed its flexibility to configure a catchment in an environment outside the U.S.

The CHLOA model results showed that if the current management practices in Darnum are maintained, the eutrophication process will be able to accelerate quickly with negatively impacts on the environment and the economy. The CHLOA model can be considered a powerful tool when integrated with AVS2000 to manage P in farmland and to avoid accelerating the eutrophication process.

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II. Model Applications

Evaluation of SWAT Streamflow Components for the Araxisi Catchment (Sardinia, Italy)

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Introduction

We describe the implementation and application of the SWAT model to the Araxisi catchment. The Araxisi is a mountain basin located in the centre of the island of Sardinia, Italy. It is a sub-basin of the larger Tirso catchment that contains the most important reservoir of Sardinia. On the basis of a classification made by the Sardinian Hydrological Survey, designating the basin as almost impermeable, pre-processing of measured data has suggested that this proposed classification has to be interpreted as absence of water loss to deep aquifer recharge.

After describing the way in which the available data (climate, topographic, land use, soil, and hydrological data) for the Araxisi were used to parameterize the SWAT model, we used observed streamflow data to evaluate the streamflow components (surface runoff and baseflow) using two different baseflow separation techniques. In particular we illustrate the performance of the SWAT utilities for automated digital filtering in relation to a proposed manual separation technique. This analysis is conducted in order to gain some insight into the relative importance of the surface, subsurface, and baseflow components of observed hydrographs in an effort to improve the implementation of the model for this study site. Results from our initial implementation of the model are described, focused on our analysis to shed light on the mismatch between measured and simulated streamflow under different precipitation scenarios.

Model Dataset

The Araxisi catchment is a 125 km^2 mountain basin located in the centre of Sardinia. The average annual temperature is around 12° C, and temperatures during the winter season can be low enough for snowfall to occur. The average annual rainfall and evapotranspiration are respectively about 1000 mm and 350 mm (Hargreaves method), less than the average regional value.

For the climatology of the basin, the available dataset is represented by daily values of precipitation (mm), and maximum and minimum temperatures (°C). These daily data are supplied by the Sardinian Hydrological Survey for the period 1946 to 1975 for two gages located within the watershed and four gages situated just outside of the catchment (Figure 1, left). To evaluate the solar radiation we used a dataset of daily values recovered from the literature, in particular the NCEP-NCAR analyses (National Centers for Environmental Prediction and for Atmospheric Research, respectively). This daily dataset for the solar radiation was considered representative of the entire basin (equivalent to one gage for the whole watershed).

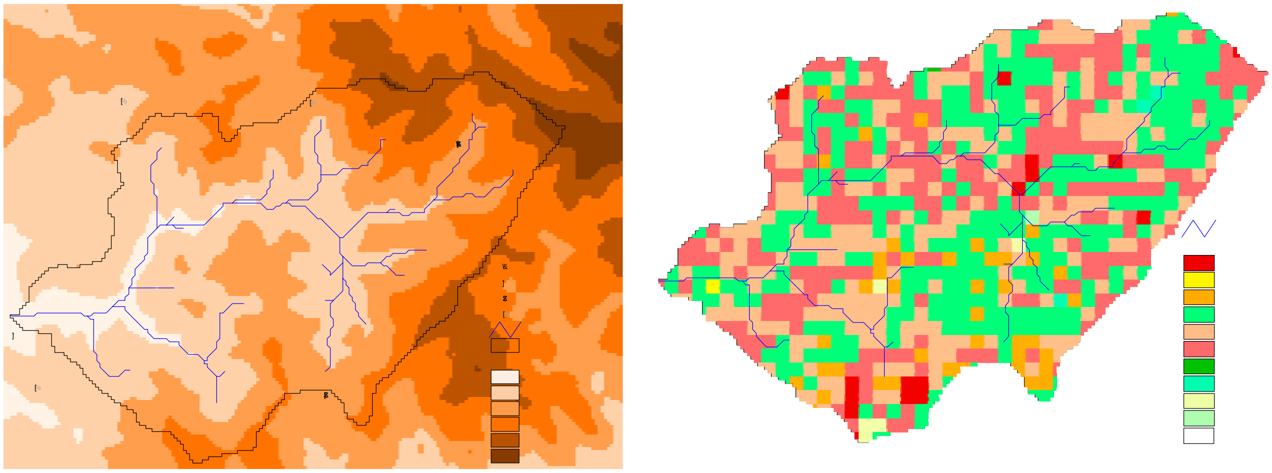

Figure 1: The Araxisi topographic map with the location of the climate gages (left) and the land use classification (right).

The delineation and the topographic characterization of the watershed were obtained from a digital elevation model (DEM) with a resolution of 100 m derived by interpolating a grid of 400 m resolution. The average elevation of the catchment is 804 m with a steep terrain slope of 30% on average. The Araxisi basin was subdivided into 41 sub-basins based on a threshold area of 200 hectares. The main outlet location corresponds to the streamflow gage. The land use characterization of the watershed was made by aggregating the classification of a more detailed map at 400 m resolution derived from a digital database (Figure 1, right). As a result of this conversion we obtained the following distribution of the prevalent land use classes : 36% “evergreen forest” (FRSE), 26% “mixed forest” (FRST), 28% “pasture” (PAST). A single soil class for the entire catchment is being used in this first phase of the work, in anticipation of a detailed soil map convertible to the SWAT classification. The main soil characteristics reported into the related database are a percentage of clay, silt and sand respectively of 5, 25 and 70%. These characteristics correspond to a sandy loam soil (SL) according to the USDA soil texture triangle classification. Concerning the soil stratification two different configurations were hypothesized (single and multiple layers).

The streamflow gage provides a set of daily discharge values for the period 1956 to 1975. We referred to this time series to evaluate streamflow components with two baseflow separation techniques and to compare the results provided by the SWAT model. This set of data was divided into two 10-year series. The first half (1956-1965) was used to calibrate the model while the second one (1966-1975) will be used to assess the reliability of the calibration.

Streamflow Assessment

In streamflow analysis it is often necessary to evaluate the different hydrograph components: surface runoff, subsurface flow and baseflow. In order to perform this separation, besides a high temporal resolution streamflow dataset, a detailed knowledge of the water paths, supplied by an intensive field study, is needed. Therefore in most practical procedures only two streamflow components, quick flow and recession flow, are recognized on the basis of response times, without any reference to the underlying physical processes. Indeed, the analysis of a hydrograph highlights the presence of spikes in response to the rain storms that correspond to quick flow, and slowly varying flow during interstorm periods.

In our case study we applied two different separation techniques to the daily records in order to estimate the baseflow component. The first consists of our implementation of a manual method based on the rainfall data: baseflow was assumed equal to the total streamflow during interstorm periods while a linear trend was estimated during storm periods. The second technique is the digital filter program proposed by the SWAT developers and described in Arnold et al. (1995) and Arnold and Allen (1999) based on the filtering of high and low frequency signals (surface runoff and baseflow, respectively). The filter passes over the streamflow data three times (forward, backward, forward), with a decreasing baseflow rate at each pass. As shown in Figure 2 the first pass provides results comparable to those of the manual technique.

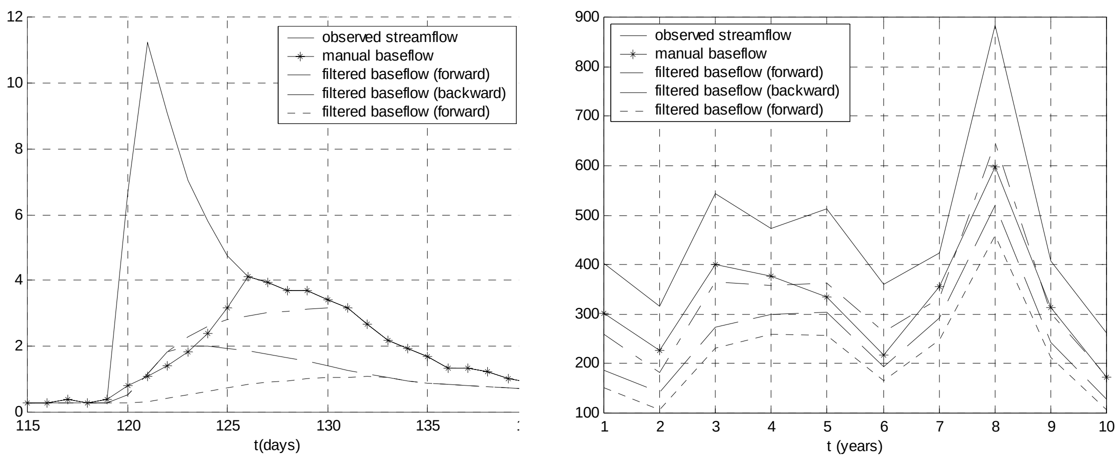

Figure 2: Comparison of manual separation and digital filter baseflow separation technique at a daily (left) and annual time step (right). Streamflow components are expressed in mm.

Another important feature of the catchment dynamics is the baseflow recession behaviour. The form of the most common baseflow recession curve is an exponential decay.

$$Q_t = Q_0 e^{-\alpha t}$$

When a regression is perfomed on logarithms of streamflow within recession periods, an estimate of the average representation of baseflow recession (α) is provided by the average or some other combination of these individual recession slopes. The first, or manual, technique assesses the alpha factor as the average slope of linear trend of logarithmic streamflows within interstorm periods. The second, or digital filter, method considers streamflow separation given by the filter; and the point at which the filter rejoins the filter curve is taken to be the beginning of a baseflow recession segment. This program considers the baseflow recession slopes only in low evapotranspiration months and combines these values with the Master Recession Curve (MRC) method (Arnold et al., 1995, Arnold and Allen, 1999).

However, the results given by the two techniques are quite different. Manual method provided an average value of 0.06 on a sample of 33 recession periods, while the automated one gave an alpha estimation of 0.0143, calculated on 18 events.

Yearly Calibration

The calibration procedure was carried out referring to the first decade (1956-1965) of streamflow data based on average annual conditions only. We focused on the comparison between the streamflow components estimated with the techniques described previously and those simulated by the SWAT model. The separation methods are derived from analytical procedures, related to considerations on response times, while the streamflow components provided by the model are obtained from physically-based equations. A reliable simulation of surface, baseflow, and total flow is an important step in the adoption of a correct schematization of watershed characteristics, since data about soil features is not currently available.

On the basis of the little available soil data, we hypothesized various likely sets of parameters, but none of them led to a realistic separation, baseflow component practically absent in all the simulations (left plot in Figure 3).

After many trials it became apparent that this mismatch stemmed from an incorrect setting of the slope length parameter (L_{hill}) in the AVSWAT interface. In order to estimate lateral flow the model uses the kinematic wave approximation described in Sloan and Moore (1984); this component results in inverse proportion to L_{hill}. A reasonable value of L_{hill} for our catchment based on the topographic data and the subbasin discretization would be 50 m, but the AVSWAT interface fixes this parameter at a very low value of 0.05 m, implying an overestimation of the lateral flow as well as a shortage of available soil water required for groundwater recharge. Correcting this parameter to 50 m led to a considerable improvement in the streamflow separation, as shown in the right plot of Figure 3.

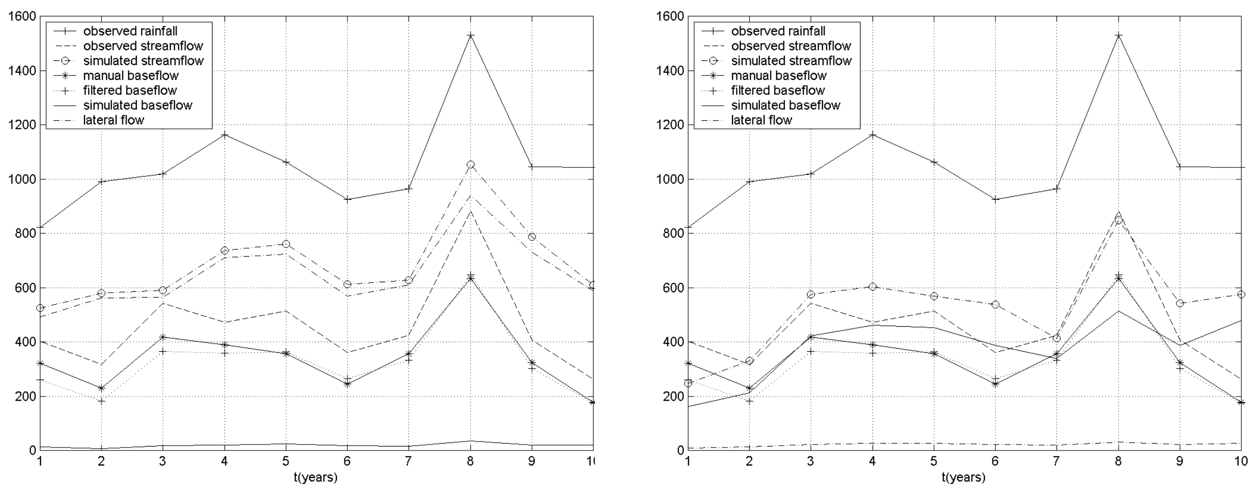

Figure 3: Simulation results obtained using L_{hill} = 0.05 m (left) and L_{hill} = 50.0 m (right). Streamflow components are expressed in mm.

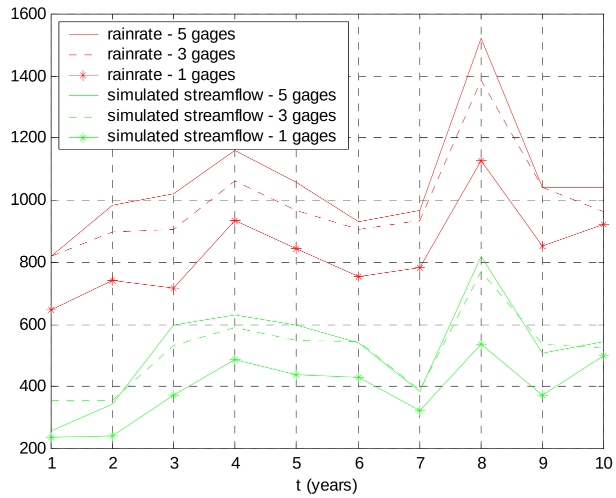

Figure 4: Comparison of precipitation data and simulated streamflow (expressed in mm) based on the use of different numbers of raingages.

Simulated and evaluated baseflow as well as total runoff still show some differences, probably related to an insufficiently detailed description of watershed features. The spatial resolution of the input rainfall data also has an important influence on the model response for a mountain basin, and so another factor for the discrepancy in these preliminary results could be due to the spatial distribution of precipitation records given by the five gages, unable to correctly reproduce the actual rainfall patterns.

An example of the influence of rainfall spatial distribution is shown in Figure 4 which compares simulation results based on the use of one, three, and all five rain gages.

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Model SWAT Application in the Alban Hills (Central Italy)

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Introduction

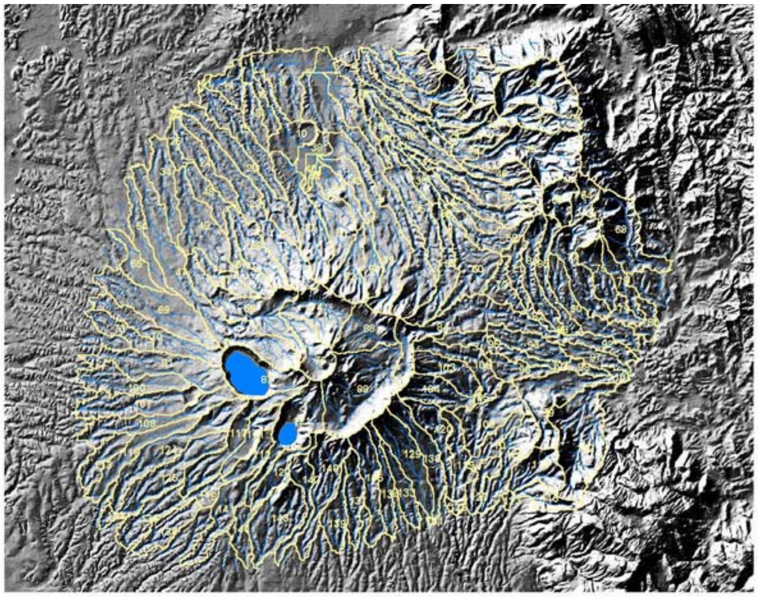
The purpose of this work has been the development of an inflow-outflow model for the middle zone of the Latian Volcano (the Alban Hills). The area of study (approximately 1.000 km^2) has been chosen for its high level of complexity and because up to now it has been studied only with traditional methodology (a regional coefficients method). Complexities belong to three different categories: geological, morphological and human pressure. Geological complexities are due to the nature of the study area; the centre of multiphase volcanic edifice with great production of lava and pyroclastic deposits, of the entire zone of the Latian Volcano. Morphologically the phases of activities of the Alban Hills volcano has produced a great territorial heterogeneity creating extended plains and soft and hard slopes with elevation that varies between sea level and 950 m. above sea level (Mt. Cavo). Morphological heterogeneity is the cause of the complexity of the various uses of the territory. Different conditions have allowed uses that vary from the agricultural use to the semi-native one, to the pasture, the vineyard, the olive groves, the orchards, the arid land and the forests. Moreover, the neighbourhoods associated with the city of Rome have carried a high level of urbanization: houses, industrial buildings, quarries, roads and transportation infrastructures.

Methodology

Balances previously realized, with traditional methodology, allowed the delineation of only 13 subbasins. By implementing the SWAT model with detailed datasets, we have tried to produce an advanced simulation instrument more realistic than those currently in use.

The topographical base is a digital terrain model (DTM) characterised by the accuracy of 20 meters, based on the data provided by the Italian Geographic Military Service (I.G.M.). The coordinate system used for the projection of the data has been the National Grid UTM (fuse 33), based on datum WGS84.

To delineate the subbasins, a small-scale map digitalised hydro-network has been introduced (scale map 1:10.000). The high level of precision of both these basic data produces high quality elaborations.



- Area of study with streams and subbasins -

The automatic delineation tool has been chosen for the subbasin identification.

The extension of 400 hectares has been set as a minimum subbasin dimension (it represents 0.4% of the entire area of study). A manual check on the correct positioning of the outlets, in order to verify the validity of the automatic delineation tool, has been done.

The result has been the delineation of 144 subbasins.

For the landscape characterisation, the land use classification of the Corine-Land Cover project has been adopted.

The initial classification of the land use was not in agreement with the model classification; therefore, a reclassification of the land use (based on its specification) has been done. The following table represents an example of land use reclassification.

Type	Reclassification
Airport	UTRN
Road and transportation infrastructures	UTRN
Complex agricultural land	AGRC
Arable lands	AGRL
Continuous urban zone	URMD
Discontinuous urban zone	URML

- Example of land use reclassification -

The model takes into consideration different management practices that during the year influence the soil characteristics (such as the beginning and the end of the growing season, irrigation, types of pesticide and fertilizer application, cycle of the agricultural crops, etc). Due to the extension of the study area, not all these practices have been simulated.

Particular attentions have been given to the soil characteristics. Soil importance finds justification, first, in its "biological filter" function. This function is due to the inner processes that occur in the ground producing a pad effect on the water quality. Second, soil constitutes a key element in the regulation and separation of water flows (runoff and percolation). The detail introduced in the soil characterisation in comparison of the other methods of balance calculation gives a great analytical valence to the model.

Code	Layer	Hydgrp	Sol_zmx	Sol_crk	Sol_z	Sol_BD	sol_AWC	Sol_k	Sol_cbn	Clay	Silt	Sand	Rock	Sol_Alb	USLE_K
LC1	1	C	400	0	400	0.99	0.037	88	0.130	9.5	31.6	58.9	0	0.160	0.2152
LC2	1	C	1000	0	1000	1.30	0.150	3	0.015	45	30	25	10	0.162	0.1384
LV	1	C	1000	0	1000	1.30	0.215	3	0.015	35	40	25	0	0.162	0.1449
RA1	1	B	650	0	300	1.59	0.110	30	0.014	10	8	82	0	0.300	0.0568
RA1	2	B	650	0	650	1.41	0.110	5	0.000	26	12	62	0	0.000	0.1146
RA2	1	C	700	0	700	1.10	0.110	5	0.020	30	45	25	0	0.162	0.1397
RA3	1	C	1000	0	1000	1.30	0.180	3	0.015	40	30	30	0	0.162	0.1328
RB	1	C	1000	0	1000	1.20	0.240	3	0.020	45	40	15	0	0.231	0.1595

- Extraction of soil database -

A complete and detailed study to produce a soil database with all the components necessary for the simulation has been done. The steps of the study were: bibliographic research, photo-interpretation, morpho-pedological unit identification, field works, laboratory analysis, and soil database development.

This study, together with the meteorological one, was the most time expensive, due to the difficulties of finding local data.

For the definition of the hydrologic response units (HRUs), the minimum possible uncertainty has been chosen, setting the multiple HRUs option with percentage of “Land Use over Subbasins area” and “Soil Class over Land Use area” equal to 0 %.

For the inflow, characterization of historical meteorological time-series has been studied. Data has been collected at 17 stations located all over the territory. Stations recorded daily values for rainfall, temperature, relative humidity and wind velocity. Time series were characterised by gaps of measured data. The causes of the gaps can include the period of maintenance for each station, station dysfunction, and the end of station recording periods.

A hydrological study to find the correlation between rain and elevation and between temperature and elevation has been necessary. The hydrological study for filling the gaps has the advantage, instead of a statistical study, to complete the temporal series with data strictly linked to the landscape.

As reference for the simulation the last five years of the collected data (1951-1999) has been chosen. The end of the period has been established by the last publication of measured data by the Italian Hydrological Service (SIMN).

The following table represent the base characteristics of all the stations (elevation, instrumentations, and years of measurement).

Station	Elev.	Instruments				Rain data collection period	Temperature data collection period
Albano CONI	384	P	-	-	-	1998-1999	1999
Albano Laziale	292	P	T	-	-	1955-1970	
Ardea	47	P	T	-	-	1951-1961;1966-1999	1951-1955;1957;1959-1961;1966-1967;1969-1971;1979-1982;1987-1999
Campoleone	56	P	-	-	-	1951-1953;1955-1967;1969-1999	
Castel di Leva	102	P	T	-	-	1953-1999	1996-1999
Castel Gandolfo	436	P	T	-	-	1995-1999	1995-1999
Cisterna di Latina	100	P	T	-	-	1958-1977;1980-1999	1998-1999
Frascati	322	P	T	-	-	1951-1958;1960-1999	1991-1999
Lunghezza	23	P	T	-	-	1992-1999	
Montecompatri		P	T	Ur	Vv	2000-2002	2000-2002
Nemi	320	P	T	-	-	1998-1999	1999
Pantano Borghese	52	P	-	-	-	1951-1955;1957-1958;1961-1983;1985-1999	
Rocca di Papa	685	P	T	-	-	1951-1957;1959-1970	1952-1954;1957;1960-1962;1965-1967;1969-1970
Salone	23	P	T	-	-	1951-1959;1961-1963;1966-1967;1975;1978-1979;1991-1997	1991-1999
Settecamini	48	P	-	-	-	1951-1954;1957;1959-1996	
Velletri	332	P	T	Ur	Vv	1951-1969;1971-1978;1982;1987-1992;1994-1999	1951-1969;1998-1999
Zagarolo	318	P	T	-	-	1951-1994;1999	

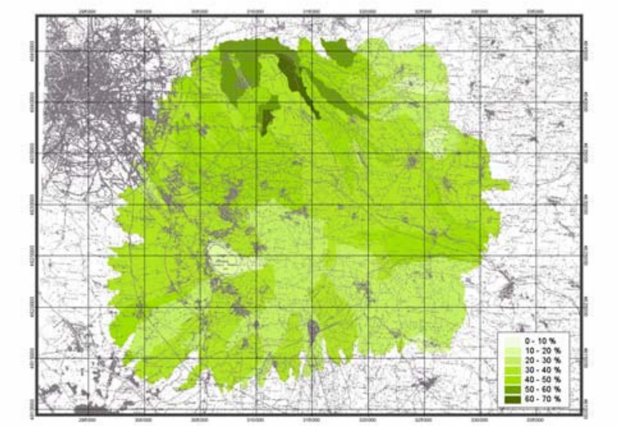
- Meteorological stations, elevation, instruments, working years -

For the simulation the following options have been chosen: - The SCS-Curve Number has been the method for the runoff computation. The Hargreaves method was used for the potential evapotranspiration computation. The soil bypass flow (crack-flow) has been admitted. Channel degradation and stream and lake water quality processes have been not activated.

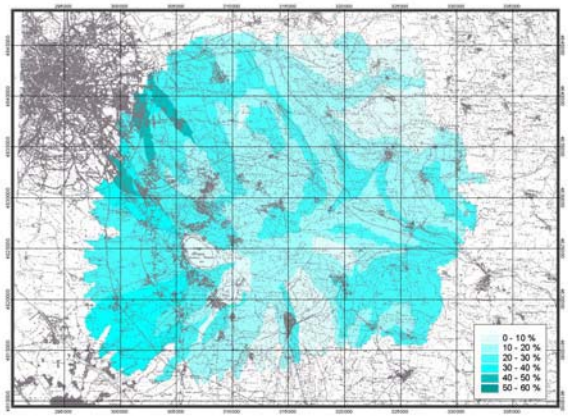
For the model calibration, first, the variation of the percentage of one single variable was tried. Data used as reference has been the outflow and infiltration literature values derived from previous studies. This calibration, theoretically correct, has the inconvenience that the reference data was derived from studies realised with old methodologies and has not been directly measured. Second, establishing the values of recharge for each unit and integrating this data with a hydrogeological study gave the determination of the underground flows. The calibration has been obtained by comparing the values of the flow measured in specific sources with the values of recharges supplied by the model. Reference data derives from literature data and from data given by the local water utilities.

Results

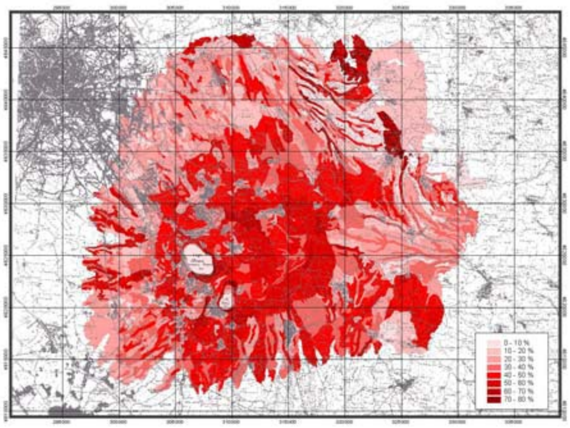
To represent the results maps at the scale map of 1:100.000 has been produced. The main result of the study has been the reconstruction of the Inflow and the Outflow for the study area.



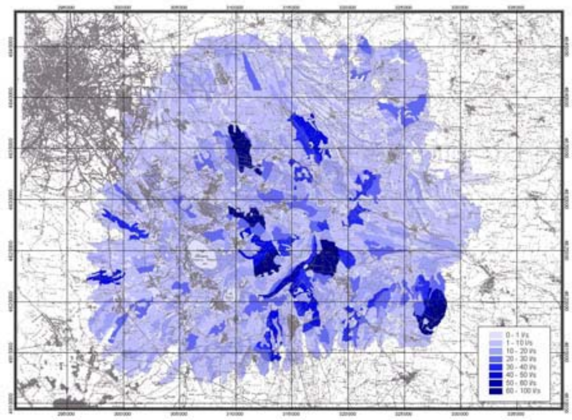
- Evapotranspiration Map -



- Runoff Map -



-Soil percolation Map -



- Groundwater recharge Map -

Furthermore, managerial valence has been given to these outputs. Following to the study results it is possible to characterize the most critical zones from the point of view of aquifer's recharge. By the means of the application of the calibrated model, a very effective management of the territory could be achieved to the benefit of the water resources protection.

Conclusion

The realisation of the model has highlighted some tangible problems of the application of this instrument. First, it was difficult to prepare a dataset in a format suitable for the simulations. Difficulties were solved with time and resources, realising specific studies or appropriate data format transformation. Second, it was difficult to simulate problems associated with hard slopes (mountainous zone), where an exact match of the balance's parameters with the literature ones has not been noticed, and where stream gage data are missing.

The use of this instrument allows a detailed representation of the hydrological cycle to be performed, which is the base for the reconstruction of the input of a more extensive hydrogeological model. The power of this methodology is the ability of adjustment to the variations of the input and the possibility to provide the results with a management valence.

Future developments of our activities are to study other significant river basins in order to better calibrate the model and to apply it in other different local realities.

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Application of SWAT in A Large Mountainous Catchment with High Spatial Variability

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Abstract

In this study we adopted a multi-variable and multi-site approach to calibration and validation of the SWAT (Soil Water Assessment Tool) model for the Motueka Catchment, making use of extensive field measurements. Not only were a number of hydrological processes (model components) in a catchment evaluated, but also a number of subcatchments were used in the calibration. The study was conducted using an 11-year historical flow record (1990–2000); 1990–1994 for calibration and 1995–2000 for validation. SWAT generally predicted well the potential evapotranspiration, water yield and daily streamflow. The predicted daily streamflow matched the observed values, with a Nash–Sutcliffe coefficient of 0.78 during calibration and 0.72 during validation. However, values for subcatchments ranged from 0.31 to 0.67 during calibration, and 0.36 to 0.52 during validation. The predicted soil moisture remained wet compared to the measurement. About 50% of the extra soil water storage predicted by the model can be ascribed to over-prediction of precipitation; the remaining 50% discrepancy was likely to be a result of poor representation of soil properties. Hydrological compensations in the modelling results derived from water balances in the various pathways and storage (evaporation, streamflow, surface runoff, soil moisture and groundwater) and the contributions to streamflow from different geographic areas (hill slopes, variable source areas, sub-basins, and subcatchments). The use of an integrated multi-variable and multi-site method improved the model calibration and validation and highlighted the areas and hydrological processes requiring greater calibration effort.

KEYWORDS. Physically based distributed hydrological models, calibration and validation, soil and water assessment tool, spatial variability

Introduction

Physically based, distributed hydrological models (PDHMs), whose input parameters have a physical interpretation and explicit representation of spatial variability (Abbott et al., 1986), are increasingly being used to solve complex problems in water resources applications (Sorooshian and Gupta, 1995), including environmental impacts of land-use changes, effects of climate change on water resources, and water planning and management in a catchment. However, problems with PDHMs include a lack of sufficient data to fully characterize spatial variability, scale problems of integration of field measurements and model parameter element, and imperfect representations of real processes in models (Beven, 1989, 1993, 2002; Grayson et al., 1992a). These factors invariably result in a requirement for model calibration and validation (Refsgaard, 1997; Anderton et al., 2002).

In many cases, the appropriate values for a model parameter are determined traditionally through a subjective trial-and-error process in which a small number of key parameters are manipulated in an attempt to achieve the desired response (Gupta et al., 1998; Anderton et al., 2002). The model calibration is usually based on a comparison between the simulated and observed streamflow, primarily depending on a modeler's hydrological expertise. Nevertheless, the potential for equifinality or non-uniqueness in complex, spatially distributed models with numerous calibration parameters has shown that a large number of alternative parameterizations can produce acceptable results. This is particularly true when a single variable, e.g. outlet streamflow, is selected as the sole calibration criterion (e.g. Beven, 1993, 1996, 2001).

The single-criterion method has been found to be limited when calibrating a complex numerical model with many parameters (Gupta et al., 1999; Anderton et al., 2002). The equifinality problem is of particular importance in PDHMs due to their distributed structure and the huge number of parameter values often required to be estimated and optimized. To tackle this problem, different calibration methods for PDHMs have been developed, e.g. the generalized likelihood uncertainty estimation GLUE (Beven and Binley, 1992). Other automatic calibration procedures with an optimization strategy include the genetic algorithms (Wang, 1991) and the shuffled complex evolution (SCE-UA) global optimization algorithm (Duan et al., 1992). However, these methods are time-consuming and computationally intensive, thus only a small set of input parameters can be optimized. Automatic methods can optimize to unrealistic parameter values unless appropriate, physically realistic constraints are included in the algorithm.

A subsystem approach to calibrating internal state variables such as evapotranspiration and baseflow can be integrated into a model calibration and validation process. This multi-variable calibration method can fully use the field measurements and it has been suggested as an effective methodology for reducing uncertainty in parameter identification for PDHMs (Fenemor, 1988; Grayson et al., 1992b; Anderton et al., 2002; Bergstrom et al., 2002), particularly in a large catchment with high heterogeneity and spatial variability.

In this study a multi-variable and multi-site approach to calibration and validation of a PDHM has been adopted, in which not only internal hydrological processes in the model have been evaluated, but also a number of subcatchments have been used in the calibration. A physically based, distributed model – Soil Water Assessment Tool (SWAT) (Arnold et al., 1998) has been applied at a large scale in the Motueka River catchment in New Zealand. The catchment has a complex mixture of geology and land use, and water availability is a critical issue with competition among multiple in-stream and off-stream users. The hydrological components used for calibration and validation in this study were precipitation, temperature, potential evapotranspiration (PET), total water yield, and baseflow. In addition, performance of the model in six subcatchments was used to calibrate and validate the model. Extensive field measurements have been used to calibrate and internally validate the SWAT model in the Motueka Catchment.

Catchment and Model Description

The Motueka River basin is situated at the north of the South Island of New Zealand. The river drains an area of 2075 km^2 and has a main stem length of approximately 36 km. It provides 65% of the major freshwater flow into Tasman Bay. Altitude exceeds 1600 m in the upper catchments of the two major tributaries, the Motueka and Wangapeka. Two-thirds of the catchment is steep country with slopes exceeding 27%.

Land uses in the Motueka Catchment comprise exotic forestry, mainly Pinus radiata (covering 25% of the catchment area); sheep and beef farming (19%); and limited but increasing dairying. Horticulture (mainly pip fruit, berry fruit, hops, vegetables) occupies a small, but expanding, area. A large area of the catchment is conservation estate with indigenous forest, scrub and tussock grassland (55%). This is mainly in the high-rainfall headwaters of the western tributaries and upper Motueka.

Geologically, the upper Motueka headwaters are underlain by Permian age ultramafic and sedimentary rocks. The western tributaries are underlain by a complex mixture of sedimentary and igneous rocks dating from the Cambrian through to Miocene ages. The middle and lower reaches of the main stem and eastern tributaries of the Motueka are underlain by thick layers of glacial outwash gravels and younger alluvium.

A digital thematic map of land cover interpreted mainly from summer 1996-97 satellite imagery was used to define land use in the Motueka Catchment, and the physical and chemical properties (Chittenden et al., 1966) were derived from the National Soils Database and Land Resources Inventory.

The Motueka Catchment has been divided into seven nested subcatchments based on measured flow records (Fig. 1), and these have a wide variety of land uses, land covers, geology, and soil types. Six subcatchments plus the Motueka Catchment at Woodstock were used to spatially calibrate and validate the model (Fig. 1 and Table 1).

Table 1. Motueka Catchment and subcatchments.

Catchment and subcatchments (Flow gauge names)	Area (km^2)	Area (%) [a]
Upper Motueka (Gorge)	163.0	9.3
Motupiko (Christies)	105.4	6.0
Tadmor (Mudstone)	88.0	5.0
Wangapeka (Walters Peak)	479.0	27.4
Stanley Brook (Barkers)	81.6	4.7
Baton (Baton Flats)	168.0	9.6
Motueka (Woodstock) [b]	1765.6	100.0

[a] Area (%) in third column is percentage of the Motueka Catchment above Woodstock.

[b] The Woodstock flow gauge provides the last river measurement for the catchment although there is still about 309 km^2 below this point.

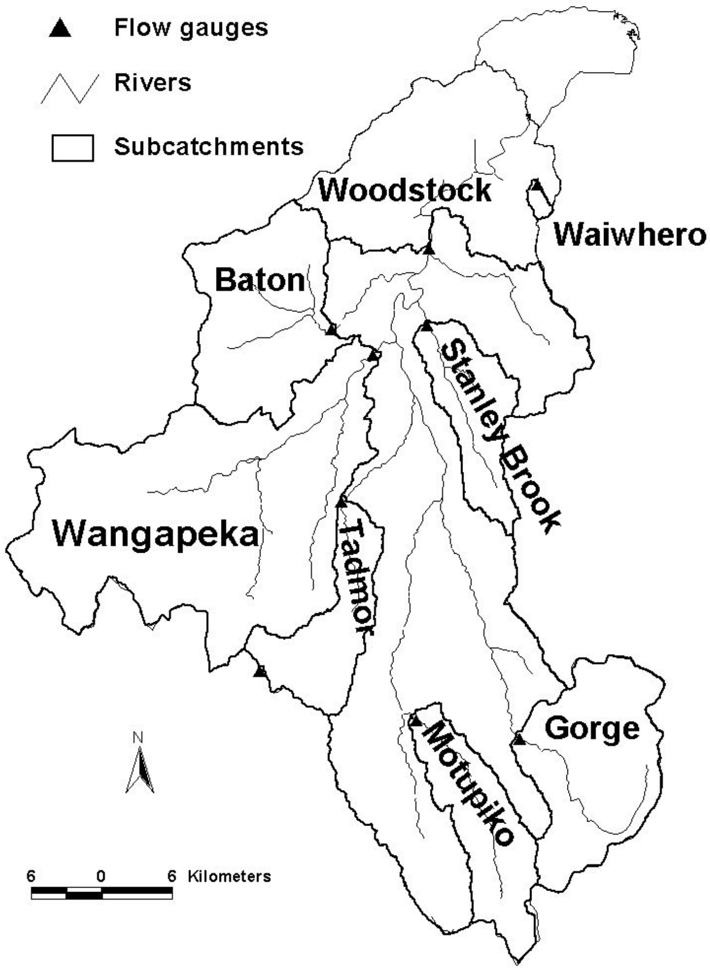


Figure 1. Subcatchments in the Motueka Catchment.

SWAT is a physically based, distributed hydrological model that operates on a daily time-step (Arnold et al., 1998). A catchment is firstly split into sub-basins according to the terrain and river channels, and then into multiple hydrological response units (HRUs) based on the soil and land cover types within the sub-basins. An HRU is a fundamental spatial unit upon which SWAT simulates the water balance. A comprehensive description of all the components in SWAT can be found in the literature (e.g. Arnold and Allen, 1996; Arnold et al., 1998; Srinivasan et al., 1998).

As part of this study precipitation adjustment has been made to the standard SWAT model. It is the spatial interpolation of precipitation among gauges and stations.

Precipitation is the key input variable that drives flow and mass transport in hydrological systems. The spatial variability of precipitation and the accuracy of the precipitation input is critical to the use of hydrological models (e.g. Beven and Hornberger, 1982; Hamlin, 1983). The annual precipitation in the Motueka Catchment ranges from about 950 mm to more than 3500 mm, with high variability due to a complex, rugged terrain. The arrangement of the mountains and the predominately westerly airflows result in a strong precipitation gradient from west to east in the catchment. There is an irregular spacing of precipitation gauges around the Motueka Catchment with 18 gauges with long enough records for use in a long-term modelling study. Unfortunately these are distributed mainly in the lower parts of the catchment. However, SWAT assigns the climate parameter values (e.g. precipitation) obtained from the closest station to a sub-basin.

A separate pre-processing model has been developed to predict the daily precipitation based on the 18 gauges and estimated annual isohyets. Assuming the precipitation at a point is more or less influenced by the adjoining precipitation gauges, the distance between the point and adjoining gauges has been used to adjust the magnitude of the precipitation as a modifier. The closer to the gauge, the stronger the influences to a point can be expected. The mean annual precipitation pattern derived from miscellaneous sources (Scarf, 1972) has been used to adjust the precipitation at the point as another modifier:

$$R(y) = \sum_j \left(\frac{g\left[D\left(y, x_j\right)\right]}{\sum_i g\left[D\left(y, x_j\right)\right]} \right) R\left(x_j\right) \frac{A(y)}{A\left(x_j\right)} \qquad (1)$$

where A() is the mean annual precipitation at a point; R() is the daily precipitation at a point; y is the prediction point; and x_j is a precipitation gauge; D(y, x) is the distance between the predictive point and the precipitation gauges. For this study, the inverse distance was used as the weighting function. The gauges with missing data were excluded from the weighting calculation. Therefore, the predicted precipitation at a point will be influenced by the 18 gauges around the catchment and the distribution of annual precipitation. A 25-km spatial filter has been used to eliminate the influence of distant gauges. The distance of 25 km was chosen after trial-and-error analyses. In summary, the method favours the gauges that are near the given point of prediction (within 25 km), and more distant gauges were excluded from the weighting calculation.

Surface runoff is estimated by the Soil Conservation Service curve number method (Soil Conservation Service, 1972). The curve number varies non-linearly from condition I (dry) at wilting point to condition III (wet) at field capacity, and approaches 100 at saturation.

A storage routing technique is used to predict infiltration through each soil layer (up to 10 layers) in the root zone. Downward flow occurs when field capacity of a soil layer is exceeded if the layer below is not saturated. The downward flow is governed by the saturated conductivity of the soil layer. A kinematic storage routing technique that is based on saturated conductivity is used to calculate lateral subsurface flow simultaneously with percolation.

A shallow aquifer storage recharged by the percolation from the bottom of the root zone is incorporated. Baseflow is allowed to enter the channel reach only if the amount of water stored in the shallow aquifer exceeds a threshold value defined through a calibration process.

Evapotranspiration is the primary mechanism by which water is removed from a catchment. Three options for estimating potential evapotranspiration (PET) – Penman–Monteith (Monteith, 1965); Priestley–Taylor (Priestley and Taylor, 1972); and Hargreaves (Hargreaves and Samani, 1985) – are included in the model. The Penman–Monteith method requires solar radiation, air temperature, relative humidity and wind speed. The Priestley-Taylor method requires solar radiation, air temperature and relative humidity. The Hargreaves method requires daily air temperature as input. The Hargreaves method (Hargreaves and Samani, 1985) was selected to calculate the PET throughout the catchment.

Results And Discussion

The SWAT calibration and validation procedure followed several steps. Firstly, the predicted daily precipitation and temperature were tested using the independent gauges in the catchment. The PET calculation in SWAT was also validated using field measurement and published data at different sites and temporal scales. Secondly, a computer hydrograph separation program HYSEP (Sloto and Crouse, 1996) was used to derive baseflow and surface runoff from measured flow data in each subcatchment. The HYSEP-derived mean annual surface runoff and baseflow were used to calibrate the simulated surface runoff and baseflow respectively. The period 1990–1994 was used for daily streamflow calibration. The daily streamflow from the whole catchment at Woodstock was calibrated to reflect contributions from annual surface runoff and baseflow. After calibration of the daily streamflow at Woodstock, the daily streamflow from subcatchments was fine-tuned. The period 1995–2000 was used for validation. Thirdly, soil moisture measured in the field was used for model validation.

Potential evapotranspiration

The Hargreaves method was selected to calculate PET throughout the catchment because some data were unavailable and the method's PET estimates were in agreement with the data from several sources and time scales. At Riwaka (Fig. 2), the Hargreaves method predicted an annual mean PET of 844 mm in the 11-year period 1990–2000, consistent with the 829 mm published by the New Zealand Meteorological Service (1986) for 1965–1983. In contrast, the other two PET methods, Penman–Monteith and Priestley–Taylor, produced a much lower PET (540 mm), and therefore were not used for model calibration. The poor performance of these is due to the interpolation of the input variables from only one site, actually outside the catchment. The predicted monthly PET by the Hargreaves method was also in agreement with the published PET data (Fig. 2) with an R^2 of 0.99 at Riwaka.

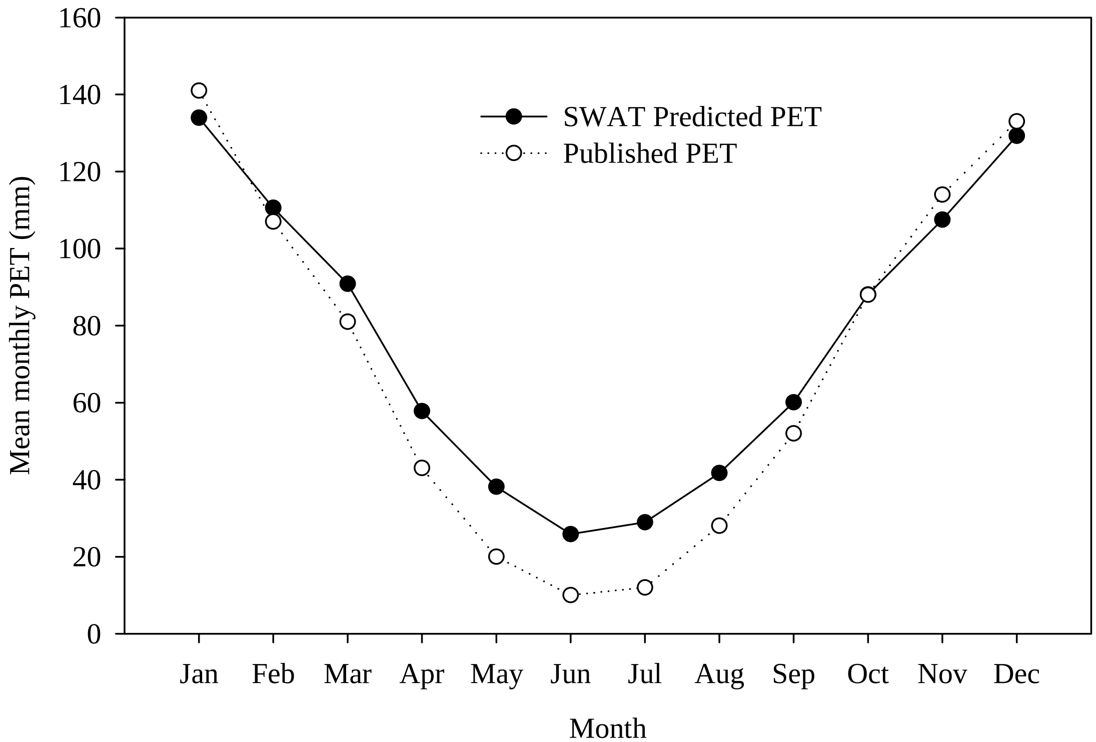


Figure 2. Hargreaves-predicted PET compared with the published data (New Zealand Meteorological Service, 1986) at Riwaka (R^2 = 0.99).

A daily PET estimate for 1996–2000 based on monitored hourly meteorological data at central Moutere (near Woodstock) using a Penman–Monteith method recommended by FAO (Food and Agriculture Organization; Allen et al., 1998) was also used for comparison. The Hargreaves method predicted an annual mean PET of 803 mm at this site, which was 34 mm higher than the 769 mm from the hourly "measured" data calculation. The mean monthly PET showed a high correlation (Fig. 3) between the Hargreaves predicted PET and the estimate based on the hourly meteorological data. Similarly, the predicted daily PET pattern also showed good agreement with the calculation based on the hourly data, with an R^2 of 0.78 (Fig. 4).

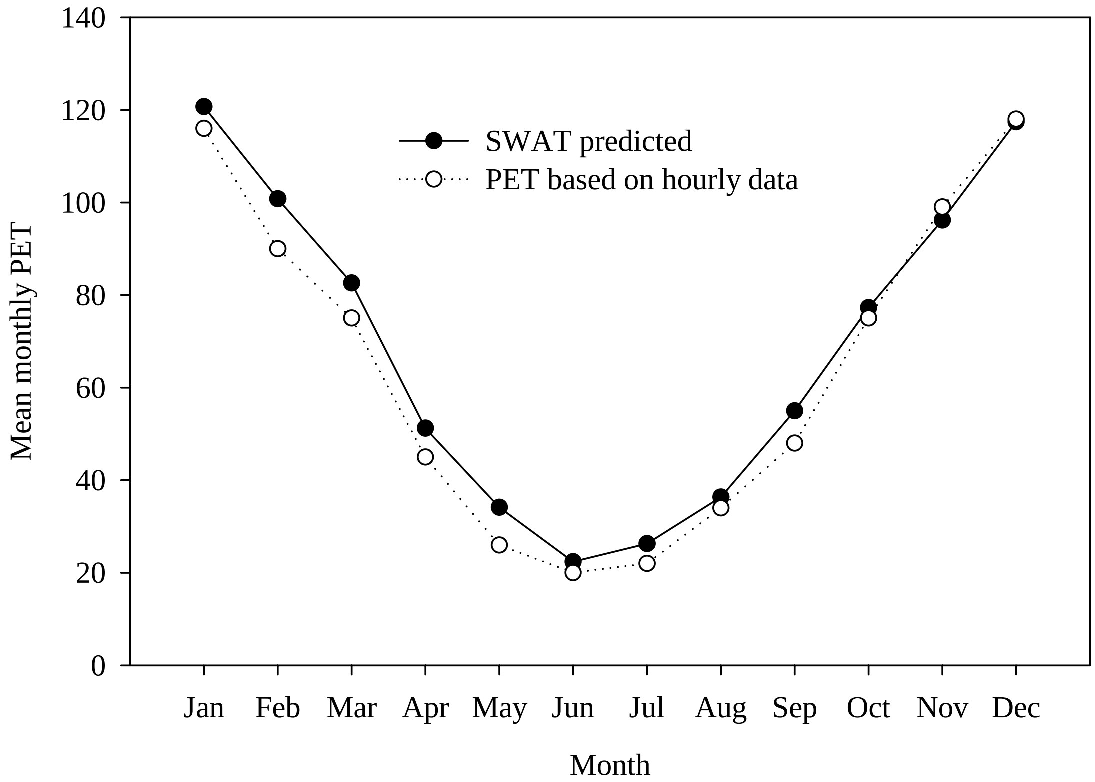


Figure 3. Hargreaves-predicted PET against calculated PET based on the hourly data at central Moutere (R^2 = 0.99)

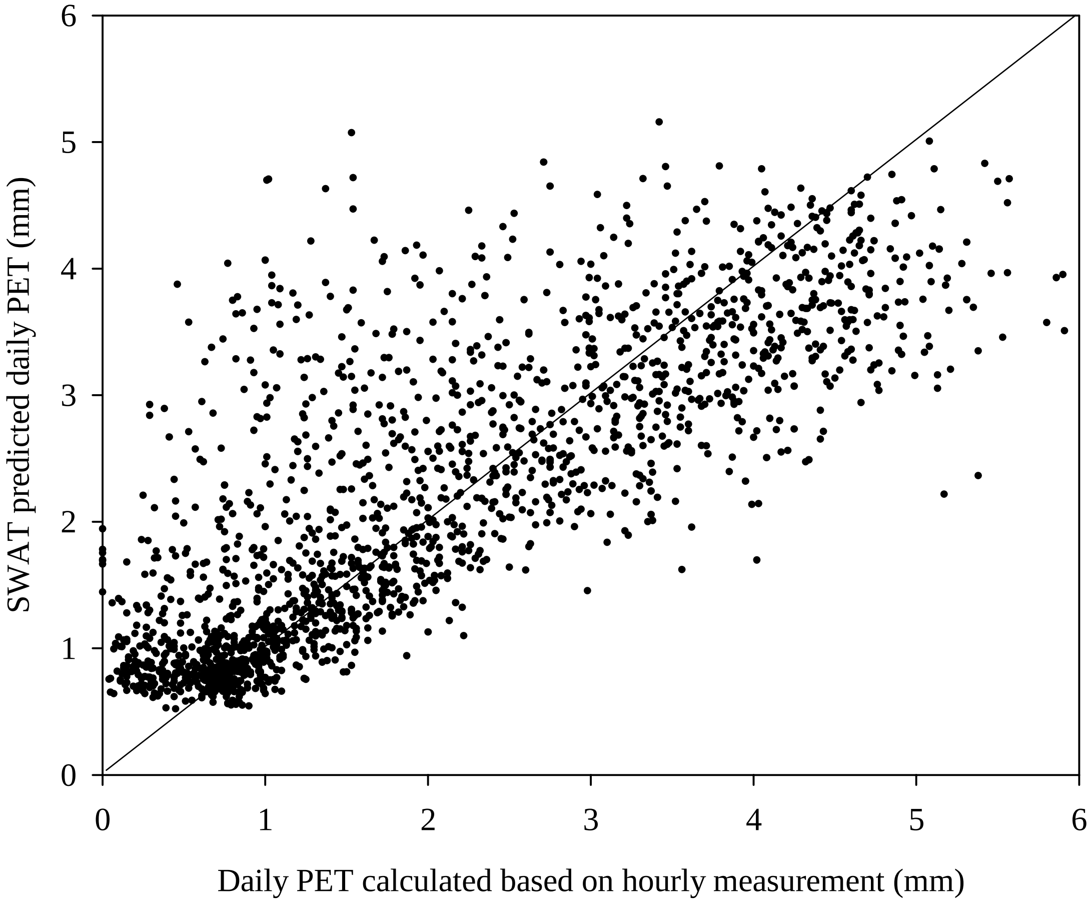


Figure 4. Hargreaves-predicted PET against calculated daily PET from 1996 to 2000 at central Moutere (R^2 = 0.78).

The results clearly show that the Hargreaves method, based on the currently available meteorological data had the best PET estimation at the yearly, monthly, and daily time scale for PET prediction in the Motueka Catchment.

Baseflow and surface runoff

The R^2 for predicted annual baseflow against the hydrograph-separated baseflow from measured flow data in 11 years at Woodstock was 0.79 (Fig. 5). This showed the model had a good performance in baseflow modelling over the whole catchment. However, the R^2 varied from 0.46 to 0.90 in the subcatchments (Table 2). A similar pattern (Fig. 5), which showed predicted annual baseflow is somewhat higher than hydrograph-separated baseflow, was observed in all subcatchments except upper Motueka Catchment at Gorge.

Table 2. Predicted and hydrograph-separated baseflow for subcatchments.

No.	Subcatchments	R^2
1	Upper Motueka at Gorge	0.70
2	Motupiko	0.75
3	Tadmor	0.90
4	Baton	0.46
5	Wangapeka	0.58
6	Stanley Brook	- *
	Motueka at Woodstock	0.79

* Note: Not enough data to calculate R^2 at Stanley Brook

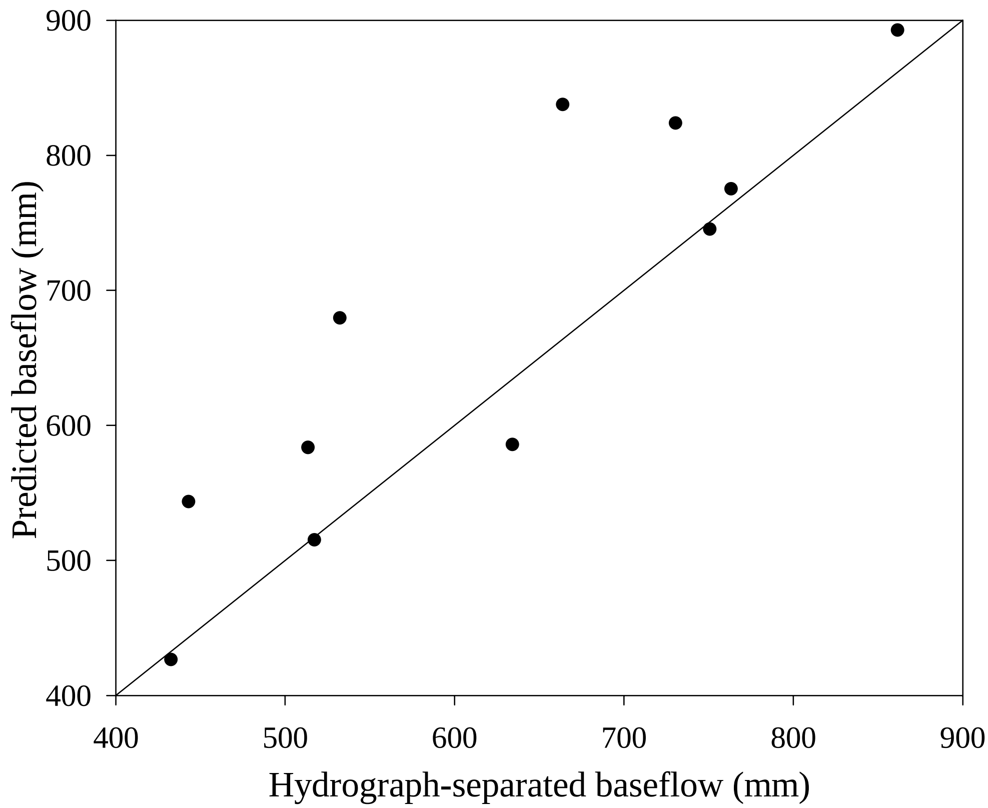
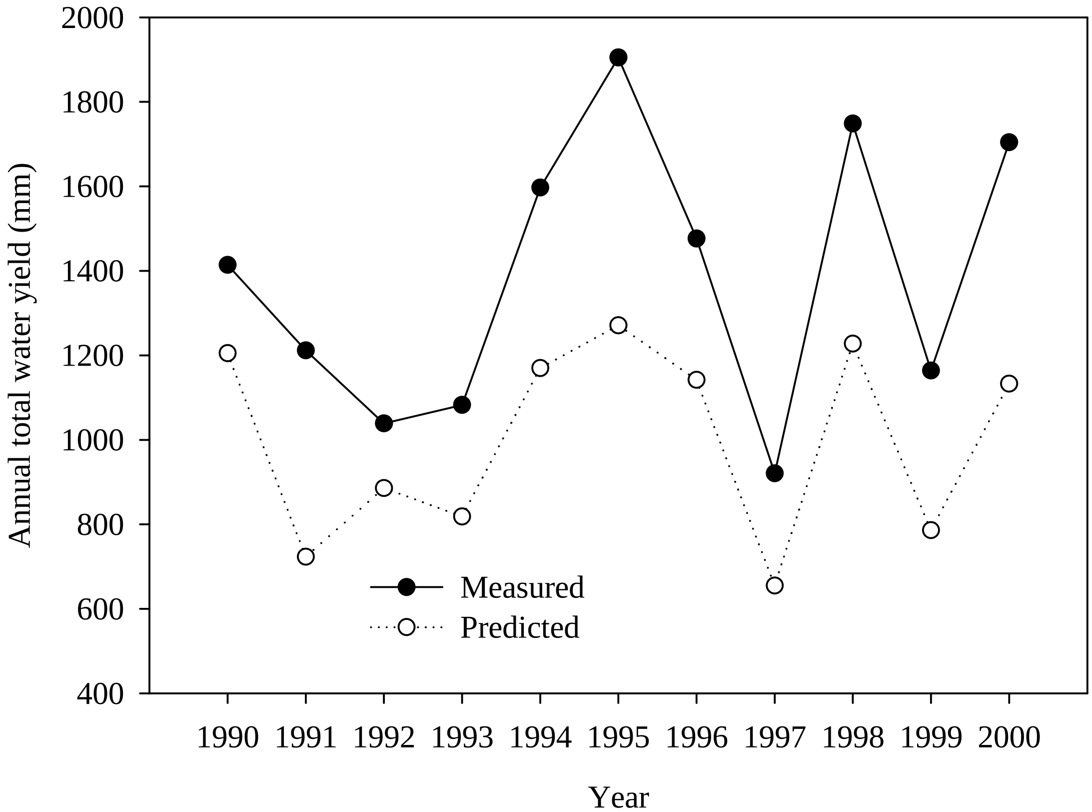


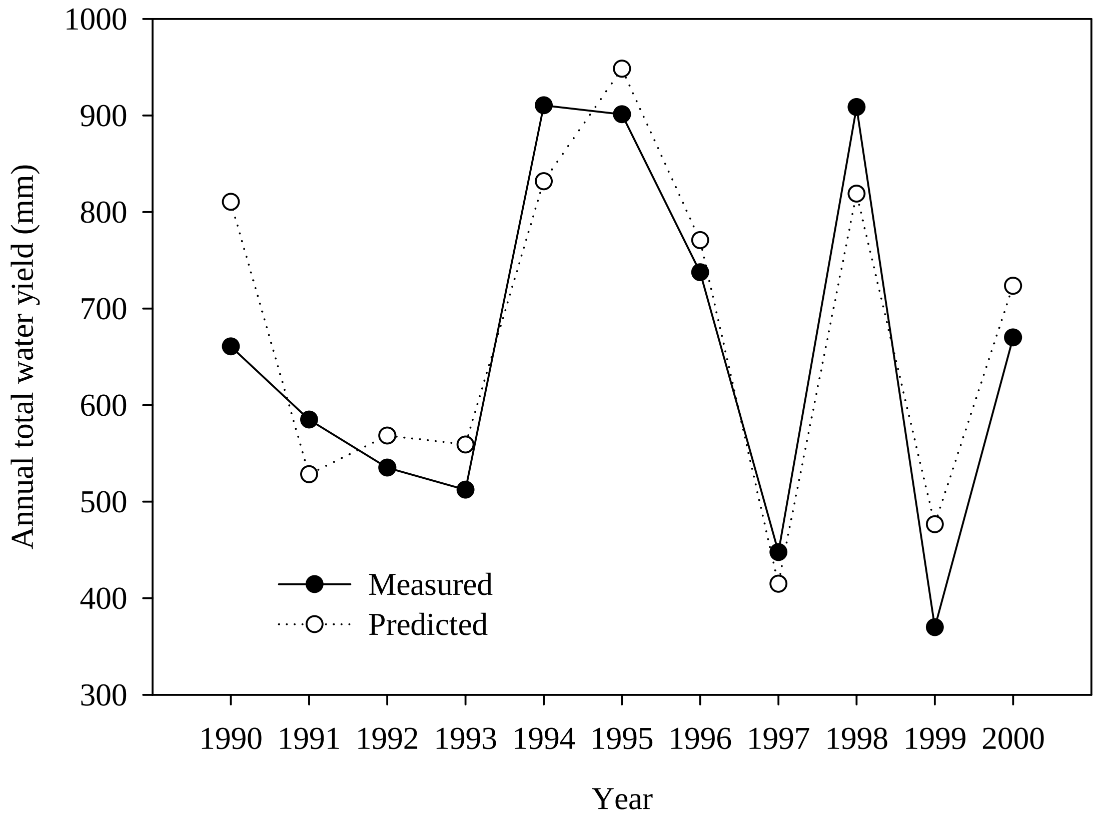
Figure 5. Predicted against the hydrograph-separated annual mean baseflow over 11 years at Woodstock.

<u>Annual total water yield</u>

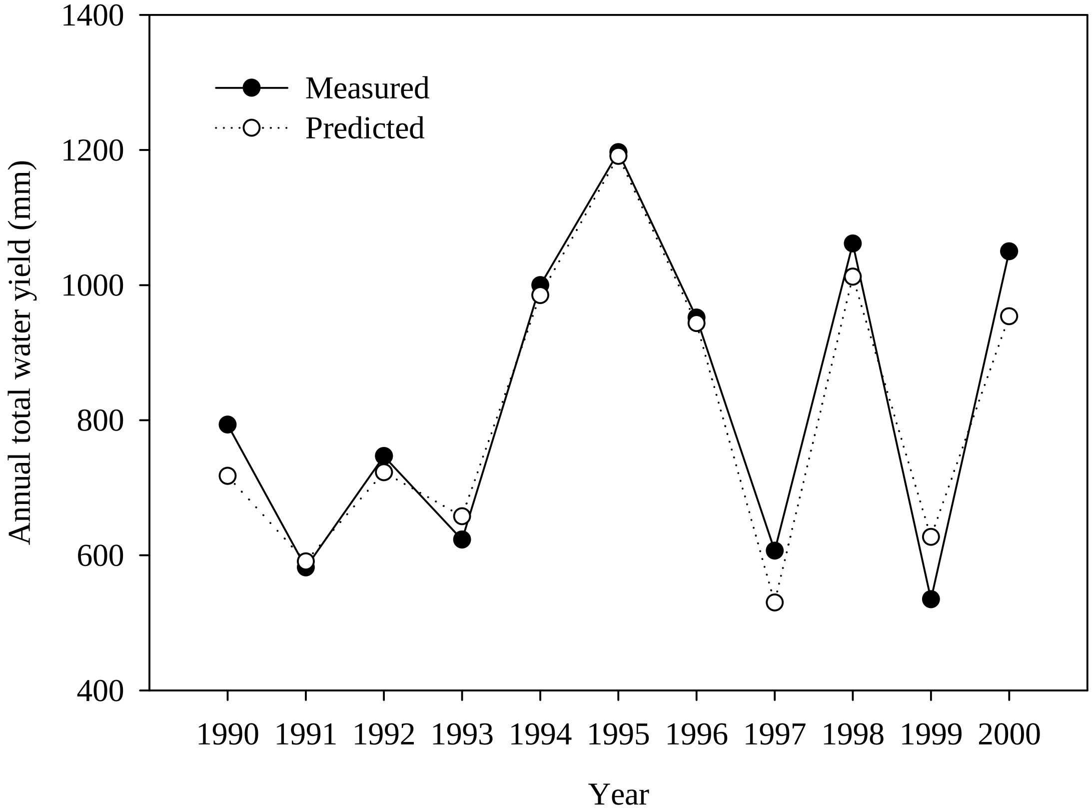
All the subcatchments are nested in the Motueka Catchment upstream of Woodstock, therefore the hydrological response at Woodstock depends on the combined behaviour of upstream subcatchments. The predicted annual total water yield well matched the measured at Woodstock with an R^2 of 0.91(Fig. 6G), and generally had an acceptable accuracy in five of the six subcatchments (Baton, Stanley Brook, Tadmor, Wangapeka and Motupiko) with R^2 ranging from 0.64 to 0.95 (Fig. 6A-G). However, in the upper Motueka (Gorge gauging site), a significant discrepancy between the predicted and measured water yield was observed (Fig. 6A).



(A) Gorge

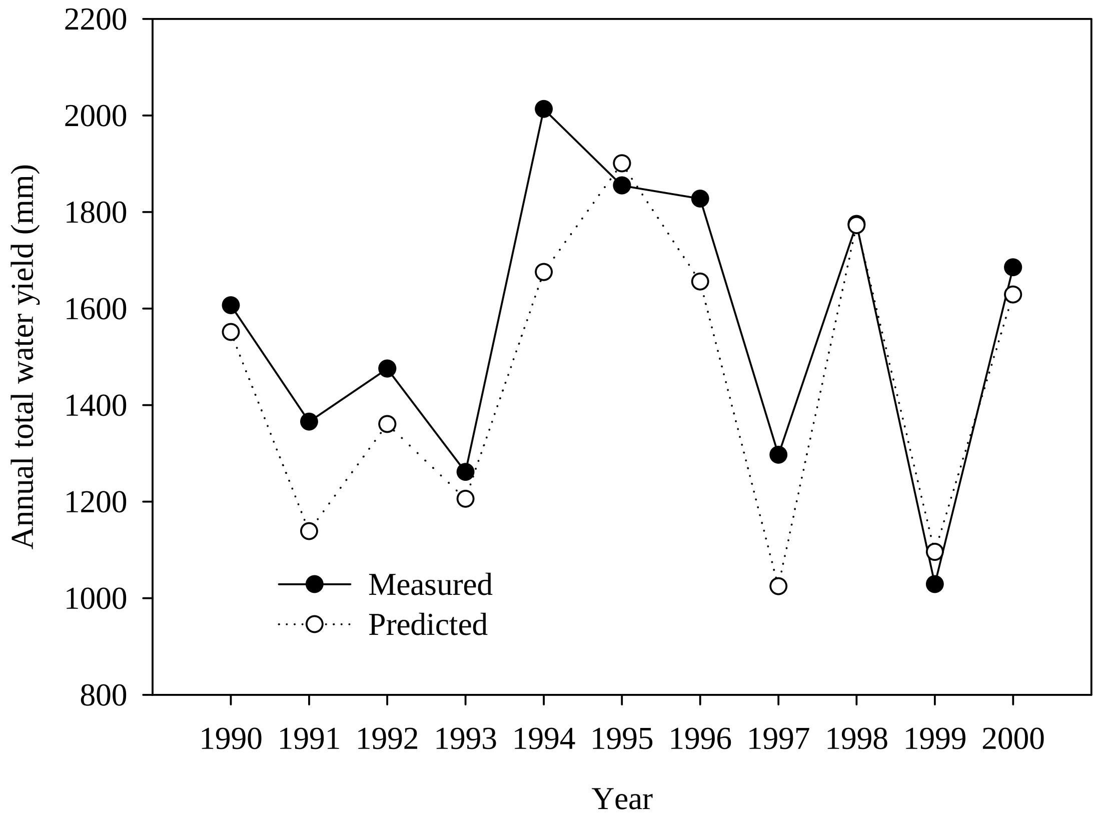

1000
900
800
700
600
500
400
300
Annual total water yield (mm)
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
Year
Measured
Predicted

(B) Motupiko



1400
1200
1000
800
600
400
Measured
Predicted
Annual total water yield (mm)
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Year

(C) Tadmor


2200
2000
1800
1600
1400
1200
1000
800
Annual total water yield (mm)
1990
1991
1992
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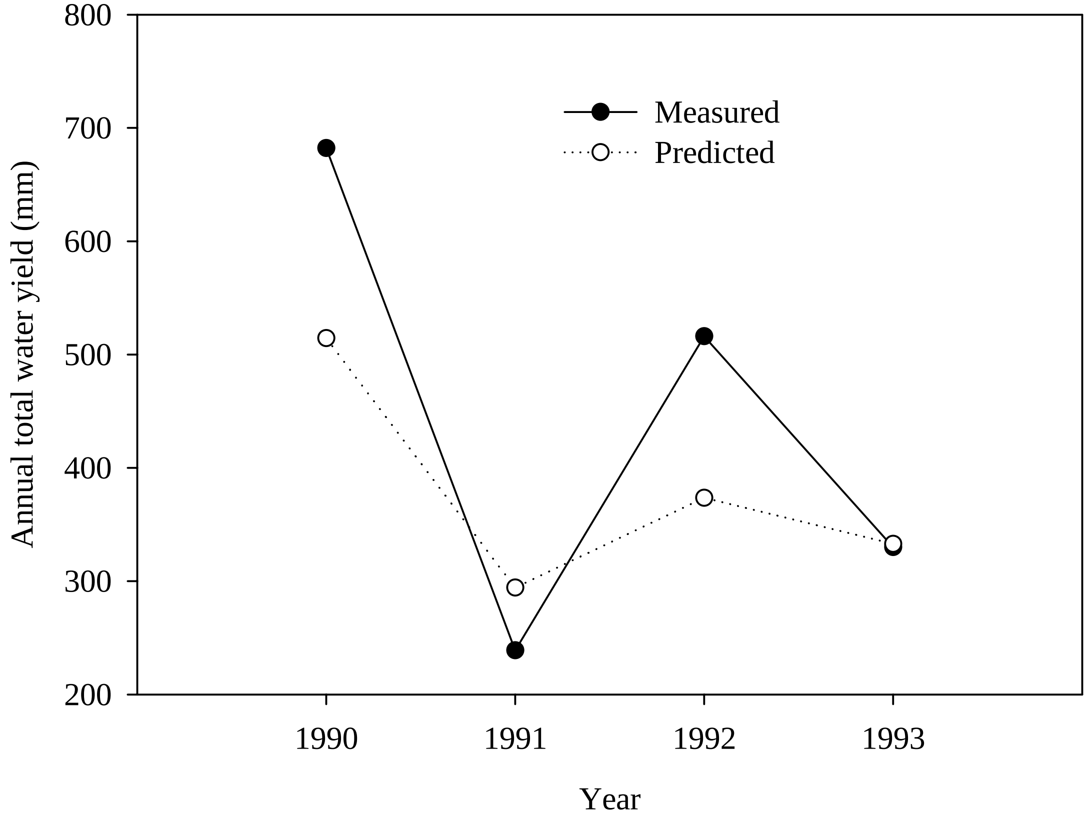
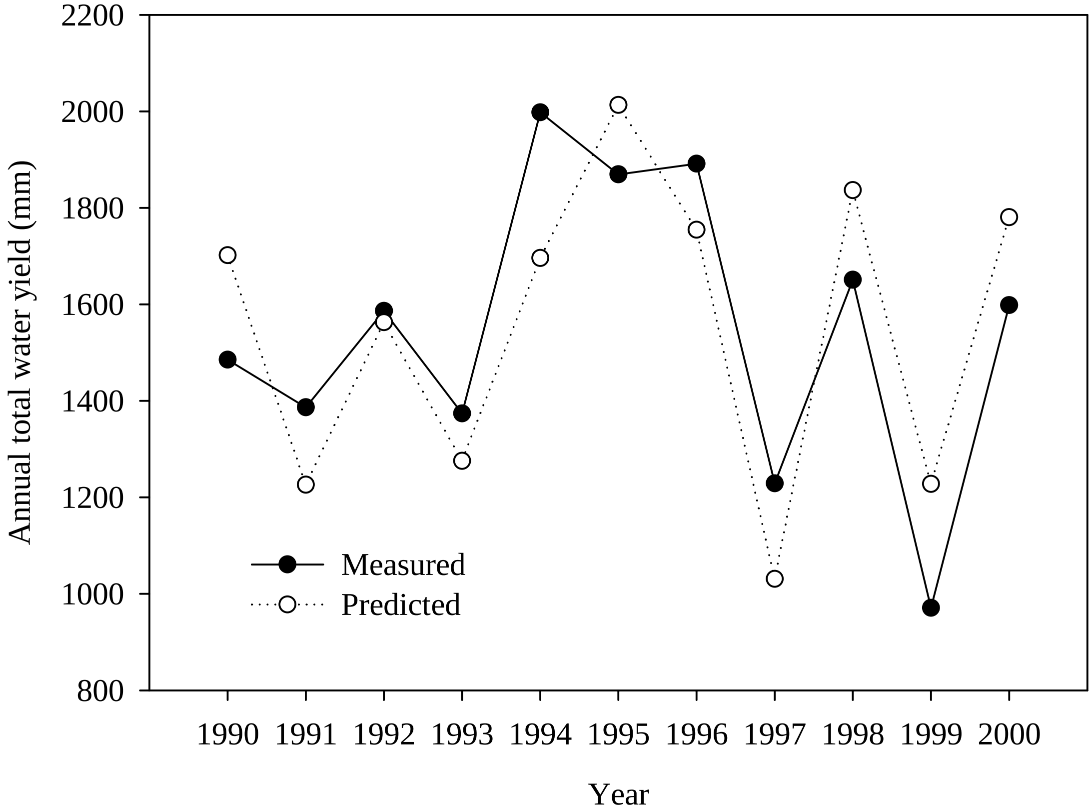
Year
Measured
Predicted

(D) Wangapeka



(E) Stanley Brook


2200
2000
1800
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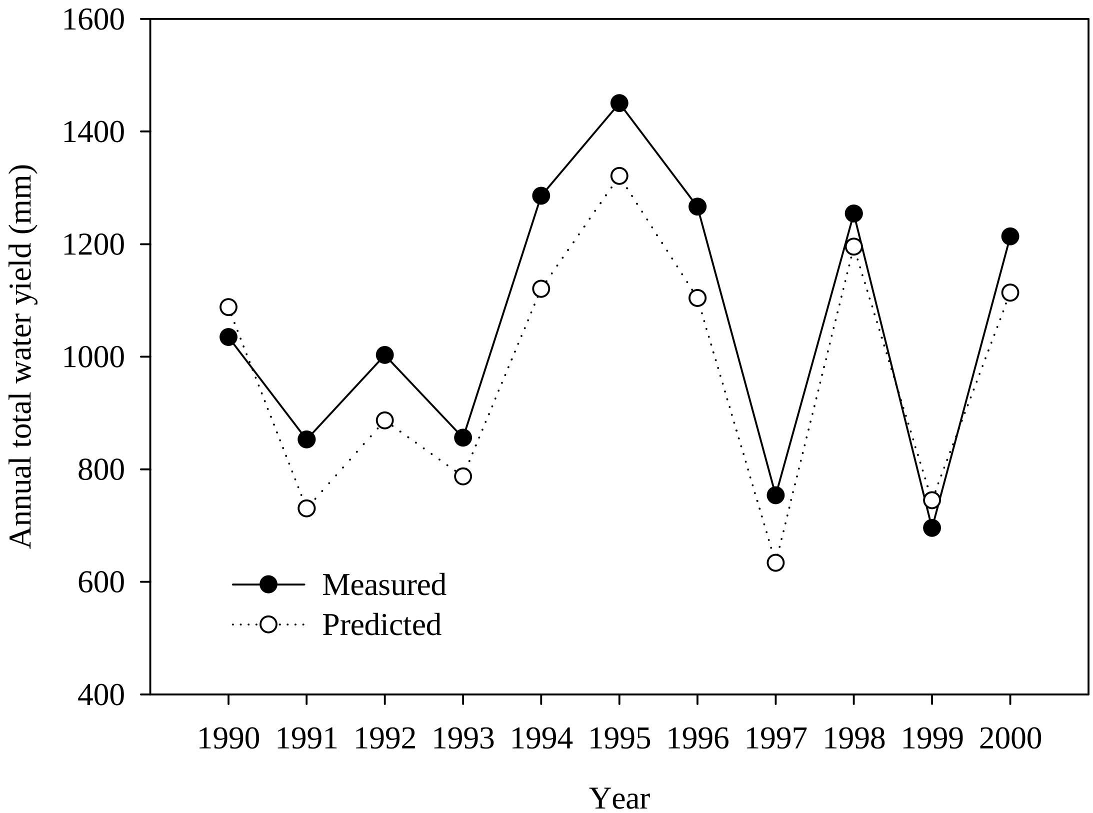
1200
1000
800
Annual total water yield (mm)
Measured
Predicted
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
Year

(F) Baton



(G) Woodstock

Figure 6 (A–G). Predicted annual water yield and that measured at Woodstock and in different subcatchments

Predicted and measured annual water yields were reasonably but not highly consistent in the Baton and Wangapeka subcatchments reflecting precipitation variability in the high-altitude and rugged terrain. At Motueka Gorge, the gap between predicted annual water yield and measured clearly indicates a poorly predicted precipitation and this deficiency in precipitation prediction consequentially contributed to the lower predicted annual water yield in the whole Motueka catchment below Woodstock (Fig.6, G). This has been recognized as a deficiency in precipitation prediction and another rain gauge has been installed in the upper Motueka area.

Daily streamflow

The Nash–Sutcliffe coefficient (Nash and Sutcliffe, 1970) at Woodstock for daily streamflow was 0.78 during the calibration period, and the value varied from 0.36 to 0.61 in the subcatchments (Table 3). For the validation period, the coefficient was 0.72 at Woodstock with a range from 0.35 to 0.57 in the subcatchments. R^2 was 0.82 for the calibration period, and 0.75 for the validation period for daily streamflow at Woodstock. R^2 exceeded 0.5 for the subcatchments except the upper Motueka at Gorge site during the validation period (Table 3). This was expected due to the insufficient predicted precipitation shown in the annual water yield comparison.

The daily streamflow was well predicted in the Motueka Catchment at Woodstock (Fig. 7). For subcatchments Wangapeka, Tadmor and Stanley Brook, the model generally had an acceptable efficiency, but the model performed poorly in other parts of the catchment, such as Baton and upper Motueka at Gorge.

As the predicted annual water yield indicated, the daily streamflow prediction verified that precipitation in Baton, Wangapeka, and upper Motueka above Gorge was highly variable. The difficulty in predicting the spatial variability of precipitation appeared to be the main contributor to the model performance in daily streamflow prediction. Obviously, prediction biases from upstream subcatchments were self-compensating at the larger catchment scale, and thus the model performed better at Woodstock.

Table 3. Daily streamflow calibration and validation results.

Subcatchments	Periods	Nash–Sutcliffe coefficient	R^2
Upper Motueka at Gorge	Calibration	0.42	0.52
	Validation	0.41	0.41
Motupiko	Calibration	0.40	0.54
	Validation	0.57	0.61
Tadmor	Calibration	0.61	0.61
	Validation	0.55	0.56
Wangapeka	Calibration	0.60	0.62
	Validation	0.51	0.53
Baton	Calibration	0.36	0.60
	Validation	0.35	0.51
Stanley Brook	Calibration	0.59	0.65
	Validation	No records available for validation	
Motueka at Woodstock	Calibration	0.78	0.82
	Validation	0.72	0.75

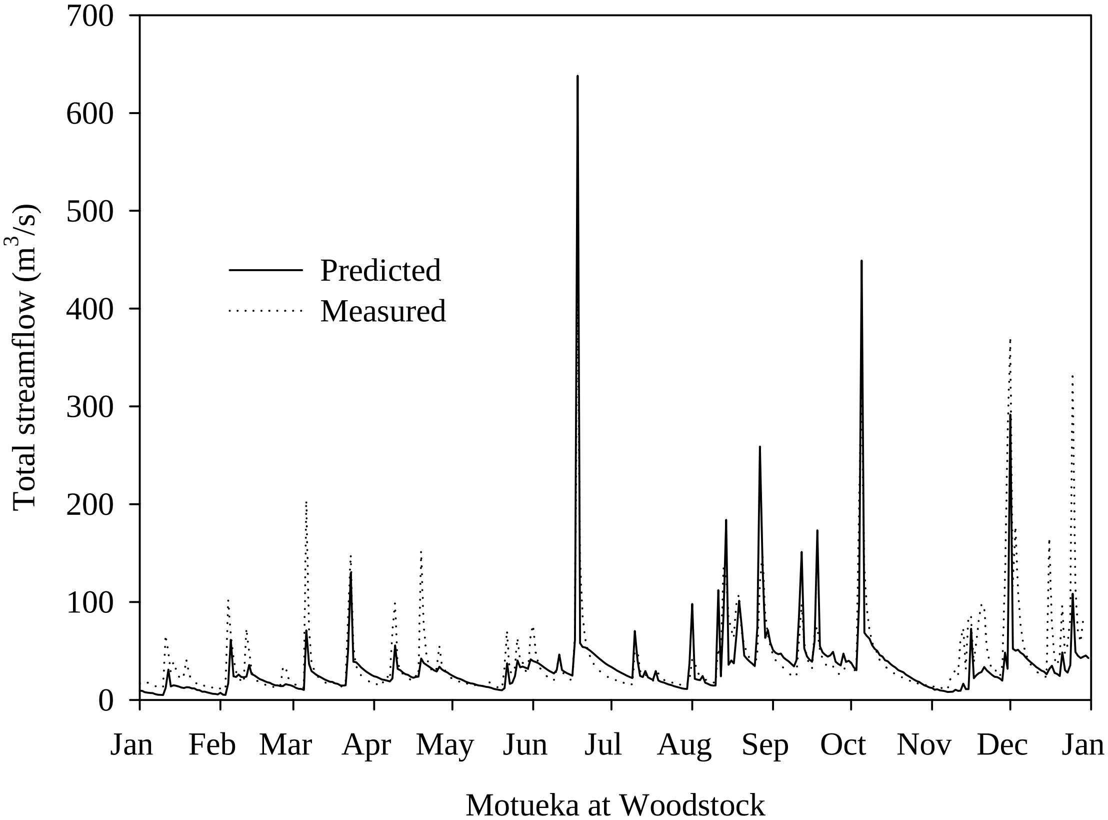


Figure 7. Predicted daily streamflow against the measured at Woodstock in 1997.

Soil moisture

Soil moisture was only available for the small Waiwhero subcatchment with an area of 3.9 km^2. A neutron probe was used to measure soil moisture in the field on a weekly basis during the late 1990s. From the catchment ridge to hillslope bottom, two soil transects were marked on one flank of the slope, and one transect on another shorter side. Six soil moisture access tubes along each soil transect and one from a sampling site near the outlet were recorded on a fortnightly basis. The soil moisture from the 19 sites has been averaged to represent the areal soil moisture for the whole Waiwhero subcatchment. This intensive sampling strategy, to some extent, resolved the problem raised by Beven (1989) that average areal soil moisture predicted by a model cannot be used for comparison with a “point” neutron probe measurement.

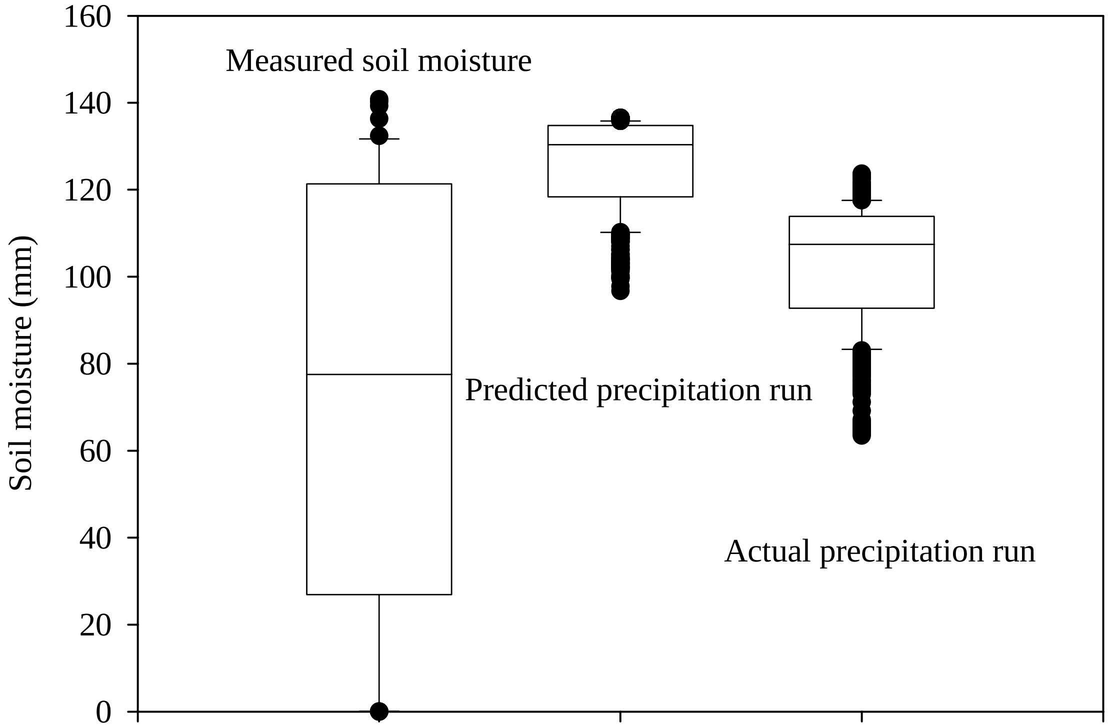


Figure 8. Soil moisture comparison between the measured and the predicted (Box and whisker figure shows the range of the moisture distribution, the line within the box shows the mean moisture value).

The soil moisture samples were recorded in a period from 30 May 1997 to 22 July 1999, and the precipitation was measured simultaneously. The measured soil moisture varied from very dry (0 mm) to more than field capacity (162.1 mm, Fig. 8). However, SWAT predicted that soil moisture would remain wet, ranging from 106 mm to 142 mm, in the same period. This significant discrepancy can be explained partly by the fact that the predicted wet days were twofold more than the measured (Table 4), and about 360 mm more precipitation was predicted in the monitoring period. The actual precipitation, which tended to be of high intensity and short duration, was different than predicted precipitation. A new SWAT run with actual measured precipitation at the site suggested the error derived from the difference between predicted and measured precipitation accounted for around an average 23 mm (about 50%) of the extra soil water storage that the model had predicted previously in the period. The remaining average 28 mm (another 50%) discrepancy was likely to be a result of poor soil property representation in the catchment.

Table 4. Predicted precipitation and that measured in the Waiwhero catchment.

	Total days (days)	Total precipitation (mm)	Wet days (days)	Mean precipitation per event (mm)	Precipitation standard deviation (mm)
Predicted	783	2688	486	5.5	7.7
Measured	783	2327	241	9.7	9.0

Discussion

A variety of factors may be responsible for the model errors when comparing measured streamflow data to simulated output. These include model parameterization uncertainty (spatial variability in climate, soil and land use), flow measuring uncertainty, errors due to sampling strategies, and errors or oversimplifications inherent in the model structure (Refsgaard and Storm, 1996). It has been shown that the accuracy of the daily precipitation prediction model depends significantly upon the precipitation gauge numbers and their location. The Wangapeka, Upper Motueka at Gorge, and Baton subcatchments are in areas of highly variable precipitation. However, no precipitation gauge records were available to record from the upper parts of the Baton and upper Motueka subcatchments, which resulted in poor streamflow prediction for Baton and upper Motueka at Gorge

It is likely that even if different individual parameters were optimal in the situations where they were determined, bringing their values together from different sources is no guarantee that they will give good results in a new set of circumstances (Beven, 2001). This reflects the problem of equifinality in PDHMs. When SWAT was applied to the larger Motueka Catchment it predicted annual and daily streamflow with an adequate degree of accuracy. However, analysis of the prediction of separate internal hydrological processes and subcatchments showed somewhat poorer predictive ability, suggesting that the result was compensating between differing factors at the larger scale. Theoretically, compensations in the model results derive hydrologically from the water balances in the various pathways and storage (evaporation, streamflow, surface runoff, soil moisture and groundwater), or geographically from the contributions of different areas (hill slopes, variable source areas, subbasins, and subcatchments) to streamflow. The use of an integrated multi-variable and multi-site calibration and validation method improved the model calibration and validation and highlighted the areas and the hydrological processes requiring greater calibration effort (e.g. understanding precipitation distribution and soil moisture change).

As emphasized by Beven (2001), limited measurements and poor understanding of subsurface processes in particular will result in equifinality. In our modeling work, although a significant contributor to model errors was verified (spatial variability of the precipitation), the calibrated parameters may be just one solution in a set of Pareto optimal solutions. The other issue arising in this study was the multiple-temporal scale tests. As the PET and streamflow prediction showed, the daily prediction in PET and streamflow did not match the measured data as well as the annual prediction did. The monthly PET prediction by SWAT at central Moutere had a high agreement with that estimated using hourly measurements, but a 34-mm difference still occurred between annual predicted and measured PET. Thus a fine-scale or multi-temporal-scale validation is strongly recommended.

Conclusion

A proposed calibration approach integrating multiple internal variables and multiple sites was used to develop a SWAT model application at a large scale for the Motueka Catchment. Daily precipitation and temperature were predicted using interpolation-based, separated models and available meteorological data. The hydrological components of the SWAT model, such as potential evapotranspiration, water yield, streamflow and baseflow, were calibrated and validated at a whole-catchment scale and for six subcatchments of the Motueka Catchment. This multi-variable and multi-site calibration and validation approach resulted in more realistic parameter values across both the hydrological processes and the geographic areas, and highlighted the areas (e.g. upper Motueka) and the hydrological processes (e.g. soil moisture) requiring greater calibration effort. However, the spatial variability of precipitation could be better-represented and contributed significantly to model errors.

Given the high spatial variability of the precipitation, the integrated calibration and validation process showed that SWAT had an acceptable hydrological performance in the Motueka Catchment. This integrated multi-variable and multi-site calibration and validation method also produced more realistic input parameters for the SWAT model, reducing the errors from the potential equifinality or the non-uniqueness problem in PDHMs. Although the conclusions drawn from such work are site- and model component-dependent, the research has nevertheless an important role to play in spatially calibrating and validating a hydrological model in a large catchment.

This work should be considered as a first step to developing a model useful for catchment planning, and much work still needs to be done on model verification. In the next phase of this research, nutrient and sediment variables will be included for spatially calibrating and validating the SWAT model against the regularly monitored data from different tributaries. A long-term research plan in the Motueka Catchment will continuously promote knowledge of the model calibration and validation, and also improve the prediction of our testing scenarios.

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Estimating Available Water Resources of the Sardinian Island Using the SWAT model

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Abstract

A 20% rainfall decrease in the last 30 years, prolonged periods of drought and 40% losses in the distribution pipes have substantially lowered available water reserves in the Sardinian island, with the result of unpopular rationing measures on municipal, industrial and agricultural uses. Up to now black-box models have been the most commonly used methodologies to estimate the regional water budget. Despite their wide use, these models have shown severe limitations in estimating watershed outlet outputs far from the monitoring stations and in covering climate changes properly. In this study, together with a critical review of formerly used models, we present the application of the physically-based distributed SWAT model to evaluate the water budget at the regional scale and to predict future scenarios. The model parameterisations (land use, soil type, surface water systems, etc.) are estimated at the regional scale on the basis of available geographic data. In order to generate daily weather inputs for the SWAT model, a statistical analysis of the Sardinian climatic data has been carried out to cluster both thermometric and rainfall records into homogeneous groups. The resulting model input data along with the watershed and hydrologic response unit (HRU) spatial discretization criteria have been carefully checked to ensure global consistency at the overall scale. The regional available water resource is estimated assembling contributions only from those mountain basins whose outlets are existing reservoirs. The calibration and validation of the model outputs have been performed against monthly measured streamflows of the time period 1922 – 1992. Using the same model setup, complementary modeling studies, for instance to map groundwater recharge and discharge vulnerability in unregulated basins of coastal areas, may be easily performed.

Review of Former Approaches

As a basis for water resources management and calculating pollutant movement in the hydrosphere, the knowledge of the water budget of a region is essential. Existing approaches for water fluxes quantification often use assumptions and empirical equations derived for special conditions that cannot simply be transferred to any other region. Easy to use, such models have been the most popular methodologies to estimate potential and real evapotranspiration values or streamflows from rainfall events. The wide use of these models has been initially conditioned by the limited data availability (rainfall, temperature, and monthly streamflow measurements) but, the operational use of these models has strongly limited the acquisition of further information about complementary climatic data (wind, solar radiation, relative humidity) and about soil type and land use. This type of information is, on the contrary, necessary to implement a physically based hydrological model. In Sardinia, the scientific community has worked mainly with the target to improve these empirical models and to properly condition them to the hydrological peculiarities of the island. The most important experience resulted in the study “Studio dell’Idrologia Superficiale della Sardegna (SISS)” [EAF, 1996]. The SISS collects rainfall, thermometric and streamflow monthly measurements for the time period 1922-1992 for more then 400 climatic gages, using a stochastic model to reconstruct missing data and to develop scenarios. The model is a combination of two popular approaches (the moving average and the autoregressive model) usually referred to as the Box & Jenkins model [1976]. It is driven by monthly climatic variables assuming natural conditions without any water utilization (i.e. no reservoirs, no artificial recharge, no artificial lakes, etc.). A large effort was devoted to implement the SISS into a geographic information system (GIS) by spatially locating the monitoring stations and structuring the alphanumeric information in a database.

In the present work we often refer to this previous study to compare results, show limitations and plan future work. Using the SWAT model [Neitsch et al., 2001; Di Luzio et al., 2001] water budget calculations are performed for several Sardinian catchments having different climatic and hydrologic conditions. These case studies will be used to test methodologies applied on the regional wide level, to improve the understanding of the recharge-discharge transformation and to estimate basin-averaged hydrologic values for a 70 year historical period (1922-1972).

Usually, existing information is not sufficient or suitable to study the water turnover on a regional scale, therefore initial assumptions and model parameterizations must be carefully checked. Three difficult questions involved with the use of a physically-based model are addressed: how to deal with inadequate availability of daily climatic data (a simple model has been implemented to generate daily rainfall synthetic series from monthly dataset); how to derive feasible spatially distributed parameterisations from point measurements (e.g. soil profiles), and how and where higher accuracy in the hydrogeological characterization is needed to account for potential and actual evapotranspiration at the local scale.

Site Description

Lying in the Tyrrhenian Sea to the east, the Sardinian Sea to the west and separated from Corsica to the north by the Strait of Bonifacio, Sardinia is located in the middle of the Western Mediterranean between 38°51'52" and 41°15'42" Lat. North and 8°8' and 9°50'Long. East. It is the second largest island in the Mediterranean Sea (24,089 km^2) with a population density of 68 p/km^2, slightly higher than a third of the Italian national average.

The morphology of the island is the result of complex tectonic processes and volcanic activity in the Cenozoic era on a mass of Paleozoic rock upthrust from the sea, later severely affected by late Paleozoic orogenesis. The Sardinian mountains are a chaotic series of deeply eroded ranges, groups, plateaus and uplands, scattered in apparent disarray. A geological characteristic is the Campidano tectonic plain filled with Eocenic and Pleistocenic deposits, which lies northwest-southeast across the south of the island, linking the gulfs of Oristano and Cagliari and dividing mineral-rich mountainous Sulcis and Iglesiente districts to the southwest, from the much more extensive mountain regions in the north and east which cover most of the island, reaching 1,834 m. (Punta La Marmora, Gennargentu). These reliefs alternate with deep valleys and winding riverbeds. With the notable exception of the Campidano in Sardinia there are few plains, usually of small extension.

Sardinian water courses are characteristically fast flowing, with a relatively high water volume in winter, reduced to a trickle in summer. The principal rivers are the Flumendosa and Cedrino to the east, the Mannu-Coghinas, emptying into the Gulf of Asinara, the Tirso, which flows into the Gulf of Oristano and the Temo, which flows into the sea near Bosa and is the only navigable river. Their waters have been harnessed and form artificial lakes (Omodeo e Coghinas) and reservoirs. The most important lagoons are located in the humid areas near Cagliari and Oristano, which are among the largest wetlands in Europe. The waters which flow underground and appear as karst springs both in the open and in caves are also of great interest. Equally important are the mineral springs flowing from fractures in the terrain due to ancient processes of volcanism dating back to the Tertiary and Quaternary; these waters have therapeutic properties and are marketed in the form of mineral water.

The Rainfall Synthetic Series

The climate of the island is Mediterranean with long hot dry breezy summers and short mild rainy winters, except at high altitudes. Average annual temperatures range from 18 °C along the coastal belt to 14 °C inland. Precipitation is largely confined to the winter months and distribution is somewhat irregular, with as much as 1,300 mm/year in the highest areas along the east coast. The rainfall regime is characterized by a peak rainfall in December, and a minimum in July, with an average value of about 780 mm/year. The prevailing wind is north-westerly, which blows over the island in all seasons, particularly sweeping the west side.

Part of the work was devoted to generate synthetic daily precipitation series for each rainfall gage of the Sardinian island using the Markov chain-skewed generator [Nicks, 1974].

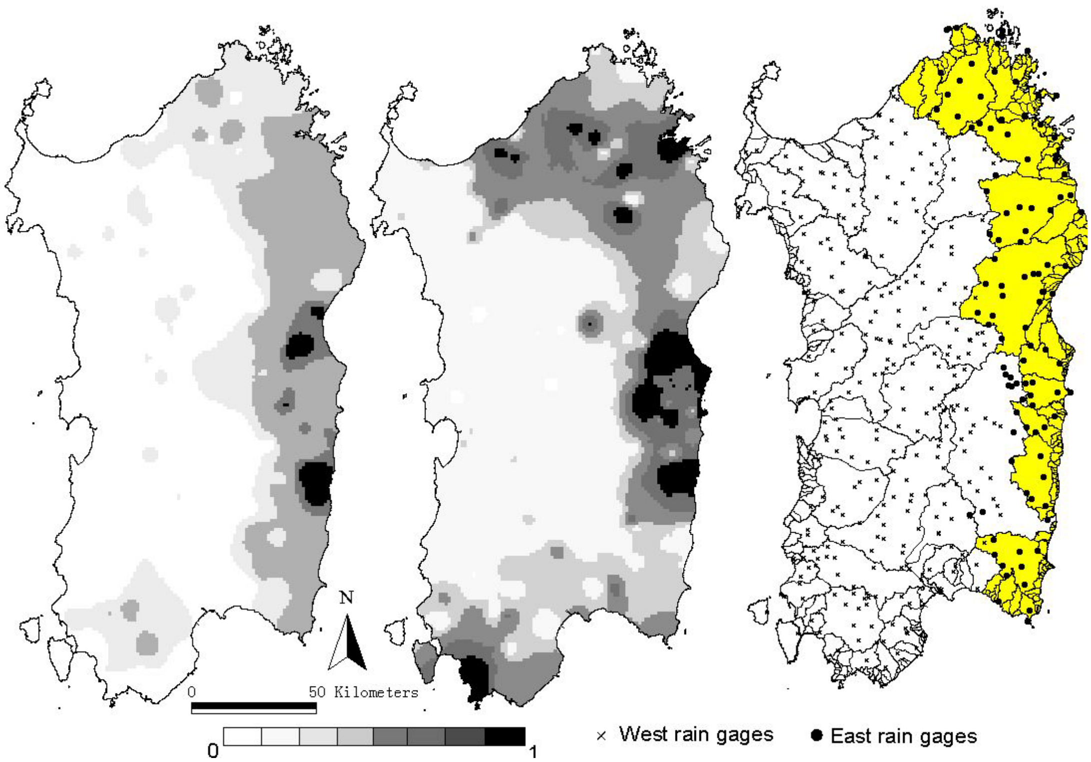

Figure 1. Normalized standard deviation (left) and skew (middle) maps for the daily precipitation records [February 1952-1992], and derived clusterization of rain gages and basins (right).

The generator works in two steps: at first it determines if the day is wet or dry, then, a skewed distribution is used to generate the precipitation amount. The skewed distribution reads as follows:

$R_{day} = \mu_{mon}+2\sigma_{mon}\cdot\{[(SND_{day}-g_{mon}/6)\cdot(g_{mon}/6)+1]^3-1\}/g_{mon}$ where R_{day} is the amount (mm) of daily rainfall on a given day, μ_{mon} is the mean daily rainfall (mm) for the month, σ_{mon} is the standard deviation of daily rainfall (mm)), SND_{day} is the normal deviate calculated for the day and g_{mon} is the skew coefficient for daily precipitation in the month. To calculate, for each station and each month of the year, the probability of a wet day to be followed by another wet or dry day, we use the available daily data registered on a cluster of 175 rain gages scattered on the Sardinia island with at least 30 year series within the time period of interest.

The Sardinian rain gages and basins have been grouped in two different homogeneous classes, referred in this study as East and West rain gages (Figure 1) using a clusterization technique based on the spatial distribution of standard deviation and skew of daily rainfall data. This was essential to produce realistic rainfall events on rain gages which showed to be climatically correlated.

By means of the Markov chain procedure, the time distribution of wet days is determined and assigned to the rain gages of the two classes and then the skewed distribution is used to generate the amount of precipitation occurring in each wet day. Finally, the sum of the daily precipitation of each month of each year is scaled to match the monthly registered rainfall for each station. The synthetic rainfall daily series (downscaling of the monthly data set) have been validated against some scattered daily rainfall historical dataset, showing a good match between the two estimates (not shown).

Data Availability for Hydrological Response Estimation

Hydrological behavior of soil is related to a number of soil properties. To obtain information about these soil properties at a regional scale a 1:250 000 soil vector map was used, where each cartographic unit was associated with one or two delineations corresponding to subgroups of USDA soil taxonomy. For the characterization of the geo-pedologic facies of the Sardinian region we referred to the *Soil Map of Sardinia* [Aru *et al.*,1991] and the *Land Classification for Irrigation of Sardinia* [Arangino *et al.*, 1986]. In the last project a collection and evaluation of the irrigational necessities was based on the census of all agronomic and geo-pedological elements. About 40 representative soil profiles (point measurements) were described and classified according to the USDA and FAO guidelines. In this study, physical and hydrogeological properties of soil profiles have been related to the corresponding cartographic units using taxonomy categories. Classical pedotransfer functions have been used to calculate dependent variables (field capacity, permanent wilting point, available water capacity, and saturated hydraulic conductivity) from the three independent variables: sand, silt and clay content. Other complementary information was obtained, for the same class of soils, using the State Soil Geographic (STATSGO) database [1994] Finally all this information was cast into a soil database formatted for SWAT. The spatial linkage between the available soil map and the soil database reduced the amount of GIS initializations drastically. For the purpose of this study and the level of detail of the spatial scale of interest, the linkage of spatially available soil information and point measurements seemed to be an acceptable compromise.

Land use can significantly affect the water cycle. As rain falls, canopy interception reduces the erosive energy of droplets and traps a portion of the rainfall within the canopy. The influence the land use exerts on these processes is a function of the density of plant cover and the morphology of the plant species. In this study we used the CORINE land cover 1:100.000 vector map (www.centrointerregionale.it). The CORINE Land Cover consists of a geographical database describing vegetation and land use in 44 classes, grouped in a three nomenclature levels. It covers the entire spectrum of Europe and gives information on the status and the changes of the environment. We converted the CORINE land cover classification codes to the SWAT land cover/plant codes.

Results

Water budget calculations have been performed for 10 drainage basins (7400 km^2) of the Sardinian island which contain the main reservoirs. In Figure 2 we show the yearly average (related to these 10 basins) of rainfall, evapotranspiration and flow rates.

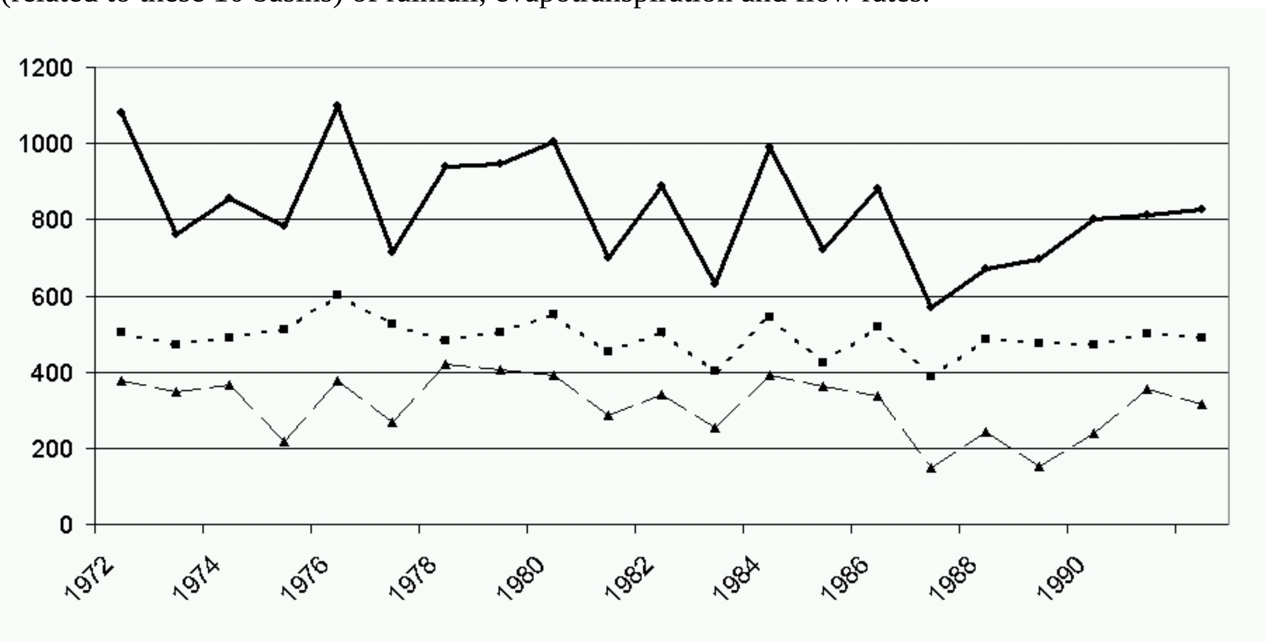

Figure 2. Yearly rainfall, evapotranspiration and streamflow on the draining basins [mm/year].

During the time period 1971-1992 the average yearly rainfall on the drainage basins is 826 mm, the evapotranspiration 490 mm and the streamflow 314 mm. Considering as draining area only the subbasins whose outlets are the actual reservoirs, the potential storage capacity is about 2325 million m^3. A correlation factor of about 0.83 was found between simulated and measured streamflows throughout all the monitoring gages, showing good accuracy in reproducing the hydrologic regime. One of the benefits of the physically based model is to account for retention time granted by field capacity of soil. In Figure 3 we show the time delay between the evapotranspiration/streamflow and the rainfall events. It is possible to map time dependent water content deficit to design optimized irrigation plans.

Future activities will be mostly related to better predict potential and real evapotranspiration, now systematically underestimated by about a 5%, by taking into account solar radiation, humidity and wind.

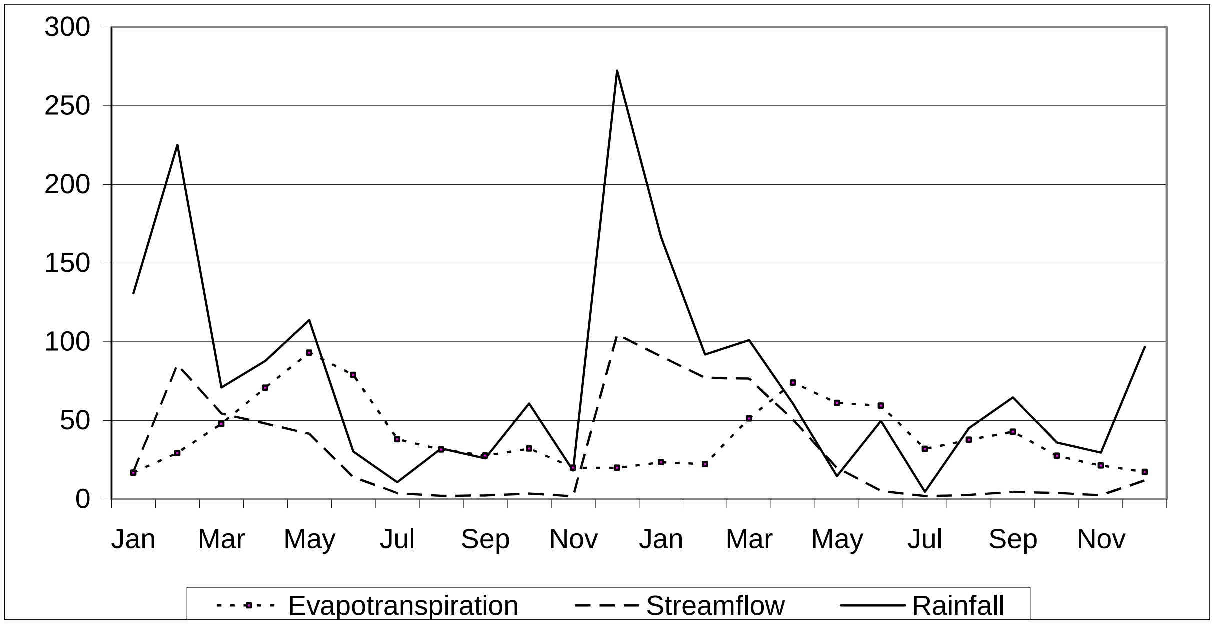

Figure 3. Water budget components for the time period 1971-1973. Note the time delay between rainfall, evapotranspiration and streamflow.

Conclusions

An extensive quality assessment of the available climatic, soil and land use data has been carried out on a regional scale. In this context we set up a GIS formatted in the SWAT fashion and applied a physical model to study the water cycle on a catchment's scale. The developed system greatly reduces GIS initializations and offers the possibility to simply rely on a regional framework database without being an expert user. Critical aspects of our study have been to infer and upscale spatial information from point measurements to homogeneous soil/land use areas, to cluster rainfall gages, and to downscale precipitation monthly data. Moreover the low quality of the soil vector map forced us to use the dominant mode criteria in the HRU discretization, reducing drastically the spatial scalability of the system. Nevertheless, for the purpose of this study, the level of detail granted by the relatively low resolution vector maps seemed to be acceptable.

The SWAT-based system we set up can be particularly useful for planning water management policies at a regional scale, and to decide when, where and how water will be distributed. In the near future, it is reasonable to predict that water resources in Sardinia will be accessed on a regional framework. With this aim the feasibility to redistribute large amount of water from the North–East basins to the West reservoirs is being evaluated. The SWAT model, in this context, can play a leading role in estimating the water budget when the human utilization needs to be considered.

Acknowledgement

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The Application of SWAT2000 to a Small, Forested Watershed on the Canadian Boreal Plain

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Introduction

The Forest Watershed and Riparian Disturbance (FORWARD) project is investigating and modeling the impact of fire and harvesting disturbances on streamflow in several small (6 - 16 km^2) and large (150 – 250 km^2) forested watersheds located on the Boreal Plain in central Alberta, Canada. The objective of the FORWARD project is fourfold. It will assess the impact of harvesting with and without riparian zone buffers on the streamflow and water quality downstream of the disturbance; determine the impact of fire on streamflow and water quality of flow downstream of the disturbance; assess the difference in watershed response to harvesting and fire; and provide a modeling tool for industry to manage the impact of harvesting.

Both harvesting and fire are disturbances that can potentially result in significant impact on downstream water quantity and quality. Numerous studies have reviewed the impact of harvesting (e.g. Bowling 2000; Buttle 2000; Jones 2001; Nichols 2001; Prepas 2001; Thomas 2001) and fire (Bayley 1992; McEachern 2000) and have compared the two disturbance types (Lamontagne 2000) and their relative impact on streamflow and water quality. However, few studies have been conducted in the Boreal Plains forest. Projects conducted in the Boreal Plains forest have focused on the impact of these disturbances on the water quality in lakes (McEachern 2000; Prepas 2001).

Figure 1 shows the location of the FORWARD project in Canada, and the watershed discussed in this paper. In total there are 16 watersheds in the FORWARD project that will be modeled using SWAT2000, five being harvested, four burned in a wildfire, and seven remaining as reference streams.

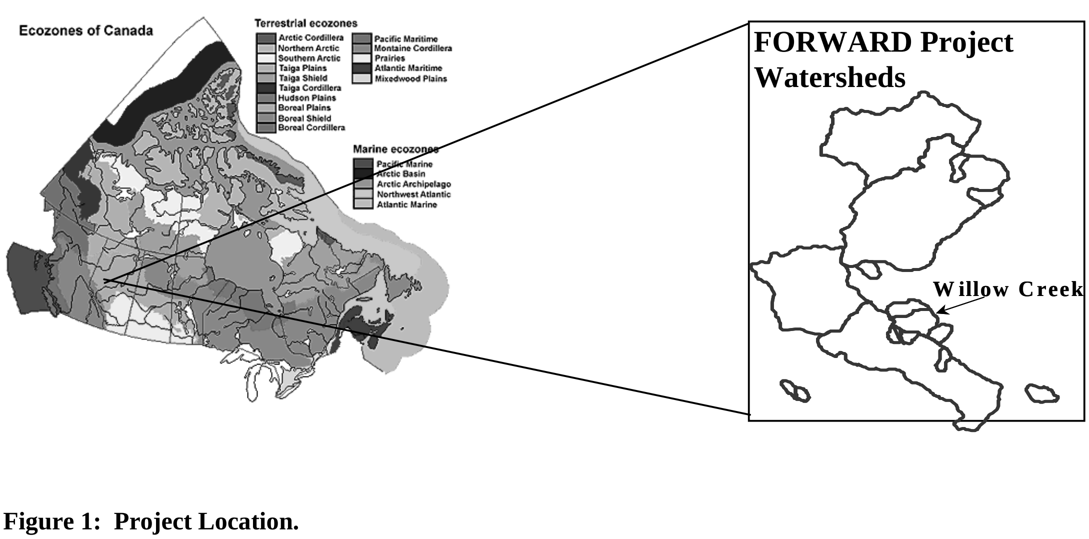


Figure 1: Project Location.

Cold winters and cool summers, typical of the Boreal forest, influence hydrological conditions in ways that are less well-understood than the hydrology of more temperate locations (Buttle 2000). Typically, the total precipitation is less than in more temperate regions. The precipitation in the Boreal forest falls as rainfall, snowfall and at times as hail or sleet. Typically, most of the Boreal forest receives in the order of 300 to 625 mm of precipitation on an annual basis. The distribution between rainfall and snowfall is approximately 75% to 25% respectively based on Canadian records. Snow is typically present in the Boreal forest from six to eight months of the year (Dingman 2002). The Boreal forest experiences a wide range in temperatures, with short summers (Woodwar 1996) and is classified as sub-arctic and cold continental (WR7 1999). The average yearly temperature is near 0^{o} C, with temperatures in the North American Boreal forest varying from a mean daily average of 15.7^{o} C in July to -19.1^{o} C in January.

The Boreal forest is composed of deciduous and coniferous species, the composition of which changes over time. In the early successional stages of growth, broadleaf deciduous trees and shrubs are dominant. The most common of the early successional species are alder, birch and aspen (Woodwar 1996). As the stand matures, coniferous species are more dominant and include spruce, fir, pine and deciduous larch or tamarack. Black spruce and larch ring the edge of boggy areas (Woodwar 1996). Pine forests flourish on sandy outwash plains and areas that used to be dunes. Larch forests are found in areas where the substrate is thin and waterlogged and are underlain by permafrost. The Boreal forests have open canopies which are conducive to an understory of shrubs, mosses and lichens (Woodwar 1996).

Soil orders found in the Boreal forest include histosols, spodosols, alfisols, and inceptisols. Spodsols (luvisols) are dominant in cool, wet climates under deciduous and conifer forests and are dominant in the study area. These soils have well-developed organic, leached and accumulation horizons.

The purpose of this paper is to present SWAT2000 model output compared to measured average monthly and daily streamflow for the Willow watershed within the FORWARD study area. This watershed has been designated a reference watershed, and will be used to assess the relative impact of disturbance (fire and harvesting) in other watersheds.

Methodology

Study Site

To-date, the FORWARD modeling effort has focused on one small watershed, Willow Creek. The watershed is 16 km^2 in size. The elevation ranges from 870 m at the mouth of the watershed to a maximum elevation of approximately 1061 m. The watershed is primarily covered by forest and has been partitioned using the United States Geological Survey (USGS) classification system. Deciduous forest covers 42% of the total area, while coniferous forest covers 28%. An additional 23% of the land is covered with a mix of deciduous and coniferous trees. The remainder is composed of rangeland and transportation right of ways, forested wetlands and non-forested wetlands. The soil data for the watershed indicates that approximately 91% is composed of the Soil Conservation Service (SCS) hydrologic soil group C, and the remainder of the watershed is composed of soils group D. These fine to very fine textured soils have a low to very low rate of water infiltration when wet, which results in high runoff potential.

Source Data

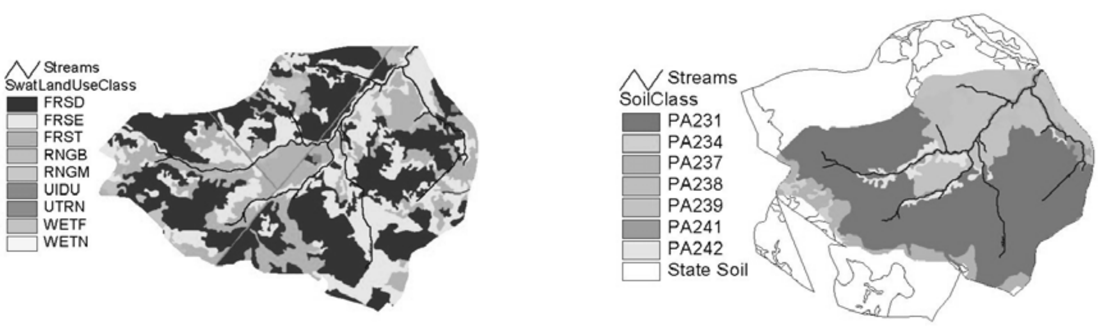
Data used in the modeling was obtained from existing geographical information system (GIS) coverages and meteorological stations as well as from field data. The existing GIS coverages included land cover, digital elevation model (DEM) and stream coverages.

Field data collected includes soils data, and stream flow data at the outlet of the watershed. Meteorological data was available from surrounding fire tower installations, an Environment Canada weather station, and in the latter half of 2002, a FORWARD meteorological station established in the Willow Creek watershed.

Model Setup

The SWAT2000 model was run in the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) environment. Initial conditions for the model were based upon both SWAT2000 default data and site-specific information. The land use/land cover, reach and soils coverages were configured to mimic the standard U.S. classification systems for input into BASINS. The land coverage was determined to be primarily deciduous coniferous and mixed tree species with a minimal content of rangeland bush, forested and non-forested wetlands and transportation as determined from the USGS classification system. Figure 2a shows the distribution of the forest cover over the basin. Soils information was constructed from available provincial government database information and field reconnaissance. These deep clay-till soils were classified as either Soil Conservation Service (SCS) soils type “C” or “D”. The number of soil horizons ranged from 5 to 6 with one of the layers representing the highly permeable forest litter layer. Lower layers have high clay content and slow the downward movement of moisture. Figure 2b shows the soils distribution over the watershed. The reach data was reviewed and formatted to match the data input requirements for BASINS.

The model was run for four years prior to the calibration period in order to remove any potential bias in initial site parameter estimates. The variable storage routing method and the Hargreaves evapotranspiration method were used during the modeling.

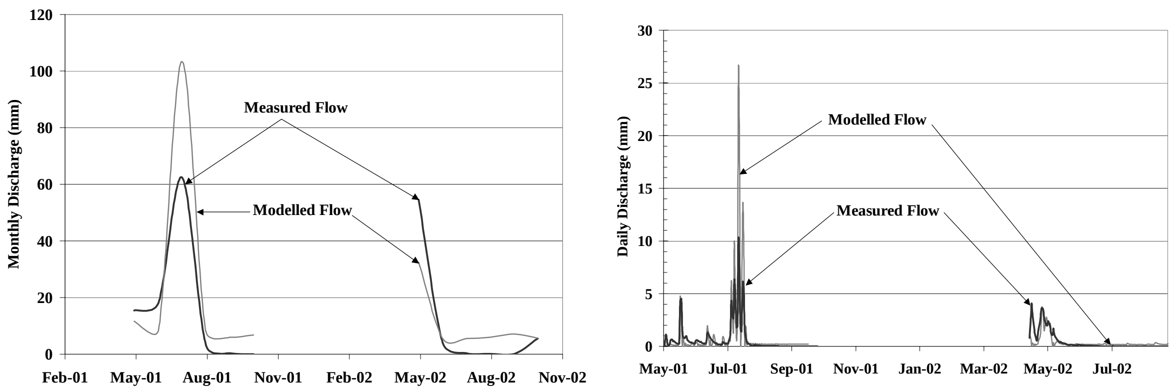


(a) (b)

Figure 2: Willow Creek Watershed (a) Land Cover Distribution; (b) Soils Distribution.

Results

Monthly and daily stream flows were modeled for the Willow watershed for 2001 and 2002. A comparison of measured and modeled results for 2001-2002 is shown in Figures 3a and 3b respectively. The modeled results generally follow the measured values with the exception of July 2001 where the modeled flows are significantly higher than the measured flows. Figure 3b shows that the inconsistency took place during four extremely high flows, which occurred in response to four large precipitation events in the area. The meteorological station used for the modeling during this time period was the most representative available. However, other stations in the area during the same time frame indicated lower precipitation rates. Therefore, it is possible that the station used experienced higher precipitation rates than those that occurred in Willow Creek watershed.



a b

Figure 3: Willow Creek Watershed (a) modeled and measured monthly discharge for 2001-2002; (b) modeled and measured daily discharge for 2001-2002.

Discussion

The modeled results are reasonable given the uncertainty of the input meteorological data, and some uncertainty in peak flow monitoring. The lack of watershed specific meteorological data for the full modeling period can reasonably result in modeled flows not directly matching measured flows. Alternate runs of the model were completed with composite precipitation data that was developed using the inverse weighting method and four precipitation gauges circling the watershed located 25 to 46 km from its centroid. However, the use of this method dampens out the peak precipitation events and creates difficulties during the calibration process. Ultimately, when onsite weather station data was unavailable, the best results were obtained when a single fire tower station was used to represent the summer precipitation input. Winter precipitation data was obtained from the Environment Canada weather station located in Whitecourt, AB (approximately 44 km away).

SWAT2000 was modified slightly for forest conditions for this work. The standard model uses the second soil layer to determine the temperature or point when the soil layers thaw. This was changed to the third layer. This allowed the SCS curve number to remain elevated for a longer period of time so the model results more closely matched measured data.

A few items in the existing model still need to be addressed for conditions in the Boreal forest. Solar radiation has significant impact on the spring melt. The existing model does not filter the solar radiation through the forest stand, resulting in melt occurring prior to measured flows. Additionally, the distribution of the surface lateral and groundwater flows may not be wholly representative of the area in question. Substantial lateral and groundwater flow in the Canadian Boreal forest has been documented (Peters 1995; Whitson In press), but the existing model tends to have higher surface flows. Finally, sublimation can be a significant factor in northern forests accounting from 13 to 40% of the fallen snow (Pomeroy 1998) which is not adequately addressed in the current model.

Conclusions

The modified SWAT2000 model provides reasonable simulations of streamflow from the Willow Creek forested watershed in the Canadian Boreal Plain. Representative meteorological data is essential in order to successfully complete a comprehensive calibration of the model. As additional data is gathered within the watershed, the calibration can be improved. An effort is under way to improve and expand the model to better represent forested watersheds, with particular emphasis on characteristics of the Boreal forest.

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Potentials and Applicability of the SWAT Model in Check Dam Management in a Small Watershed

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Abstract

The Soil and Water Assessment Tool (SWAT) is a versatile, physically distributed model with spatial variability consideration, for simulating runoff and sediment transportation from watersheds and river basins. However, its applicability to monitor and manage sediment transport from small watersheds in monsoon and concentrated flow areas with varied land use patterns has not been tested. The present work attempts to analyse the potential applicability of SWAT in managing check dams constructed as on-stream reservoirs and impoundment structures. The results reveal about 70% of sediment reduction from the watershed due to on-stream check dams.

Introduction

In the monsoon regions, watersheds dominated with loamy and sandy soils suffer from intense erosion problems. Monsoon precipitation has a tremendous impact on the semi-arid, sub-humid climatic regions with varied land use patterns. During four months of monsoon rains (mid-June to mid October), most of the precipitation falls during 30-40 events. The heavy rains cause floods that wash out much of the topsoil layer and discharge high rates of sediments to surface water storage bodies like dams, which are used for electricity generation, sanitation, irrigation, etc. There are a variety of controls to manage storm water runoff from a watershed or a catchment Anderson et al. (2002) that address different aspects of runoff: storage of runoff water, infiltration of storm water to groundwater, and treatment of pollutants in storm water Davies (1996), Bren et. al (1997). Properly controlling the peak runoff rate helps to prevent adverse impacts such as stream channel scouring and stream bank alteration and erosion, and minimizes downstream flooding.

Check dams primarily allow settling of sediments (including fine sediments) and removal of soluble pollutants Butts et. al. (1983). They also control peak discharge rates by storing some runoff. This storm water will remain until displaced by runoff from another storm event. Increased settling time allows particulates, including fine sediments, to deposit. The permanent pool also serves to protect deposited sediments from resuspension during large storm events. The measurement and quantification of the sediment entrapped by the check dams is quite difficult by any deterministic procedure, because it slowly reduces the effectiveness of check dams with by reducing storage in capacity. The present study has therefore been undertaken to study the applicability of SWAT in quantification of the effectiveness of on-stream check dams in reducing sedimentation problems in a small watershed and thus the possible management of check dams for sustainable, long time use.

Methods and Procedures

Study Area

The studied watershed, named BANHA, is situated in DVC command of Hazaribagh, Jharkhand, India, Figure 1. The watershed is in a sub-humid climatic region with semi-arid characteristics. The area of the watershed is about 1695 ha and can be divided into five sub-areas based on the drainage and land cover characteristics. The watershed has three on-stream check dams constructing reservoirs with storage capacities 0.18, 0.25 and 0.27 mm^3 respectively (constructed and became operational in 1996, 1998 and 1997). Almost 50% area of the watershed is under forest, 10% under barren land and remaining 40% under crop cultivation. The average annual rainfall of the area is 1200 mm of which more than 80% occurs during the monsoon months (June to October) and the rest in the winter months from December to January.

Figure 1: BANHA Watershed of DVC command at Hazaribagh, Jharkhand, India.

The slope of the watershed ranges from a minimum of 1.0% to a maximum of 18% with an average slope of about 1.9 %. Bulk density of the soils varies around 1.5 g/cc. The texture of the soil varies from loam to loamy sand with a low hydraulic conductive behavior and the saturated hydraulic conductivity ranges from 9.7 to 16.8 cm/day.

Data Collection

Data has been collected and processed for daily rainfall, runoff and sediment discharge (June to October), and maximum and minimum temperature for the watershed during 1993 to 2001, Figure 2.

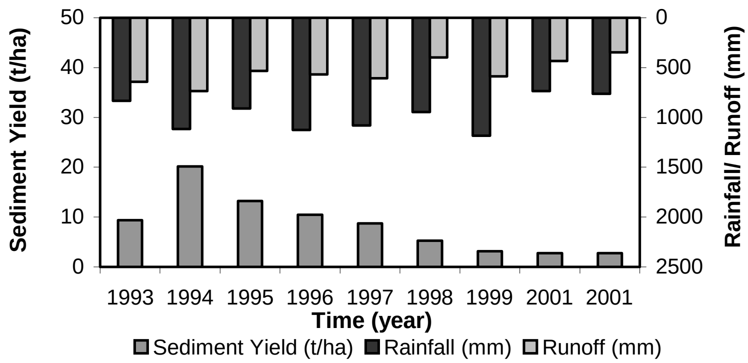

Figure 2: Measured Rainfall, runoff and sediment (June to October).

Model Approach

In the SWAT model, four types of water bodies (ponds, wetlands, depressions and potholes, and reservoirs) are modeled. Ponds, wetlands, and depressions/potholes are located within a subbasin off the main channel. Water flowing into these water bodies must originate from the subbasin in which the water body is located. Reservoirs are located on the main channel network. They receive water from all subbasins upstream of the water body. In this paper, small, uncontrolled reservoirs constructed on the main channel network of the watershed, have been studied. The SWAT module (.res) designed for small uncontrolled reservoirs has been applied. The volume of excess water, which exceeds the storage or embankment, is released at the specified rate within one day. Because impoundments slow down the flow of water, sediments fall from suspension, thereby removing nutrient and chemicals adsorbed to soil particles. Stoke's Law governs settling of sediment in the reservoir whereas the concentration of sediment in the reservoir is estimated using a simple continuity equation based on volume and concentration of inflow, outflow, and water retained in the reservoir.

Data Analysis

The watershed has been divided in 5 sub watersheds based on the drainage and land use pattern. SWAT inputs were prepared and arranged to calibrate the model for 1996, Figure 3. The SWAT model then has been successfully run with the daily data of the complete monsoon season for nine years (1993 to 2001) for the watershed area and validated by comparing the measured water yield and sediment load at the watershed outlet with their measured counterparts for the year 1996. The measurements were made on daily basis during the monsoon season (June to October).

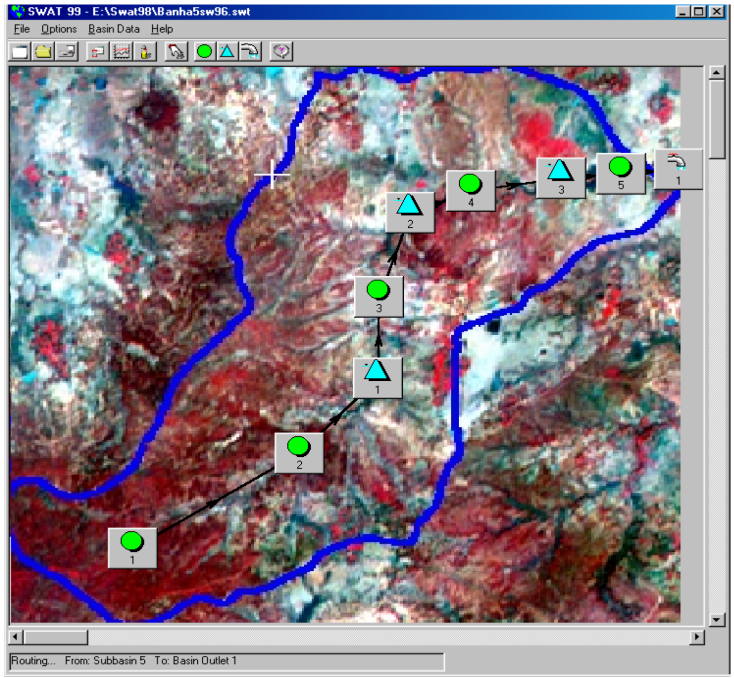

Figure 3: Schematic presentation of watershed in the SWAT Model.

Results and Discussion

The monthly scattergrams of the observed and predicted water yield (Figure 4) and sediment transported (Figure 5) at the watershed outlet shows the satisfactory applicability of the SWAT model to the watershed with respective R^2 values of 0.9995 and 0.9962. Based on the 1996 calibration criteria, the model has been run for 1996 to 2001 and the sediment estimation is presented in Figure 6 with measured counterparts. The results show quite good accuracy in “Real Watershed Scenario” presentation with a R^2 value 0.9704.

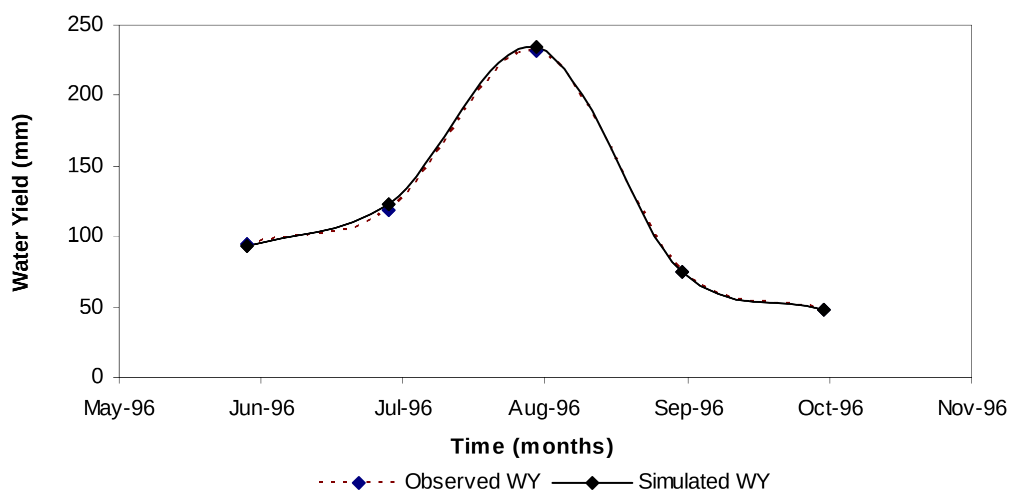

Figure 4: Water Yield Calibration for 1996.

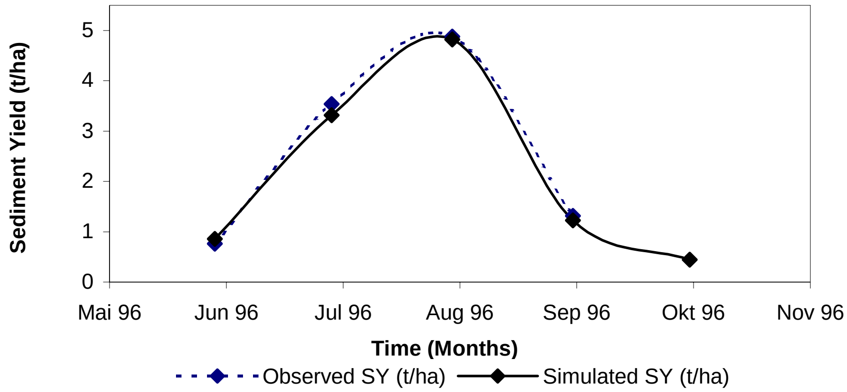

Figure 5: Sediment Yield Calibration for 1996.

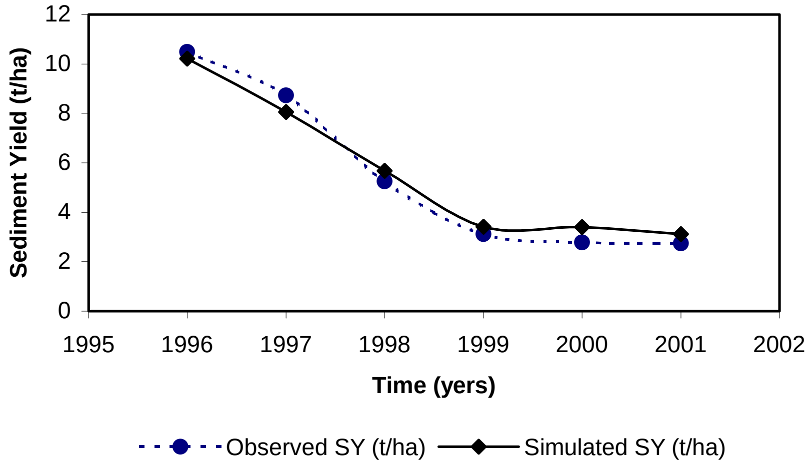

Figure 6: Sediment Yield Comparison during 1996-2001 with real situation.

To study the on-stream check dam effectiveness, to control the sediment transportation from the watershed, the model has again been run for 1996 to 2001 without the existence of check dams in the area. The result shows a high transport of sediment from the watershed (Figure 7). The existence of check dams reduces the sediment transportation from the watershed as much as 70.13% (Table 1). At the same time this deposited sediment reduces the effective storage capacity of the check dams. Reduction of capacity reduces the quantitative control of water and results in less time to settle the suspended sediment particles, more resuspension from the dam storage bed, further reducing sediment control due to less deposition and high scouring of the channels during high intensity rainfall events.

Table 1. Sediment yield reduction by check dams

Year	Sediment out from Watershed (tons)	Sediment generated from watershed (tons)	Sediment controlled by check dams (tons)	% Reduction in sediment out from watershed
1996	17780.55	22035.00	4254.45	19.33
1997	14797.35	18356.85	3562.89	19.41
1998	8898.75	11966.70	3067.95	25.57
1999	5288.40	17712.75	12475.20	70.13
2000	4729.05	7390.20	2678.10	36.18
2001	4644.30	7271.55	2627.25	36.16

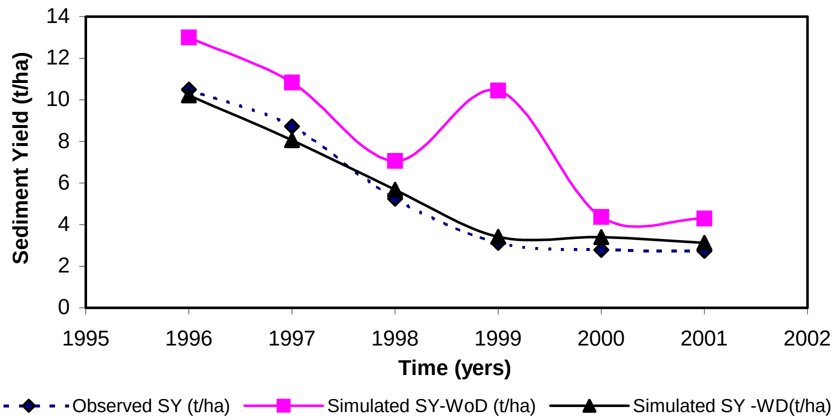

Figure 7. No check dam situation, Sediment Transport.

Conclusions

The study reveals how the construction of check dams provides effective reduction of sediment transport in this watershed. Based on the results, the following conclusions can be drawn,

- Check dams contribute to enormous reduction of sediment transport from the watershed,
- The simulated and observed sediment transport from the watershed compares closely and thus shows a strong applicability of the SWAT model in accounting for these processes in small watersheds,
- SWAT uses the individual sub-basin and reach sediment loading to account for the whole watershed which can be utilized in site selection for the check dam construction,
- SWAT makes an accurate estimation of the deposited sediments in check dams, and how the removal of sediments and sands over time can improve watershed management.

Other uses (e.g. cooperative fish farming by the local societies or soil reuse) will benefit from frequent sand and sediment removal from check dams, and will benefit from a more comprehensive, model that supports check dam management.

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Use of the SWAT Model for Evaluation of Anthropic Impacts on Water Resources Quality and Availability in the Celone Creek Basin (Apulia – Italy)

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Introduction

Erosion, hydrogeologic collapse, floods, desertification, groundwater salinisation, water pollution, and decreasing potable water supplies, are problems that occur more and more frequently that environmental policy-makers and scientists have to tackle in many nations. In the whole Apulia region (South West Italy) and particularly in Tavoliere (the province of Foggia), water represents a strategic question because this region is at high risk of desertification.

The purpose of this work is to analyse forestry and agricultural impacts on water resources quality and availability in this critical area using the Soil Water Assessment Tool (SWAT) model. The study area is the Celone Creek basin, which is located in the Tavoliere plain, an important intensive agricultural area. The focus of the study is to evaluate the hydrological balance components and water quality and to estimate sediment yield and N and P movement.

The catchment has an elongated shape oriented from SW to NE and hosts Celone and San Lorenzo creeks. Springs of both creeks are located in the mountain area called “Sub-Appennino Dauno”. Celone, the principal stream, springs approximately at 1000 m elevation. After crossing the Tavoliere plain, its waters reach Candelaro Creek and finally flow in to the Adriatic Sea. Overall the Celone basin has a surface area of 24,702.57 and elevations are between 65 m and 1.125 m above sea level.

In the northeast part of the catchment, precipitation is generally concentrated in winter and do not exceed 500 mm/year. Often, a dry period exists in summer, the late spring, and early autumn months. Average temperature is about 17° C with the summer maximum exceeding 40° C. In the mountain parts in the southwest, precipitation often reaches 900 mm/year and is concentrated in winter with peaks in March and October. The average temperature is below 16° C.

Soils are mainly alluvial and very fertile, allowing extremely intensive agriculture, mainly based on winter wheat, tomatoes and olive groves. Forests and scrubs are located principally in the mountain part of basin while some extent of riparian forest is present along the river network.

This research focused on the part of the basin (spread 14,596.36 ha) which supplies the San Giuliano reservoir, which can contain 25.82 million m^3 of water and is currently managed by the local water management consortium (Consorzio per la Bonifica della Capitanata).

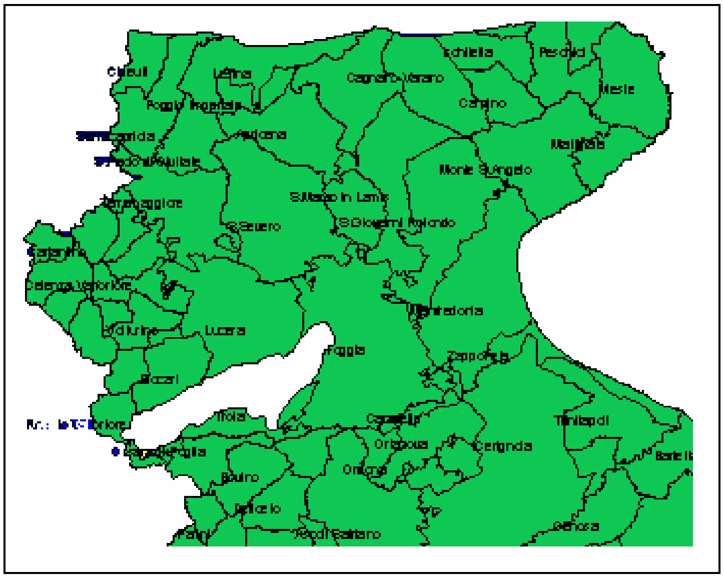

Figure 1. Celone Basin location

Methodology

Data were gathered, both in tabular and in digital map format, from local mapping bodies regarding land use and soil types. Vector and raster maps were then obtained and polygons were digitized on-screen from ortophoto-planes. A digital terrain model was obtained by interpolating from a contour line coverage at a pixel resolution of 40 m.

Daily rainfall and maximum/minimum temperature data were obtained from tabular data provided by the local hydrological service for the period 1978-1994, while wind speed, relative humidity and evapotranspiration data were obtained for a shorter time series recorded at a monitoring station operated by the local water management consortium. Daily flow measures in two sections along the creek were used for calibration of the model.

Soil characteristics were obtained from the database associated with the “Soil Map of the Apulia Region” that was drawn by the Agriculture School of the Bari University, while agricultural management data came from experts’ knowledge.

Five principal crops and eight soil types have been identified, which together provided 15 different combinations of “land-use/soil-type” that are spread within the catchment. The watershed has been subdivided into 96 subbasins. Each subbasin has been individualized according to relatively homogeneous characteristics and constitutes a unique hydrologic response unit (HRU) that refers to dominating combinations of “land use/soil type”.

Results

Average annual rainfall was 617 mm, trends show there are two peaks in the spring (70 mm in April) and autumn (93 mm in November). The minimum value was 23 mm, in July.

Total runoff annual average value amounts to about 200 mm and it has a trend similar to rainfall with peaks in spring and autumn and the minimum value in summer. Generally, runoff never exceeds 25 mm; only in November does runoff total 27 mm.

Annual average surface runoff amounts to about 90 mm. Even in this case, it shows a trend similar to rainfall and total runoff and its value is equivalent to half the value of total runoff.

Lateral flow is occurs only in early months of the year and it amounts to about 16 mm.

Return flow reaches the average annual value of 100 mm and constitutes the greatest contribution to the outflow in the stream. Its trend increases in the period from December to March when it reaches the maximum value of about 14 mm; then it decreases gradually and constantly to the minimum value of about 4 mm in December.

Potential evapotranspiration exceeds 1.100 mm with the maximum value in the summer months (196 mm in July) and the minimum value in the winter (21 mm in December). Real evapotranspiration constitutes about 50% of potential evapotranspiration (over 550 mm) and it has a trend similar to potential evapotranspiration, except in June, when there is a strong reduction. This reduction is correlated to the harvest of wheat, the most widely grown crop. It is important to underline that the water quantities used to irrigate are about 150 mm in July and 100 mm in August and these quantities are distributed mainly to tomato crops, cultivated in succession with winter wheat.

Percolation amounts to about 125 mm and it occurs mainly in January and February (respectively 60 and 51 mm), but it is negligible in the rest of year (0 from June to September).

Soil water content is greater in the winter months (the maximum value is 195 mm in January), but is more or less constant in the rest of the year (the middle value is about 130 mm), but in May and July it falls to 56 mm and 33 mm respectively. Its value increases in June (64 mm) because real evapotranspiration is lowest at that time.
Principal water balance components (in volume) can be assumed as follows (Table 1):

Rainfall	**90,1 millions m^3**
Real evapotranspiration	**81,3 millions m^3**
Total runoff	**29,1 millions m^3**
Groundwater recharge	**18,3 millions m^3**
Water deficit	**38,5 millions m^3**

Table 1 – Water balance in volumes.

Examining water balance in reference to single crops, the main results can be synthesized as follows.

Surface runoff assumes the lowest value both for pastures (less than 7 mm) and forests (24 mm) while it is the highest for olive groves (184 mms). This trend is consistent with the "curve number" commonly attributed to these land uses.

There is the maximum return flow contribution for forests (140 mms) and a minimum return flow contributions for the winter wheat/tomato crop sequence (19 mms). This is strictly related to percolation trends described below.

Lateral flow quantity shows great differences among various land uses. Its value is highest both for pastures (66 mm) and woods (60 mms) while it is practically equal to 0 for olive groves and winter wheat. These values are related to different soil layer structures. In fact, forests produce a spongy humus layer rich in organic matter with temperatures lower than intensive crops.

Percolation shows maximum values for forests (234 mm) while it assumes minimum value for the winter wheat/tomato crop sequence (78 mms).

Evapotranspiration is highest for pastures (582 mm) while it is similar for other land uses (with values included between 441 and 488 mm).

When the water balance is examined in terms of volume and the surfaces covered by every land use are considered, the winter wheat/tomato crop sequence causes the evaporation of about 50% of the total water volume involved in the whole basin's water balance. This is certainly linked with excessive groundwater use for irrigation during warm sunny months.

To better analyze issues related to the basin water balance, it is worthwhile to examine some data related to land uses which are the most diffused and water consuming (Table 2):

Winter wheat /Tomato area	**11.000 ha**
Area percentage	**75,4 %**
Groundwater recharge	**8,2 millions m^3**
Irrigation (groundwaters withdraw)	**35,0 millions m^3**
Recharge/Withdraw	**25 %**
Annual Water Deficit	**26,8 millions m^3**
Groundwater Drawdown	**1 m / 4 years - 12 m / 48 years**

Table 2 – W Wheat/Tomato crop sequence data.

Single HRU results show that (referring to the area) units that contribute most to surface runoff are the "land use / soil type" combinations of "forest / clay" and "olive groves / clay" (184 mm). In absolute terms (referring to the volume), the "winter wheat – tomato / clay" combination make the greatest contribution to surface runoff (1.3 million m^3).

The annual average value of sediment yield for the basin amounts to about 4.2 t/ha, (Figure 2), corresponding to a total volume exceeding 53.000 t/years. Its medium trend during the year is marked by two peaks, in February and October, and another very low peak in April. This trend is similar to surface runoff.

The October peak coincides with precipitation increases and with the absence of soil cover on winter wheat crops and deciduous forests. The February peak is correlated to the relatively high surface runoff due to the shallow soil horizon saturation.

Results of the examination for single land uses display rather different contributions. In effect, the maximum value is linked to olive groves with 51.9 t/ha (due to combined effects of slope and poor soil cover), while the minimum value is 2.3 t/ha and is linked to winter wheat crops and pastures (due to high soil coverage and, especially for the wheat, to low slopes). In absolutes terms, volumes vary from about 23.800 t, for wheat areas, to 255 t, for pastures.

The analysis for HRUs shows that, for single units, combinations that mostly contribute to sediment yield are "olive groves / clay" with about 51.9 t/ha and both "forest / clay" and "tomato / fine sand", with about 18.4 t/ha. The minimum value is originated by "tomato / silt-clay" (0,7 t/has) and "winter wheat-tomato / silt-clay-loam".

In conclusion moved volumes vary from 149 t/yr for "tomato / silt-clay" to 14.758 t/yr for "olive groves / clay".

Concerning the nutrient balance, results show that organic N on the whole basin reaches about 10 kg/ha; and its monthly trend during the year is similar to the course of sediments through which it is moved.

Nitrate losses because of runoff amount to about 9 kg/ha and their monthly trend is characterized by two peaks, as it happens especially for surface runoff. The first peak is in January-February and the second is in October-November. However it should be noted that the peak for runoff occurs in early months of the year and is higher than values found in autumn. Nitrate values in runoff are probably related to low vegetative activity in autumn, which reduces the absorption of nitrates by vegetation. Therefore, nitrate become available for runoff.

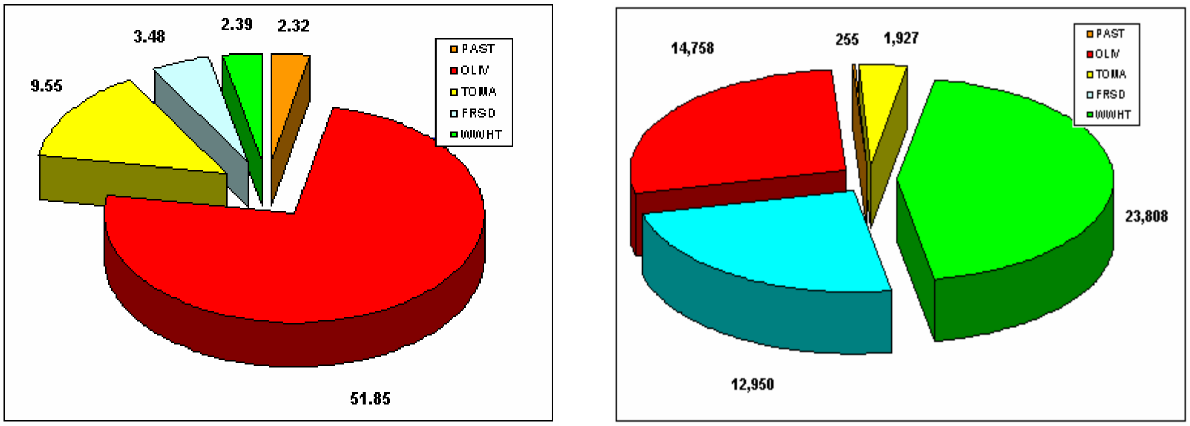

Figure 2 – Erosion for land use in t/ha (L) and tot t (R).

Nitrate quantity in percolation amounts to about 23 kg/ha per year. These quantities leach in groundwater almost entirely in January and February (about 95%), and in that time analogous peaks are observed in percolation trends. It has to be considered that in a large part of the region, crops need a considerable fertilization in February.

Nitrate quantity absorbed by vegetation is equal to 220 kg/ha per year. The highest values are reached both in March/April (50% of total) and in July (25%). Probably the two peaks have to be related to the resumption of vegetative activity and to maximum growth of winter wheat (the first peak) and tomato crops (the second peak).

Soluble P loss amounts to about 2 kg/ha per year and it is characterized by an usual distribution with two peaks (in January/February and September/October).

The same distribution is shown for insoluble P whose annual average quantity amounts to about 11 kg/ha. Moreover, concerning phosphorus, it is necessary to remember that in February and October there are fertilizations and plowings that contribute fairly good quantities of nutrients in the soil.

In table 3 some conclusions, deriving by examination of simulation results, are shown.

Nutrient	Max Losses (HRU)	Min Losses (HRU)
Organic N	W wheat-Tomato/Clay	W wheat-Tomato/Silt-Clay Pasture/Fine Sand
N in subsurface flow	Pasture/Fine Sand	W wheat-Tomato/Silt-Clay
N in surface runoff	W wheat-Tomato/Clay-Loam	Forest/Sand
NO3 in percolation	Forest/Fine Sand	W wheat-Tomato/Silt-Clay
Insoluble P	W wheat-Tomato/Clay	Forest/Sand Pasture/Fine Sand
Soluble P	W wheat-Tomato/Clay- Loam	Forest/Sand Pasture/Fine Sand

Table 3 – Nutrients Losses for HRU.

Discussion

Simulation results can be synthesized as follows.

1) Sediments brought to the streams and lakes because of the physical geography of mountain ranges (orography) and do not represent a risk factor. The greatest contribution to

sediment yield is from subbasins where tree crops (olive groves) are grown. These areas could be protected simply respecting the agricultural best management practices and undertaking soil and water conservation works.

2) Actual land management does not represent a risk factor concerning nutrient mobilization. In fact, where agricultural activities are more intensive there is a regulated fertilization use, while in areas characterized by less human activity the nitrogen and phosphorus concentrations respect normal loads released by transformation processes of organic matter.

3) The most important problem that emerges from the results of this analysis is the water deficit caused by the huge groundwater withdrawal (not always authorized). These are almost exclusively for the winter wheat-tomato crop sequence, for which irrigations are essential in summer months. These irrigations are focused when there are high temperatures and few precipitation events.

4) The research has shown that aquifer recharge areas coincide with forests which assume, therefore, great importance to save groundwater resources. Forest management should not only be devoted to normal production, but also (and above all) to those strategies that improve the water absorption capability of soils and increase effective infiltration.

Conclusion

This analysis underlines current land use irrationality (winter wheat/tomato alternation) which cannot be sustainable for long time periods. Groundwater abuse, on one hand, is slackening the artificial reservoir filling, making its building costs vain (economic and environmental). On the other hand, groundwater use can damage aquatic ecosystems, since the water quantity is less than the minimum flow requisite for flora and fauna survival in freshwater.

Uncontrolled withdrawals are determining the consistent groundwater drawdown observed in the last several years. That perhaps represents the greatest damage because it can produce risks for the entire area, such as aquifer salinisation, subsidence and groundwater exhaustion. The importance of these problems is related to the strategic role of groundwater to deal with drought conditions for the study area. In fact, Capitanata is one of the Italian areas at high risk of desertification.

These results raise a complicated issue. In fact, it is true that environmental costs produced by a similar land use are unbearable, but it is true also that land management is consolidated in the study area and it has a fundamental economic role.

However, if we look at the data related to the woody areas, the SWAT simulation suggests that alternative land management measures may be able to mitigate these risks by restoring works and, where possible, by reforestation programs.

In the long term, these actions could provide more benefits related not only to environmental protection and timber production, but also to landscape value and naturalistic importance, especially near the lake. So this region, in which intensive agriculture currently prevails, could become an interesting attraction for tourists and current inhabitants.

In conclusion, it is important to underline that the comparison of the SWAT results along with the available experimental data confirms the reliability of SWAT outputs. That confirms the utility of the model, together with the GIS technology in the evaluation of land use impacts (referring particularly to diffuse pollution). In general terms, this study confirms the applicability of SWAT to study issues in this region. Thanks to these tools, it is possible not only to define the types of damage to water resources and ecosystems, but also to identify the exact position of key issues in the study area. In this way it is possible to identify rehabilitation works that will have the greatest effectiveness and that will be most economically rational.

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Application of the SWAT model for the Sensitivity Analysis of Runoff to Land Use Change

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1. Introduction

Land use changes which are biophysically, or more commonly in the last years, artificially based (Skole and Tucker, 1993) often have significant effects on the surrounding environment and the hydrological cycle. Although the empirical knowledge of the consequences of a land use change is generally common (i.e. deforestation causes increases in discharge), it is often very difficult to make an explicit quantification of these consequences. It is the scope of this study to present a method for quantifying the impacts from specific land use changes on the runoff of basins by examining the case study of the Pinios catchment in Thessaly, Greece. The water cycle was simulated with the use of the Soil and Water Assessment tool (SWAT), and the land use change scenarios were created using the Land Use Development Model (LADEMO) (Menzel and Blongewicz, 2000). LADEMO is a prototype created within the EUROTAS project (funded under the 4th Environment Framework, ENV 63/846).

2. Study Area and Land Use Data

The SWAT model was implemented in the catchment of the Pinios River in the outlet of Ali Efenti. The catchment has an area of 2796 km^2 and is located in the Thessaly plain in central Greece, between the parallels 39.30' South to 40.00' North and 21.20' West to 22.10' East (Mimikou, 1999, Varanou et.al., 2001). The mean elevation of the basin is 540 m, with mountainous landscape appearing in the north and west part and large plains in the central and south east.

Land use patterns were derived from the European Corine project by processing the data in the ArcView environment. Known uses were categorized in larger groups, and unknown uses were integrated into neighboring knowns and subsequently cross-referenced to the appropriate uses included in the land use database of the SWAT model. Previous studies of the Pinios River have used the SWAT model with four types of land uses (agriculture, forest, urban and water) and with 10 types of land uses (i.e., more detailed representations of agricultural land, different forest types, etc.). This process pointed out a small sensitivity of the model in the detail of land use data. In particular, although the calibration indexes seemed to be quite sensitive to factors such as groundwater variables or soil data, it proved to be rather insensitive to the increment of land uses from 4 to 10. Details on this analysis are beyond the scope of this study and can be found elsewhere (Tsotsonis, 2000, Pikounis et al., 2001). Since the LADEMO prototype could only be applied on limited land uses, the coarser calibration of the model was used, thus this application used four land uses.

3. The Method and the Land Use Change Scenarios

LADEMO is a technique that makes use of spatially distributed information of the landscape and generates a dynamic evolution of land use patterns based on a given scenario target. Basic input is gridded information on actual land use. For an optional refinement of the procedure, spatial information on natural conditions like topography or soils is required. The result of a model run is a digital map of future land use according the predefined scenario conditions (Menzel and Blongewicz, 2000). The method is user-based, meaning that it is designed as an interactive dialogue with the user in order to integrate expert knowledge into the procedure. The user defines the land use class which is assumed to increase or decrease in its spatial extent (source class) and the land use classes, which are considered to be affected by an area change of the source class (target classes). When two or three target classes are selected, each of these is assigned a priority. In this case, the target class with the highest priority will be considered first, if possible. If the user has selected to take into account additional available information on natural conditions, such as the topography and the soil, he can reclassify the data to represent good, medium and poor conditions for the development of the target scenario. In addition, the user can assign different weights to the selected themes in order to give a certain theme a higher preference. For example, the user might consider soil to be of higher importance than the slope in a scenario where agriculture is decreasing.

In the final step of the procedure, the spatial distribution of the different land use types as well as neighbourhood relationships are considered (focal analysis) and a pixel-wise modification of the source land use are modified until the altered land use map is in accordance with the predefined scenario target. The modified land use map can then directly be used as an input for hydrological modeling.

Being a prototype, the LADEMO procedure has several limitations that are worth mentioning that affected the chosen target scenarios.

- Only four types of land uses at a time are considered.
- It allows only for 100% deforestation of a watershed.
- The mechanism and the algorithms that are used for the modification of the land use dictate the percentage of land use change and the user may come up with too precise percentages for hypothetical cases (why 21% and not 20%?).

Considering the above, the following three land use changes scenarios were considered:

- *Expansion of agricultural land.* According to this scenario, the agricultural land area was expanded by 21%. To balance this expansion, the forestry area lost 15% of its original size, while urban and water areas remained intact. The original digital map of present conditions is shown in Figure 1a, while the land use pattern after the implementation of this scenario is presented in Figure 1b.
- *Deforestation of the Trikala subbasin.* The procedure only allows the full (100%) deforestation of a watershed. This scenario can only be described as excessive in this part of Pinios River basin, with a total area of around 3000 km^2 where 57% of this area is occupied by forest. The ability of the SWAT model to partition the basin into subbasins was implemented in this case by specifying a point in the stream network just downstream the town of Trikala. SWAT was then used to assign a subbasin to this outlet. The deforestation of this subbasin, with an area of 270 km^2, is not as improbable as the option of complete deforestation, and therefore this scenario was chosen instead of a 100% deforestation of the entire basin, as shown in Figure 1c. The selection of the specific point used to assess the changes in the river discharge (mainly after floods) is the branch of the river that trespasses a large town of the Thessaly plain.
- *Expansion of urban areas.* This scenario was also applied in the Trikala subbasin, since the percentage of urban land in this area is greater than the percent in the whole watershed, thus intensifying the effects of the change. According to this scenario, depicted in Figure 1d, urban land expand by 132%, primarily over the agricultural land and by a smaller percentage over the

forestry areas. Although the percentage exceeds 100%, the small proportion of the urban areas in the subbasin (3%) results in a rational amount of land use change (about 12 km^2.) To balance the expansion of urban areas, there was a decrease in agricultural land by 5.6% and forestry by 2.4%.

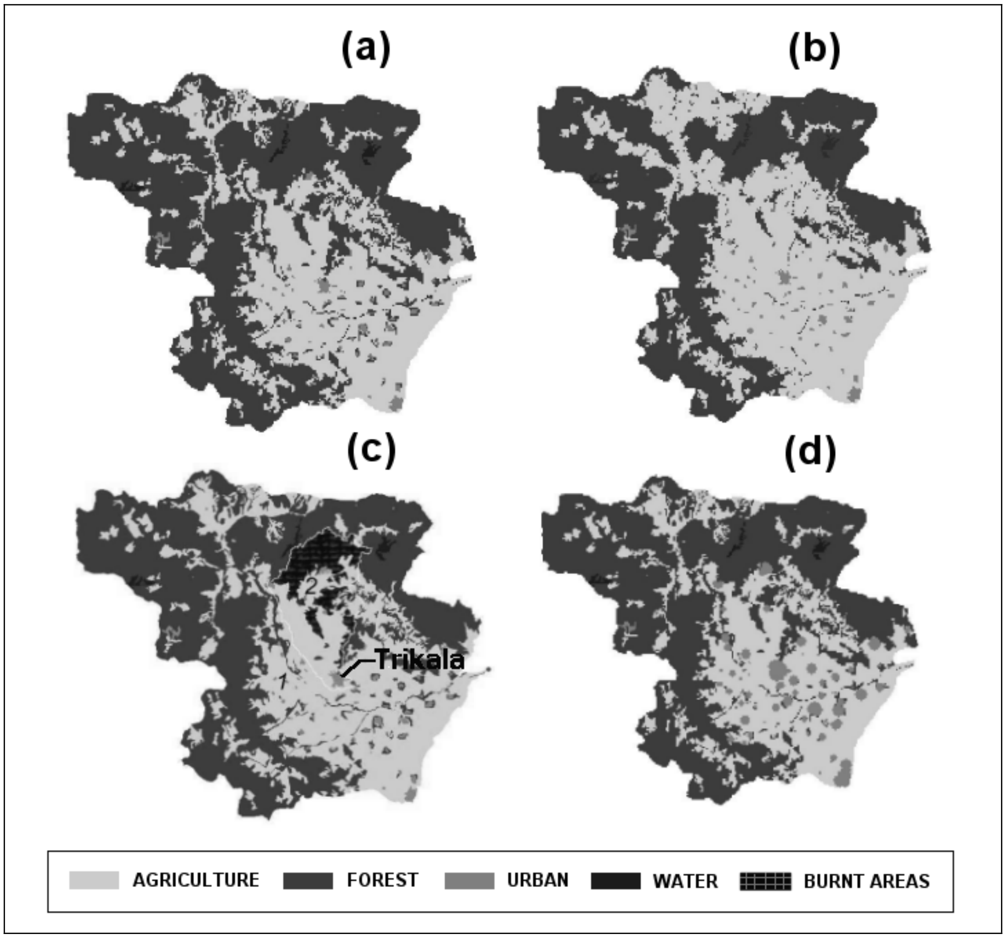

Figure 1: Digital maps of land use: (a) Original pattern of land uses, (b) after the expansion of agricultural land, (c) after the deforestation of the Trikala subbasin and (d) after the expansion of urban areas.

4. Results and Discussion

The application of the SWAT model for the three land use change scenarios gave an increase in discharge during wet months, and a decrease during the arid months. Details about the response of the basin to each scenario are shown below (Table 1):

- By expanding the agricultural land over forest by 20%, a mean monthly increase in the river discharge of up to 3% was observed from October to April, and a reduction from May to September, which reached 6% in July. In a daily time step, discharge increases of approximately 20% were observed after intense precipitation incidents, followed by reductions in base flow.
- The deforestation of the Trikala subbasin scenario gave substantial increases (23%) in mean monthly discharge for wet months, while during the summer, discharge decreased by up to 38%. The related increases in a daily time step were on the order of 130%.

- The final scenario of expansion of urban land by 130% over agriculture and forest gave similar results to the agricultural expansion scenario. Smaller reductions in discharge were predicted during summer months, and a significant increase of 5% was estimated during October. In the daily step, increases were as high as 35%.

Table 1: Maximum and minimum values of discharge change percentages for the three implemented scenarios.

Scenario	Maximum mean monthly increase %	Maximum mean monthly decrease %	Maximum daily increase %
A. Expansion of Agricultural Land	3.0	-6.0	20.0
B. Deforestation	23.0	-38.0	130.0
C. Expansion of Urban Land	5.0	-2.0	35.0

5. Conclusions

An observation of the results makes evident that the land use change which is causing a greater modification of daily and monthly total discharge is the change introduced by the deforestation scenario. However, this should be used with caution and any generalizations should be avoided, since the scenarios refer to specific percentages of land use changes implemented in a particular basin. Nevertheless, the deforestation scenario is shown to increase daily discharges by as much as 130% and underlines the potential flood risk in the case of forest fires. This is not unusual considering the prolonged warm summers in Greece.

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Application of SWAT to Model the Water Balance of the Woady Yaloak River Catchment, Australia

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Abstract

The widespread land use changes that are expected to occur across the Corangamite region in southwest Victoria, Australia, have the potential to significantly alter the water balance of catchments. Adoption of the Soil and Water Assessment Tool (SWAT), which is a long-term water balance model, as a tool for predicting land use change impacts on catchment water balance for the Corangamite region is currently being considered. This paper describes the initial application of SWAT to the Woady Yaloak River catchment, located within the Corangamite region, to carry out an evaluation of its abilities for simulating the long-term water balance dynamics of the catchment. The performance of the model for predicting runoff at annual and monthly time scales was found to be very good. The excessive recharge of the shallow aquifer that occurred during winter, despite the subsoil being relatively impermeable, ultimately contributed to overestimation of baseflow and underestimation of interflow. The actual evapotranspiration from hydrologic response units (HRUs) containing eucalyptus trees was significantly less than that from HRUs containing pasture, a problem attributed to the incorrect simulation of Leaf Area Index (LAI) and biomass by the model for mature stands of eucalyptus trees and also to assigning inadequate values for two parameters that directly influence evapotranspiration. SWAT has very good potential for being used as tool to study land use change impacts across the Corangamite region provided that several modifications are made to the model to overcome some of the shortcomings and deficiencies that were identified in this initial application.
KEYWORDS. SWAT, water balance model, catchment hydrology, land use change

Introduction

The landscape of the Corangamite region in southwest Victoria, Australia, has undergone significant change since the arrival of European settlers to the region almost 200 years ago. The most prominent change in the landscape has been the clearing of large expanses of native vegetation which was predominantly perennial, deep-rooted eucalyptus forests. Annual, shallow-rooted pastures and crops have since been established on the cleared land. Such extensive modification of the natural environment that existed prior to European settlement has altered the water balance of catchments significantly. The change in the water balance is primarily due to the reduction in evapotranspiration. Eucalyptus forests intercept more rainfall in their canopy and extract water from the soil profile at greater depths than pastures or crops and therefore have higher rates of evapotranspiration. Hence the replacement of eucalyptus forests with pastures or crops has led to a decrease in evapotranspiration and subsequently an increase in surface runoff and groundwater recharge. Dryland salinity is another major environmental problem that has arisen as a direct consequence of the land use change. Dryland salinity is caused by the excessive groundwater recharge raising the saline groundwater to the land surface (Cox and McFarlane, 1995). An alarming escalation in the occurrence of dryland salinity has been observed across the region.

Large-scale afforestation across the region has been proposed in recent years as a remedial measure to prevent any further degradation of land and water resources that is occurring as a consequence of dryland salinity. An assessment of the extent and future risks of dryland salinity in Australia by the National Land and Water Resources Audit led to the conclusion that "in the face of an estimated three-fold increase in the area at risk of dryland salinity over the coming decades…the amount of change needed in the water balance, and therefore in land use, is substantial" (NLWRA, 2001). However catchment managers have expressed considerable concern over this recommended course of action since it has the potential to significantly diminish the water yield of catchments, a topic which has received much attention in the past few years as a result of a prolonged drought period. It is unquestionable that the implementation of land use change for management purposes involves serious issues because if the changes are allowed to proceed unchecked the impacts to the water balance of catchments across the region could be devastating. Therefore it is critical that catchment management authorities are able to have access to tools that enable the impacts of land use change to be predicted when deciding upon future management practices for land and water rehabilitation at a regional scale.

Hydrologic models have been recognised as tools that can be utilised to investigate the potential consequences of future land use change scenarios. Therefore hydrologic models will play a vital role in the decision making process of catchment management authorities in regards to dealing with future land use change. Despite the recognition that land use change has the potential to detrimentally affect the quantity and quality of runoff from catchments, very few modelling studies have been conducted in the Corangamite region with the intention of analysing land use change impacts. One of the main reasons for this lack of modelling work is that very few large-scale catchment water balance models have been developed in Australia for predictive purposes.

A number of water balance models have been developed in Australia over the years including the AWBM (Boughton, 1995), Monash (Porter and McMahon, 1971), SDI (Kuczera et al., 1993) and SIMHYD (Chiew et al., 2002) models. These are all examples of lumped, conceptual models. Although the application of these models has contributed significantly to water balance studies in Australia, they have very little practical use for evaluating the impacts of land use change on water balance dynamics. This is because the tremendous heterogeneities of hydrological responses resulting from the spatial and/or temporal variability of climate, topography, soils and vegetation across large-scale catchments are ignored by these models (Sivapalan et al., 1996b). Another major limitation of lumped, conceptual models is their lack of physical basis.

At the other end of the spectrum are TOPOG (Vertessy et al., 1993) and THALES (Grayson et al., 1992a), both of which are fully distributed, physically based models. These models are only appropriate for studying hydrological responses of hillslopes and small catchments and are not deemed appropriate for predicting the dynamics of water balance for large catchments (Sivapalan et al., 1996a). For management purposes it is more appropriate to use "simpler, less pretentious models in which data requirements are low, assumptions are clearly stated and results are generally qualitative" (Grayson et al., 1992b).

Lumped, conceptual or fully-distributed, physically based models are not considered suitable for modelling land use change impacts in large-scale catchments. It is imperative that any model to be used for planning and management purposes has a sound physical background, but also at the same time be computationally efficient enough to allow for a long term simulation to be carried out as it is essential to perform a proper risk assessment (van Griensven, 2001). Therefore a more appropriate type of model to use is a semi-distributed model which offers some compromise between the constraints imposed by the other model types described above.

A widely applied semi-distributed model is SWAT (Neitsch et al., 2001). SWAT was developed primarily for use in the United States but has since become prominently used worldwide by land and water resources managers for land use change studies. SWAT has not been widely adopted in Australia yet, but a number of direct applications of the model in different regions across the country have been reported very recently (Conolly, 2002; Rattray et al., 2002; Dougall et al., 2003). This is a strong indication that SWAT is now beginning to be recognized and accepted as a model with very good potential for modelling the water balance and water quality of large catchments in Australia. Several geographic information system (GIS) interfaces (ArcView and GRASS) have been developed for SWAT. The interfaces enable detailed spatial data sets to be handled and manipulated very easily. In addition, all the input files required to operate the model are setup by the GIS interfaces. These are important advantages that will become more widely appreciated in the future. Due to the number of applications of SWAT overseas for land use change studies, and also because of the clear lack of models developed in Australia that are suitable for predictive purposes, SWAT is currently being considered for adoption to conduct a comprehensive study of future land use change impacts across the entire Corangamite region.

This paper describes the initial application of SWAT to the Woady Yaloak River catchment. The objective is to evaluate the performance of SWAT for predicting the water balance of the catchment and also to review the process descriptions of the model to determine their suitability for the study area and the wider region. It is also recognized that the availability and accuracy of data sets is a very important consideration in hydrologic modelling and this factor will be carefully considered in the overall evaluation process of SWAT.

Study Area

The catchment selected for the initial application of SWAT was the Woady Yaloak River catchment located in the Corangamite region in southwest Victoria, Australia (Figure 1). The source of the Woady Yaloak River is in the Central Victorian Highlands, to the west of the city of Ballarat. The river proceeds to flow south for approximately 60 kilometres before it drains into Lake Martin, which in turn overflows into Lake Corangamite, the largest permanent natural lake in Australia (Russ, 1995). Streamflow is measured at the Pitfield and Cressy gauging stations (Figure 1). The catchment area drained to the gauging stations is 306 and 1157 km^2 respectively.

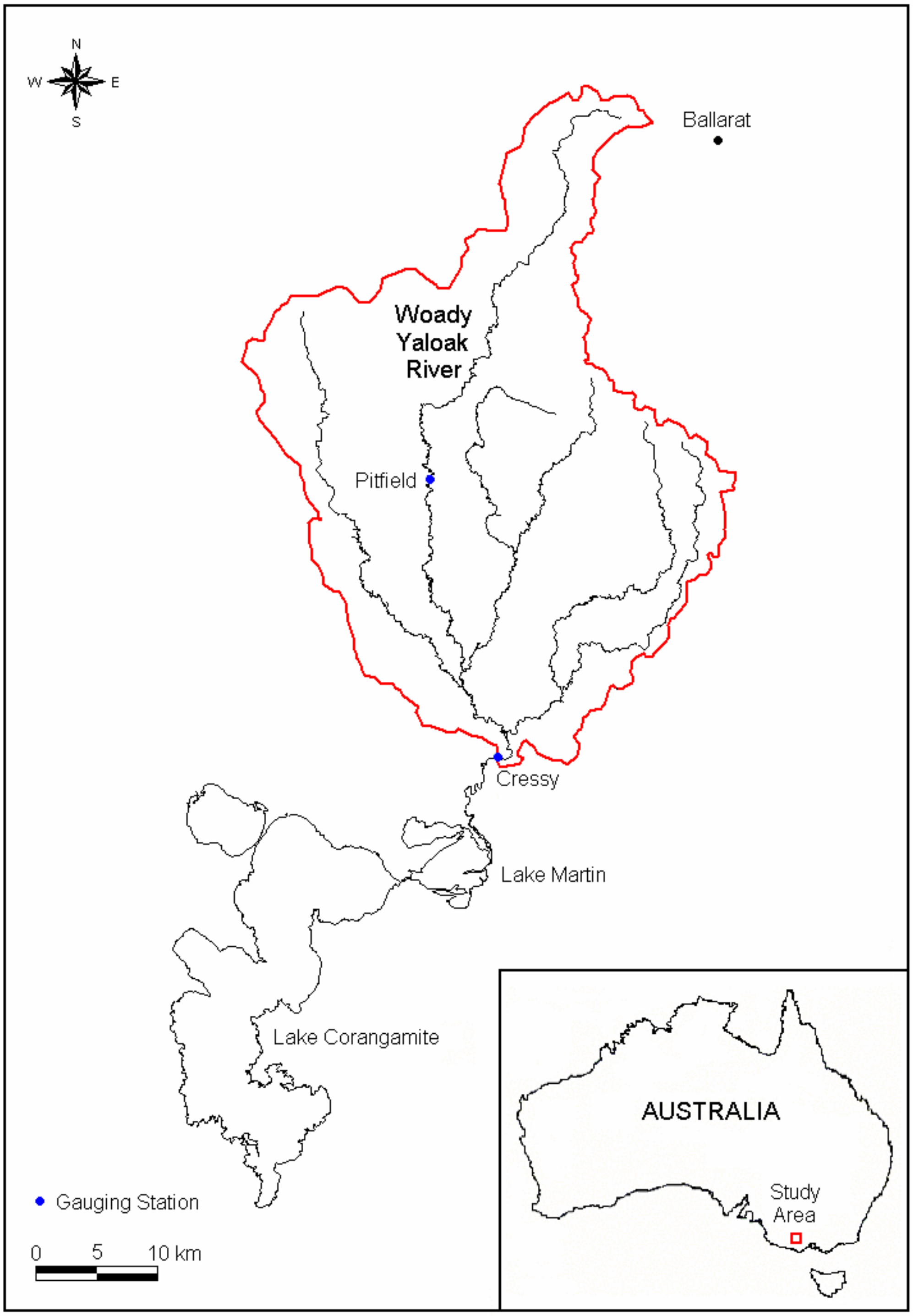


Figure 1. Location of the Woady Yaloak River catchment.

There are a multitude of land uses in the Woady Yaloak river catchment. The majority of land is used for agriculture with the main commodities being grazing livestock (beef cattle, sheep and prime lambs) and crops (oats, wheat, barley and canola). There are also large expanses of remnant, native eucalyptus trees found in the north. Soils throughout the catchment are predominantly duplex (Maher and Martin, 1987). A common morphological feature of duplex soils is an abrupt textural contrast between the A horizon (topsoil) and B horizon (subsoil) (Chittleborough, 1992; Cox and McFarlane, 1995). The A horizon soils are typically shallow (100–600 mm) and highly permeable. The underlying B horizon soils are generally found to depths of 1–1.5 m in most areas and are relatively impermeable. The terrain in the north varies significantly from that in the south. The southern half of the catchment exhibits very little relief and drainage patterns are generally poor. Slopes in the northern reaches of the catchment are mostly mild to steep and drainage development is more clearly defined, with the river and its tributaries being deeply incised. The climate is distinctly Mediterranean with hot, dry conditions prevailing during the summer months while the weather during the winter months is cold and wet. Annual rainfall varies from 500 mm at the very bottom of the catchment to 750 mm at the top end. Average daily temperatures range from 26°C in February to 5°C in July. The average annual Class A Pan evaporation is approximately 1380 mm.

Model Setup

Rainfall and climate data were obtained from SILO (www.bom.gov.au/silo), who have constructed continuous, daily time step records using spatial interpolation algorithms to estimate missing data for more than 4600 stations across Australia (Jeffrey et al., 2001). Daily rainfall records were interpolated using ordinary kriging while all other climate data was interpolated using a thin plate smoothing spline (Jeffrey et al., 2001). Rainfall data were obtained from six stations located in or at close proximity to the catchment, while climate data could only be sourced from three stations. It is highly unlikely that the low density of rainfall stations has enabled the spatial variability of rainfall over the catchment to be captured, although very little can be done about this.

At the beginning of the study, no suitable land use map for the area was available. The principle author had to collaborate with the State Chemistry Laboratory (SCL) to produce a suitable land use map for this study. The resultant land use map, developed from Landsat satellite images and an extensive ground-truthing campaign, was in accordance with Australian Land Use and Management (ALUM) Classification scheme (BRS, 2001). The scale of the newly developed map was 1:100,000.

The only sufficiently detailed map of soils for the study area was acquired from the Centre for Land Protection Research (CLPR). The map, developed by Maher and Martin (1987) at a scale of 1:100,000, does not strictly show the individual soil types. Instead the map shows compound soil-landform units, referred to as map units, which are characterised by different and particular collections or associations of soils. The dominant soil type found in each map unit was taken to be the soil type for the entire map unit. Although the underlying attributes of the map are basic, its use was deemed sufficient for this modelling exercise because detailed soil and land use maps are not useful in SWAT since only the most common combinations appear in the HRUs and less common soil types disappear (van Griensven, 2002). No measured field data were available for the properties of the soils within the catchment. Therefore estimates of soil properties had to be obtained from McKenzie et al. (2000) instead. McKenzie et al. (2000) have estimated various soil properties for most of the soils found in Australia using a simple two-layer model of the soil consisting of an A and B horizon.

The Woady Yaloak River catchment was discretized into 29 subbasins. Based on a 10% threshold level for both soils and land use, a total of 92 HRUs were established by the ArcView GIS interface. In this application of SWAT the SCS-CN method was used to calculate surface runoff, the Priestly-Taylor equation was used to calculate potential evapotranspiration and the variable storage routing method was used to route channel flow.

Results and Discussion

A long simulation period was considered necessary because the dynamics of the water balance can change significantly over long periods of time (years) in response to the variability of rainfall from year to year. Applying the model to an extended period of the record is regarded as a more stringent test than if the model was only applied to a short period because it will show whether the model is able to capture the long-term dynamics adequately. The model was applied to simulate the water balance of the Woady Yaloak River catchment for a 24 year period. The model was calibrated for the period of 1978–1989 and then validated for the period of 1990–2001. This is essentially a split-sample test which according to Klemeš (1986a) is the minimum requirement needed to test models for operational applications. To reduce the number of plots only the results achieved at the Cressy gauging station, which is the catchment outlet, have been presented here. Presented in Figures 2 to 4 are the observed and predicted runoff volumes at annual, monthly and daily time scales.

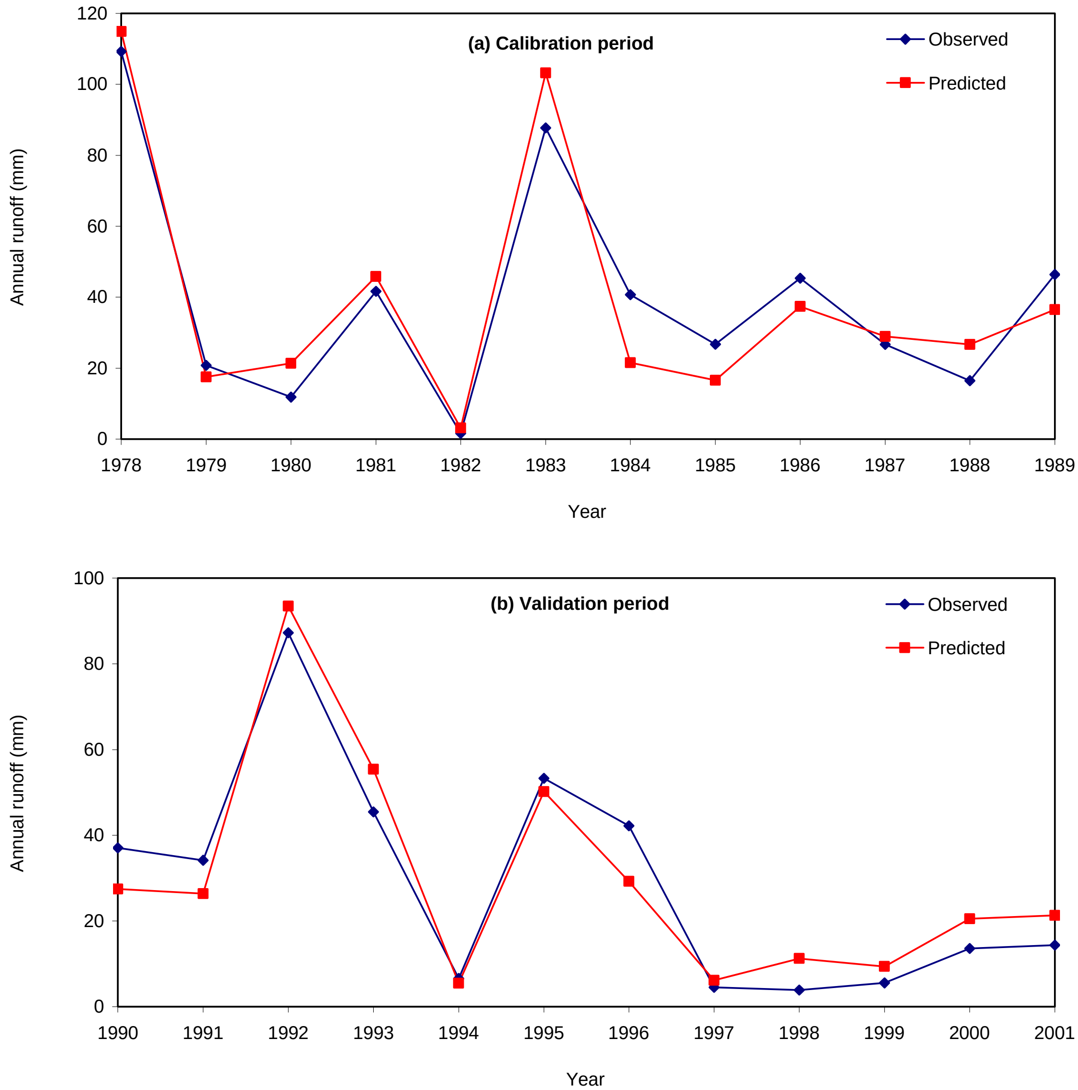
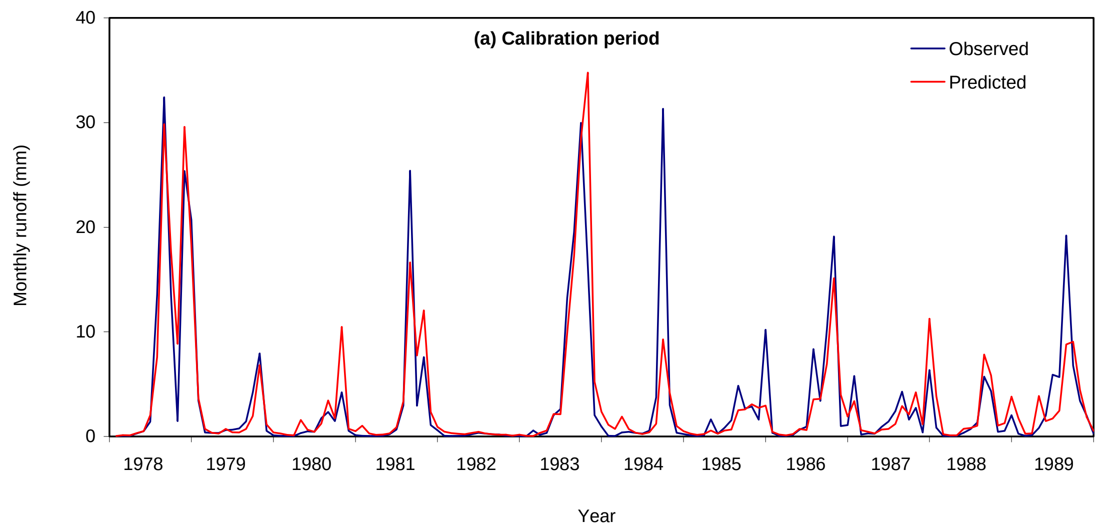


Figure 2. Annual observed and predicted runoff volumes at Cressy for (a) calibration period, 1978–1989 and (b) validation period, 1990–2001.



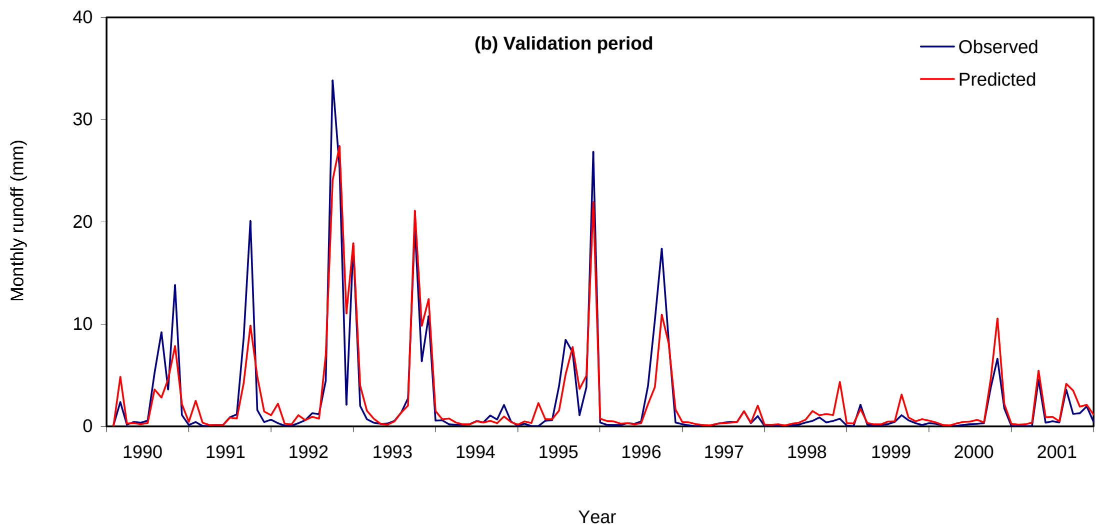


Figure 3. Monthly observed and predicted runoff volumes at Cressy for (a) calibration period, 1978–1989 and (b) validation period, 1990–2001.

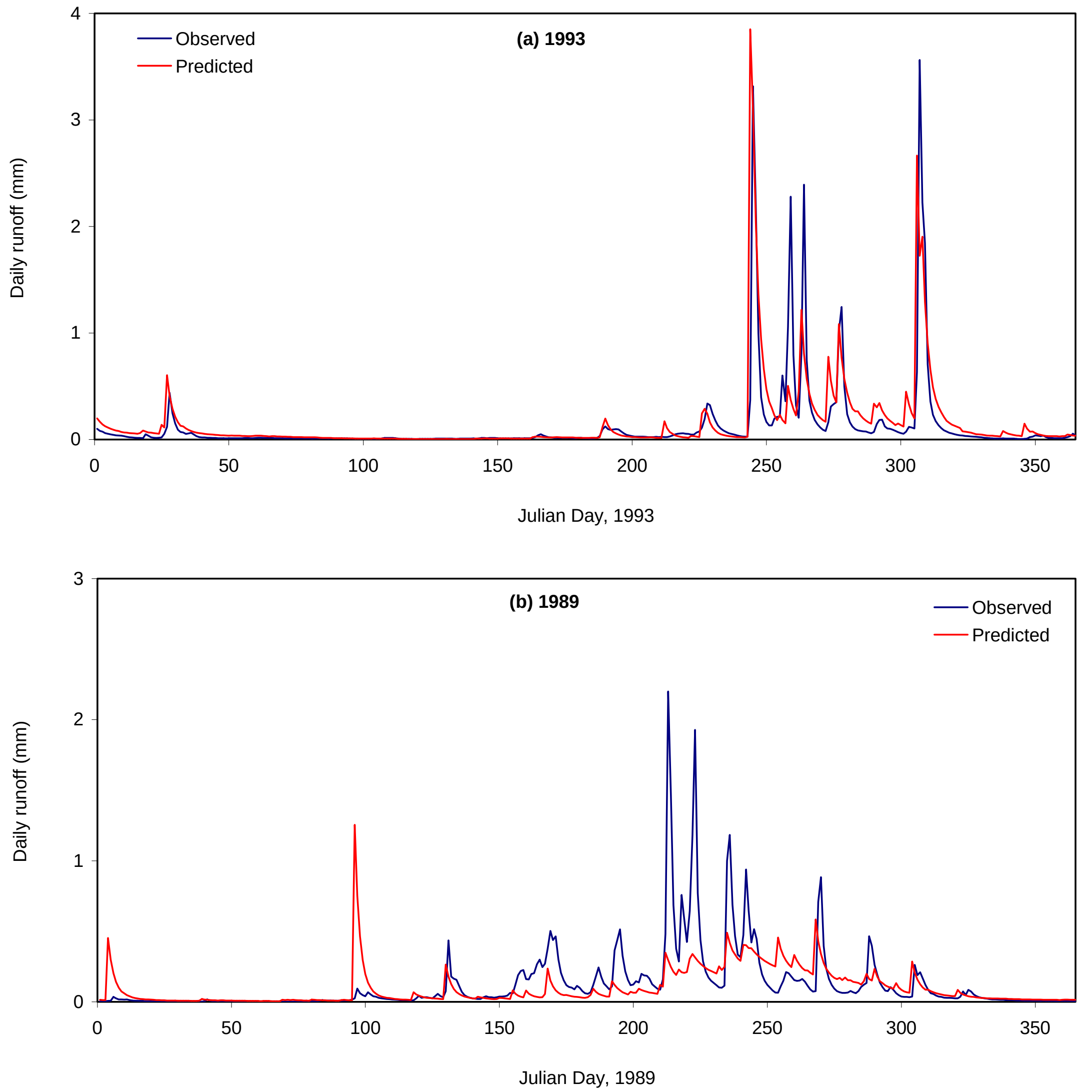


Figure 4. Daily observed and predicted runoff at Cressy for (a) 1993 and (b) 1989.

Figure 2 indicates that the performance of SWAT for predicting annual runoff volumes was exceptionally good. The comparison of the observed and predicted monthly flow hydrographs in Figure 3 shows that results achieved by SWAT on a monthly time step are also very good, with the seasonal trends being accounted for relatively well. The results for daily runoff predictions were, however, considerably mixed. Daily runoff was reasonably well predicted for some years (Figure 4a), whereas for other years the results were considerably poorer (Figure 4b).

The statistics and objective measures used to assess the performance of SWAT for predicting runoff are presented in Table 1. The very high coefficients of determination and efficiency obtained for annual runoff predictions for both operational testing periods confirm that the performance of SWAT on an annual time step was excellent. The results also clearly indicate that the prediction of monthly runoff volumes by the model were also very good, particularly for the validation period. Results for the daily runoff measurements were considered to be only average. The coefficient of efficiency for the calibration and validation periods (0.52 and 0.51 respectively) indicates only a reasonable fit between the observed and predicted data was obtained at a daily time step. The observed and predicted mean daily runoff were in close agreement but the difference between the standard deviation of observed and predicted daily runoff was 28.2 and 34.2% for the calibration and validation periods respectively. The standard deviation of runoff is considered to be an important statistical characteristic in hydrologic modelling and it is warranted that this characteristic be preserved.

Table 1. Statistics and objective measures achieved by SWAT at Cressy for calibration and validation periods.

	Calibration			Validation		
	Annual	Monthly	Daily	Annual	Monthly	Daily
Observed mean (mm)	39.6	3.3	0.11	29.0	2.4	0.08
Predicted mean (mm)	39.5	3.3	0.11	29.7	2.5	0.08
Observed stand. dev. (mm)	31.2	6.4	0.46	25.7	5.4	0.38
Predicted stand. dev. (mm)	34.5	6.0	0.33	25.6	4.6	0.25
Coeff. determination	0.92	0.75	0.52	0.91	0.85	0.52
Coeff. efficiency (Nash and Sutcliffe, 1970)	0.89	0.74	0.52	0.91	0.85	0.51

It is concluded from the results presented above that SWAT has done a very good job at representing the long-term runoff of the Woady Yaloak River catchment, considering the tremendous variability of runoff on an annual basis (Figure 2) and also that extreme conditions (flood and drought) have occurred throughout the selected record used to evaluate the model. Although SWAT is intended as a long-term yield model rather than a hydrograph prediction model (Beven, 2001), it would be desirable to be able to achieve better results on a daily time step given that the model does operate at this time step. Although these results are very promising, it is important to realize that insights into the water balance of a catchment cannot be fully gained from considering streamflow predictions alone.

The soil moisture content of the A and B horizons averaged over the entire catchment is presented in Figure 5. Both soil storages clearly exhibit very strong seasonal fluctuations on a year to year basis. The long-term trend clearly shows that both horizons are replenished during the wetter months only to be depleted significantly during the drier, hotter months. The A horizon responds quickly to storm events, unlike the B horizon which can be observed to have a slight delay time to when the maximum moisture content for the year is reached. The soil moisture content of the B horizon in 1982 was exceptionally low. This can be explained by the occurrence of a drought in 1982, estimated to have a recurrence interval of 100 years.

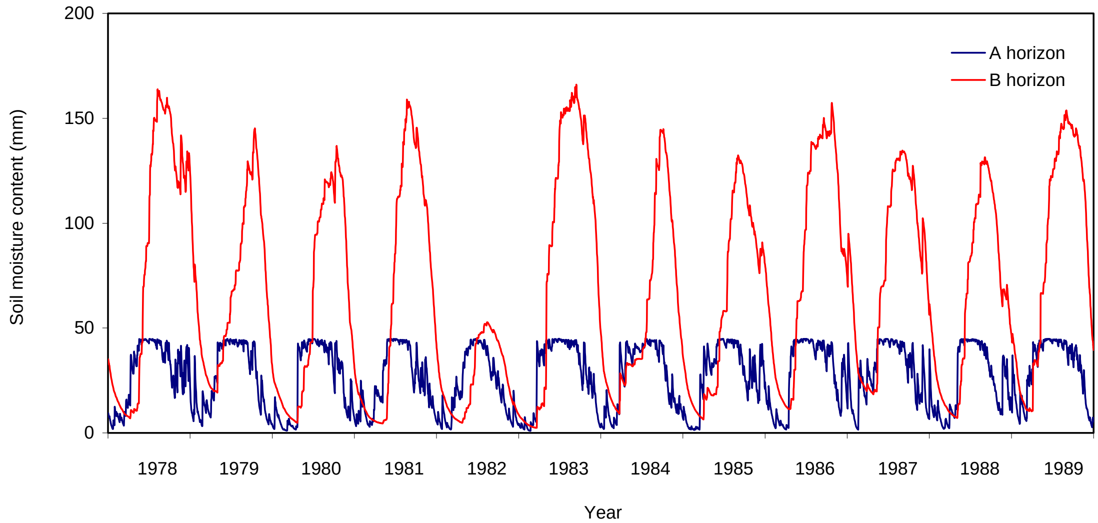


Figure 5. Soil moisture content of the A and B horizons averaged over the entire catchment for the calibration period, 1987–1989.

Williamson and Turner (1979) measured the soil moisture content of the A horizon at fortnightly intervals between 1976 and 1977 in the Warrambine Creek catchment, a small research catchment located directly next to the Woady Yaloak River catchment along a section of its southeast boundary. The general trend of the soil moisture content of the A horizon predicted by SWAT over the duration of a year (Figure 5) corresponds very well to the trend observed by Williamson and Turner (1979). That is, the SWAT predictions and measured values of Williamson and Turner (1979) both indicate that the A horizon storage was replenished during winter and spring in response to heavy rainfall and was severely depleted over summer. This comparison of the variations in soil moisture content displayed throughout the year has no direct quantitative significance, but rather it simply highlights that the model has captured the essential features of the A horizon variations. Williamson and Turner (1979) did not measure the soil moisture content of the B horizon.

The moisture content of the A horizon is extremely important in the generation of runoff in the Woady Yaloak River catchment. The infiltration capacity of the soil is not considered to be a limiting factor in runoff generation in the catchment because the low rainfall intensities very rarely exceed the high infiltration capacities of the A horizon soils. Instead the variation of the moisture capacity of the upper soil and its current moisture content governs this response (Williamson and Turner, 1979). Saturation excess runoff is therefore considered to be the dominant runoff generation mechanism in the catchment. Given that saturation excess runoff is recognized as the dominant process in most catchments across the Corangamite region, it is deemed that the incorporation of a saturation excess mechanism into SWAT to calculate surface runoff would be more appropriate for the widespread application of the model to catchments throughout the region.

It is imperative that the hydrological fluxes that make up streamflow (overland flow, interflow and baseflow) are predicted accurately by a hydrologic model if the outcomes obtained from the model application are intended to support the implementation of management decisions. Consider the monthly volumes of each hydrologic flux predicted by SWAT for the calibration period presented in Figure 6. Surface runoff shows a strong seasonal response as was expected. Baseflow also shows a strong seasonal response although such an occurrence is very surprising. Comparison of the interflow and baseflow components over time indicates that the contribution of baseflow during the winter months is excessively high while interflow is considerably lower. Recharge of the shallow aquifer during these periods was discovered to be very high because the model simulated too much percolation through the soil profile despite the B horizon being relatively impermeable.

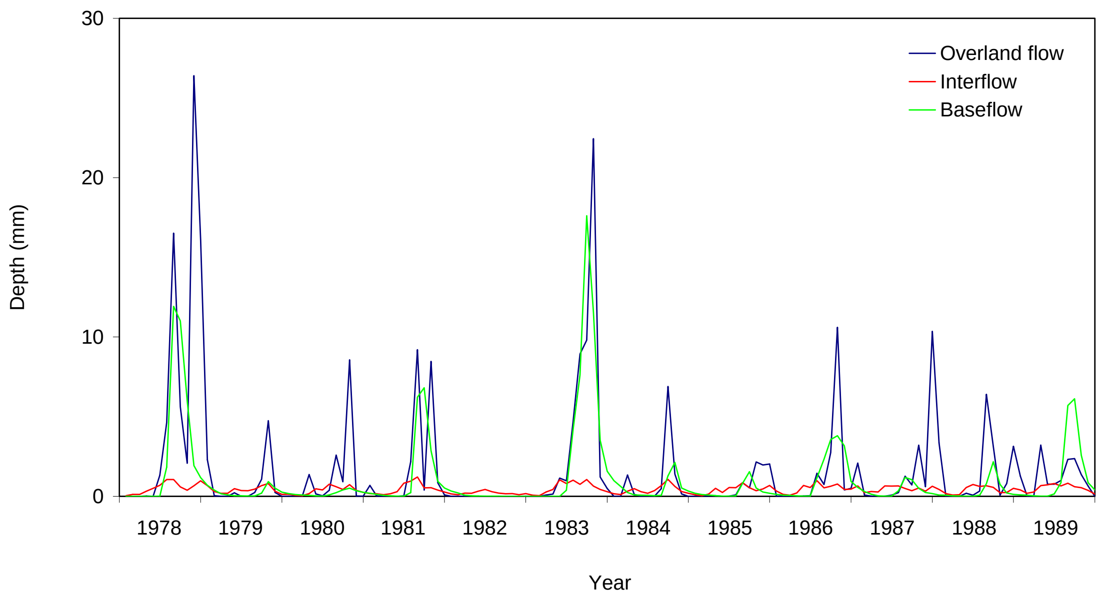


Figure 6. Monthly volumes of overland flow, interflow and baseflow predicted by SWAT at Cressy for the calibration period, 1978–1989.

It is apparent that the model has significantly underestimated interflow during the wetter months of the year. Dahlhaus and MacEwan (1997) and Heislers and Pillai (2000) have reported that interflow is the dominate process in many areas of the Woady Yaloak River catchment and that groundwater recharge is low due to the relative impermeability of the B horizon. In general it has been shown that for many duplex soils, significant quantities of water travel on top of the B horizon, facilitating increased interflow (Cox and McFarlane, 1995; Cox and Pitman, 2002).

Evidently, the amount of water that percolates out of the bottom of the soil profile and recharges the shallow aquifer is too great despite there being a lack of vertical flow capacity in the B horizon. Also as the B horizon storage fills during winter (Figure 5) it would be expected that inflow from the A horizon would be limited in favour of enhanced interflow as the moisture holding capacity of the B horizon diminishes. The model is not able to represent the dynamics of the catchment adequately and as a consequence this has led to the overestimation of baseflow during many of the periods of high rainfall in the record. A somewhat similar problem was encountered by Eckhardt et al. (2002) when SWAT was applied to a catchment in Germany characterized by shallow soils overlying a hard rock layer.

It must be stipulated that the volume of each of the fluxes presented in Figure 6 are only hypothetical since the partitioning of a hydrograph into its separate components is arbitrary (Klemeš, 1986b). There is no available information for the Woady Yaloak River catchment to support the representation of each flux by the process descriptions incorporated into SWAT. This highlights the weakness of calibrating and validating hydrologic models to streamflow data alone (Kuczera et al., 1993).

It has been shown elsewhere that SWAT cannot adequately simulate the LAI and biomass of mature stands of eucalyptus trees due to the model forcing the trees to go dormant and loss all their leaves every autumn (Watson et al., 2003). Dormancy is an unrealistic occurrence for eucalyptus trees and as a consequence future applications of the current version of the model should be constrained solely to agricultural catchments that do not contain significantly large areas of eucalyptus forests or plantations. Similarly, the establishment of eucalyptus forests or plantations in an agricultural catchment as a future land use change scenario would also not be applicable.

Evapotranspiration makes up a very large proportion of the water balance of the Woady Yaloak River catchment, where approximately 90% of the annual rainfall is lost through evapotranspiration (Holmes and Sinclair, 1986). Extensive research worldwide has established that forests have higher rates of evapotranspiration than grasslands (Zhang et al., 2001). It is of the utmost importance to ensure that the rate of actual evapotranspiration simulated by SWAT for forested and pastured HRUs appears reasonably correct, even if measurements are not available. The cumulative actual evapotranspiration from two HRUs, one of which contains pasture and the other eucalyptus trees, is presented in Figure 7. It can be observed that the actual evapotranspiration from the HRU containing eucalyptus trees is significantly less than that of the HRU containing pasture. This is contrary to what was expected since Holmes and Sinclair (1986) clearly demonstrated that the rate of evapotranspiration of forests was greater than that of grasslands in Victoria. It should be noted that the two HRUs are located in the same subbasin and that the same trend was also observed in other subbasins in which both pasture and eucalyptus trees were grown.

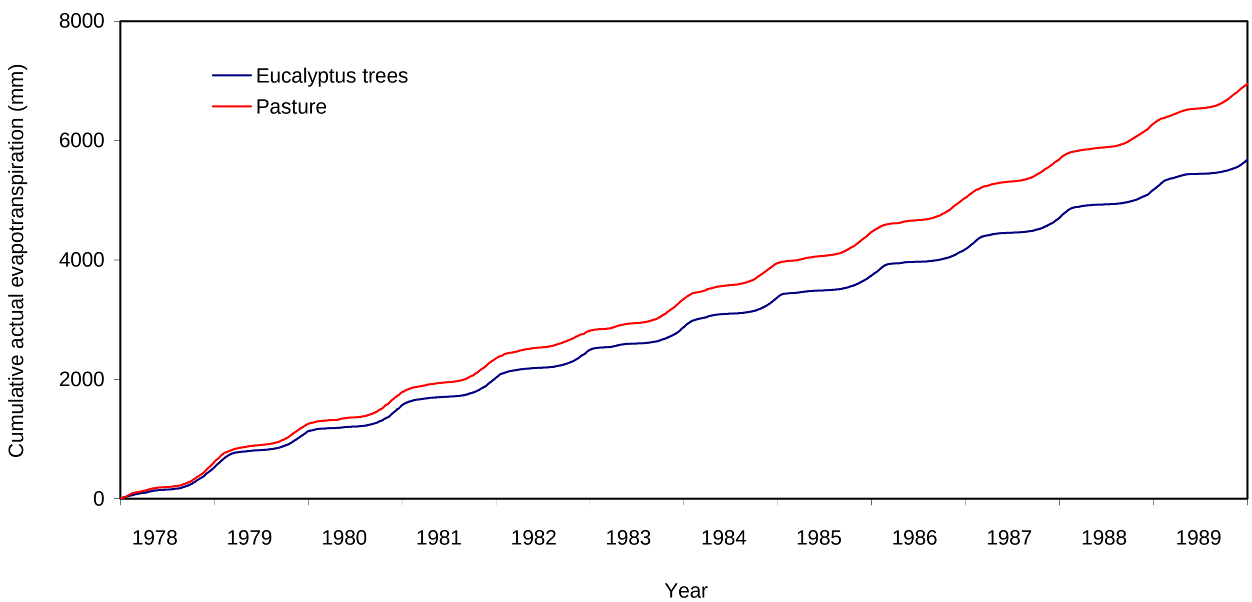


Figure 7. Cumulative actual evapotranspiration from HRUs containing pasture and eucalyptus trees for the calibration period, 1978-1989.

The source of the problem is attributed to two factors. Firstly, the incorrectly modelled LAI and biomass for the eucalyptus trees had a detrimental impact on the amount of actual evapotranspiration calculated from HRUs containing eucalyptus trees. The calculation of soil evaporation and plant transpiration, both of which are components of actual evapotranspiration, depend on daily LAI and biomass values. Modifications must therefore be made to the model to simulate the growth of mature eucalyptus trees much more accurately.

Secondly, it is apparent that the current values for the plant uptake compensation factor (EPCO) and the maximum canopy storage (CANMX), both of which influence evapotranspiration, are not entirely sufficient. The default value of EPCO (1.0) was applied to all HRUs regardless of the land use. In light of the findings presented here, it is not adequate to adopt the default value of EPCO for all land uses, given that pasture cannot access soil moisture from the same depths as trees can and therefore the water uptake rate of pasture is not as great as that of trees (Zhang et al., 2001). CANMX was left as 0 in this study because the CN method was used which "lumps canopy interception in the term for initial abstractions" (Neitsch et al., 2001). While curve numbers are adjusted for changes in soil moisture over time, they are not adjusted for canopy changes. Therefore it is considered acceptable to calculate canopy interception separately to account for canopy changes over time (J. Arnold, USDA, personal communication, 2003). Greater consideration will be given to these parameters in future applications.

Summary and Conclusions

This paper has presented the results of an application of SWAT to the Woady Yaloak River catchment located in the Corangamite region of southwest Victoria, Australia. The model was shown to predict annual and monthly runoff extremely well while the results on a daily time step were considered to be average. The soil moisture content of the A horizon, as predicted by the model, was shown to increase significantly in response to winter rainfalls and then become severely depleted over summer, a trend that was observed in a nearby research catchment where soil moisture levels were measured. The model had a tendency to overestimate baseflow during the winter period while at the same time underestimate interflow appreciably. This is very important because interflow is a significant contributor to streamflow in the catchment due to duplex soils being the dominate soil type of the catchment. The LAI and biomass of mature stands of eucalyptus trees cannot be simulated accurately at all by SWAT due to forced dormancy. It has also been shown that in the current calibrated version of the model to the Woady Yaloak River catchment, the amount of water lost through evapotranspiration in HRUs with pasture is greater than that for HRUs containing eucalypts. This is fundamentally wrong and highlights the need to consider all the major components of the water balance when calibrating SWAT instead of only streamflow predictions, otherwise fundamentally erroneous conclusions may be reached and consequently the management practices to be implemented could be seriously flawed.

The results achieved from this study were very promising even if some components of the water balance were not simulated adequately. Efforts will now be undertaken to address these issues so as to ensure the dynamics of the water balance are simulated more accurately. In some cases the source code will have to be modified to accommodate the new process descriptions that need to be incorporated into the model. This initial application of SWAT to the Woady Yalaok River catchment has revealed a number of beneficial insights into the operation of the model. It was also found that most of the required data sets were, in general, readily available and were sufficiently accurate for this modelling exercise. Provided that the necessary modifications are made to the model and that further rigorous testing is carried out, SWAT appears to have very good potential for being adopted as a management tool to predict the impacts of future land use change across the Corangamite region.

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Trace Element Levels in the Dubasari Reservoir of the Dniester River

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Abstract

The Dniester River, the main water artery of the Republic of Moldova, is a transboundary river with a total length of 1,352 km and common catchment area of 72,100 square km. The river is of great importance for a wide variety of uses, and it serves as a source of drinking water for about 10 million people in Moldova and Ukraine, facts which impose high requirement for its quality. This paper describes pollutants in the region, including industrial emissions and atmospheric relapses. The data refer to the severely polluted areas around the industrial activities in the Rezina-Rabnitsa zone. Trace elements investigated in this paper include Mercury (Hg) (II), Cadmium (Cd) (II), Lead (Pb) (II), and Copper (Cu) (II). Both dissolved and particulate forms of these trace metals exceed the level revealed in atmospheric depositions (fresh snow), which denotes the influence of anthropogenic factors in this content. In the neighboring soils of the industrial complex, the trace metal content of studied metals exceeds the background level from 2 to 11 times. Mathematical processing of data demonstrated that trace element contents in dissolved form in the case of Hg (II) and Cd(II)) have a ratio of $r = 0.95$-0.99, compared to the trace metal content in sediment and suspended particulate matter, respectively.

Introduction

The importance of water for living things is so evident, that it needs not to be insisted here. Major problems related to water pollution by trace elements may be expected following more intensive agricultural development, industrial wastewaters, sewage discharges, and urban runoff. Diffuse sources play a key role in trace element pollution of water-related ecosystems in Moldova.

Trace elements have become an ecotoxicological hazard of prime importance and ever-growing significance. Among the metals with high toxicity potential, attention must be focused on Mercury (Hg), Cadmium (Cd), and Lead (Pb) [1]. The content of these metals are regulated by the World Health Organization at the level of 1–50 mkg/l.

As a consequence, strong efforts to control trace metal levels in foods and drinking water are required. Scientific assessment is a key element of management programs, because it provides a method to estimate impacts on the state of the environment in the region.

The aim of this study was to evaluate the contents of trace elements in the Dniester River and the Dubasari Reservoir. The findings for Mercury, Copper, Lead and Cadmium are presented in this paper.

Materials and Methods

During 2000-2002, samples of water, sediment and soil were collected from three stations (upper, medium and lower parts), describing the Dubasari reservoir for all longitudinal distance. Samples were collected during expeditions in seven seasons (except winter). For each station, the content of both dissolved and particulate metal forms were determined, as well the content of trace metals in sediment and neighboring soils.

Water samples were collected manually, in polyethylene bottles, 30-50 cm under the surface stratum of water, with precaution to avoid inaccuracy of the data due to contamination. Some required pretreatment *in situ* (acidulation up to 0.2% HNO_3) has been done.

Snow samples were collected in non-industrial areas, far from highways, a few hours after snowfalls, from the upper stratum of 15-20 cm. Soil samples were collected from the stratum of 20 cm of non-disturbed soil (the average sample from five points distributed mutually perpendicular at 2-5m distance from each other).

Sediment samples were collected from the top 10 cm using tube-drags. The soil and sediment samples were dried at 20±1˚C (open air) and 105±3˚C respectively, crumpled up and sieved, and hermetically closed in a plastic container. The digestion was done for 0.1-0.2g aliquots (we withdraw the aliquot by inserting a narrow Teflon tube, thus sampling the total depth of the container), by adding 5-10 ml of bi-distilled water and 2.5 ml HNO_3+1ml $HClO_4$. Samples were heated with reflux at 95±3˚ C for 1.5-2 hours.

EAAS (Cu, Pb) and DPASV (Hg(II), Cd(II), Cu(II), Pb(II) methods were used to determine the concentration of investigated trace elements. The CV AAS method was used to compare the content of mercury for all samples, determined by DPASV, and a cylindrical carbon-fiber microelectrode (l=10 mm, d=30 mkm) was used as an indicator electrode. All reagents were of the quality grade Merck "pro analysis" or "suprapur". The "standard" metal solutions were Multi-element Synthetic Reference Material SRM water samples, and Standard Reference Material SRM-N 10-2-11b (sediment samples).

Statistical processing of results has been done for the probability equal to P=0.95.

Results and Discussion

The status of the environmental quality is an increasing preoccupation. One of the most exciting topics is the influence of trace elements and the effect of their presence for the environment.

The Dubasari reservoir, with a total length of 125 km, and a volume of 485 million m^3 represents an essential contribution to the formation of the Dniester River water quality. The more-or-less constant hydrodynamic regime makes it possible for a more accurate elucidation of the factors that influence water quality. One of the most important factors is the content of trace elements, which exercise a strong toxic impact upon living organisms [2].

The results of seasonal monitoring (2000–2002) have shown the maximal concentration of Mercury (II), Cadmium (II), Lead (II), and Copper (II) (dissolved + particulate forms) in waters between the upper and medium parts of reservoir. The Rezina-Rabnita industrial complex (consisting of two cement plants and one metallurgical plant, with an annual capacity of 4.4 million t/year of cement and 0.7 million t/year of steel), is located on both sides of the Dubasari reservoir in this zone. It is a potential source of trace element pollution.

Concentration of studied metals in the analyzed objects varies from 9 ng/l for Cadmium (II), in dissolved form, to 43 mkg/l for Lead (II), in particulate form. In the sediment, this domain is within the values of 36 ng/g for Hg (II) and 37 mkg/g for Cu (II).

To identify the anthropogenic trace element pollution in river water, the study of the impact of atmospheric precipitation (fresh snow) was carried out. Sampling took place immediately after snowfalls. The dissolved and particulate forms of investigated metals have been determined. All analyzed samples exceed, by 3-4 times, the maximum admissible level of Mercury, Copper and Lead in non-polluted waters. Both dissolved and particulate forms are approximately at the same level; this fact can be explained by the presence of suspended particles (dust) in the atmospheric precipitation of local or non local provinces.

The results obtained show a similarity between the content of metals independent of snowfall, a fact which demonstrate the influence of the nature of atmospheric depositions. The total content of studied metals in snow are significantly less than those in Dniester River water (Table 1). This fact makes it possible to draw the conclusion that the pollution of the Dniester River with Hg (II), Cu (II), Pb (II), and Cd (II) through atmospheric precipitation (transboundary pollution) is not significant. The relatively higher concentration of investigated metals in the Dniester River (except Cadmium) compare with those in fresh snow, and can be accounted for by local diffuse pollution sources.

Table 1. Comparative date of the content of trace elements in fresh snow and river water (Dubasari Reservoir, Dniester River)

Metal	Snow (n=5, P=0.95)			Water from the Dniester River (n=12, P=0.95)		
	Dissolved form, mkg/L	Particulate form, mkg/L	Total content, mkg/L	Dissolved form, mkg/L	Particulate form, mkg/L	Total content, mkg/L
Hg(II)	0.00 – 0.73 0.33	0.19 - 0.97 0.58	0.52 - 1.3 0.91	0.30 - 0.64 0.47	0.76 - 1.9 1.34	1.2 - 2.4 1.81
Cu(II)	1.1 - 3.2 2.2	0.0 - 5.0 2.0	1.0 - 7.0 4.0	1.2 - 7.2 4.2	0.3 - 3.9 2.1	3.3 - 9.3 6.3
Pb(II)	1.6 - 8.8 5.2	0.5 - 5.3 2.9	4.5 - 11.0 8.1	2.0 - 18 10	0.0 - 13 6.0	8.0 - 24 16
Cd(II)	0.00 - 0.1 0.049	0.011 - 0.069 0.040	0.036 - 0.14 0.089	0.022 - 0.040 0.031	0.021 - 0.075 0.048	0.052 - 0.11 0.079

The data from this investigation indicates a substantial growth of trace metal content in the river water when the concentration of suspended particulate matter is above 10 mg/L (the medium part of reservoir during summer 2000, and spring 2002 expeditions). This fact allows the identification of potential sources of pollution of the reservoir with trace elements. The polluting effect can be caused by the soil superficial layer with a high content of heavy metals which, as the result of natural factors and actions (wind and atmospheric precipitation) are transported to the aquatic basin.

The study of Hg (II), Cu (II), Pb (II) and Cd (II) in the soil (Figure 1) demonstrates that, as in the case of water, the concentration of heavy metals varies considerably in the same zone within a diameter of about 20 km that covers the Rezina-Rabnita industrial complex. The maximum content of analysed metals was detected in the close vicinity (1-5 km) of this complex. In the vicinity of this industrial complex, the Mercury and Cadmium content in the soil is 8 and 11 times higher, respectively, than the level registered in the lower part of the reservoir (Malovata station, situated 50km south), while Copper and Lead concentrations are about 2 times higher. The background levels of Cadmium and Mercury in the soil are less 1 mkg/kg, according to the registered concentrations of 3.3 and 2.8 mgk/g, respectively [3]. This concentration can be related to a medium level of pollution, according to the classification scale [4].

These data prove the influence of the industrial complex on the content of trace elements in the ecosystem. Taking into account the erosion process from the drainage basin, one of the purposes of this study was to estimate the influence of trace element contents from sediment on their concentrations in water, assessing whether or not these parameters have a linear interdependence.

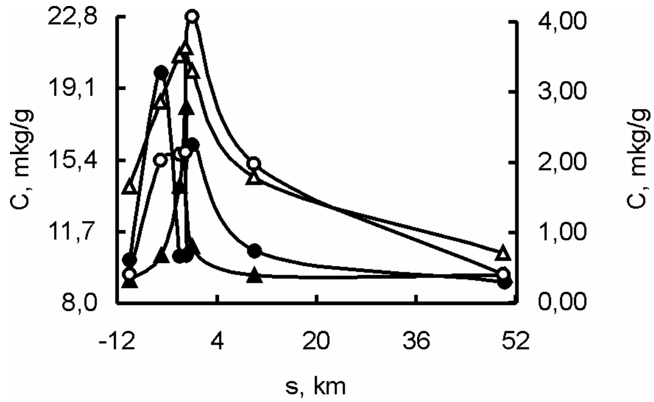

Figure 1. The trace element contents in soil (North – negative values; South – positive values) Cd(●)-(the ordinate axis is tenfold multiplied); Hg(▲)- right ordinate axis; Pb(○), Cu(Δ)- left ordinate

The sediments from the aquatic basins have a special impact on the biological and physical-chemical processes that occur in these ecosystems. To a great extent, it is due to their specific properties connected with their aggregation state and chemical composition. Sediments are less flexible to changes in the liquid phase, somehow attenuating them. Sediments can accumulate trace elements from the liquid phase, contributing to the latter's quality improvement as well as its elimination in this phase, thus worsening water quality. The direction of the heavy metal transition process depends on many factors, the most important of them being the physical-chemical composition of sediments, of the liquid phase, the metals content in sediments and the hydrodynamic regime of the aquatic ecosystem [5]. The hydrodynamic regime of the Dubasari Reservoir (the average velocity of the surface water layer flow is usually less than 1m/s) limits the distance to which the soil that penetrates into the basin under the influence of natural factors can be transported. It can be expected that the distribution of heavy metals from the sediment is similar to the values registered for the soil. The results of investigated metals dosing in sediments (Figure 2) confirms this supposition. Variation of trace element contents from sediments between stations is not as pronounced as in the soil. This could be explained through the attenuation effect caused by the flowing regime of the water in the basin. However, the maximum values of trace element content in sediments are registered in the same zone as they are for the water and soil, i.e. the zone that includes the Rezina-Rabnita industrial complex.

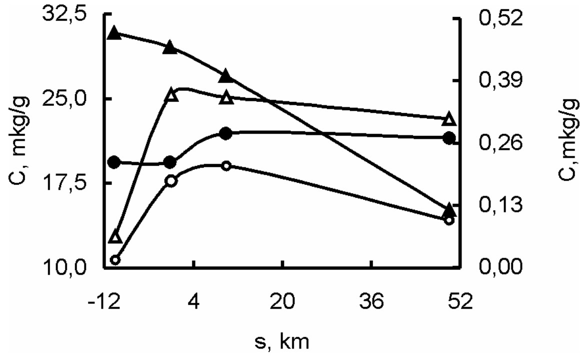

Figure 3. The trace element content in the bottom sediment of the Dubasari Reservoir Cd(●)- (the ordinate axis is tenfold multiplied); Hg(▲)- right ordinate axis; Pb(○), Cu(Δ)- left ordinate

The mathematical processing of data demonstrated that metal content in dissolved form has a ratio of r = 0.95 to 0.99 with its content in sediment and particulate form, respectively.

This investigation demonstrated unequivocally the predominant influence of the metal content in the sediment upon the content of this metal in the other forms.

A simple model has been developed to assess short-term prognostication of trace element content both in sediment and dissolved form. In the dry season, the predicted values correspond satisfactory with measured concentrations and confirm the negative impact of the industrial complex on trace metal content in the Dubasari aquatic ecosystem.

The utilization of the model for data interpretation in cases of abundant atmospheric precipitation, decrease the errors between measured and calculated values and denote conclusively that the polluted soil from the neighboring industrial complex are the main source of the heavy metal pollution of the Dubasari aquatic ecosystem.

The positive value of the parameter that describes the contribution of metal content from sediment on levels in dissolved form indicates that Mercury and Cadmium, the trace elements with the higher toxicity potential and higher content in neighboring soils, are transported downward from the top for all longitudinal reservoir directions. For Copper and Lead, this process is observed only downstream, which is explained by the low velocity of suspended particle sedimentation.

Conclusions

These studies show the highest anthropogenic enrichment factor for Mercury and Cadmium, the elements with the highest toxicity potential, in the neighbouring area within a radius of about 20km of the industrial complex Rezina-Rabnitsa, affecting the medium part of the Dubasari reservoir and the Dniester River. These waters are a source of drinking water for a population of 10 million people.

For the metal levels in dissolved form, an increasing influence of trace metals in particulate form is demonstrated. The influences of metal content from sediment on the level of trace metals in dissolved form practically are predominant for all reservoir longitudinal distance.

The elaboration and implementation of the strategy and tactic to better manage anthropogenic activities is required.

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Soil Erosion Evaluation and Multi-temporal Analysis in Two Brazilian Basins

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Abstract

The aim of this work, performed in the framework of a European Union Project (INCO-DC), was to evaluate the soil erosion in the Pantanal area, the largest wetland in the world (South-Central Brazil, Mato Grosso do Sul). The land use changes during the last 30 years in the highlands, in particular from native vegetation to agriculture and cultivated pasture, caused extended erosion processes, resulting in heavy sedimentation in rivers and streams, as well as in the occurrence of large gullies. Areas with high risk of environmental degradation were identified by the application of the SWAT model, by simulating different scenarios and foreseeing short-term and long-term evolution, by means of a multi-temporal analysis. The analysis was based on land uses related to 1966, 1985 and 1996 years, derived from digitizing and processing of topographic maps and satellite images; the digital elevation model (DEM) came from digitizing of topographic maps.

In this paper, the application of SWAT for two basins is presented: the first one (Rio Taquarizinho) is smaller (150,000 ha) and suffered more land use changes; the second (Rio Aquidauana) is bigger (1,520,000 ha) and less anthropized. The model simulations, supported by extended calibration using local data, gave satisfactory results and showed the importance of management practices. In particular it was found a high specific soil loss (about 40-50 t/ha) for a single crop versus strong reductions (2-8 t/ha) on areas with crop rotations. Similarly, a correct management of pasture areas resulted in decreases of specific soil loss (from 12 to 0.6 t/ha).

KEYWORDS: agriculture, basins, best management practices, environmental control, erosion, image processing, land management, land use, model calibration, multi-temporal analysis, Pantanal, pastures, satellite imagery, sediments, soil types.

Introduction

The present work was performed in the framework of an EU project (INCO-DC, 2000). Its aim was to evaluate the sediment load in the Pantanal area, the largest wetland in the world (South-Central Brazil, Mato Grosso do Sul, see Figure 1) during the last 30 years and to suggest territorial management guidelines.

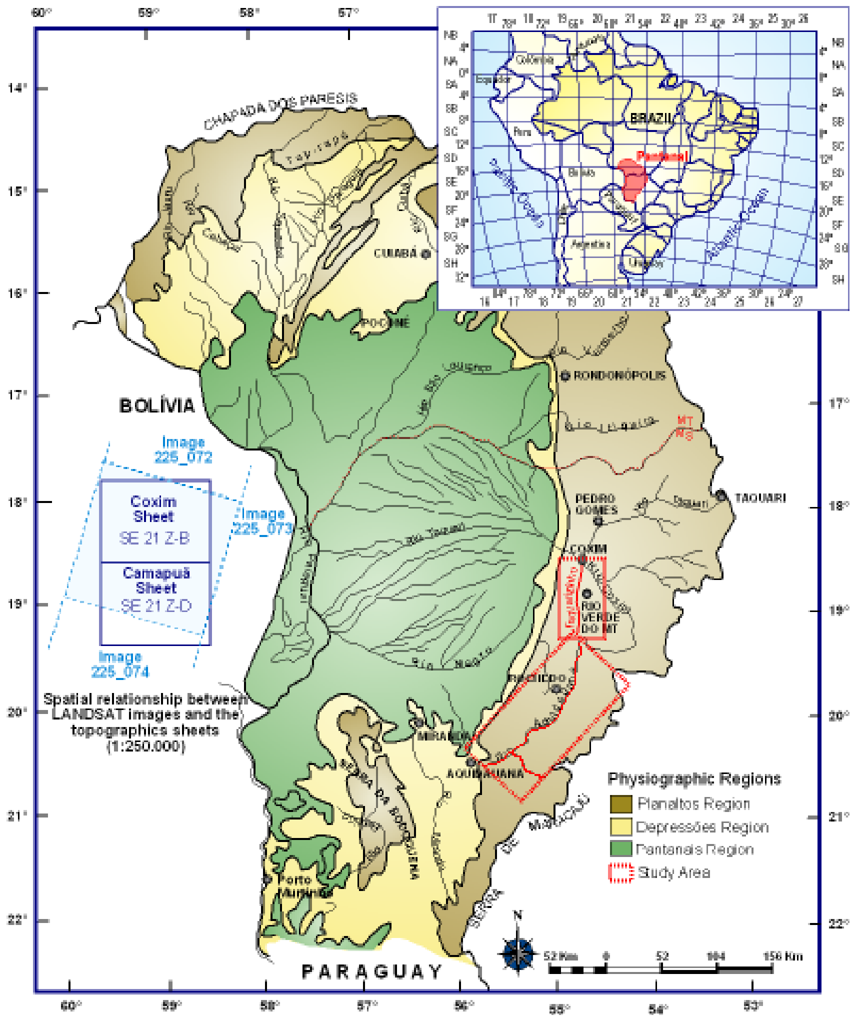


Figure 1. Study Area.

The land use changes in the highlands, in particular from native vegetation to agriculture and cultivated pasture, caused extended erosion processes, resulting in heavy sedimentation in rivers and streams in the plateaus surrounding the Pantanal (Planalto), as well as in the occurrence of gullies (canyons up to 1 Km long and 30-40 m deep). For this reason, two sample river basins in the Planalto area were studied, namely the Rio Taquarizinho (150,000 ha, highly anthropized) and the Rio Aquidauana (1,520,000 ha, little anthropized).

Input Data for SWAT Simulations

GIS data: The Digital Elevation Model (DEM) of the two basins was obtained by digitizing Brazilian topographic maps at a scale of 1:100,000 (based on aerial photos of the years 1964-1966). The maps provide elevation, hydrographic and land cover data, representing the oldest homogeneous land cover documentation for the whole study area. The maps were rasterized and georeferenced, and then elevation contour lines, spot heights and land cover were vectored in order to obtain the geographic databases of topography and land cover (year 1966). The DEM (with a 10 m resolution, improved for a correct delineation) was built by processing the database of topography through the TIN and "topogrid" procedures implemented in the ESRI ARC/INFO software.

Landsat 5 TM images of the dry season (July - October) of the years 1985 and 1996 were pre-processed through spatial registering to the topographic maps and topographic normalization based on the Lambertian reflectance model (ERDAS, 1982-1999) to reduce the difference in illumination due to the slope and aspect of the terrain. The land cover databases for the years 1985 and 1996 were created by performing the following steps: Landsat 5 TM image segmentation based on function of soil properties (in order to minimize the occurrence of land use classes having similar spectral properties), maximum likelihood classification of image segments, segment mosaicing, raster to vector conversion, accuracy assessment and photointerpretation check based on fieldwork data. The three land cover databases (1966, 1985 and 1996) were finally codified according to the E.U. CORINE land cover nomenclature (Heymann Y. et al., 1994) , then transcoded according to the SWAT land use database. Post-classification topological intersection allowed researchers to obtain the land cover multi-temporal data base and the statistics of changes from 1966 to 1985 to 1996.

The soil map and its vertical profile were taken from a Brazilian work (PCBAP, 1997). The soil types of the basins and their related coding are as follows:

AQa: Quartzose alic sandstone;
PVa: Yellow-red podzolic alic;
PVd: Yellow-red podzolic distrophic;
PVe: Yellow-red podzolic eutrophic;
LEa: Dark red alic latosol;

LRd: Red distrophic latosol;
LVa: Yellow-red alic latosol;
HGPd: Little humic “glei” distrophic;
HGPe: Little humic “glei” eutrophic;
Ra: Litholic alic;
V: Vertisol.

Agricultural data: On-site interviews of local agricultural organizations allowed set-up of the following site-related suitable management schedules for soybean monocrop, soy-soy-corn rotation and pasture, equal for both basins.

Rotation Soybean – Soybean – Corn (3 years)

Year 1-2

1st March	Pesticide application (insecticide)
20th April	Corn (Soya bean) harvest and kill
1st November	Tillage operation (plowing)
10th November	Fertilizer application
11th and 20th November	Tillage operation (harrowing)
21st November	Soya bean planting
6th and 20th December	Pesticide application (herbicide + insecticide)

Year 3

15th May	Soya bean harvest and kill
20th October	Tillage operation (plowing)
1st November	Fertilizer application
2nd November	Tillage operation (harrowing)
16th November	Fertilizer application
17th November	Tillage operation (harrowing)
18th November	Corn planting
28th November	Pesticide application (herbicide)

Meteorological data: Rainfall histories and statistical data were collected (and/or evaluated) for two weather stations within the basins. The statistical parameters were particularly difficult to evaluate (lacking official data), e.g. the parameters RAIN_HH and RAIN_6H (10-year frequency 0.5 and 6 h rainfall) were estimated by means of the following formula, commonly used in that area (T is the return time in years, t is the rainfall duration in minutes and the I is the rainfall intensity).

$$I = \frac{(43019)\,T^{0.55}}{(t+62)^{1.405T^{0.053}}}$$

Hydrology: To keep into account the hydrologic characteristics of the Planalto region, with an aquifer sustaining the streams, it was decided to set the deep aquifer percolation fraction (RCHRG_DP) and the threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN) to 0.

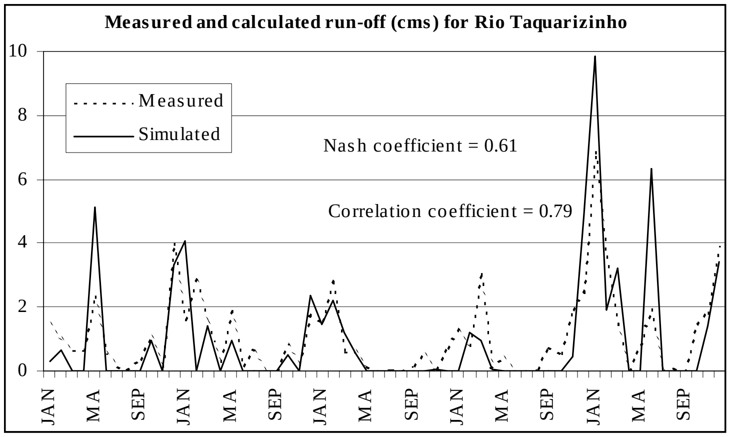
SWAT Calibration

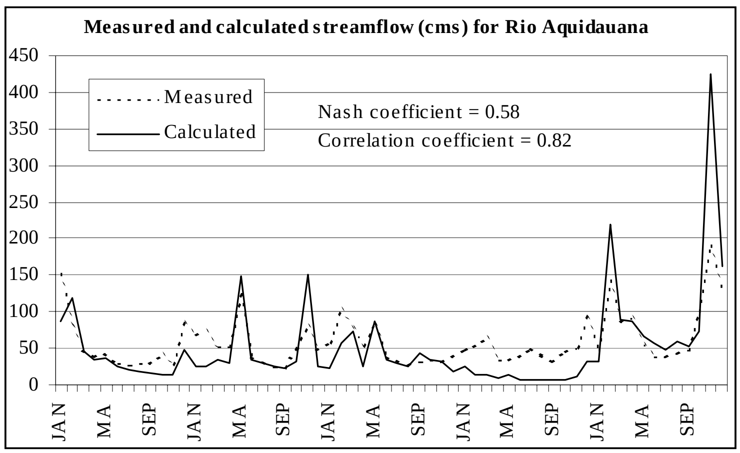
The calibration was performed in three steps:

Step 1: Run-off and total streamflow

1. Acquisition of daily total flow data from ANEEL (Agencia Nacional de Energia Eletrica, Report, 1996);
2. Use of USGS HYSEP software (Sloto R. A. et al., 1996) to separate run-off and base flow from total flow;
3. SWAT run and confrontation with HYSEP results (monthly averages, see Figure 2 below);
4. Use of the calibration tool to modify the following parameters: Curve number, available water capacity and soil evaporation compensation factor.

Figure 2. Confrontation between calculated and measured run-off and total flow.

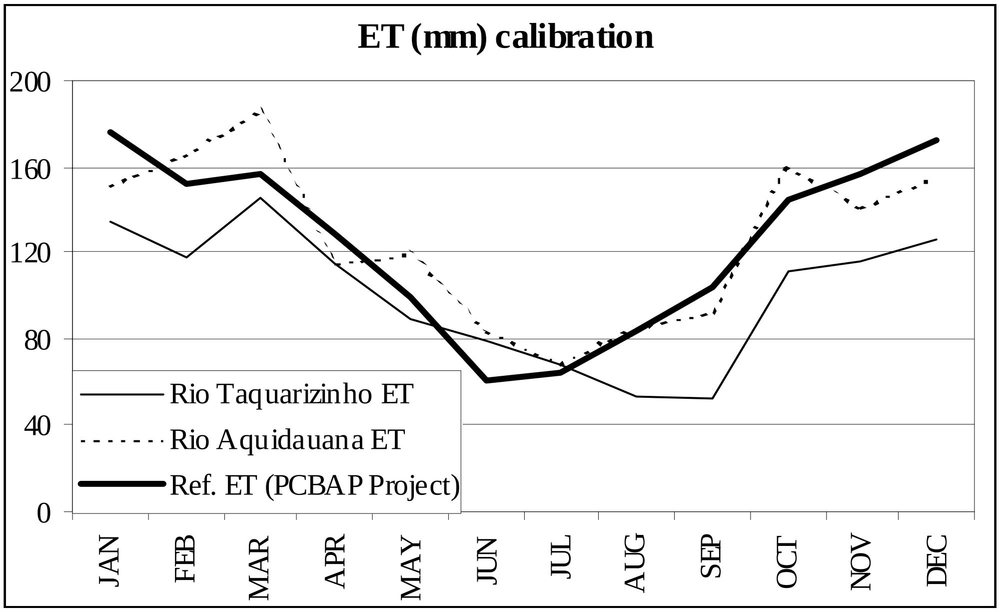




Step 2: Evapotranspiration (ET)

The PCBAP Project performed an evaluation of the monthly averages of ET for an area in the proximity of the basins so that values could be used for the confrontation with SWAT results (see Figure 3 below). The modified parameters were the groundwater “revap” coefficient (also influences run-off) and threshold depth in the shallow aquifer for “revap” to occur.

Figure 3. Confrontation between calculated and literature ET.



<u>Step 3: Sediment flow</u>

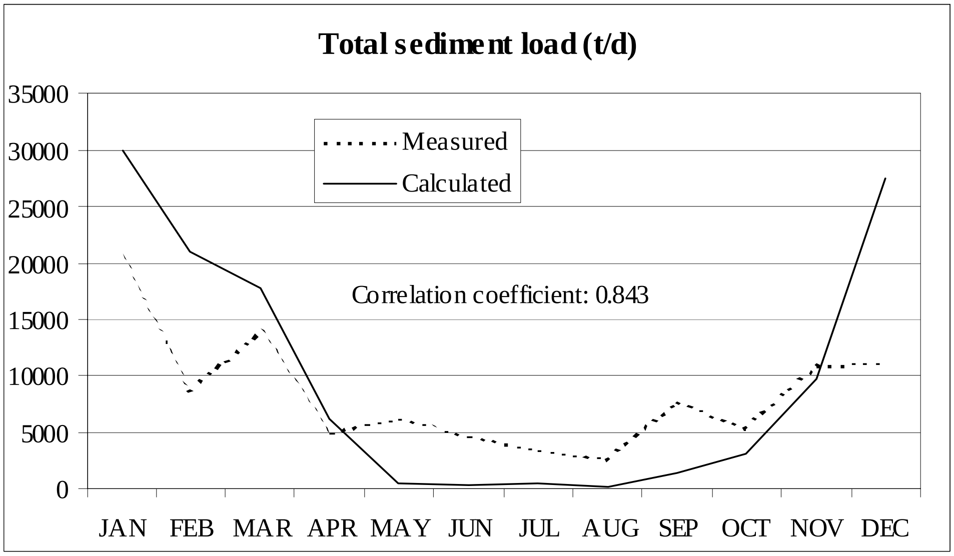
Due to lack of data two different methods were used for the basins.

For Rio Taquarizinho, the confrontation data were evaluated from literature measurements of sediment flow (Padovani C. R. et al., 1998; Walling D. E. et al., 1998) on similar watersheds with the following procedure:

1. Acquisition of literature data of sediments loads and stream flows in Rio Taquarì streams (period 1995-1997);
2. Calculation of coefficients a and b of the equation expressing the relation between *suspended* sediments loads (Qs, t/d) and stream flow (P, m^3/s): $\ln Qs = a + b \cdot \ln P$ using the above data;
3. Evaluation of the mean annual Rio Taquarizinho water flow at the outlet, by means of the conservation of the specific flow measured at an intermediate gauged station; calculation of the mean annual *suspended* sediment flow using the previous correlation (point 2);
4. Evaluation of mean annual total sediment load from the ratios "total load"/"suspended load" taken from the literature data at point 1.;
5. Confrontation with SWAT results;

For the Rio Aquidauana, the confrontation was made more straightforwardly with monthly averages reported in the PCBAP Project (see Fig. 4 below).

Figure 4. Confrontation between calculated and measured sediment flow for Rio Aquidauana.



For both basins, the parameters modified were those related to the sediment re-entrainment in channel routing phase.

SIMULATIONS AND MULTI-TEMPORAL ANALYSIS

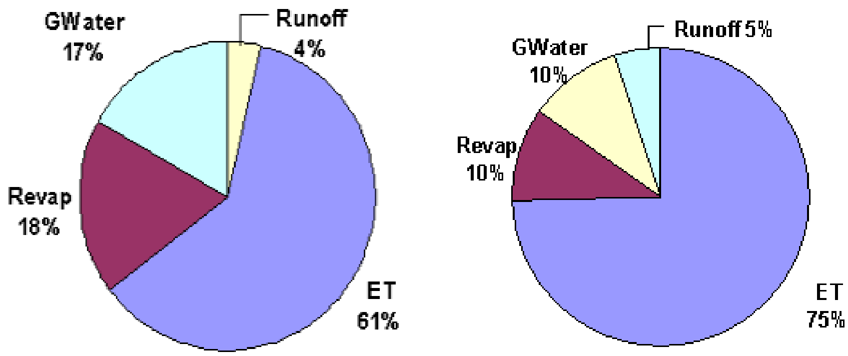
In simulations performed are summarized in Table 1 (* yearly averages).

Table 1 – SWAT Simulations

Basin	Subbasins	HRUs	Sim. Years	Rain (mm)*	Runoff (mm)*
Rio Taquarizinho	113	215	1969-1972	1325.5	22.0
		337	1981-1983	1439.0	60.3
		285	1993-1997	1296.8	50.8
Rio Aquidauana	184	467	1968-1972	1,264.9	50.5
		453	1978-1982	1,528.0	81.0
		434	1994-1998	994.8	26.7

The first result checked was the hydrologic balance that showed, in both basins, relatively high values for ET and revap (see Fig. 5). Further interviews with Brazilian researchers confirmed this situation.

Figure 5 – Hydrologic Balance: Rio Taquarizinho (left), Aquidauana (right).



The target of the multi-temporal analysis is to investigate some of the links between human-induced land use modifications and the soil erosion trend. It is important to stress and precisely define an important concept: as expressed by the USLE equation: The main factors influencing output parameters indicating soil erosion are the quantity and quality of rainfall (duration, intensity, etc.), and the coupling between soil types and land use. Obviously, they change from the various scenarios. That means that it is difficult to compare and say what is "best" and what is "worst." One cannot merely read the run-off and sediment output data and understand these complex relationships.

Some environmental variations associated with the climatic changes (the "greenhouse effect") can introduce further elements of uncertainty in the analysis, in particular for the meteorological data).

As an example, the greater amounts of runoff and the soil loss in the 1978-1982 period is strictly linked to the total amount of rainfall in this period. Conversely, their reduction in the 1994-1998 period is linked to the decrease of rainfall (see Table 2). So a simple comparison of parameters (runoff, revap, evapotranspiration, total soil loss) does not produce useful elements for a multi-temporal analysis for the reasons listed above.

Table 2 – Results of Simulations.

River Basins	Parameters	Simulation periods 1968-1972	1978-1982	1994-1998	1978-1982 l. u. 1996
Rio Aquidauana	Rainfall (mm)	1,264.9	1,528.0	994.8	1,528.0
	Runoff (mm)	50.48	80.98	26.70	87.75
	Total soil loss (t/y)	67,000	118,000	44,000	143,600
	Tot. stream flow (mm)	106.32	253.07	40.51	248.4
Rio Taquarizinho	Rainfall (mm)	1325.5	1439.0	1296.8	----
	Runoff (mm)	22.0	60.3	50.8	----
	Tot. soil loss (t/y)	28,280	94,330	75,640	----
	Tot. stream flow (mm)	159.5	337.4	219.6	----

Then, in order to have some clues on the correct interpretation of Table 2 data, it was decided to perform a test simulation, not necessarily conform to the reality for Rio Aquidauana, keeping the rain of the 1978-82 period and the land use of 1996. The examination of results (see Tab.2) allowed to hypothesize a growing trend for the total sediment load.

Figures 6 and 7 show the land use changes for the two basins in three simulation periods. The effect of the anthropization is clear: increasing of pasture (Brachiaria grass areas) and noticeable decrease of forested areas (FRSD, RGNB and RNGE).

Figures 6 and 7 – Land Uses Trends

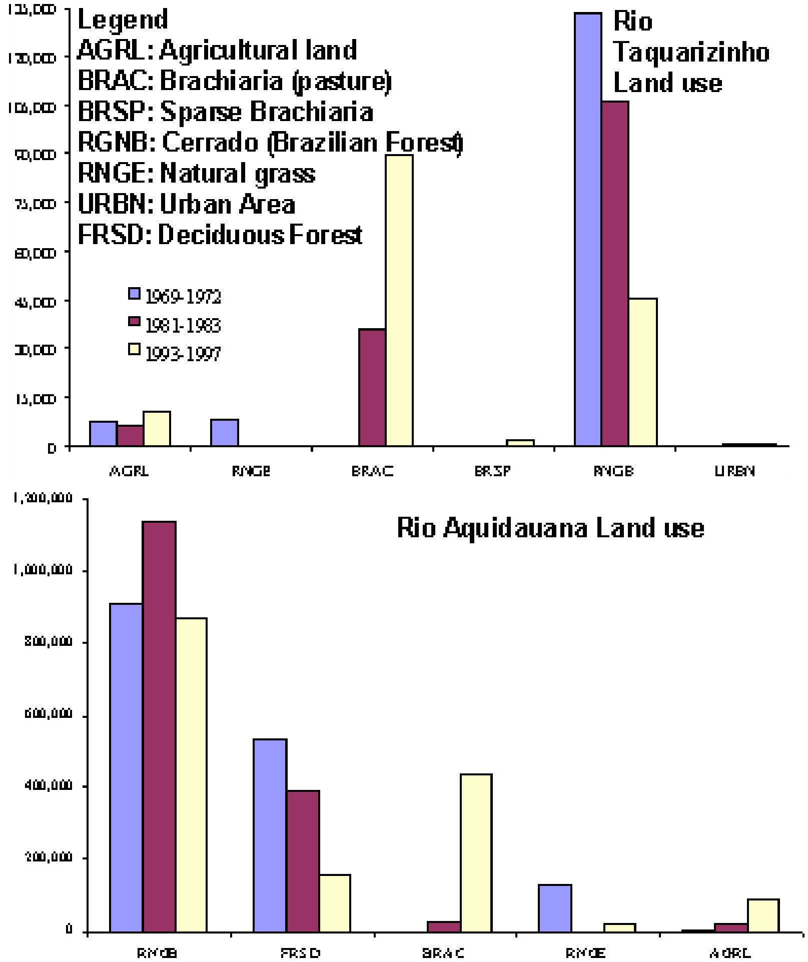


Table 3 shows the changes occurred in the simulation periods by aggregating the SWAT tabular data related to “anthropized” lands (namely agricultural and pastured lands) and the “natural” ones (namely forests and prairies):

Table 3 – Simulation Results.

		Land use Scenarios		
		1966	1985	1996
"Anthropised" Land Uses Rio Taq.	Surface (ha)	7,160	43,020	103,210
	Total soil loss (t)	309,672	488,774	467,705
	Specific soil loss (t/ha)	43.2	11.4	4.5
"Natural" Land Uses Rio Taq.	Surface (ha)	141,860	106,000	45,810
	Total soil loss (t)	18,686	542,471	31,693
	Specific soil loss (t/ha)	0.1	5.1	0.7
"Anthropised" Land Uses Rio Aquid.	Surface (ha)	3,014	48,222	572,846
	Total soil loss (t)	5,632	908,297	1,167,524
	Specific soil loss (t/ha)	1.9	18.8	2.2
"Natural" Land Uses Rio Aquid.	Surface (ha)	1,570,742	1,525,479	1,046,741
	Total soil loss (t)	2,472,388	3,315,230	656,492
	Specific soil loss (t/ha)	1.6	2.2	0.6

With the aid of the above table the following considerations were made:

Rio Taquarizinho:

- A significant decrease of natural areas from 95% (1969-1972) to 31% (1993-1997) of the total basin area.
- The deforested areas became mainly pasture areas (Brachiaria grass).
- The extension of the agricultural areas is relatively small, about 5% of the total basin area, with no significant variation in the three simulation periods, even if the agricultural lands migrated from PVe (the most erodible soil) to LEa soil types, with a consistent reduction of soil loss, also due to the change in agricultural management.
- In the period 1993-1997 the land use BRSP (sparse Brachiaria) takes into account that the pasture areas have lower spatial density, either because they are neglected or because the soils are not suitable for an optimal growing of that grass.

Rio Aquidauana:

- The “natural” areas gradually decrease from the 1968-1972 period, when they practically covered almost the whole basin to the 1994-1998 period when they are about two thirds of the basin extension. That can be considered an always increasing anthropization of the basin, most of which occurs from the second to the third simulation period. In particular the extension of the agricultural areas is relatively small: it varies from about 0.2% of the total basin area in the 1968-1972 period, to about 6% of the total basin area in the 1994-1998 period.
- The soil loss shows a noticeable increase already in the 1978-1982 period, in spite of the small anthropized surface, because of the agricultural activities are performed on soils highly sensitive to erosion (AQa soil type).
- In the 1994-1998 period it can be noticed that, for the first time, the anthropized section of the land (about one third of the total) causes a soil loss equal at almost the double of that coming from the “natural” lands.
- The deforested areas became mainly pasture areas (Brachiaria grass).

Conclusions

Recently in the Planalto (Boddey R. M. et Al., 1996) it was observed that Brachiaria pastures (that are increasing in area) are often degrading in productivity with time. Such a degradation and its causes are at present poorly described and understood and that, more than the deforestation itself, have a negative impact on the environment in terms of soil erosion.

The calculation results confirm that the erosion effectively increases with the decreasing of grass density. That may be prevented with the rotation of Brachiaria with legumes since that improves the fixation of nutrients in the soil (this practice is increasing).

The use of the model allowed to perform good estimations to evaluate the correct choice of soils and management practices.

We presented above two ways for describing simulation results in multi-temporal analysis. However, in order to try to describe a scenario of soil erosion and allow easier confrontations among different ones, further investigations are necessary, in our opinion. For instance, it would be useful to define some synthetic parameters, independent (as far as possible) from the natural phenomena (like rainfalls) and capable to lead to the determination of a threshold for a “sustainable” erosion both from the economic and environmental point of view.

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Modeling the Long-Term Impacts of BMPs in an Agricultural Watershed

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Abstract

Watershed management efforts often involve the use of hydrological modeling to estimate the water quality impact of agricultural activities. The use of best management practices (BMPs) are strongly recommended by federal and state governments in the United States to reduce the nutrient and sediment load leaving agricultural areas. While the immediate impact of these practices is fairly understood, the long-term impact is not. The Black Creek Watershed Project in Indiana, USA presents the authors of this paper with the unique opportunity to model the long-term impact of the best management practices. This paper presents the methodology used to determine the most appropriate technique for simulating grassed waterways, grade stabilization structures, field borders and parallel terraces using the Soil and Water Assessment Tool (SWAT). Preliminary SWAT results for the simulation of BMPs within the Black Creek watershed are presented.

Introduction

One of the first water quality demonstration projects to study the relationship between agricultural practices and the use of specific BMPs to improve water quality was the Black Creek Project (1973-84). Funded by the United States Environmental Protection Agency (US EPA) and administered by a group of Purdue University scientists, the project's purpose was to determine whether the most recent soil and water conservation techniques, if applied throughout the Black Creek, Indiana USA watershed, about 5000 ha in size, would improve the water quality of the surrounding waterways, including the Maumee River and Lake Erie. The project included educational outreach efforts, land treatment costs, and research to document project impacts, and estimated the effectiveness of various practices. The project centered on reducing the sediment and phosphorus that flowed into Lake Erie from the watershed. More than 44 structural and non-structural BMP types were implemented to monitor their ability to reduce phosphorous and sediment (Morrison and Lake, 1983).

Many of the BMPs implemented during the Black Creek Project (1973-84) are widely used for water quality protection today. The short-term benefit of these measures is well documented in published reports (EPA, 1973: Lake, 1977: Morrison and Lake, 1983). However, the long-term impact of these practices is not known. It would be useful to know if the short-term water quality benefits of these watershed management improvement efforts continue and if there are any long-term ecological responses that negate the short-term benefits of these measures. A present-day analysis of the watershed will quantify the long-term impacts of the Black Creek Project.

One of the main objectives to assess the BMP long-term impact is to: Test and improve existing computer simulation models to assess their capability and effectiveness in simulating and promoting past and current water quality BMPs.

Currently, many successful watershed management efforts involve the use of hydrological models to determine the impact a landowner's management scenario has on the water quality leaving a watershed. A more thorough analysis of possible solutions for curtailing negative water quality impacts is done with the simulation of BMPs in hydrological models. BMP simulation allows the user to predict and, to a certain extent, ascertain the direct impacts associated with the implementation of various BMPs. Simulation of BMPs in models has been commonplace for a while, but a standard BMP simulation protocol for SWAT has not been developed. A detailed depiction of appropriate BMP representation in SWAT is needed. The in-depth water quality studies and monitoring conducted during the Black Creek project and the present-day evaluation of a select group of practices provide the unique opportunity to model the Black Creek watershed and to simulate the effects BMPs have on the watershed. This paper proposes BMP representation techniques in SWAT for grassed waterways, grade stabilization structures, field borders and parallel terraces. The results of these BMP representations within SWAT as applied to the Black Creek watershed are discussed.

Literature Review

Adequate structural BMP simulation requires modification of model parameters to reflect changes occurring in the watershed due to the practice. Some hydrological models, such as ANSWERS and APEX, incorporate directly the impact of BMPs. ANSWERS uses the relationship between practices and its model parameters to represent BMPs, i.e. grassed waterways affect hydraulic conductivity, surface roughness, C factor and Manning's coefficient (Batchelor, 1994). A routine in ANSWERS simulates ponds, parallel tile-outlet terraces, grassed waterways and field borders (Beasley and Huggins, 1982). The routine permits the modeler to simulate the major functions of the BMPs, like trapping efficiency for ponds and parallel terraces and slope steepness adjustment for grassed waterways and field borders.

The APEX (Agricultural Policy/Environmental Extender) model, a daily time step model, can be used to evaluate various land management strategies including terraces, grassed waterways, and filter strips (Williams, 2000). Grassed waterways are simulated in APEX by entering channel dimension values, adjusting the channel cover factor and soil erodibility factor and modifying the conservation practice factor "P" for terraces and filter strips (Dybala, 2002).

Other models allow users to choose which parameters to modify. For example, filter strips are simulated in AnnAGNPS by increasing the roughness factor and adjusting the slope length to represent the strip length (Yuan, 2002). A study by Mostaghimi et al. (1997) simulated grassed waterways in AGNPS by modifying Manning's roughness coefficients and including 0 gully sources. Vache et al. (2002) simulated riparian buffers, grassed waterways, filter strips and field borders by modifying the channel cover factor and channel erodibility factor in SWAT to model the cover density and erosion resistance ability of the structures.

Santhi et al. (2002) used SWAT to model a watershed before and after BMP implementation. Grade stabilization structures were simulated by modifying the slope and soil erodibility factor. Filter strips were simulated using a program that simulates their ability to trap sediment and nutrients based on the strip's width. Riparian forest buffer areas were simulated with crop growth and management parameters and at times, these areas were modeled similar to filter strips.

Methods

BMP simulation parameters to modify were chosen by reviewing published literature pertaining to BMP simulation in hydrological models and considering the hydrologic and water quality processes simulated. The selected BMP model parameters were reviewed with members of the SWAT development team, Jeff Arnold and Raghavan Srinivisan, to determine the final list of parameters to modify for BMP representations in SWAT. Next, a list of values to use for the short-term and long-term conditions was compiled. Lastly, three separate SWAT runs were performed for the short-term condition of grassed waterways, parallel terraces and without BMPs to get a general estimate of the impact each practice type had on the nutrient and sediment loads leaving the watershed. The SWAT run was performed using a 30m National Elevation Dataset (NED) DEM (digital elevation model), 1978 land use data, SSURGO soils data, and SWAT simulated weather data. Calibration, validation and sensitivity analysis was not performed for the preliminary runs presented in this paper. The SWAT runs were conducted to observe solely the impact of the BMPs in the watershed.

Results

A list of parameters to modify for each practice was compiled as well as the parameters values for reflecting the perfect condition (immediately after BMP implementation) and current condition of the practice. This information was discussed with Jeff Arnold and Raghavan Srinivisan to obtain the final parameters and appropriate values to represent the BMPs. The list of parameters presented to Arnold and Srinivisan is provided in Table 1, and comments for appropriate representation of the practices are provided in Table 2.

Table 1 SWAT Parameters Recommended for Modification for BMP Simulation.

Practice	Parameters Suggested to be Modified for Practice Simulation
Grassed Waterway	CH_COV: Channel cover factor
	CH_EROD: Channel erodibility factor
Grade Stabilization Structure	CH_S2: Average slope of main channel along the channel length
Field Border	CH_COV: Channel cover factor
	CH_EROD: Channel erodibility factor
Parallel Terrace	USLE_P: USLE support practice factor
	SLSUBBSN: Slope length

Table 2 Comments from Arnold and Srinivisan about BMP Simulation Parameters

Practice	Comments
Grassed Waterway	1. Primarily affects the cover factor of a channel.
	2. Manning's n will probably increase, so this value should be modified as well when simulating grassed waterways.
	3. When simulating, look at grassed waterway as a buffer.
Grade Stabilization Structure	1. May want to use the depth of the structure and land elevation to get the actual slope reduction.
	2. If structure is not performing well, may want to possibly add sediment as point source in SWAT.
Field Border	1. May want to use the filter strip equation in SWAT that calculates the trapping efficiency by assuming the buffer is in good condition and asks for the buffer width.
	2. Can modify CH_COV and CH_EROD as long as field border does not overlap with a grassed waterway in the same subbasin.
Parallel Terrace	1. Include modification of the curve number to model the terrace's effect on runoff.

Black Creek watershed BMPs were assumed to be in good condition for the historical scenario, or short-term impact of the practice immediately after implementation. All practices were assumed to be in good condition and fully functional. Parameter values used for the short-term impact are shown in Table 3. Multiple BMPs in a single subbasin were simulated by assigning one practice in the subbasin to a certain land use or hydrologic response unit (HRU) and the other practice to another land use or HRU. Preliminary model results for the runs incorporating the BMPs are presented in Figures 1-3. SWAT was run for 10 years (1970-1979), but the years of interest for the short-term impact of the practices is 1975-1978 as shown in the graphs.

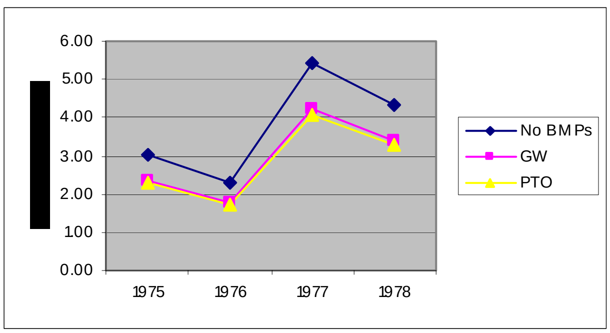
The long-term impact of a practice will be modeled based on current condition scores assigned to a subset of practices in the Black Creek watershed. This will be done with an evaluation tool developed to compute the present day condition and functionality of a practice based upon comparison to initial design parameters and physical inspection (Bracmort, 2003). Evaluation tools were developed for grassed waterways, grade stabilization structures, field borders and parallel terraces based on the characteristics found to be the most important to the long-term functionality of the practices, USDA NRCS design standards, and recommendations from experienced conservationists (Bracmort, 2003). The evaluation tool rates BMPs on a 3-point scale, whereby a score of 3 is indicative of a practice that is fully functional and still meets its original design intentions and a score of 1 is indicative of a practice that no longer performs as intended. In total, 33% of the conservation practices randomly selected for evaluation no longer exist (Bracmort, 2003). The condition score means in descending order by BMP type were grassed waterways, field borders, grade stabilization structures and parallel terraces. This suggests that grassed waterways and field borders may have a longer impact on water quality than grade stabilization structures and parallel terraces.

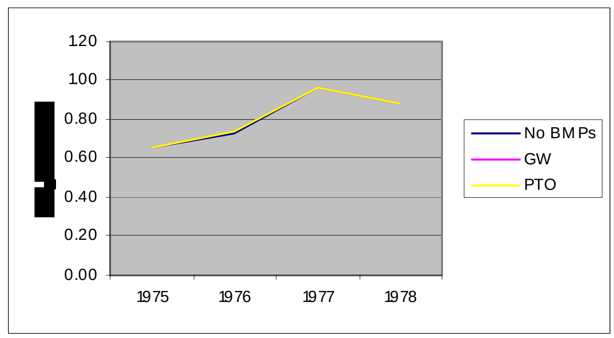
For the current condition BMP simulations, parameter values will be modified to match the condition score assigned to each practice. An explanation of how the parameters will be modified for grassed waterways and terraces assigned a score of 3 (good), 2 (fair) and 1 (poor) is presented in table 4. Similar measures will be followed for the current condition simulation of field borders and grade stabilization structures.

Table 3. Parameter Values Used to Determine Short-Term Impact.

Practice	Parameter Values
Grassed Waterway	CH_COV = 0, CH_EROD = 0.02, CH_N2 = 0.24
Field Border	CH_COV = 0, CH_EROD = 0.02, CH_N2 = 0.20
Parallel Terrace	SLSUBBSN = reduce slope by 75%, USLE_P = 0.1, CN = 77
Grade Stabilization Structure	CH_S2 = reduce by 75%

Figures 1-3 Predicted Yearly Sediment, N0$_3$ and Organic P Loading Graphs for 1975-1978.





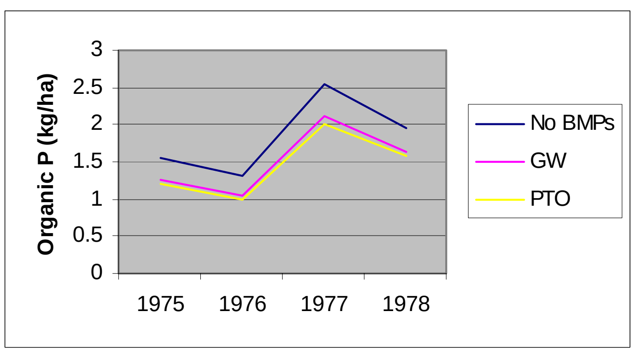


Table 4 Parameter Values Used to Determine Long-Term Impact

Condition Score	Practice Type	Parameter Values
3 - Good	Grassed Waterway	Assume good cover, a low erodibility rate, and assign Manning's N according to the vegetation of the waterway.
	Parallel Terrace	Assume the slope length is reduced by 75% or more, the conservation practice factor reflects a low sedimentation factor, and curve number is approriate for the area of interest .
2 - Fair	Grassed Waterway	Assume fair cover, a moderate erodibility rate, and assign Manning's N according to the vegetation of the waterway.
	Parallel Terrace	Assume the slope length is reduced by 50%, the conservation practice factor reflects a moderate sedimentation factor, and curve number is approriate for the area of interest.
1 - Poor	Grassed Waterway	Assume poor cover, a high erodibility rate because of the poor cover, and assign Manning's N according to the vegetative cover of the waterway.
	Parallel Terrace	Assume the slope length is reduced by 25%, the conservation practice factor reflects a high sedimentation factor, and curve number is approriate for the area of interest.

Conclusion

A method was devised for simulating grassed waterways, grade stabilization structure, field borders and parallel terraces in SWAT. Practices are simulated by modifying parameters that have a direct impact on the watershed as influenced by the practice. Preliminary model runs suggest that grassed waterways and parallel terraces reduce the sediment and organic phosphorus load leaving the watershed. The model runs indicate that grassed waterways has a slightly larger impact than that of parallel terraces. The BMPs seemed to have no effect on reducing the amount of NO_3 leaving the watershed. It should be mentioned that placement of the BMP and the number of BMPs implemented within a subbasin can greatly affect the output results.

The BMP simulation method presented in this paper will be pursued further in the near future for two sub-watersheds within the Black Creek watershed after SWAT calibration, validation and sensitivity analysis has been performed. SWAT model runs will include simulations for grassed waterways, grade stabilization structures, field borders and parallel terraces to determine the practices' short-term and long-term impact. An explanation and discussion of the BMPs and the suggested changes in parameter values will be explored in greater detail in the full version of this paper.

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Application of the SWAT Model in a Decisional Framework for the Caia Catchment, Portugal

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Abstract

We will describe the implementation and application of the SWAT model to the Caia River catchment in Portugal. The Caia catchment is one of the study sites in the European MULINO project (MULti-sectorial, INtegrated and Operational) decision support system (DSS) for sustainable use of water resources at the catchment scale. The MULINO project aims to develop a DSS for application to six case studies (in Italy, Portugal, Romania, Belgium, and the UK). The 780 km^2 Caia River catchment is located in a region of South Portugal, the Alentejo, near the border with Spain. A reservoir created by the Caia dam stimulated (over the last 30 years) the conversion of the agricultural system from rainfed farming to intensive irrigated production, with the total irrigated area now encompassing 72 km^2. In this catchment, agriculture is competing with other sectors for the use of water, rendering the management of water quantity and the preservation of water quality very significant issues.

After describing the way in which the available data for the Caia region was used to parameterize the SWAT model and the decisional context for the study, the way in which the hydrological model can be used to provide support for the DSS is investigated. A decision support system provides a user, such as a policy maker or other stakeholder in a given watershed, a set of tools to set up and analyze the data relevant to a decisional process in an easy and efficient manner, taking into consideration the interplay between social, economic and physical factors. The hydrological model in our case represents one of the physical components, providing the levels of contamination in soils or the streamflow at the catchment outlet in response to various scenarios such as land use or climatic changes. We will illustrate the use and the performance of the SWAT model in generating alternative scenarios, such as comparing the catchment's surface, soil and stream water distributions under single dam (current configuration) and multiple dam (possible future configuration) hypotheses and under different release rules proposed by the model.

KEYWORDS: Watershed, hydrologic modeling, dicisional context, decision support systems

Data Elaboration and Model Setup

Climate data

A Mediterranean climate characterizes the region although its distance from the sea accentuates some climatic features such as temperature extremes. The average annual rainfall and evapotranspiration are respectively 500-600 mm and 400-500 mm (Hargreaves method) while the average annual temperature is around 16° C. For the climatology of the basin, the available data is represented by monthly values of precipitation (mm), maximum and minimum temperature (°C), and insolation (number of cloudless days per month). This monthly data, supplied by the Portuguese Hydrological Survey for the period 1960 to 1990 for 17 gages located within the watershed, are not in a form compatible with the SWAT model, which requires either actual daily values or averaged monthly data obtained from multi-year records. In this second case, which corresponds to our situation, it is however necessary to calculate a set of statistical parameters such as the probability of a wet day following a dry day in any given month or the average number of days of precipitation in a month. To estimate these statistics, we used a dataset of daily values recovered from literature: the NCEP-NCAR analyses (the National Center for Environmental Prediction and the National Center for Atmospheric Research, respectively). These daily datasets for precipitation, temperature, and solar radiation were considered representative of the entire Caia basin (equivalent to one gage for the whole watershed). From these time series it was then possible to calculate the statistics related to precipitation, maximum and minimum temperature, and solar radiation. In order to improve the spatial distribution of this basin-scale information, the extracted parameters (e.g., average number of days of precipitation in a month) were combined with the observation data for the 17 gages (e.g., the measured cumulative rainfall for each month), so that a weather generator database is effectively linked to each of these gages. To summarize, by means of this procedure we can produce the weather generator input file that contains the statistical data needed to generate representative daily, monthly, and yearly climate data for the basin.

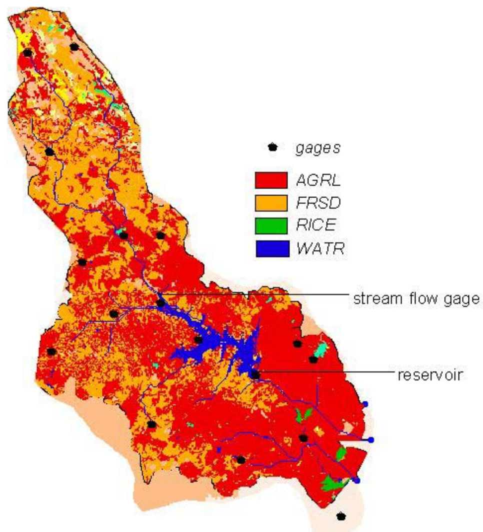


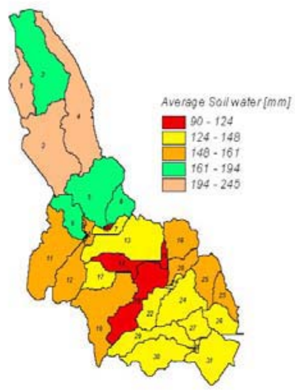
Figure 1: The Caia land use map with the location of the climate gages, the streamflow gage within the watershed, and the reservoir.

Topographic, land use, and soil data

The delineation and the topographic characterization of the watershed was obtained from a digital elevation model (DEM) with a resolution of 100 m derived by interpolating a 1:25000 topographic map with 10 m contours. The average elevation of the catchment is 334 m and the terrain is gently sloping (0-5%) except in the upper reaches where slope angles can be as high as 35%. The Caia catchment was subdivided into 32 sub-basins based on a threshold area of 1100 hectares. The stream network was refined to add an outlet corresponding to the streamflow gage situated within the watershed (the area drained by this outlet is about 30% of the entire catchment). The land use characterization of the watershed was made by aggregating the classification of a more detailed CORINE map at 100 m resolution. The resulting land use classes are: 56% “generic agricultural land” (AGRL), 31% “deciduous forest” (FRST), 5% “mixed forest” (FRSD), and 3% “water” (WTRN). As shown in Figure 1 agricultural production is concentrated in the southern portion of the catchment, and consists of rice, maize, tomato, and other crops. A single soil class for the entire catchment is being used in this first phase of the work, in anticipation of a detailed soil map that can be converted to the SWAT classification. The main soil characteristics reported into the related database are a percentage of clay, silt and sand respectively of 10, 30 and 60, corresponding to a sandy loam (USDA classification) , while for the soil depth we hypothesized a single layer of 1m.

Hydrological data

The streamflow gage located within the watershed provides a set of monthly discharge values for the period 1960 to 1990. This set of data was divided into two 15-year series, with the first half (1960-1974) used to calibrate the model and the second (1975-1990) used to assess the reliability of the calibration. The calibration procedure was carried out referring to average annual conditions only, and without observations that would have allowed separation of surface runoff and base flow components from the discharge hydrograph. In the future, it will be necessary to assess the validity of applying the calibration results to the whole catchment based on streamflow data for only 30% of the catchment. Ideally a gaging station should be added to the outlet of the entire Caia watershed.



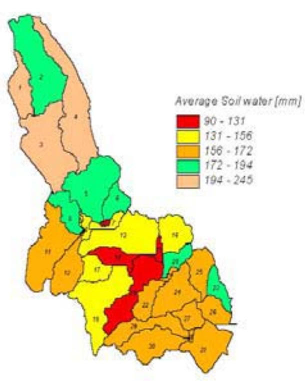


Figure 2. The Caia soil water content distribution generated from the SWAT model for different scenarios: nonoperational reservoir (left) and operational reservoir (right) combined with the auto-irrigation module.

Decisional Context for the Caia Study

In the Caia catchment multi-purpose water management is a necessity. Although the main water use is associated with agriculture (91.2%), which is also the main land use in the region, there are two other significant water uses in the catchment: industrial (8.7%) and public supply (0.1%) for two municipalities. Furthermore, water uses such as those related to recreational activities and ecological interests are relevant from a socio-economic viewpoint. The decision context to which the tools (SWAT model and DSS) are applied is a demand management problem. The basic steps of multicriteria decision analysis as implemented in the DSS are as follows. The decision process starts with problem structuring, during which the problem to be solved is explored and available information is collected. The possible options are defined and criteria aimed at assessing their feasibility are identified. This is the interaction phase between the DSS and SWAT. In the next step, the performance of the options is scored and an analysis matrix is constructed. The scores are transformed to values on a uniform scale so that the assessment can be made in a standardized manner . Finally, a sensitivity analysis evaluates how robust the selected option is to eventual bias or small changes in preferences expressed by the decision maker.

Scenario-Generaiton for the DSS

Once a satisfactory calibration was obtained, we focused on the entire watershed (including the dam) and generated scenario simulations representing different water management practices as suggested by the DSS analysis matrix. As an example, Figure 2 compares the results of a simulation whereby two different options are selected. The left figure shows the soil water distribution of the Caia catchment under climatic input only. As a result we find that the southern part of the basin is characterized by lower values and that the spatial distribution of this output variable is in accordance with that of the rainfall. Indeed, the upland northern reaches of the catchment normally register higher annual rainfall. From this base case we can evaluate the influence on the soil water content of applying an irrigation program to the downstream area from the dam (right plot in Figure 2). For this simulation the auto-irrigation module in SWAT was selected, specifying the reservoir as the source of irrigation water and the “generic agricultural land” and “rice” as the irrigated land use classes.

In terms of interaction between the SWAT model and the DSS, one of the main problems is to define how the information extracted from the time series output provided by the model can be transformed and integrated into the analysis matrix of the DSS, and how to take into account differences between distributed (soil water content) and point (streamflow discharge) quantities. One possibility being currently studied involves the consideration, according to the criteria defined in the DSS, of average, maximum, minimum, or standard deviation values computed from time series of the point or integrated model output variables. As concerns distributed outputs, in order to obtain a single value we can apply a multi-step procedure. We can consider for each subbasin the model result, and then evaluate the weighted average for the area of interest, which can be (for the example presented) above the irrigation perimeter south of the dam. In this way we obtain an element xij of the decision matrix that indicates the performance of an option aj (e.g., operational dam) evaluated in terms of a decision criterion cj (e.g., the soil water content of the area of interest resulting from the switch from rainfed farming to intensive irrigated agricultural production).

Conclusions and Future Work

We are investigating the performance of the SWAT model as a support tool (e.g,, scenario generator) in a decisional context, focusing primarily on the water balance as affected by different irrigation practices. Our interest is also in improving the manner in which the SWAT model and the DSS interact, and in this regard an already existing "hydrological model" menu within the DSS can probably be elaborated into an interface to SWAT, once the level of post-processing in SWAT (to derive appropriate indicators, for example) and the hydrological information required by the DSS for its analysis matrix are compatibly identified. Finally, given the importance of water quality problems (e.g., nitrate levels in groundwater) for the Caia catchment, future efforts will be devoted to coupling the water balance studies currently underway to solute transport modeling, and to extending the Caia DSS to consideration of various water quality issues.

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Modeling Diffuse Pollution at a Watershed Scale using SWAT

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Introduction

Diffuse sources are responsible for the majority of the nutrient pollution in agriculturally intensive watersheds. Understanding the movement of water and associated pollutants is therefore very crucial for maintaining the environmental well-being of such watersheds. Conceptual and physically based mathematical models offer a sound scientific framework for watershed analyses of water and pollutant movement. These models, after extensive calibration and validation, have proved to be efficient and effective tools for evaluating movement of sediment and nutrients under various agricultural management practices (e.g., Santhi et al., 2001). The objective of this paper is to describe initial results of applying the Soil and Water Assessment Tool (SWAT) model to the Raccoon River Watershed located in west central Iowa, to help identify which alternate management practices or land use changes can potentially help mitigate water quality problems of the region. Results are presented for the calibration and validation of the streamflows for the watershed, both on an annual and a monthly basis. Initial uncalibrated results are also presented for the SWAT sediment and nitrate predictions at the watershed outlet.

Materials and Methods

The SWAT model is a long-term, continuous simulation watershed model. It operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields. The model is physically based, computationally efficient, and capable of simulating a high level of spatial details by allowing the division of watersheds into smaller subwatersheds. Major model components include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management. In SWAT, the watershed is divided into multiple subwatersheds, which are then subdivided into unique soil/land use characteristics called Hydrologic Response Units (HRUs). Flow generation, sediment yield, and non-point source loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, or reservoirs to the watershed outlet. Detailed descriptions of the model components can be found in Arnold et al. (1998).

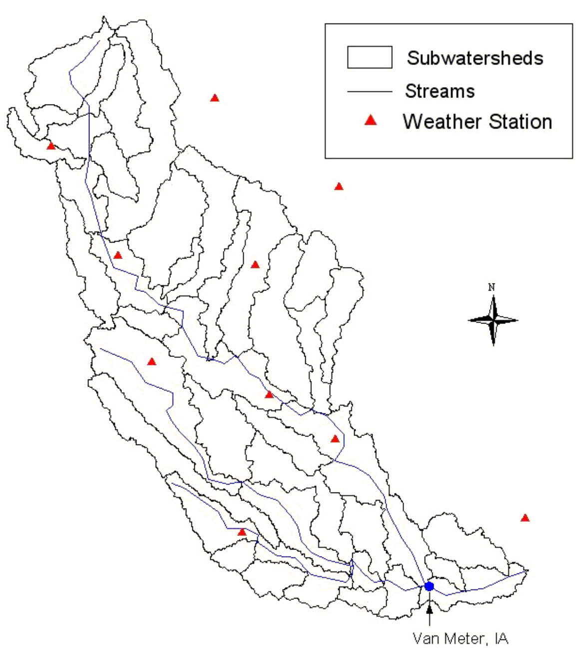


Figure 1 Raccoon River Watershed and delineated subwatersheds for the SWAT analysis.

The Raccoon River Watershed encompasses approximately 9,500 km^2 of prime agricultural land in west central Iowa (Figure 1). The Raccoon

River is the primary source of drinking water for more than 370,000 residents in Des Moines and other central Iowa communities. The watershed historically has been one of the highest nitrate-yielding watersheds in United States due to the following characteristics: high organic matter soils, 75% of the land in row crops (mostly in corn and soybeans), a concentration of animal-confinement units, and a high percentage of land drained by subsurface drainage tiles. These conditions of the watershed cause high nitrate movement to subsurface tiles or nitrate losses via overland flow, which both ultimately contribute to elevated nitrate concentrations in the Raccoon River.

Basic input data required to set up a SWAT run are topography, weather, land use, soil, and management data. Topography data were obtained from the U.S. Geological Survey in digital format at a resolution of 90 m (USEPA, 2001). Then the SWAT ArcView interface (AVSWAT) was used to develop SWAT input files for the watershed. A total of 38 subwatersheds were delineated; the boundaries follow the boundaries of 12-digit watersheds, which are subwatersheds within the larger 8-digit Hydrologic Cataloguing Unit (HCU) watersheds described by Seaber et al. (1987). Weather data (daily precipitation and temperature) was collected from 10 climate stations located in or near the watershed (http://www.ncdc.noaa.gov/). Information on missing data and other weather information such as relative humidity, solar radiation, and wind speed were generated by the model's built-in weather generator. Land use, soil and management data were obtained from the Natural Resource Inventory (NRI) database (http://www.nrcs.usda.gov/technical/NRI**)** and other data sources. The NRI is conducted by the Natural Resources Conservation Service (NRCS), a U.S. Department of Agriculture (USDA) agency, in cooperation with the Iowa State University Statistical Laboratory. The NRI data are spatially identifiable by polygons, which are obtained by overlaying three spatial layers: 8-digit HUCs, county boundaries, and Major Land Resource Area (MLRA) boundaries. The sampling design guarantees that inferences at the national, regional, state and multi-county levels are statistically reliable. The NRI information was extracted at an 8-digit watershed level (the Raccoon River Watershed is comprised of two 8-digit watersheds). Based on landuse, soil and management information, a total of 294 HRUs were created that were aspatially located within each 8-digit HUCs. Then available land use maps were used to locate the aspatial HRUs in the most probable locations. For example, urban areas are placed in locations where land use maps suggest they should be present. Table 1 lists some information of the input data.

Table 1 Input information on the Raccoon River Watershed.

<table>
<tr><th>Land use categories</th><th>% of watershed</th><th colspan="2">Tile in the Watershed</th></tr>
<tr><td>Continuous Corn</td><td>1</td><td colspan="2" rowspan="2">Tiled area = 40% of the watershed</td></tr>
<tr><td>Corn/Soybean</td><td>65</td></tr>
<tr><td>Corn/Corn/Soybean</td><td>7</td><td colspan="2" rowspan="2">Total N and P application (kg)</td></tr>
<tr><td>Corn/Corn/Alfalfa</td><td>3</td></tr>
<tr><td>Pasture</td><td>9</td><td rowspan="2">Fertilizer</td><td>N = 74,133,733</td></tr>
<tr><td>Bermuda grass</td><td>3</td><td>P = 8,891,720</td></tr>
<tr><td>Urban area</td><td>10</td><td rowspan="2">Manure</td><td>N = 3,353, 399</td></tr>
<tr><td>Forest area</td><td>2</td><td>P = 1,398,928</td></tr>
</table>

Measured data on streamflow, sediment and nitrate on Raccoon River are available at Van Meter (http://www.umesc.usgs.gov/data_library/sediment_nutrients/sediment_nutrient_page.html) from 1978 to 1994. The first 3 years were considered as an initialization period, the next 10 years (1981-1990) were used to calibrate SWAT, and the final 4 years (1991-1994) were used for the SWAT validation. The coefficient of determination (R^2) and Nash-Sutcliffe simulation efficiency (E) were used to evaluate the model predictions.

Results and Discussion

Measured streamflow data of 1981-1990 were used for the calibration of SWAT model. In the calibration procedure, baseflow was separated from surface flow for measured streamflows using an automated digital filter technique (Arnold and Allen, 1999). The technique estimated the baseflow to be about 65% of the streamflow for the Raccoon River Watershed. Model parameters were adjusted from the AVSWAT initial estimates within acceptable ranges to achieve the desired proportion of surface runoff to baseflow. Reducing the curve numbers (CNs) by 8% and the available soil water capacity (SOL_AWC) values by 0.04 mm resulted in a proportion of 60% baseflow and 40% surface runoff on an annual basis. The calibration yielded a good agreement between measured and predicted annual streamflow (Figure 2) with a strong correlation as indicated by R^2 of 0.95 and E of 0.93. A time-series plot of monthly streamflows (Figure 3) indicates a good correspondence with R^2 equal to 0.79 and E equal to 0.79.

Figure 4 shows the annual and monthly comparisons of measured and predicted streamflows for the validation period (1991-1994). In the validation process, the model was run with without changing the input parameters that were set during the calibration process. The statistical evaluation of the predicted streamflows yielded an R^2 of 0.93 and E of 0.86 for the annual predictions, and an R^2 of 0.88 and E of 0.86 for the monthly predictions. Overall, the model was able to predict the Raccoon River streamflow very well.

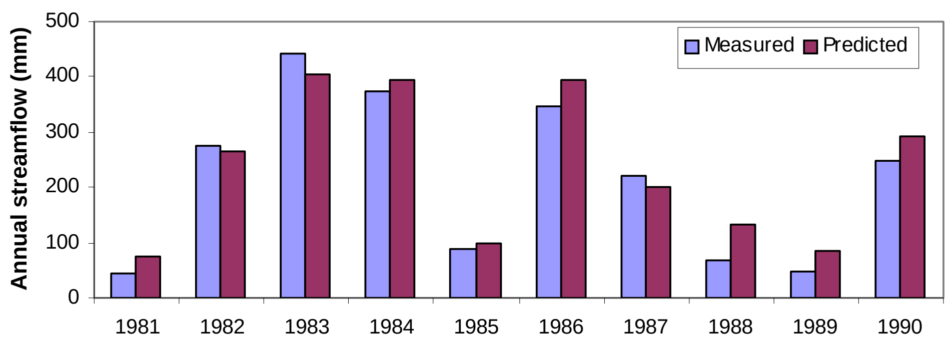


Figure 2 Comparison of annual streamflows at Van Meter for the calibration period.

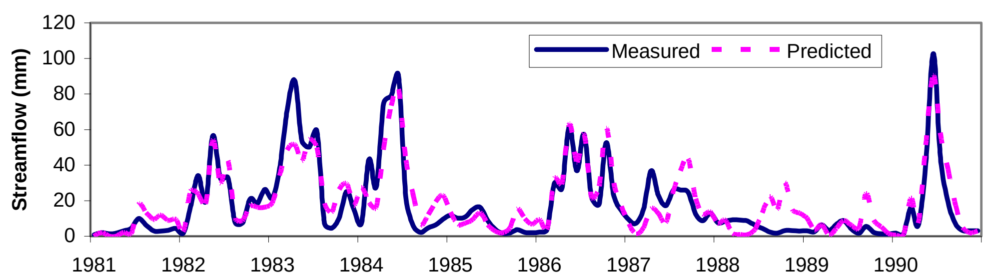
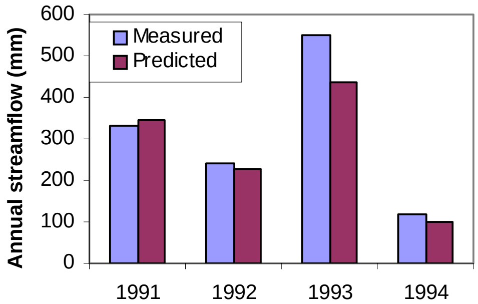


Figure 3 Comparison of monthly streamflows at Van Meter for the calibration period.



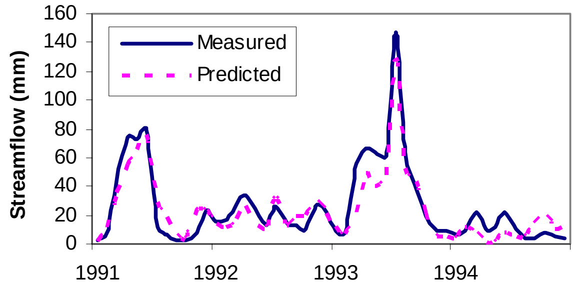


Figure 4 Comparison of annual and monthly streamflows at Van Meter for the validation period.

Initial results are also presented here for the sediment and nitrate loadings. Figure 5 shows the time series plots for both the uncalibrated predicted and measured monthly sediment loads at Van Meter. The predicted peak monthly periods matched the corresponding measured peak periods well. There is a general tendency of overprediction, especially during the low-flow periods; however, the pattern follows trend of flow prediction very well. In general, the results show that the SWAT model was reasonably successful in predicting the sediment load in the watershed even without any calibration. Figure 6 shows the uncalibrated time-series plot of nitrate load at Van Meter. In general, the model is not predicting nitrate very well, except in 1990. However, the model is accurately tracking the general trend of the nitrate losses. Further research is being conducted to improve the nitrate load prediction, including insertion of reservoirs and point source inputs and improved data on fertilizer rates.

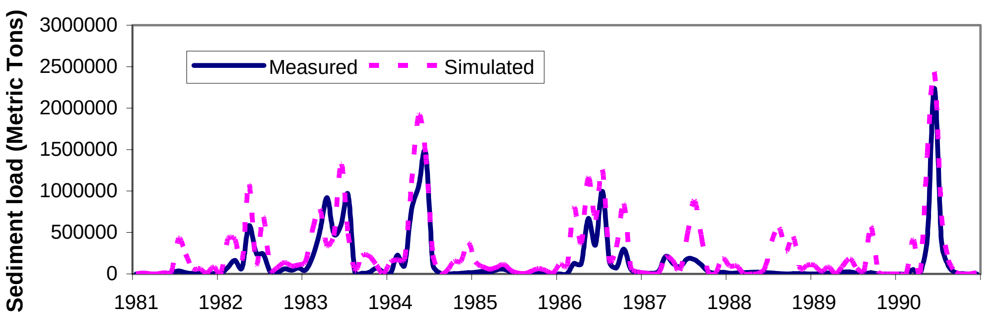


Figure 5 Comparison of monthly sediment yield at Van Meter.

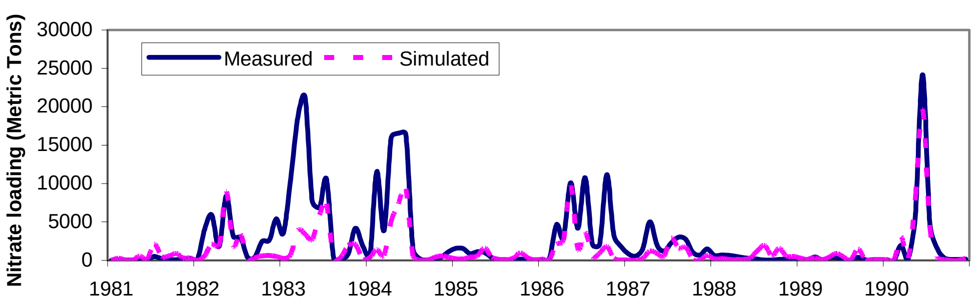


Figure 6 Comparison of monthly nitrate loadings at Van Meter.

Conclusion

The SWAT model was applied to the Raccoon River Watershed which is located in west central Iowa. The model was calibrated for the flow and initial results are presented for the sediment and nitrate loadings in the watershed. The model was found to predict flow and sediment very well, and further research is being carried out to improve the nitrate predictions. Successful calibration of SWAT for nonpoint sources in the watershed will provide further insight as to which management and/or land use strategies could potentially help mitigate water quality problems in the region.

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Modelling Pollutants in Runoff from the Colworth Experimental Catchment

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Introduction

Pesticides reach water sources in either dissolved or bound form, posing health risks to human beings and aquatic species. The greatest contribution to the overall pesticide pollution of waters comes from agriculture (Bach et al. 2001). Important risk and management decisions regarding control of such pollution are made based on rough estimates of agricultural pollution, which do not consider interaction between climate, crop soil and hydrology (Thorsen et al. 1996). Collecting data and conducting field experiments to assess this kind of pollution is becoming prohibitively expensive and so there is a need for appropriate prediction tools. Accurate representation of the processes responsible for transport and transformation of pesticides is crucial to obtain desired results. Based on a review of available models, the Soil and Water Assessment Tool (SWAT) was selected for predicting the environmental fate of pesticides for our study area. The following criteria were considered for the review.

1. capability for application to large catchments
2. capability for interface with a geographic information system (GIS)
3. proper representation of hydrological and contaminant transport processes
4. data requirements
5. availability of the model and user support

Study Area

The study area is located in Sharnbrook, Bedfordshire, U.K. (in an area bounded by National Grid References 495000, 263000 and 499000, 263000). The total area is about 142 ha. The predominant soil series is Hanslope, consisting of a clay loam soil over stony, calcareous clay. A group of eight fields forming approximately half of the catchment area is directly controlled by Unilever, and a rotation of wheat, rapeseed oil, grass, beans and peas is grown. All eight fields are drained by means of tiles.

Data Availability

About four years of data are used for the hydrological modelling. Sub-daily rainfall (at 30 min interval) and daily maximum and minimum temperature data were recorded for the catchment. Wind speed, solar radiation and dew point data were downloaded from British Atmospheric Data Centre web page for the Bedford station. Management operations carried out in the catchment were obtained from Unilever along with the date and type of operation. Rates of application of fertiliser and pesticides were also obtained from Unilever for the entire span of simulation. Recorded streamflow values at the catchment outlet were available from Oct. 1999 to Dec. 2002 at 30 min interval.

Our Requirements

The amount of pesticide loss via runoff water is a complex function of rainfall timing, the hydrologic and soil characteristics of the field, and the chemistry, formulation and persistence of the chemical itself (Wauchope & Leonard, 1980). Reasonably accurate modelling of pesticides is possible only if the predicted streamflow values are matched with observed values. To develop acceptable simulations in hydrological modelling, it is essential to properly simulation the processes driving the water balance. The simulation of crop growth and evapotranspiration were analysed critically because they are the major drivers of water balance. Necessary modifications were introduced within and outside the model to meet these requirements.

Calibration and Cross-Calibration

Hydrological modelling was carried out from 01-09-1999 to 09-12-2002. The period from 01-09-1999 to 23-10-1999 serves as a warm-up period for the model. Data from 24-10-1999 to 31-12-2000 were used for calibration and the remaining data for validation. There was a problem with the rain gauge for two months from 05-06-2002. For analysis, only results until 31-05-2002 are considered. For the sake of completeness, the remaining data up to 09-12-2002 is used in the simulation. The two seasons considered for calibration and validation were hydrologically very different (wet and dry). Hence it was decided to try cross-calibration of data as well, to determine the best way of modelling streamflow and pesticides. In cross-calibration the data available between 24-10-1999 and 31-12-2000 is used for validation as well as warm up for the model (Figure. 1).

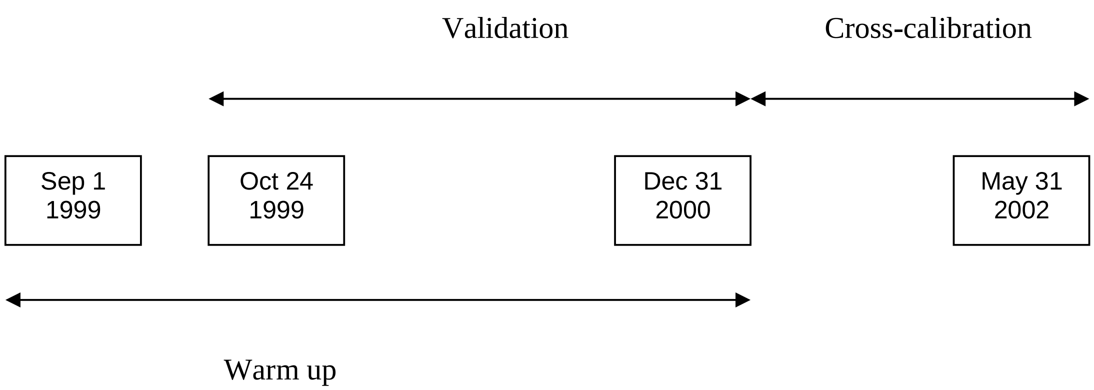

Figure 1 Cross-calibration calendar.

The United States Department of Agriculture Natural Resource Conservation Service (NRCS) Curve Number method and Green and Ampt infiltration method are available in SWAT for rainfall-runoff modelling. Both of them were used in this study, along with Hargreaves and Penman-Montieth evapotranspiration methods in four different combinations. Many parameters in SWAT are sensitive to streamflow. Hence it was decided to vary parameters in a sensible way, covering the whole range in a few steps. Three ranges were considered for each parameter: low, medium and high values. The values for parameters were varied one at a time covering all the different possible combination of parameters. Sensitivity analysis, calibration and cross-calibration of the model were done together in one modelling run using a semi-automated calibration setup. The calibration setup called AUTORUN is developed using FORTRAN and PERL script. It copies all the input files required to run the SWAT model in a separate directory, reads the different combinations of parameters (given), runs SWAT for every combination of parameters and calculates model performance and breakdown of water balance components.

Results and Discussion

Among the different possible combination of parameters, the combination which gives the best model performance is selected in every calibration and cross-calibration scheme based on model performance evaluation criteria. For evaluating model performance, percent bias (PBIAS), persistence model efficiency (PME), Nash-Sutcliffe efficiency and daily root mean square estimation criterion were considered. Apart from model performance, the breakdown of different components of the water balance was also checked. Water balance, simulation of crop growth (Figure. 2) and evapotranspiration were checked for every hydrological response unit (HRU). Simulated crop growth of winter wheat is shown in Figure. 2 in the form of leaf area index and biomass growth for one HRU. The pattern and extent of crop growth is comparable with observed values in the field and published data. Simulated evapotranspiration values are also realistic. For hydrological modelling, the NRCS curve number method with Hargreaves evapotranspiration method turned out to be the best possible option for calibration. The same result also was obtained in the case of cross-calibration. Therefore, the curve number method with Hargreaves evapotranspiration method was used for modelling pesticides.

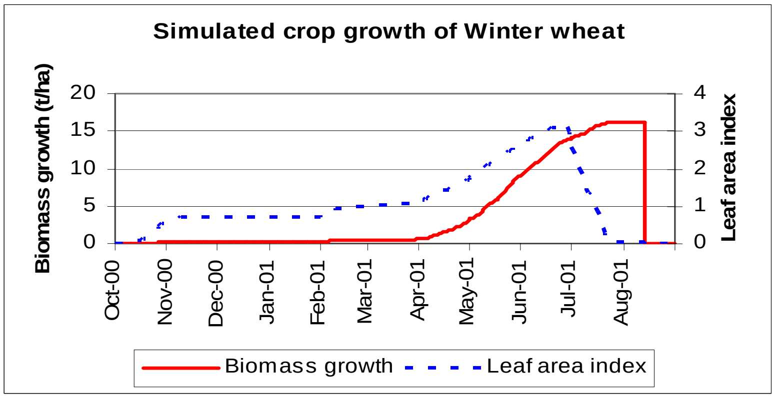

Figure 2.

Table 1 Performance evaluation of hydrological modelling.

Period	Method	PBIAS	PME	NSE	DRMS
Oct. 1999 to Dec. 2000 (wet conditions)	Calibration-Validation Validation-Cross-calibration	14.84 26.20	57.35 53.38	61.20 57.59	0.80 0.84
Jan. 2001 to May 2002 (dry conditions)	Calibration-Validation Validation-Cross-calibration	-3.15 12.39	51.46 53.18	59.57 61.00	0.74 0.72

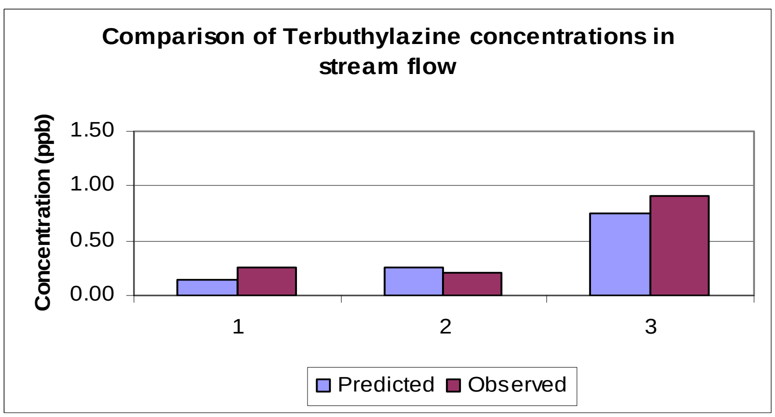

Figure 3.

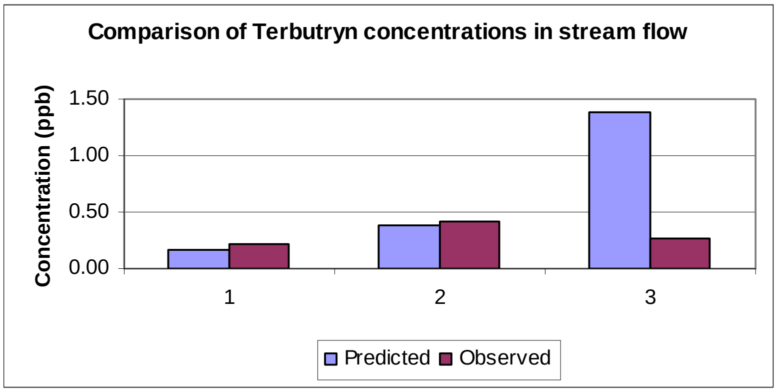

Figure 4.

Model performance evaluation criteria are listed clearly for two hydrologically different periods of the simulation for two different ways of calibration namely calibration-validation, and validation-cross calibration (Table 1). From the table, it is evident that all the performance evaluation criteria show better values during the period when the model is calibrated and vice-versa. The calibration-validation method is noticeably better during Oct. 1999 to Dec. 2000 and marginally worse during Jan. 2001 to May 2002. However the validation-cross-calibration is noticeably worse during Oct. 1999 to Dec. 2000 and only marginally better in Jan. 2001 to May 2002. Therefore, the right choice is the method that gives noticeably better performance. i.e. calibrating the model with data from Oct. 1999 to Dec. 2000 and validating it with data from Jan. 2001 to May 2002. In other words, better results can be obtained if we calibrate the model with wet season data than dry season data. This statement can be generalised after further testing for different catchments.

Modelling was carried out for many pesticides using mean values of soil half-life and soil adsorption coefficients. Because of the limited set of data, calibration was not done separately. Observed representative pesticide concentration values are available for a few runoff events. The predicted pesticide concentration values were worked out using a similar strategy to that used in field monitoring and compared with observed values (Figure. 3 and Figure. 4). Predicted Terbuthylazine concentration values were very close to observed results. In the case of Terbutryn the predicted concentration values are comparable with the observed values. However, the concentration of Terbutryn was over-estimated for the third event. The timing and quantity of streamflow predicted by SWAT was correct for that particular runoff event. Use of soil specific half-life and adsorption coefficients for the pesticide modelling might have eliminated this problem.

Conclusions

1. Calibrating SWAT for wet conditions gives better results than calibrating for dry conditions.
2. The curve number method can be used to simulate streamflow under United Kingdom conditions
3. SWAT adequately simulates streamflow with simultaneously correct simulation of processes controlling water balance
4. SWAT can be used as a tool to understand pesticide behaviour.

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Phosphorus Lake Loads from Basin Land Use: Proposal for a New Simple Evaluation Method

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Abstract

The general aim of this work is the assessment of agricultural, non-point nutrient sources and related control methods, principally based on agricultural land management. In particular, the focus of this paper is phosphorus (P) that is mobilized from agricultural land and bound to sediment. The experimental site (the Lake Vico basin, Central Italy) was consequentially selected because P is the major environmental problem in this basin, since agricultural land use became more intensive 30 to 40 years ago.

The quantitative evaluation of P load at a basin scale and related landscape classification to assess areas of higher risk is a management problem. The aim of this paper is to illustrate an easy method to contemporarily satisfy the simple approach and the interpretation of complex environment and anthropogenic interactions.

Introduction

The nature of non-point source pollution (NPS) is diffuse in space, intermittent in time and deeply related to land use, not only from a loads point of view (principally, nutrient and pesticide exports from agricultural land), but also from the system vulnerability point of view: climate, soils, topography or presence of landscape structures (buffer systems such as riparian vegetation, hedges and wetlands that intercept sediments and runoff or denitrify water). This means that only very long time, detailed and expensive monitoring could be sufficient to manage environmental concern from NPS.

First of all, the identification of high risk areas or “hot spots” is fundamental (Schoumans et al., 2002), and requires the knowledge of a series of natural and anthropogenic factors: topography, meteorology, hydrology, soil characteristics, crop type and management. In consequence, a models approach is fundamental and the literature offers a number of different approaches to estimate watershed nutrient losses to waters. Reliable estimation and prediction of diffuse pollutant exports at a basin scale is fundamental to an understanding of the water quality of aquatic systems and, thus, is critical to the development of strategies to limit impacts in water bodies.

Focusing on phosphorus, the main environmental concern of the study area, various methods are available to evaluate P export, from the simple export coefficients methods (Dillon & Kirchner, 1975; Beaulac & Reckhow, 1982) to the sophisticated physical (dynamic) models.

In any case, land use planning and related modelling (at a field or basin scale) are the key factors in control strategies. But land managers do not always have the possibility to validate models because this can be time-consuming and expensive. Due to the insufficient monitoring of the system or the lack of spatially distributed input data and scarce calibration data, the accuracy of model results often depends on the experience of the user (McKee and Eyre, 1999).

So, it could be vain to pursue the complexity of non-point sources behaviour by complex dynamic models, while it could be more effective to highlight land use and to investigate its correlation with nutrients export by simple methods. Land managers need fast results on a variety of cases and this means that it is strategic to compare to land use scenario comparisons and land information systems. These methods require less sophisticated model applications.

The proposed method is a compromise between detailed simulations and simple approach to evaluate phosphorus export into a lake.

The experimental site is the Lake Vico basin, in Central Italy (Figure 1). It is optimal to investigate NPS, because land use impact is almost all due to intensive agriculture, while urban and industrial settlements are negligible or absent. Land cover is prevalently forest (about 55%) and agriculture (about 45%). Phosphorus and nitrogen concentration have sharply increased in the past 30 to 40 years (Franzoi, 1997) in concomitance with land use change in the 1960s and 1970s, when past agricultural practices gave way to the present practices of intensive hazel orchards (Leone & Ripa, 1998).

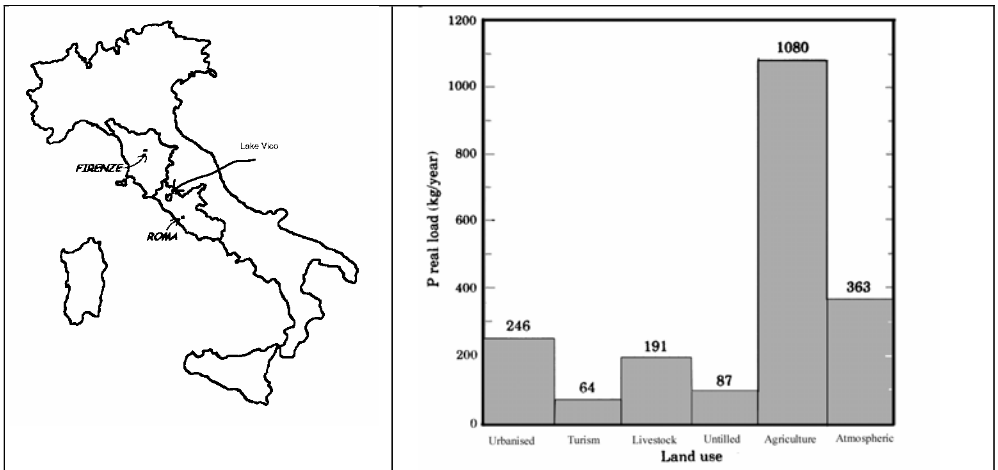

Figure 1: Lake Vico and its loads evaluation by simple export coefficients.

Materials and methods

First of all, the suitability of a field scale best management practice (BMP) has been evaluated. It consists in leaving herbs (weeds) under hazelnut trees to protect soils against erosion. This practice has been adopted for some years and is economically supported by the 2078/92/CEE arrangement. This scenario has been compared with conventional practices, which left bare soils to facilitate mechanized nuts harvesting. This practice exposed soil to heavy erosion and, contemporarily, phosphorus and nutrient levels in the lake increased.

The SWAT (Soil and Water Assessment Tool, Neitsch et al., 1999) model has been tested as a way to identify sources of phosphorus in this watershed. But the application of SWAT was revealed to be unsatisfactory from the point of view of sediment yield and phosphorus exports, the main environmental concerns of the Vico basin. While hydrological results of SWAT simulations are congruent with real-world conditions, sediment yield is clearly underestimated because topographic conditions are not properly described. Probably, this is due to the very steep slopes in the higher part of the basin that are abruptly interrupted downhill where the landscape suddenly becomes flat. This means that the sub-basin approach of semi-distributed models such as SWAT can be inadequate, because it would require a very refined digital terrain model (DTM) and a division of a large number of sub-basins. Developing sub-basins at a scale of 25 meters makes it difficult to understand phosphorus issues.

In consequence, a new approach for critical areas was developed. It is all based on field scale runs of GLEAMS, whose results allowed evaluating sediment (A) and phosphorus (P) yield for different slopes, the main parameters influencing water quality processes. The new method is based on field scale runs of 50 hydrological years through the use of the GLEAMS model (Leone et al., 2001). Because slope is the main limiting factor of the process, a meta-model was developed using a simple regression between the P export simulated by GLEAMS and the slope.

For agricultural land (conventional and with BMP), for example, equations are:

$$P_{conv} = 13{,}42x^{0{,}23} \qquad P_{BMP} = 5{,}47x^{0{,}38} \qquad [1]$$

where P is phosphorus export (kg/ha/year), and x is the slope (dimensionless). They are simple formulas, explicitly related to the main limiting factor, but all other factors of the complex environmental and anthropogenic systems (tillage, soil type, meteorology, hydrology etc.) are not rejected as is the case in other simpler methods. These factors are present in implicit form in the equation 1 coefficients (13,42 and 0,23; 5,47 and 0,38, respectively).

These simple formulas also allow GLEAMS results to be applied to the basin, using a geographic information system (GIS) and a digital terrain model (DTM). Figure 2 shows an example of how to develop scenarios to compare these trends.

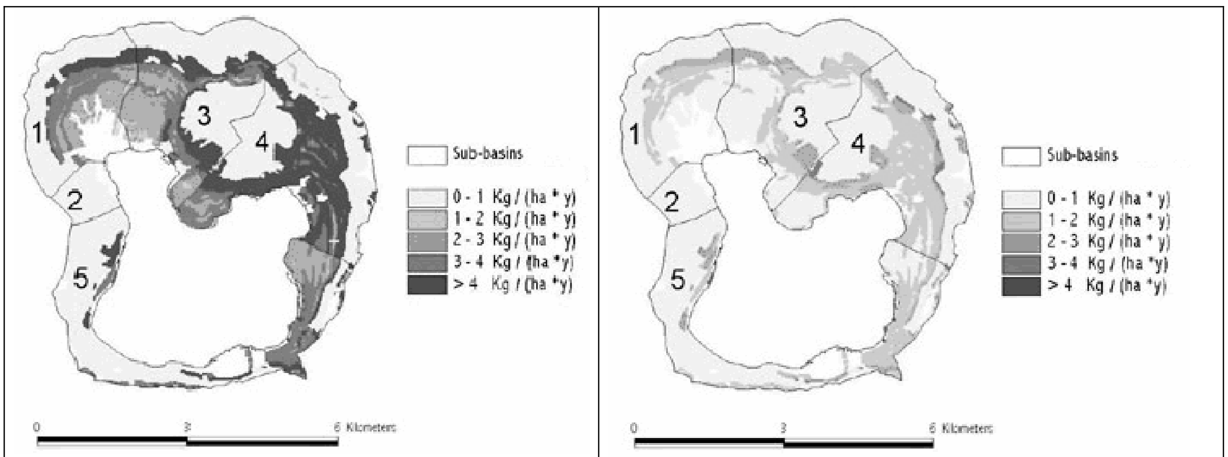

Fig.2: P export for conventional and BMP scenario.

These results provide P yields for each cell and not the export into the lake. The real impact of land use on water quality in the lake is due to such factors as the distance from waterways and slope change. The next step was the evaluation of actual P loads through the concept of sediment delivery ratios (SDR) and the phosphorus transmission coefficient (see Novotny & Chesters, 1989). These equations develop P loads from data on soil erosion and P bound to soil particles. The SDR is the ratio of the sediment yield to the gross erosion rate, expressed as a dimensionless number or a percentage.

SDR-PTC evaluation is empiric and a large number of formulas are available in the literature (see Ouyang and Bartholic, 1997). Considering the experimental evidence, an analysis of the formulas performances has been carried out using the most reliable methods.

Results provide a quantitative P lake load for both scenarios (with and without BMP). This allows for the application of the Vollenweider model (1976):

$$[P]=\frac{L(P)t_w}{z(1+\sqrt{t_w})} \qquad [\mu gL^{-1}] \qquad [2]$$

where: [P] is the equilibrium P water concentration (consequence of long term land use); $L(P)$ = real P lake load = lake surface area and total phosphorus loading ratio [kgP×km^{-2}/year]; t_w= hydraulic residence time [year]; z = mean lake depth [m]. Calculus is illustrated in table 1.

It shows a 48.1 μgL^{-1} concentration of P in lake waters for conventional management and 22.5 μgL^{-1} for the adopted BMP, against an experimental figure of 40 μgL^{-1} (present conditions) and a natural status of 14 μgL^{-1}.

Considering the difficulty of directly validating models, indirect methods have also been applied. They confirm that results in Figure 2 are quite reasonable, because soil erosion zoning is congruent with the evidence (sediment on the roads down the valley when heavy runoff occurs) and with other models results (see Leone et al., 2000). This model check is confirmed also from a P point of view, because export zoning data is within literature ranges (Frink, 1991; Mattikalli & Richards, 1996). Finally, P export corresponds to P concentrations in the lake that are close to the experimental figures (see table 1).

Table 1: P load evaluation and its water concentration by Vollenweider model.

Sub-basin	**Phosphorus loads (conventional tillage)**	**Phosphorus loads BMP)**	
1	448.0	150.7	
2	9.6	5.5	
3	915.2	291.1	
4	1250.4	496.7	
5	560.3	215.5	
Total from basins	3183.3	1154.8	
Other P productions			
Urbanised	246	246	
Tourism	64	64	
Livestock	191	191	
Atmospheric	363	363	**Lake characteristics**
Total	**3792.3**	**1763.8**	Lake surface = 12.1 km^2
Vollenweider P conc. (μgL^{-1})	**48.1**	**22.5**	Renewal time, t_w = 17.0 years Mean lake depth, z = 21.6 m

Conclusions

Compared to other methods, the immediate advantage of this proposed method lies in its ability to satisfy management necessities, because it evidences the use of identifying “hot spot areas.” This allows for the development of optimal land policy and avoids long and expensive approaches. In this way, any sustainable agricultural measure and planned BMP can be spatially located, forcing, in consequence, more effective funds management. This will allow water managers to not spend funds in low risk zones and instead allocate them to high risk areas.

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III. Techniques- Autocalibration and Uncertainty

Sensitivity, Optimisation and Uncertainty Analysis for the Model Parameters of SWAT

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Introduction

The SWAT program (Arnold et al., 1994) has a large number of parameters, several output variables and a complex structure leading to multiple minima in the objective function. Therefore general optimisation methods based on random sampling as GLUE or local methods such as PEST are not applicable. For such models, optimisation methods have been developed and applied that use some intelligence to find the global optimum. The Shuffled Complex Evolution algorithm (SCE-UA) is such a method (Duan, 2003). While optimisation tools are very useful to point out the best solution, they do not provide information on the uncertainty of the parameter identification and the implications of this uncertainty on model output. This paper presents ParaSol (Parameter Solutions), a method that selects equally good parameter solutions by combining the SCE-UA optimisation algorithm and statistical methods to perform uncertainty analysis. The method calculates uncertainty estimates for parameters and model outputs in an efficient and effective way.

The LH-OAT Sensitivity Analysis

A LH-OAT sensitivity method combines the one-factor-at-a-time (OAT) design and Latin Hypercube (LH) sampling by taking the LH samples as initial points for an OAT design (Figure 1).

The concept of LH Simulation (McKay et al., 1979; McKay, 1988) is based on Monte Carlo simulation but uses a stratified sampling approach that allows efficient estimation of the output statistics. It subdivides the distribution of each parameter into N ranges, each with a probability of occurrence equal to 1/N. Random values of the parameters are generated such that each range is sampled only once. The model is then run N times with the random combinations of the parameters.

In the OAT design as proposed by Morris (1991), only one parameter is changed for each run, so the changes in the output in each model run can be unambiguously attributed to the input parameter that was changed. The output is usually some lumped measure like total mass, sum of squares error (SSQ) or sum of absolute errors (SAE). The OAT design is a very useful method for SWAT modelling (Francos et al., 2002; van Griensven et al., 2001) as it is able to analyse sensitivity for a large number of parameters.

The LH-OAT sensitivity analysis method uses the Latin Hypercube samples as starting points for the OAT sampling and thus combines the robustness of the Latin Hypercube sampling, which ensures that the full range of all parameters has been sampled, with the precision of OAT design. This assures that the changes in the output in each model run can be unambiguously attributed to the input changed in such a simulation. This leads to a robust sensitivity analysis method. The method is also efficient, as for m intervals in the LH method, a total of m*(p+1) runs are required.

PARASOL

The Shuffled Complex Evolution Algorithm

This algorithm is a global search algorithm for the minimization of a single function for up to 16 parameters (Duan et al., 1992). In a first step (zero-loop), SCE-UA selects an initial "population" by random sampling throughout the feasible parameters space for p parameters to be optimized (delineated by given parameter ranges). The population is portioned in to several "complexes" that consist of 2p+1 points. Each complex evolves independently using the simplex algorithm. The complexes are periodically shuffled to form new complexes in order to share the gained information. SCE-UA has been widely used in watershed model calibration and other areas of hydrology such as soil erosion, subsurface hydrology, remote sensing and land surface modeling (Duan, 2003). It has been generally found to be robust, effective and efficient (Duan, 2003).

The SCE-UA has also been applied with success on SWAT for hydrologic parameters (Eckardt and Arnold, 2001) and hydrologic and water quality parameters (van Griensven et al., 2002).

Objective Functions

The sum of the squares of the residuals (SSQ): similar to the Mean Square Error method (MSE) it aims at matching a simulated series to a measured time series.

$$SSQ = \sum_{i=1,n} \left[x_{i,measured} - x_{i,simulated} \right]^2 \tag{1}$$

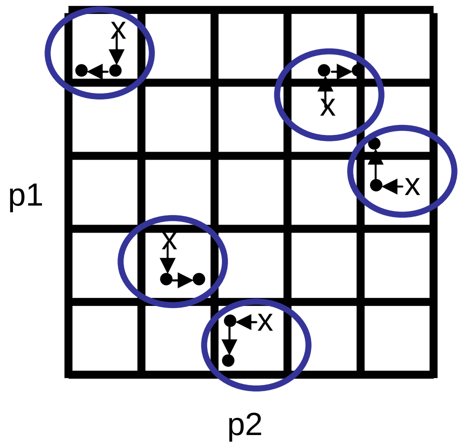
with n the number of pairs of measured ($x_{measured}$) and simulated ($x_{simulated}$) variables

The sum of the squares of the difference of the measured and simulated values after ranking (SSQR): The SSQR method aims at the fitting of the frequency distributions of the observed and the simulated series. As opposed to the SSQ method, the time of occurrence of a given value of the variable is not accounted for in the SSQR method (van Griensven et al., 2002).

After independent ranking of the measured and the simulated values, new pairs are formed and the SSQR is calculated as

$$SSQR = \sum_{j=1,n} \left[x_{j,measured} - x_{j,simulated} \right]^2 \tag{2}$$

where j represents the rank.



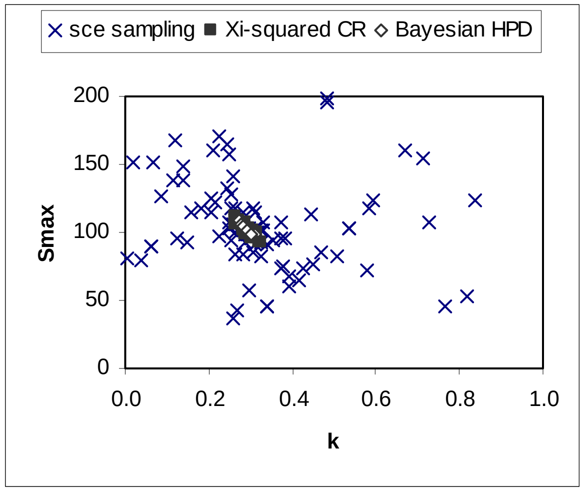


Figure 1: Illustration of MC-OAT sampling of values for a two parameters model where X represents the Monte-Carlo points and • the OAT points.

Figure 2. Confidence region (CR) for the χ^2-statistics and high probability density (HPD) region for the Bayesian statistics for a simple 2-parameter test model.

Multi-objective Optimization

Several SSQ's can be combined to a Global Optimization Criterion (GOC) using (van Griensven and Meixner, 2003):

$$GOC = \frac{SSQ_1 * nobs_1}{SSQ_{1,\min}} + \frac{SSQ_2 * nobs_2}{SSQ_{2,\min}} \qquad \textbf{(3)}$$

The probability is related to the GOC according to (van Griensven and Meixner, 2003):

$$p(\theta \mid Y_{obs}) \quad \propto \quad \exp[-GOC] \qquad \textbf{(4)}$$

The sum of the squares of the residuals provides weights that are equal to the number of observations divided by the minimum. This equation allows also for the uncertainty analysis as described below.

Parameter Change Options

Parameters affecting hydrology or pollution can be changed either in a lumped way (over the entire catchment), or in a distributed way (for selected subbasins or hydrologic response units or HRUs). They can be modified by replacement, by addition of an absolute change, or by a multiplication of a relative change. It is never allowed to go beyond predefined parameter ranges. A relative change allows for a lumped calibration of distributed parameters while they keep their relative physical meaning (soil conductivity of sand will be higher than soil conductivity of clay).

Uncertainty Analysis Method

The uncertainty analysis divides the simulations that have been performed by the SCE-UA optimization into "good" simulations and "not good" simulations. The simulations gathered by SCE-UA are very valuable as the algorithm samples over the entire parameter space with a focus of solutions near the optimum/optima levels. There are two separation techniques, and both are based on a threshold value for the objective function (or global optimization criterion) to select the "good" simulations by considering all the simulations that give an objective function below this threshold. The threshold value can be defined by χ^2-statistics where the selected simulations correspond to the confidence region (CR) or Bayesian statistics that are able to identify the high probability density region (HPD) for the parameters or the model outputs (Figure 2).

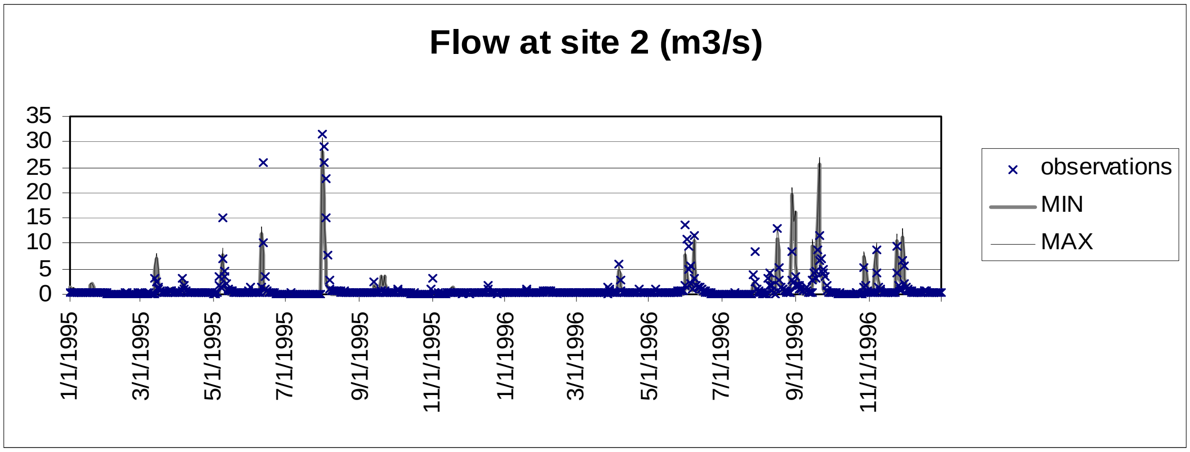


Figure 3: Confidence range for flow calculations using 2 years of data.

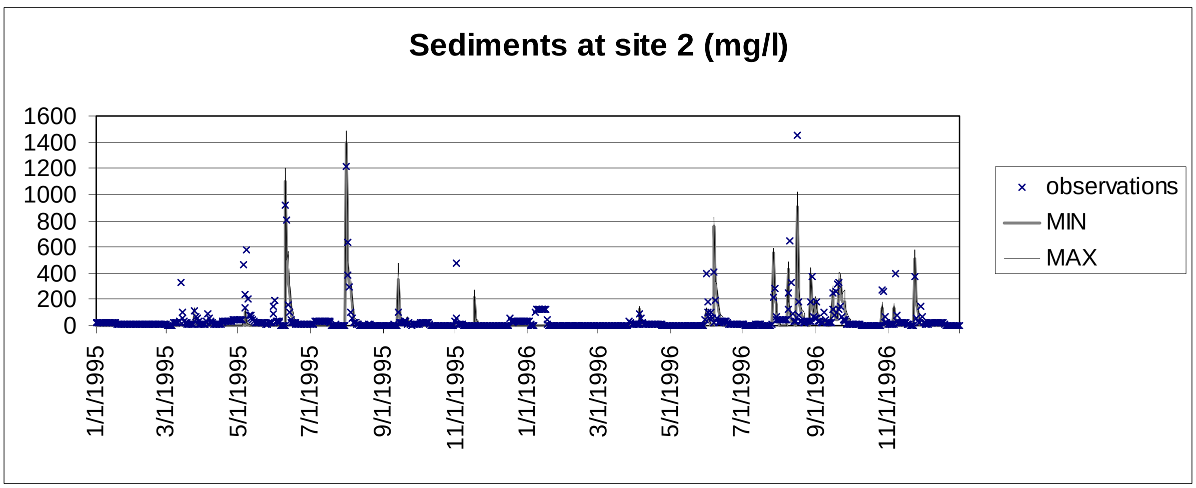


Figure 4: Confidence range for sediment concentration calculations using 2 years of data.

χ^2-method

For a single objective calibration for the SSQ, the SCE-UA will find a parameter set Θ* consisting of the p free parameters (θ^*_1, θ^*_2,… θ^*_p), that corresponds to the minimum of the sum the square SSQ. According to χ^2 statistics, we can define a threshold "c" for "good' parameter sets using equation

$$c = OF(\theta^*) * (1 + \frac{\chi^2_{p,0.95}}{n-p}) \qquad \textbf{(5)}$$

whereby n is the number of observations, p the number of free parameters. The $\chi^2_{p,0.95}$ gets a higher value for more free parameters p.

For multi-objective calibration, the selections are made using the GOC of equation (6) that normalizes the sum of the squares for n, equal to the sum of nobs1 and nobs2, observation. A threshold for the GOC is the calculated by:

$$c = GOC(\theta^*) * (1 + \frac{\chi^2_{p,0.95}}{nobs1 + nobs2 - p}) \qquad \textbf{(6)}$$

Bayesian method (Box and Tiao, 1974)

In accordance to the Bayesian theorem, the probability ($p(\theta|Y_{obs})$ of a parameter set θ is proportional to the GOC (equation 4). After normalizing the probabilities (to ensure that the integral over the entire parameter space is equal to 1), a cumulative distribution can be made and hence a 95% confidence regions can be defined. As the parameters sets were not sampled randomly but were more densely sampled near the optimum during SCE-UA optimisation, it is necessary to avoid having the densely sampled regions dominate the results. This problem is prevented by determining a weight for each parameter set θ_i by the following calculations (van Griensven and Meixner, 2003).

The "c" threshold is determined by the following process:

a. Sort parameter sets and GOC values according to decreasing probabilities

b. Multiply probabilities by weights

c. Normalize the weighted probabilities by division by PT with

$$PT = \sum_{i=1}^{T} W(\theta_i) * p(\theta_I \mid Y_{obs}) \qquad \textbf{(7)}$$

d. Sum normalized weighted probabilities starting from rank 1 till the sum gets higher than the cumulative probability limit (90%, 95% or 97.5%). The GOC corresponding to the latest probability defines then the "c" threshold.

Results and Conclusions

The sensitivity analysis method LH-OAT and the optimisation/uncertainty method ParaSol are very useful for catchment modeling. The sensitivity analysis provides a ranking list for the importance of the parameters on model performance and model outputs (van Griensven et al., 2003). This information can be used to select the parameters for further calibration and/or uncertainty analysis. ParaSol provides in an efficient way the best parameter set-- "good" parameter sets that determine the 90%, 95% or 97.5% confidence regions for the model output or model parameters (van Griensven and Meixner, 2003). These parameter solutions provide confidence regions based on the model output time series. This result is illustrated with a multi-objective optimization for flow and sediment concentrations at an observation site within the Bosque river basin in Texas USA (Figure 3 and Figure 4), using daily observations for a period of 2 years. The results show a small uncertainty bound around the model outputs, indicating that the parameter uncertainty is very small when enough data are available.

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Spatial Consistency of Automatically Calibrated SWAT Simulations in the Dill Catchment and Three of its Sub-Catchments

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Abstract

Parameters of hydrological models cannot always be derived from readily available input data. When measured streamflow data are available, automatic calibration can be used to determine optimal values for the unknown parameters by minimizing the difference between modeled and observed streamflow. We used a version of SWAT adapted to low mountainous regions (SWAT-G) and the Shuffled Complex Evolution algorithm developed at the University of Arizona (SCE-UA) for automatic calibration. SCE-UA is a global optimization algorithm that has successfully been used to find optimized model parameters within the bounds defined by the user. Because it is not feasible (and meaningful) to optimize all parameters for a spatially distributed model, we chose 11 parameter values and adjusted the others in fixed ratios. With this approach, SWAT-G was calibrated to 3 years of discharge measurements for the Dill catchment (Germany) and three of its sub-catchments. The four sets of optimized values were only partly consistent. However, the parameterizations of the subcatchments could be applied in the Dill catchment without a strong decrease in the quality of the simulations. A multi-objective calibration showed that it was possible to define one parameterization that performed well in the Dill Catchment and the three subcatchments.

Introduction

Spatially explicit hydrological modeling is an accepted method to investigate the impact of land use change on the water cycle in general, and hydrological components such as surface runoff or groundwater recharge, in particular. In such modeling approaches, it is common to analyze various land use scenarios with different land management practices and/or vegetation covers, assuming that the model is capable of reflecting the different conditions in the scenarios. One prerequisite for such a model application is that the model is transferable in space and time. Whereas a classical approach for temporal model transferability is the split-sample test described by Klemeš et al. (1986), spatial transferability can be tested by cross application of the model with identical parameterization in adjacent catchments.

The aim of this contribution was to test the spatial transferability of automatically calibrated SWAT simulations in the Dill catchment and three of its subcatchments. Therefore, parameter sets derived from automatic calibration in single subcatchments and the main catchment are cross-applied in all subcatchments to test for that parameter, and hence model transferability. In a further step, a simple multi-objective calibration was conducted simultaneously for the Dill catchment and the three subcatchments in order to test whether a single optimized parameter set exists that performs well for the Dill catchment and the three subcatchments.

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Methodology

The Dill catchment is a low mountainous catchment in Germany (Figure 1) with an area of 693 km^2. The catchment is covered by 30% deciduous forest, 25% coniferous forest, 30% pasture, 6% crop land and 9% residential area, as determined from a composite of Landsat TM5-scenes from 1987 and 1994 (Nöhles, 2000). Soil data are available in the 1:50000 digital Hesse soil map (HLUG, 1998). For the SWAT simulations, the catchment was divided into 48 subbasins and 765 hydrological response units.

We used a version of SWAT adapted to low mountainous regions in Germany (SWAT-G, Eckhardt et al., 2002). One of the main differences between SWAT-G and other versions of SWAT is that SWAT-G includes an anisotropy factor between vertical and horizontal saturated hydraulic conductivity to account for the strong tendency for lateral flow in these types of catchments.

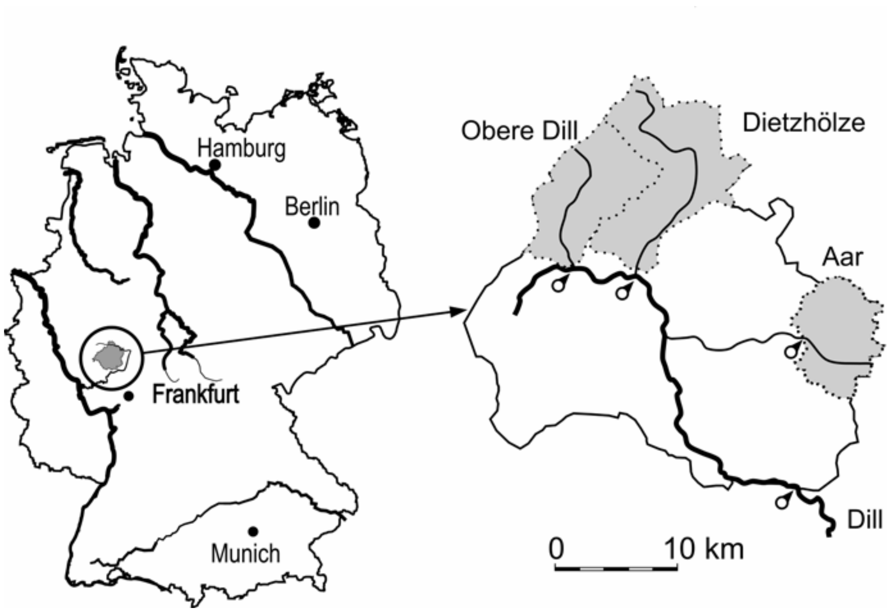

Figure 1. The Dill catchment and three of its subcatchments.

SWAT-G was automatically calibrated to three hydrological years of daily discharge measurements (1986-1988) available for the gauging station at the catchment outlet and to three other stations draining subcatchments of the Dill: Aar (134 km^2), Dietzhölze (81 km^2) and Obere Dill (63 km^2). The results of the calibration were validated on daily discharge measurements for the years 1989-1991. Hence, calibration and validation period correspond to the period of the land use classification performed by Nöhles (2000).

For automatic calibration, we used the Shuffled Complex Evolution algorithm developed at the University of Arizona (SCE-UA). SCE-UA has proven to be a powerful tool for finding the global minimum in the parameter space defined by the user (Duan et al., 1992). Because it is not feasible (and meaningful) to optimize all parameters for a spatially distributed model, we chose 11 parameter values and adjusted the others in fixed ratios as proposed by Eckhardt and Arnold (2001). The prior parameter ranges for the automatic calibration are given in Table 1 for each of the optimized parameters. The ratios of the soil physical parameters were based on the soil map data. The surface runoff and groundwater parameters were set equal for all subbasins.

Table 1. Prior parameter ranges used in automatic calibration.

	Lower Bound	Upper Bound
Surface runoff lag time (d)	1.000	5.000
Manning N surface runoff ($m^{-1/3}s$)	0.200	0.500
Groundwater recession coefficient (d^{-1})	0.030	0.060
Delay of groundwater recharge (d)	1.000	20.000
Deep aquifer percolation factor (-)	0.000	0.800
Bulk density soil ($g\ cm^{-3}$)	1.500	1.600
Bulk density bedrock ($g\ cm^{-3}$)	2.510	2.650
Available water content ($m^3\ m^{-3}$)	0.160	0.200
Saturated hydraulic conductivity Soil I ($mm\ h^{-1}$)	1.000	45.000
Saturated hydraulic conductivity Soil II ($mm\ h^{-1}$)	10.000	85.000
Anisotropy factor (-)	2.000	8.000

In the automatic calibration, we minimized the sum of squared residuals (SSR) between measured and modeled discharge for the Dill catchment and the three subcatchments separately. A minimization of the SSR corresponds with an optimization of the Nash-Sutcliffe (NS) index (Nash and Sutcliffe, 1970). We also calibrated SWAT-G for the Dill catchment and the subcatchments simultaneously. In this rudimentary 'multi-objective' calibration, we minimized the sum of the 4 SSRs, weighted by the inverse of the variance of each of the 4 discharge time series:

$$SSR_{tot} = \sum w_i SSR_i \quad \text{with} \quad w_i = \left(\sigma^2_{meas,i}\right)^{-1} \qquad [1]$$

The use of equation [1] assures that improvements in the individual SSRs contribute equally to improvements in the overall objective function.

Results and Discussion

Table 2 presents the optimized parameter sets for the Dill catchment, the three subcatchments and the multi-objective calibration. Four out of the 11 parameters that were optimized show distinct differences between the catchments (first four rows in Table 2). The parameter set derived by multi-objective calibration is most similar to the Dill parameter set.

Table 2. Resulting parameter sets of the optimization for the Dill, Aar, Dietzhölze (Dtz), Obere Dill (Obd) and the 'multi-objective' calibration (MO).

Parameter	Dill	Aar	Dtz	Obd	MO
Groundwater recession coefficient (d^{-1})	0.030	0.038	0.035	0.044	0.031
Delay of groundwater recharge (d)	19.500	1.090	9.060	9.060	19.200
Deep aquifer percolation factor (-)	0.351	0.024	0.010	0.045	0.344
Saturated hydraulic conductivity Soil I ($mm\ h^{-1}$)	44.800	44.500	44.900	1.150	45.000
Saturated hydraulic conductivity Soil II ($mm\ h^{-1}$)	84.800	84.900	84.600	84.700	84.900
Surface runoff lag time (d)	1.000	1.000	1.000	1.030	1.000
Manning N surface runoff (m 1/3s)	0.497	0.480	0.495	0.477	0.499
Bulk density soil ($g\ cm^{-3}$)	1.600	1.600	1.600	1.580	1.600
Bulk density bedrock ($g\ cm^{-3}$)	2.620	2.630	2.640	2.630	2.640
Available water content (m^3m^{-3})	0.200	0.200	0.200	0.194	0.200
Anisotropy factor (-)	7.990	8.000	7.960	7.800	7.990

As an example of the quality of the SWAT-G model application after automatic calibration, modeled and measured daily discharge data for the Dill catchment are shown in Figure 2. Whereas the overall pattern of discharge is matched by SWAT-G, the peak discharge is slightly underestimated and the recession is slightly too slow for some events. The NS-index for the simulation shown in Figure 2 is 0.80.

NS-indices for all calibration and validation periods of the Dill catchment and three subcatchments are presented in Table 3. The quality-of-fit is excellent for all automatic calibration runs, as indicated by the underlined values in Table 3. The NS-index was highest for the Dill catchment (0.85) and lowest for the Obere Dill subcatchment (0.80). The decrease in NS-index from the calibration to the validation period was acceptable for all catchments except the Obere Dill, where the NS-index dropped from 0.80 to 0.61. A common explanation for such a strong decrease is that the calibration data do not represent the validation data. In this study, the calibration data are three relatively wet years and the validation data are from three relatively dry years. It is well known that the use of the SSR in calibration emphasizes the correct depiction of the runoff peaks, but may not produce a correct depiction of medium and baseflow conditions. This might lead to inadequate parameterizations. This explanation for the strong drop in model efficiency between calibration and validation periods is supported by the fact that the low NS-index for the Obere Dill in the validation period is caused by an overestimation of the discharge peaks.

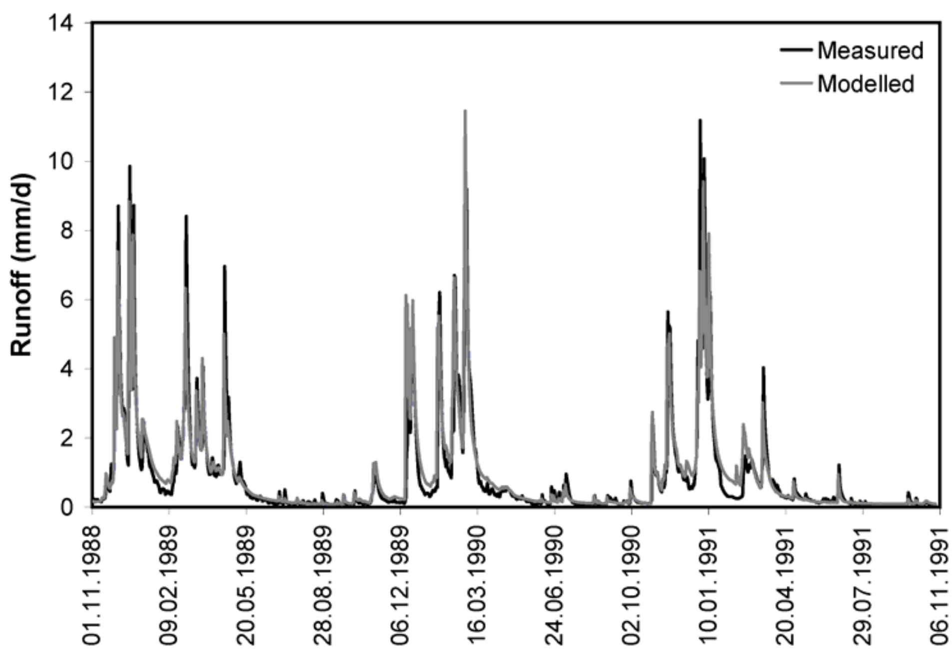

Figure 2. Measured and modeled daily discharge at the Dill catchment, Germany.

To test the spatial transferability, the SWAT parameterizations of each the four catchments were applied to the other catchments. Table 3 shows that the results are surprisingly good despite the large differences in the parameterization of some parameters in Table 2. For example, the calibration of the Dill catchment has a NS-index of 0.85, whereas the Aar parameterization and the Dietzhölze parameterization result in a NS-index of 0.84 for the Dill catchment. The results of the cross-application are also good in the validation period, except for the Obere Dill parameterization which performs poorly for all catchments in the validation period. The higher NS-index of the other parameterizations in the Obere Dill catchment as compared with the Obere Dill parameterization itself also indicates that the automatic calibration was less successful for this catchment.

The similar NS-indices in the cross-application, despite the differences in the model parameters shown in Table 2, illustrate that conclusions on the spatial transferability should not be made solely on the basis of a comparison of the calibrated model parameters. Clearly, the sensitivity of the model results towards the optimized parameters should also be included. For example, the sensitivity of the delay of groundwater recharge is low, and, therefore, the large difference in the parameterizations for this factor does not strongly impact the quality of the fits. The soil physical properties are known to be sensitive parameters in SWAT, and for these parameters the parameterization tends to be much more similar.

The results of the 'multi-objective' (MO) calibration are also presented in Tables 2 and 3. The quality of fit of the MO-calibration is almost as good as the quality of fit of the automatic calibration for each individual catchment in the calibration and validation period. As expected, the average performance for all catchments was best for the MO parameterization, although the difference with the performance of the other parameterizations was relatively small. It can be concluded that there is a single parameterization that provides excellent simulation results for all the sub-catchments and catchments simultaneously.

Table 3. Nash-Sutcliffe index for daily discharge measurements. Parameter sets Dill, Aar, Dtz, Obd and MO used in calibration and validation are taken from Table 2. Underlining indicates simulations where data of that particular catchment have been used in the calibration. Other indices indicate the quality-of-fit in cross-application in a different catchment.

Parameter set	Dill	Aar	Dietzhölze	Obere Dill
		CALIBRATION		
Dill	<u>0.85</u>	0.82	0.82	0.79
Aar	0.84	<u>0.83</u>	0.83	0.80
Dtz	0.84	0.83	<u>0.83</u>	0.80
Obd	0.83	0.75	0.83	<u>0.80</u>
MO	<u>0.85</u>	<u>0.83</u>	<u>0.83</u>	<u>0.80</u>
Parameter set		VALIDATION		
Dill	<u>0.80</u>	0.82	0.77	0.65
Aar	0.78	<u>0.83</u>	0.78	0.65
Dtz	0.77	0.82	<u>0.78</u>	0.65
Obd	0.67	0.69	0.71	<u>0.61</u>
MO	<u>0.79</u>	<u>0.82</u>	<u>0.78</u>	<u>0.65</u>

Conclusions

Automatic calibration with SCE-UA resulted in a high quality-of-fit in the Dill catchment and two of its three subcatchments. The parameterizations that performed well in the calibration and validation period also performed well in the cross-application in a different catchment despite the apparently large differences in the optimized values of some parameters. This project concluded that SWAT parameterizations could successfully be transferred from subcatchment to subcatchment and from a subcatchment to the entire catchment that was the focus of this study. Of course, such a successful transfer is not self-evident, and we attribute it to the consistency and high detail of the soil map.

Acknowledgements

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Evaluation of the Optimal Location of Monitoring Sites Based on Hydrologic Models and GIS Technology

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Introduction

Surface water represents an important source of drinking water in Italy. The protection of this resource from contamination is, consequently, a task of increasing importance. For this reason many legislative efforts have been developed in order to protect water systems (DPR236/88, DL132/92, L36/94, L152/99).

In particular, in intensive agricultural areas, water pollution from diffuse sources represents an important problem (Leone et al., 1996). Surface water pollution caused by agricultural activities is strongly conditioned by soil physical and chemical properties, geomorphology, land use, management practices, and climate. The evaluation of surface water quality, therefore, has to be based on the knowledge of the water flow and of the chemical, physical and bio-chemical processes in the whole watershed. In this frame, the capability to forecast pollutant flows and their relative concentration becomes of particular interest for a sound management of the water resources.

Schematic and synthetic tools to assess water quality and quantity are urgently required by river authorities throughout the world. Mathematical models to simulate pollutant transport in surface water seem to be a very profitable approach. Because models require field data for calibration and validation, monitoring represents one of the most important activities to evaluate water availability and quality.

Existing surface water monitoring networks can be extensively used to gather water quality information. Nevertheless, monitoring networks are often designed considering several already available or easy to reach monitoring points in a watershed; this approach often decreases the sampling cost but sometimes does not produce enough extensive and reliable information.

The first step to correctly define a monitoring program is the identification of the optimal location of monitoring points to manage water quality. The second step consists of defining the sampling frequency. The selecting criteria with reference to both steps are generally driven more by economical than technical constraints. For this reason, a practical strategy should be able to determine where and when to sample at the lowest costs.

Several methodologies for designing a monitoring network and optimising the sampling procedures are reported in literature (Rosenthal and Hoffman, 1996; Lo et al., 1996)

In this paper the results of the application of a methodology based on the integrated use of a hydrologic model and a geographic information system (GIS) to evaluate the optimal location of the monitoring sites within the Enza River basin (northern Italy) are presented.

Inherent in the examined methodology is the possibility to predict how land use, climate, and water management can affect water movement, and sediment and chemical production and transfer in medium to large river basins.

In particular the Soil Water Assessment Tool (SWAT) model (Arnold et al., 1999) has been used. The parameters to be monitored, the location of the monitoring points and the sampling frequencies are automatically determined through the establishment of several critical points defined as the outlet of the sub-basins of a watershed that the model indicates to mostly contribute to the loading of each water pollutant.

This work has been undertaken within the framework of the EU R&D project "EUROHARP" (EVK-CT-2001-00096).

Materials and Methods

The Enza River, a tributary of the Po River, originates from the Apennines at the border between Tuscany and Emilia Romagna, (Figure 1).

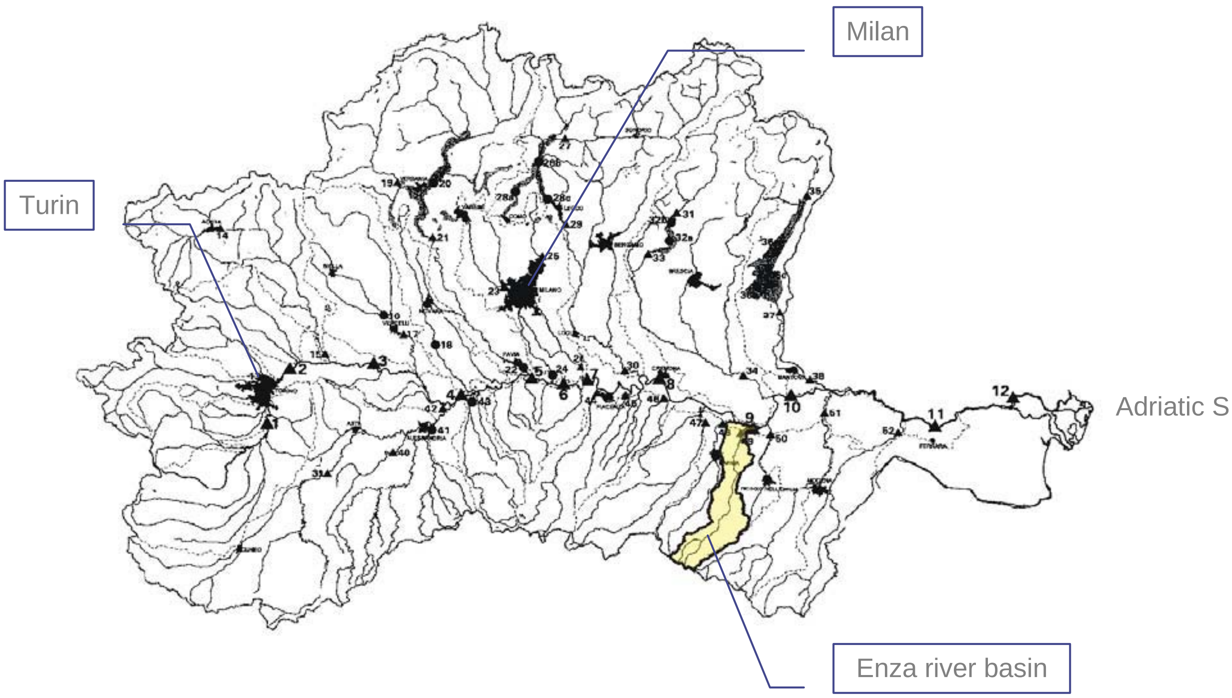


Figure 1: The Po River basin and the Enza River test site.

The river flows for about 99 km and drains a catchment area of 884 km^2 that can be coarsely divided into mountains, hills, and plains. The main tributaries of the Enza River are the torrents: Termina and Tassobbio.

The annual rainfall in the catchment is characterized by a mean value of about 950 mm with two periods, in spring and autumn, of significantly higher values and with mean annual values of about 1150 and 850 mm in the higher and in the lower part of the basin respectively. The annual snow precipitation is about 60 cm and it usually remains on the ground for about one month. Mean flow at the Po River confluence is 10 m3/s.

The mountain region, in the southern part of the basin, is predominantly covered by hardwood forest. The central hilly region is characterized by pastures and bushes while in the northern plains the basin is intensively cultivated. Spring and winter cereals represent more than one half of the agricultural land use, although sugarbeets are also common in this area.

Fertiliser application rates are relatively high. The mean annual values are 50 kg/ha phosphorus and 170 kg/ha nitrogen. In addition, 10 t/ha/year of dairy cattle and pig manure are spread over the agricultural soils.

In the upstream part of the watershed the soil is mainly clayey and silty. Downstream, sandy soils mixed with sandy loam soils are rather diffuse.

From the geologic standpoint, the plain between the Apennines on the south and the sedimentary basin of the Po River on the north is characterized by a system of alluvial fans created by sediments of the Enza River and the secondary stream network. The Apennines are mainly constituted by clay sequences that date back to the Pliocenic-Calabrian marine cycle. The sediments of the low alluvial plain, which extends to the Po River consist of sand with a significant fraction of mud and clay. In the apical part, gravel and sand alternate with pelitic bodies whose thickness gradually increases approaching the distal section of the fans.

The population in the catchment is 275,000 inhabitants. The largest urban areas are located along the Via Emilia which connects the towns of Parma, Reggio Emilia and Modena. More than 40,000 persons are employed in industry: 50% in the mechanical sector, 20% in the food industry, 10 % in chemical and paper mills, and 8 % in the textile and tannery industry.

The effluent of several civil wastewater treatment plants is discharged into the Enza River. The total incoming flow is up to 0.2 m^3/s (2% of the average discharge into the river) and it is characterized by 25 mg/L BOD and 68 mg/L COD.

Major activities in the catchment	Estimation of % contribution to total load of Nitrogen	Estimation of % contribution to total load of Phosphorus
Agriculture	60	50
Aquaculture	0	0
Domestic sewage	10	5
Industry	30	45
Others	0	0

Table 2: Estimated N and P loads from major activities in the Enza river basin

The Enza River is moderately clean. Diffuse pollution from agriculture is by far the main cause of pollution (see table 2).

Data

Data required to run the model were gathered from different territorial environmental agencies. The Digital Elevation Model (DEM), available in raster format, was characterized by a 200 m mesh. The Emilia Romagna Regional Administration provided a vector contour lines layer (25 m resolution). General-purpose maps having a 1:25.000 and 1:50.000 scale were also available, issued by the Italian "Istituto Geografico Militare" (IGM). All these maps were digitized to produce a georeferenced raster topographic base. From these maps, a detailed river network layer was derived in vector format.

The raster DEM was characterized by a rather coarse spatial resolution and several inconsistencies were pointed out during the initial exploratory data analysis. Consequently, a very detailed vector contour lines coverage was derived and digitized from the IGM 1:25.000 map with a one meter resolution. This coverage has been rasterized and accurately patched onto the available DEM. Temperature and precipitation data were derived from 30 years records related to the weather stations of Parma and S. Polo .

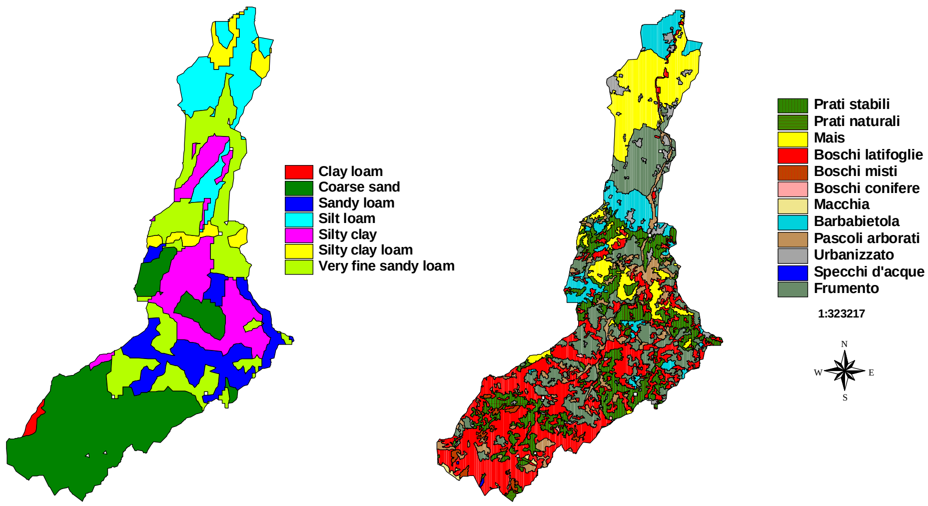


Figure 3. Soil map (left) and land use map (right)

A raster soil map (figure 3), characterized by a 200 m mesh grid, was gathered with data provided by the local regional administration while a land use map was derived by clipping a larger CORINE land cover map. A great deal of work was on this cover information was needed in order to split the general class "arable land" into the different land covers belonging to the SWAT crop database.

Concerning the management input data, values derived from literature and information provided by several experts were combined, whereas flow and water quality data at various locations and times were obtained by local environmental agencies. Since no data were found regarding forested area management and some of the crop parameters, the SWAT database values were used with this reference.

Results and Discussion

The Enza River network was automatically delineated by the GIS. Unfortunately, this operation was easily performed in the upstream part of the watershed characterized by a mountain area where the gradients were evident, but it failed in the plains of the basin because of the very low elevation gradients (less than 1%).

The model greatly improved the correspondence between the real and the modelled stream when the digitised stream delineation was "burned" onto the DEM.

However, even in this case, the extent of the modelled network did not completely match the real one, and about 10% of the network was not correctly delineated. This was principally caused by the sub-basin shape and extension.

In this study, only one hydrologic response unit (HRU) per sub-basin was considered, assigning the most common landuse/soil type combination to the whole subbasin. According to this scheme, 44 sub-basins (HRU) were defined within the catchment. Stream flow, sediment and nutrient loading were estimated using actual climate data from 1980 to 1997.

SWAT estimated values of water balance, erosion, nutrient and pesticide fate, and crop growth in every subbasin/HRU. Discharge and water quality values were also estimated at each sub-basin outlet and at key nodes. The key nodes were associated with several river cross-sections where water quality and discharge were monitored, in order to calibrate and validate the model results.

Nevertheless, when this work was started, monitoring data only consisted of instantaneous values sampled monthly; consequently, the calibration was affected by this lack of data and the results were rough. This calibration was performed comparing simulated and monitored flow data, first at the most upstream monitoring station (Vetto) and then at the downstream stations along the river (Figure 4).

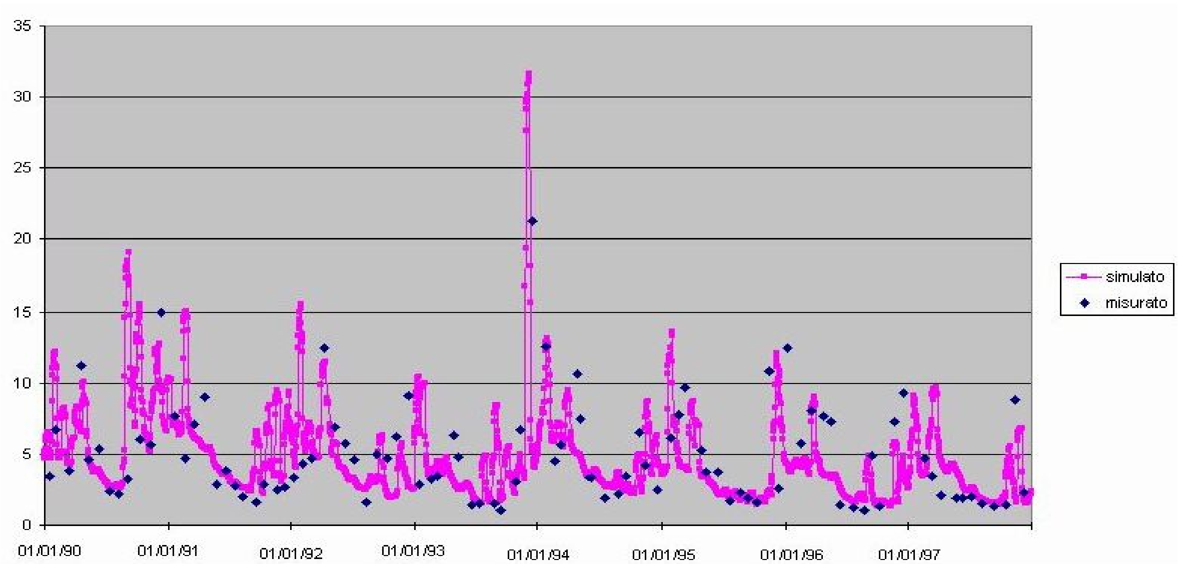


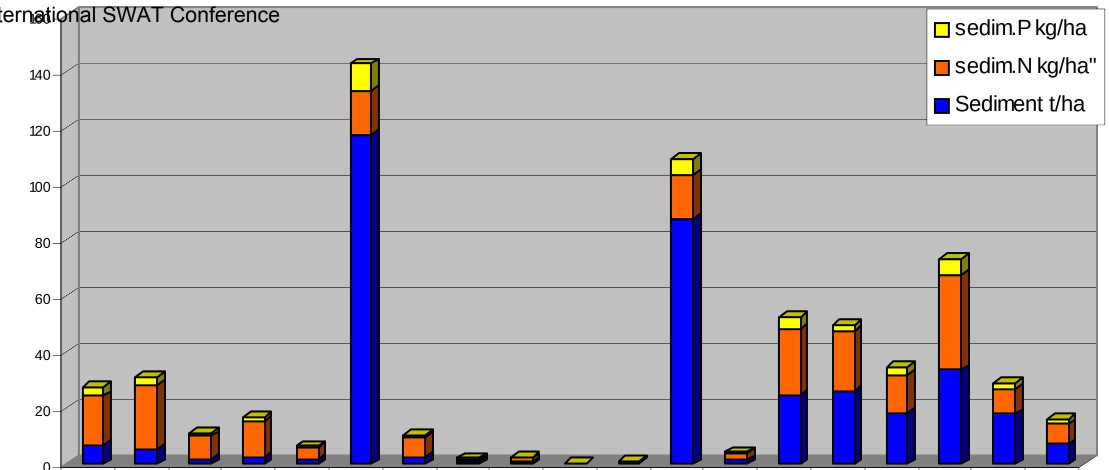
Figure 4. Measured vs. simulated flow (m^3/s) at the Vetto gauge.

Daily values of flow and nutrient concentrations are now available for a larger number of outlets and it is possible to develop to a better calibration-validation scheme as required by the EUROHARP protocol.

SWAT results at the basin scale revealed the contribution of each landuse to each component of the water balance. Deciduous forest (FRSD) were shown to be highly responsible for water yield while they poorly contributed to percolation, evapotranspiration, surface runoff and sediment load. Corn (CORN) and sugar beet (SGBT) behaved exactly oppositely. Winter wheat (WWHT) and alfalfa (ALFA) showed an intermediate behaviour.

With reference to nutrients, sediment-bound P from SGBT was 37 times higher than from FRSD and 25 times than from WWHT. Runoff nitrogen from FRSD and WWHT was lower than from CORN (30 times) while leached nitrogen from SGBT and WWHT was lower than from CORN (9 times).

Results obtained at the HRU scale clearly highlighted which land use/soil combinations are responsible for the highest pollutant contribution to the stream. The combinations of CORN/silty clay and SGBT/coarse sand were shown to represent the main sediment source and (together with WWHT/sandy loam) were shown to be the main source of sediment-bound P (Figure 5). CORN/silty clay was the main source soluble P, while CORN/silty clay, CORN/silty loam, CORN/very fine sandy loam and ALFA/sandy loam were the main sources of leached nitrogen.



	ALFA coarse	ALFA sandy loam	ALFA silty clay	ALFA v.f.sandy	CORN silt loam	CORN silty	CORN v.f.sa	FRSD coarse	FRSD sandy loam	FRSD silty clay	FRSD v.f.sandy	SGBT coarse	SGBT silt loam	SGBT v.f.sandy	SWRN v.f.sa	WWHT coars	WWHT sandy	WWHT silty clay	WWHT v.f.sa
sedim.P kg/ha	3,2	2,8	1,0	1,6	0,5	9,6	0,9	0,1	0,2	0,0	0,1	5,5	0,5	4,3	2,5	2,7	6,1	2,3	1,6
sedim.N kg/ha"	17,7	22,9	8,1	12,6	4,0	15,8	7,0	1,0	1,4	0,3	0,7	16,2	2,3	23,6	21,4	13,4	33,7	8,7	7,2
Sediment t/ha	6,7	5,3	2,0	2,8	1,9	117,5	2,6	1,0	0,8	0,3	0,4	87,2	1,5	24,6	25,9	18,2	33,6	17,9	7,2

Figure 5. Sediment and sediment-bound nutrients per HRU.

The location of such HRUs was known thanks to the GIS database, consequently those which were mainly responsible for water pollution were easily located and proposed for the application of alternative management practices.

Finally, this led to the selection of the reaches where monitoring devices should be placed or manual sampling activities should be carried out. Consequently, several sites were selected as possible monitoring places because they were representative of the sub-basins in which they were located, in terms of water pollution load contribution (Figure 6).

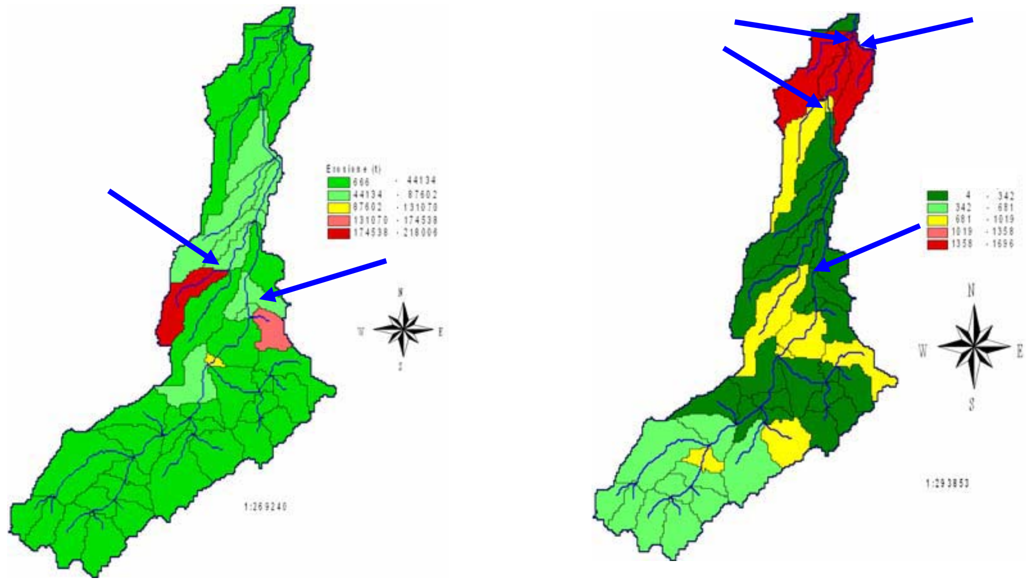


Figure 6. Sediment (left; tons) and nitrogen load (right; kg); arrows indicate outlet where monitoring station should be placed.

Monitoring stations should be placed where model simulations pointed out that sub-basins were in a critical position (i.e., watersheds between areas responsible for high pollutant loads and more pristine streams). These are shown as yellow areas in Figure 6. These sub-basins should be regarded as "stressed" areas that must be thoroughly surveyed in order to avoid pollution worsening.

Conclusions

The study demonstrated that this methodology (integrated use of GIS and hydrological models) is suitable to evaluate the response of a natural system to agricultural land-use. This methodology can strongly support water management authorities when actions have to be taken to reduce pollution (e.g. location of buffer strips and other BMPs), but water managers need to realize where these programs are really necessary.

The study also establishes that the general knowledge needed to apply the proposed methodology to areas where a monitoring network does not exist. It also allows water resources managers to perform a preliminary screening of the location of the monitoring sites, representing a valuable aid in terms of both cost reduction and maximizing effectiveness.

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Linkage of the ArcHydro data model with SWAT

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The use of the ArcHydro spatial and temporal data model for integrating hydrologic computer applications is presented. In particular, the linkage between ArcHydro and SWAT is discussed. ArcHydro is a template for storage of spatial and temporal hydrologic data, in which the different objects of the system are assembled together by virtue of their connection to the river network. Additionally, its use as a standard data model would help expedite collaboration between multiple users, agencies, and companies on water resources projects.

After preprocessing topographic, soil, land use, and other spatial and temporal data, the resulting information is stored in ArcHydro as spatial data (i.e., sub-basin boundaries, hydrologic response units), time series (precipitation, flow, loads), or tables (sub-basin parameters).

Data exportation from ArcHydro to SWAT, and importation of results back from SWAT into ArcHydro, is then accomplished using an extensive markup language (XML) based utility. This utility extracts all relevant information from ArcHydro for SWAT. It extracts spatial and temporal information from the SWAT output file and stores it in ArcHydro.

Sensitivity of the SWAT Model to the Soil and Land Use Data Parametrization: a Case Study in the Thyle catchment, Belgium.

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Introduction

Spatially distributed hydrological models are useful tools to support the design and evaluation of water management plans. A blueprint of this type of models was already presented in the late 1960s by Freeze and Harlan(1). The spatially distributed nature of these hydrological models allows users to evaluate explicitly the impact of spatially variable forcing terms such as soil and land use on the hydrological responses. This property makes spatially distributed hydrological models attractive for the evaluation of land and water management options.

Unfortunately, the use of spatially distributed modelling technology in water management decision making suffers from a series of drawbacks (2). First, the data demands for spatially distributed models are considerably high. Secondly, distributed modelling is exhaustive in terms of computer power and data processing. Advanced GIS (geographical information systems) and computer technology is needed to efficiently process data with these modelling types. Finally, there is a lack of scientific understanding of the robustness, sensitivity and validation of these models in relation to different parametrisation schemes. In particular, questions are raised about the appropriate resolution of the spatially distributed input data. As has already been proven in numerous studies (3), the resolution and the aggregation of the GIS data does have a considerable impact on the modelling of the rainfall-runoff processes with distributed hydrological models. Therefore the parametrisation of the soil, the vegetation and the climate in distributed hydrological modelling should be analysed in detail for different distributed hydrological models and different hydrological catchments, and this prior to any modelling calibration.

To contribute to this last challenge, we analyse in this paper the sensitivity of the distributed hydrological model SWAT (Soil and Water Assessment Tool) (4) to the soil and land use parametrisation for simulating rainfall-runoff processes in a small agricultural catchment in the central part of Belgium. And more precisely we analyse how the available soil and land use data can be prepared for modelling with the SWAT model and also how the internal aggregation procedures affects the simulation of the rainfall-runoff processes.

Materials and methods

Model Description

In this case study, the AV-SWAT version of the model was used. This version is integrated with ArcView™ and has been fully documented by Neitsch (5) and is available at http://www.brc.tamus.edu/swat/. In AV-SWAT, the pre-processing of the data is done by applying some of the ArcView™ GIS functionalities. This involves the creation of the river network, the catchment area, and the sub-catchments. The latter step is crucial, since it creates the boundaries for further simulation and is connected with the definition of the sub-catchment size threshold value (CSTV), which is the basis for the definition of the Hydrological Response Units (HRU) where the aggregation process of the input data takes place.

The Catchment Area

The studied area is the Thyle catchment (sub-catchment of the Dyle river) situated in the central part of Belgium (Brabant Wallon), southeast of Brussels. The land use in the Thyle catchment is dominated by agriculture (66.37 % of the total area). Forest represents 27.18% of the area, urban 5.6%, industrial 0.8% and open water only 0.05%. The total surface area of the Thyle catchment equals 59 km².

General Input Data

The digital elevation model (DEM) used for the modelling has been created by the local government authorities and it has been used in previous studies for the Dyle catchment. The weather data for 1999 used in this study were obtained from the Belgian Royal Meteorological Institute (KMI-IRM). This data set includes the daily precipitation rate, the daily maximum/minimum temperature, the mean monthly values of wind speed, and solar radiation.

The 1999 land use map was created using the SIGEC (crop growth) data set, combined with Landsat TM satellite images and the IGN topographical map 1/50,000. For the application of the SWAT model two types of the land use map were used. To evaluate the impact of the aggregation of the land use on the hydrological modelling performance, a detailed land use map with 23 classes was derived and later a generalised 6 class land use map was defined.

For the case study two different soil maps were used: i) a soil association map which is available at the scale of 1:500,000 (Comité National de Géographie) (6) referred to as generalised soil map; and ii) a detailed soil map which is available at the scale of 1:25,000 (IRSIA) (7). The association map represents 39 associations for the Belgian territory (8). The study catchment is characterised by 3 associations and 60 detailed soil mapping units. To parameterise the soil map units of the two different soil maps, use was made of the Belgian analytical soil data base AARDEWERK (9). This analytical database needs to be matched with the different soil map units of the two soil maps. After extraction of the soil data the needed soil parameters were calculated by using the pedotransfer function of van Orshoven (1993b). For calculating derived soil attributes at the map unit level, different averaging procedures were considered which later on were used as a one of the scenarios option.

Modelling scenarios

Four values for the CSTV were considered in our scenario-analysis: sub-catchment size corresponding to the maximum area (1 sub-basin); sub-basin size suggested by the model developer (27 sub-basins of size below 100 ha); a CSTV of 60 ha (47 sub-basins); and a CSTV of 20 ha (145 sub-basins). Lower threshold values were not possible due to computational limitations.

The combination of the two soil maps with two land use maps, two soil analytical data averaging schemes, and four CSTVs results in total in 32 different modelling scenarios. For characterizing the soil type and land use in each HRU, the dominant soil and land use was considered. All other SWAT parameters were set to their default values, and no calibration was performed.

Results and Discussion

Evaluation of the Pre-processing

Since the HRU attributes are internally defined by overlaying the input soil map and land use map with a sub-catchment map, input soil and land use information will be transformed. A visual comparison was made between the input maps and derived maps by the SWAT model after CSTV application. This basis comparison should give some indication about the loss of information in the internal aggregation procedure used by SWAT. A visual comparison however does not allow users to elucidate the differences in a synthetic way. Therefore the visual comparison was completed with the calculation of 5 map indicators in ArcView™ and 7 map indicators using Fragstats (10). The latter tool is a public domain software program designed to compute a wide variety of landscape metrics with the emphasis on the distribution of map patterns.

Evaluation of the Land Use and Soil Map

The impact of the CSTV on the input land use and soil map is remarkable. The geometry of the patches of land use classes changes significantly, as well as the total area and the shape of the land use class patches. In addition, some land use classes disappears in the aggregation procedure. The change of shape of the land use class patches is of concern for the hydrological modelling. Actually, as compared to the generic land use map, land use class patches are much more dispersed throughout the catchment and that affects significantly the fast response of the catchment to intense rainfall.

As it was expected, the aggregation used by the SWAT model results in a considerable loss of information. The change in the distribution of the class patches and the disappearance of some of them in the generated maps is illustrated by the grid indicators in terms of CSTVs in Figure 1.

Evaluation of the hydrological modelling

Preliminary results with the SWAT model showed that the baseflow component in the catchment is not appropriately modelled. Therefore separation of the base flow component from the surface flow component in the observed hydrograph data by means of an automated separation technique (11) was performed and the modelled surface flow was compared with estimated surface flow.

The impact of the different aggregation and soil parametrisation procedures on the predicted rainfall-runoff was evaluated by a set of parameters and the most well know (Nash – Sutcliffe index) is illustrated in the Figure 2. It has to be underlined that the model was not calibrated, therefore the used model performance indexes are not high. However taking into consideration that there is a lot of uncertainty in the input data (e.g. rainfall data and discharge measurements), the results obtained with the uncalibrated SWAT model are satisfactory.

Conclusions

This study has shown that the SWAT model is very sensitive to the pre-processing of the soil and land use data. Consequently the input data resolution and classification will be transformed prior to the hydrological modelling by the model's internal aggregation procedure. Therefore, it is advised to take a lot of precautions before applying an integrated model. Users should see how the model pre-processes the soil and land use input data, and to what degree some of the input transformations affect the modelling. The threshold value for the sub-catchment size is a critical parameter in the SWAT model, driving the internal aggregation and therefore its impacts on modelling performance.

Acknowledgements

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Figures

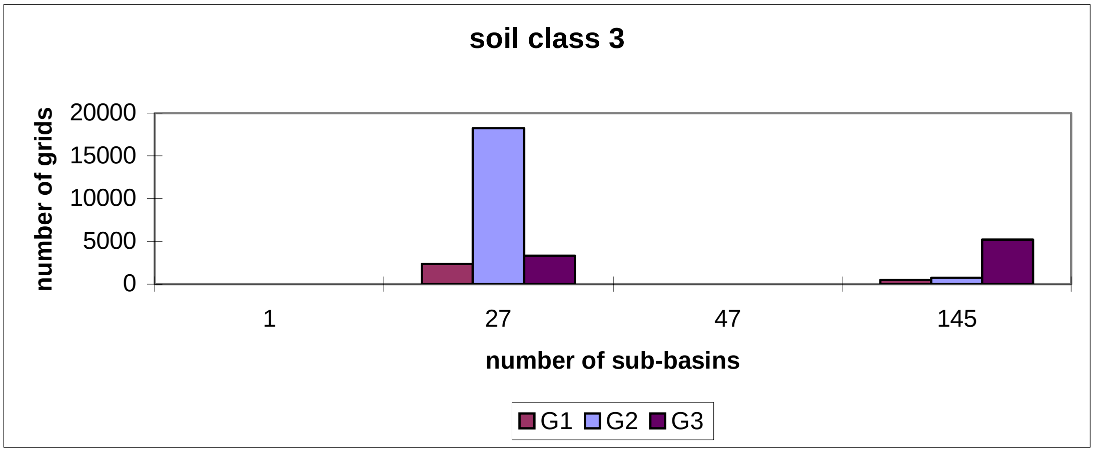

Figure 1. Evaluation of the number of grid indicators for a certain soil class (soil class 3) for different threshold values for the sub-catchment size, (G1- Number of grids of class x that after aggregation correspond to the original map,G2- Number of grids assumed to be a different class,G3- Number of original grids not used for simulation).

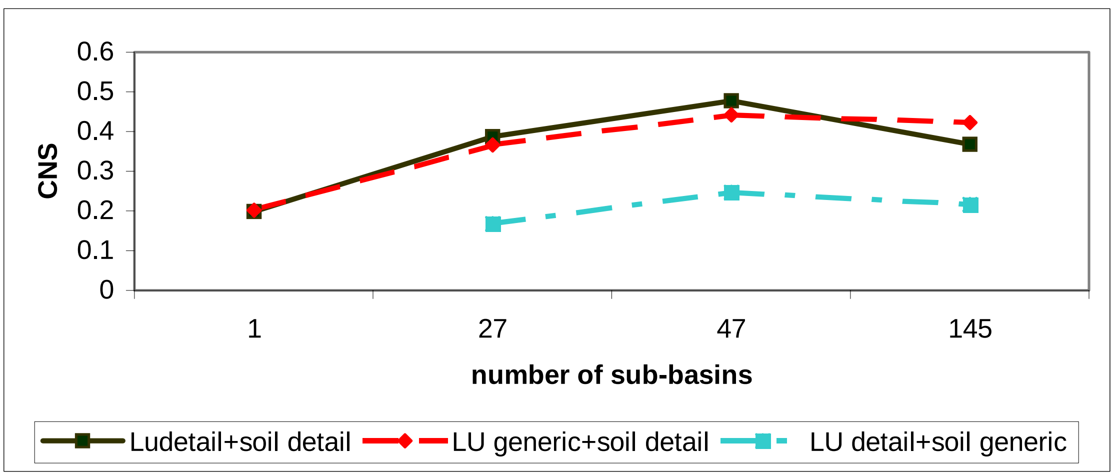

Figure 2. The Nash-Sutcliffe coefficient for different map inputs combination and different amount of sub-catchments (LU- land use map type).

IV. Supporting Tools for SWAT

DSIRR: A DSS for an Economic and Environmental Analysis of Irrigation and Water Policy

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Abstract

In Europe irrigated agriculture consumes about 60% of total water supply and is very important in terms of area, value of production and employment. Simulation models and Decision Support (DS) can play an important role in the definition of basin plans, as requested by the Water Framework Directive. This work presents a tool called DSIRR "Decision Support for Irrigation" designed to conduct an economic-environmental assessment of the agricultural activity focusing on irrigation. The DS is designed to facilitate stakeholders' participation in the planning process generating shared information and can incorporate the decision makers' own insights. A graphical user interface lets the final user run the simulation in a transparent and replicable manner. The program simulates farmers' choices via mathematical programming techniques. A decomposition approach is adopted to identify the relevant cropping systems in a catchment. The tool permits users to describe irrigation in terms of crops, types of soil, and technologies, with consideration of climate. Farmers' preferences are represented via a multicriterial approach. Short and long term analyses can both be conducted; the latter includes innovation in irrigation technology. The DS includes the consideration of environmental and ecological aspects for the sustainable management of land and water in the catchments. Sensitivity analysis of the key parameter and scenario analysis are used to reduce uncertainty. The program is particularly suited to analyze alternative measures of intervention both in water and agriculture. An Italian case study focusing on water pricing in the Po Basin is presented. The results confirm the utility of the proposed tool to define a more environmental, social and economic sustainable policy.

KEYWORDS: Decision Support, Water, Agriculture, Irrigation, Economic analysis, Environmental assessment, Pricing, Policy

Introduction

There is now a strong agreement that water is a strategic resource which requires protection and intervention. Reduced water consumption and in general a more efficient water allocation represent priorities in a context of growing scarcity due to population increase, economic development and environmental constraints, but an integrated approach at catchments scale is necessary for the environmental, social and economical sustainability of the system.

The 2000/60/EC Directive, known as Water Framework Directive WFD, defining the basic principles of sustainable water policy in the European Union EU, states: "Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such." The main goal of the Directive is to reach within 2015 a "good status" for all water (point 11): "As set out in Article 174 of the Treaty, the Community policy on the environment is to contribute to pursuit the objectives of preserving, protecting and improving the quality of the environment, through prudent and rational utilization of natural resources, and to be based on the precautionary principle and on the principles that preventive action should be taken, environmental damage should, as a priority, be rectified at source and that the polluter should pay."

To reach the previous ambitious goal, great attention is given to economic instruments (point 38): "The use of economic instruments by Member States may be appropriate as part of a programme of measures. The principle of recovery of the costs of water services, including environmental and resource costs associated with damage or negative impact on the aquatic environment should be taken into account especially in accordance with the polluter-pays principle. An economic analysis of water services based on long-term forecasts of supply and demand for water in the river basin district will be necessary for this purpose."[2]

The recognition of local specificity is introduced at point 13 where the subsidiarity principle is suggested. "There are diverse conditions and needs in the Community which require different specific solutions. This diversity should be taken into account in the planning and execution of measures to ensure protection and sustainable use of water in the framework of the river basin. Decisions should be taken as close as possible to the locations where water is affected or used. Priority should be given to action within the responsibility of Member States through the drawing up of programmes of measures adjusted to regional and local conditions."

The development of integrated water resources management policies is a very complex and difficult task; it requires the involvement of different physical domains and the integration of socio-economic, natural sciences and engineering. Simulation models and DSS can play an important role to support the participative policy process requested by the WFD to define the Basin Plans, the planning document which must find feasible solution to implement the Directive.

An enormous activity is currently observed throughout the world in the field of integrated catchment modeling. In fact, the analysis and modeling of complex human-technology-environment systems and the implications of complexity and uncertainty for management concepts and decision making represent a promising approach which requires the contribution of scientists working in different fields and disciplines.

The present paper presents a program called DSIRR "Decision Support for Irrigation", which focuses on water demand, use and policy in agriculture, integrating economic models with agronomic and engineering information to tackle the water allocation and management problem at catchment's scale. It is an interactive, flexible, and adaptable computer based information system specially developed for supporting the recognition and solution of complex strategic management problems for improved decision making. It uses data and models, provides a graphical user-friendly interface, and can incorporate the decision makers' own insights. The previous characteristics are relevant to favor stakeholders' involvement in the basin plan definition process, as requested by WFD. The program could be adapted to new and specific

[2] Article 9, Recovery of costs for water services, reinforces this point stating: "Member States shall take account of the principle of recovery of the costs of water services, including environmental and resource costs, having regard to the economic analysis conducted according to Annex III, and in accordance in particular with the polluter pays principle."

situations and integrated into a more comprehensive decision support system.

This paper is organized as follows. First the complex relation water/agriculture is briefly analyzed. In the second section the Decision Support DS is presented in a non technical way. Results from an Italian case study focusing on water pricing in the Po Basin are illustrated in the next section. The final section presents conclusions and suggestion for further development based on the described model.

Water and Agriculture

The relevance of agriculture for water demand can be summarized by one figure: irrigation represents over 50% of the total consumption in most countries. But the relation of water and agriculture cannot be reduced to the quantitative dimension; it should be addressed in all its complexity.

For farmers water represents a production factor, which modifies substantially the set of choices in terms of crops and technology, substantially enlarging it. Irrigation can increase production in quantitative terms, but for many crops and situations this is not the main effect, in fact the use of water increases the quality of production and plays an import role in reducing risk due to uncertain and unstable climate conditions, particularly for vegetables and fruit. Furthermore water permits a standardized production as requested by market. Irrigated agriculture contributes to Gross Domestic Product GDP and export in a substantial way (ISTAT, various years).

Many irrigation techniques exist, some more efficient than others. Consider that furrow irrigation is only 40-50% efficient, while drip irrigation can be over 90%. In between are sprinklers, pivots, and self moving guns, etc. Technologies differ also for other important aspects, among which investment and operative costs, labor and energy requirement.

Water supply is also articulated: private wells and basins on one side, public or common network on the other, these latter differentiated in open channels or pipes. Often more sources are available and farmers integrate, shifting from one to another. Among them important differences exist in terms of environmental impacts as well enforceable policy. To pump water from a well or to use water from external sources have the opposite effect on the local aquifer: the former reduces the available stock, while the latter recharges it.

It is commonly accepted that farmers behave considering a few conflicting objectives, basically income, risk and labor, but their activities also have important impacts on the landscape and environment. In our countries, most of the natural environment is an artifact and in many circumstances agriculture is mainly responsible for water drainage and the preservation of fragile environments. On the other hand, pollution due to agriculture is sometimes a serious problem.

There is strong evidence that the use of water in agriculture favors a more intensive activity which is often associated with a higher use of chemicals. But the link between irrigated agriculture and “non-point” environmental pollution is not so strict. Pollution is due to the qualitative alteration of the environment by chemicals, not by the use of water itself. Therefore a proper comprehension and description of the production process is necessary to define suitable measures of intervention. Organic farming and intensive chemical agriculture represent two extremes of a large spectrum of alternatives, characterized by different technologies, use of inputs and outcomes in the socio-economical and environmental dimensions.

An adequate quantitative representation of the agricultural production and irrigation processes, in physical and economical terms, and how decisions are made is therefore essential for a tool designed to support policy definition and to guide the system toward more sustainable patterns.

The Program

DSIRR is a scenario manager for agro-economic models solved via mathematical programming techniques (MPT) implemented in GAMS (General Algebraic Modeling System) (Brooke, 1992). The present beta non-commercial demo version operates as a 32-bit Windows application, on a PC with at least 32 MB of RAM, more is recommended to improve speed and problem dimension. The code is written in Visual Basic. GAMS package should be installed on the PC. A copy of the program is available from the author. For more information see Bazzani (2003) and Bazzani and Rosselli Del Turco (2003).

DSIRR is a simulation tool which reproduces choices taken by farmers and estimates impacts in the social, economical and environmental dimensions. The models integrate the economic theory, enriched by the multicriteria paradigm, with institutional, agronomic and environmental aspects.

The relevant aspects of the production and irrigation problems are considered: farming conditions, technology, crop diversification, water availability, as well as labor and capital requirement and environmental dimensions. Seasonality can be considered. Different types of farms can be modeled and aggregated ranging from small scale family farms to large commercial ones, from intensive fruit and horticulture productions to extensive cereals and industrial crops.

Indexes can be estimated to assess environmental pressure deriving from agriculture: nitrate, chemicals, energy use and soil covering are considered. Their quantification permits users to assess trade-offs with economic performance, employment, and water use, to support the policy process.

The user can run the simulation without any specific knowledge of MPT and modeling techniques thanks to a Graphical User Interface GUI, predefined equations which adapt to the context, and internal logical rules which verify the coherence of the users' choices and modifiable databases to introduce coefficients. The subsequent steps, i.e. set definition, parameter setting, equation writing, model resolution, output generation, are controlled by the main menu, the toolbar and the dialog windows of the GUI. Utilities permit users to access and modify databases, view reports and tables, create charts, and adapt the working environment to specific needs.

The present version can export the results to Excel in table and graphical form and store them in text form permitting an easy interfacing with other models and programs. Standard output includes: land use (i.e. crop mix), economic balance sheet, irrigation level adopted by crop and technology, labor and water requirements, environmental indices included water consumption.

The program adopts a decomposition approach which can be carried out in a flexible way to reach the scale level adequate to the management issues at hand. The temporal and spatial scales can be defined to describe in sufficient detail the complexity of the analyzed reality. The decomposition of the basin in homogenous sub-basins, the identification of the relevant cropping systems, the construction of representative farms, the selection of the relevant objectives and their weighting distinctly by farm, the choice of parameters describing the production and irrigation processes is conducted via an interactive process open to end-users.

Scenario analysis is adopted to explore different states of the world related to macro-economic conditions, subsidies, environmental taxes, quota, technology innovation or environmental conditions. Their use permits to deal with uncertainty in a practical way.

Another important advantage of the program is the capability to perform the different steps requested by the analysis in a transparent and replicable manner as requested in participatory processes.

DSIRR represents an effective interface between science, policy and end user; the software tool and the information background remain in the background as one of the main issues for operational exploitations of the DS potentials in practice.

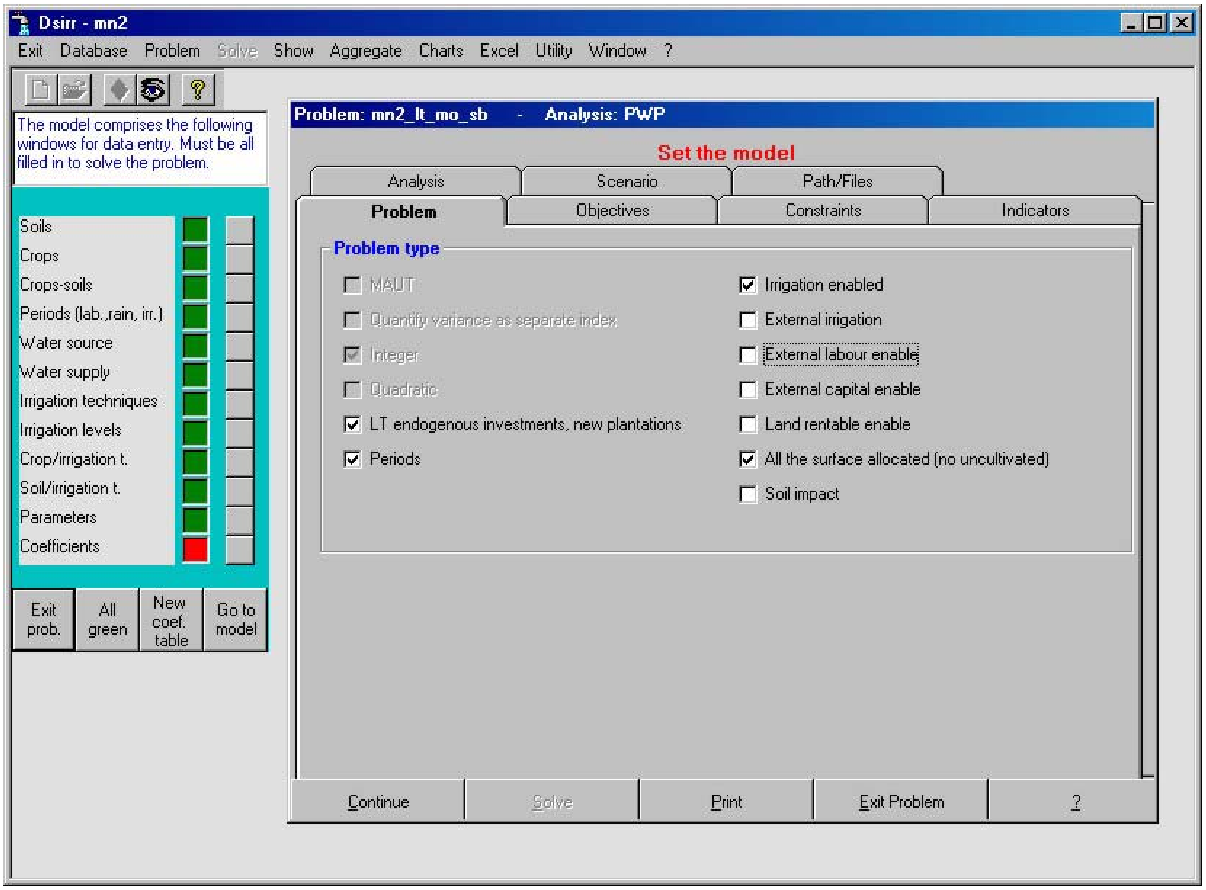

Figure 1 DSIRR GUI

The Models: a Non-Technical Description

A review on modeling water resources management at catchment scale is presented by McKinney D. C. et al. (1999). Review of the existing literature shows that economic models seem well suited to describe and analyze decision process and policy.

A body of economic literature focuses on models dealing with agriculture and irrigation, most of them describe the water price/quantity relation in terms of a function called *demand curve.* Such a function permits users to generate relevant information, i.e. water consumption, farmers' income and water agency revenue at different water rates, and to see their variation in response to price changes (Howitt, 1980) on the basis of land use and technology choices. The curve is generally estimated using MPT (Doppler et al., 2002; Garrido, A., 2000; Varela-Ortega et al., 1998). Following this approach DSIRR analyses the conjoint choice of crop mix, irrigation level, technology and employment as an optimization problem. The problem is cast as constraint maximization.

The stakeholders' preference consideration and their inclusion into models is an important requirement to predict the effect of policy intervention. Recent literature shows that farmers' behavior can be better captured and described via the multicriteria MC paradigm (Berbel et al., 1998; Gómez-Limón et al., 2000 and 2002). In DSIRR the objective function, the operating rule which the model follows reproducing the farmer's behavior, can be specified distinctly by farm. The Multi Attribute Utility Theory (MAUT) paradigm with a linear utility specification is adopted (Ballestrero et al., 1998). Income is included among criteria to maximize. Risk, labor and a difficulty management index, measuring farmer's concern of technical and organizational complexity, represent objectives to minimize.

From an economic point of view, important differences exist between short term (ST) and long term (LT) analysis in terms of variables, objectives and constraints (Ward, 2002). Both can be conducted in DSIRR. ST represents the preseason moment in which the farmer decides the crop mix, the agronomic aspects and the irrigation scheduling constrained by the existing investment in land, orchards and equipments. In the ST no new plantations are possible, neither farm size variation or technology innovation while seasonal labor can vary. Income, a relevant farmer objective, is generally defined as operating income, i.e. differences between sales plus subsidies and operating costs. Constraints are reduced in the LT since it represents the planning period in which the farmer can modify completely the farm structure and make new investments. The size of the farm can be changed, new orchards can be planted, and irrigation technology can vary. Net income, which also considers investment costs or profit, identifies the income objective.

Water availability is defined at farm gate distinctly for periods and delivery systems. Water prices can be differentiated among periods and for level of water consumption. Irrigation techniques are distinct in fixed systems (furrow and drip irrigation) and moveable systems (sprinklers and guns), according to the possibility to use the same equipment in different plots. Each technique is characterized by proper coefficients defining: capacity, efficiency at farm level, energy and labor requirements, and investment costs as annual depreciation, conservation and interest.

Water yield functions describing crop responses to water can be constructed starting from experimental data or pseudo number generated by other models. The consideration of only few relevant points keeps the model linear. A water balance verifies that water consumption, quantified on the basis of crop irrigation requirements, does not exceed farm water allotment which can be exogenously fixed. If seasonality is considered, a total per year water availability constraint can be introduced, water allocation among periods is endogenously determined.

Labor is diversified in family and external. Labor balances by periods are present; such equations consider labor irrigation requirements which are diversified among technologies. Rotational constraints can be easily included to represent agronomic aspects determining links among crops. Separate equations permit to analyze financial aspects.

Different agricultural regulations can be described. One option reproduces the per hectare subsidy approach adopted by the CAP with Agenda 2000, another option completely decouples subsidy as suggested by the Mid Term Review. Environmental conditions, i.e. rain, water table and crop evapotranspiration, can be considered.

A Case Study

The case study here presented considers the Po Basin, the largest irrigated plain area in Italy. The Basin is characterized by homogeneous climate and environmental conditions, with cold winters and hot summers. Agricultural statistical data available at national and regional level show that different production systems coexist according to local specificity. The analysis compares the impact of a pricing policy (Joahansson et al., 2002) on two important cropping systems: extensive annuals and fruit. In both cases family farm is the prevailing form.

Data integrate official statistics (ISTAT) with private sources represented by the water board archives, farmer and producer association records and *ad hoc* on-field inquiries conducted in the previous years via direct interviews to farmers.

Seasonality in the dry period May-August is explicitly considered on a monthly basis. Experimental research conducted in recent years by the Reclamation Board for Emilia Romagna Channel (CER, 1986) permitted to estimate water-yield functions. Prices and quantities refer to an average of the period 2000-2002.

<u>The annual extensive crop system</u>

The annual extensive crop system is relevant in terms of surface covered; furthermore cereals and soy bean are highly subsidized by the current Common Agricultural Policy (CAP). Sugar beets represent an important crop for the higher return offered. Set aside complies with the existing CAP (10%). Wheat represents a feasible alternative in dry farming. The representative farm considered is about 40 ha of arable land and requires one working unit.

Flat rates for water fees are currently used, the simulation analyzes the impact of a pricing policy. Figure 1 presents water demand (WD), farm net income (NI) and water agency revenue (WAR) for the annual cropping system.

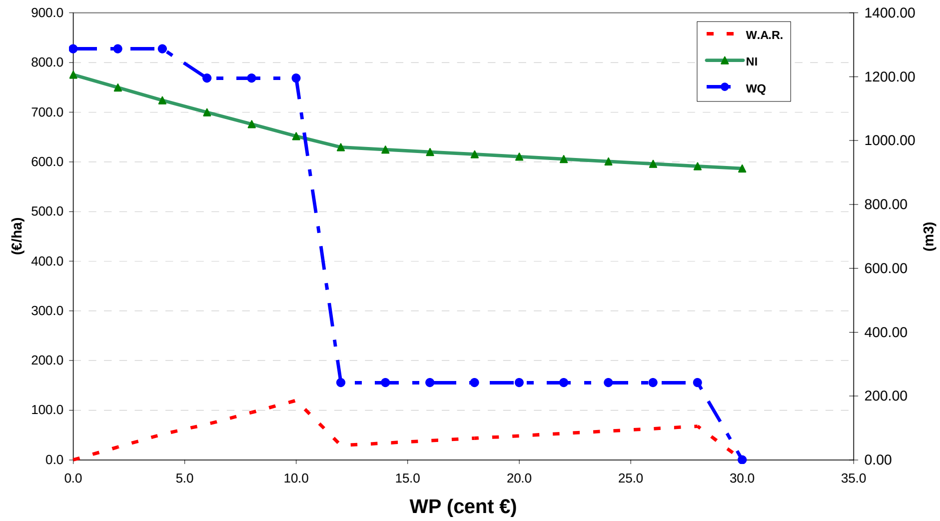

Figure 2. Water pricing on annual crops system

All the figures estimated describe the main trend and should be interpreted more as indicators of a possible and probable path than exact numbers. In this context this information will be used in a relative way, to compare the impact of the same policy on another system.

Water consumption is reported on the right vertical axis. At zero cost of water the optimum crop mix is given by maize (52%) sugar beet (29%) and soybean (12%), all full irrigated, plus the set-aside requirement. This mix reproduces well the observed reality and determines a WD about 1300 m^3/ha. The prevailing irrigation technology in the district is represented in this case by self moving gun. Having calibrated the model at the current zero price, water demand function was derived for the current CAP with a fixed subsidy of 420 €/ha for cereal and oleoprotoleaginous COP. Rising of the WP determines three interlink adaptations regarding irrigation levels, technology, crop mix, which are all endogenous to the models. In fact a WP around 10/12 cent €/m^3 splits the curve into two regions. Maize characterizes the first region but leaves the field to rain-fed wheat in the second, which determines a sharp drop in the demand. The smaller jumps along the curve are due to the progressive decrease of the crop irrigation levels. Water consumption becomes null at a WP of 30 cent €/m^3 where the crop mix is reduced to wheat and set aside.

The impact on NI and WAR can be visualized on the left vertical axis by the continuous and dotted line respectively. Income decreases from 775 €/ha at zero price to 630 €/ha at WP 12 cent €/m^3 (81%) and to 586 €/ha at 30 cent €/m^3 (76%). WAR has a maximum at WP 12 cent €/m^3 at about 120 €/ha where the entire surface is irrigated. Higher WP reduces WAR due to the reduced water consumption.

Table 1 reports the main indicators for three price levels, which identify the current situation (WP=0), medium (WP =15), high (WP=30). For a complete description on the methodology adopted see Bazzani et al. (2003a).

WP	WQ	NI	WAR	SUB	GDP	LF	LE	ENE	NIT	PES
0	1287	776	0	371	928	16	0	-146420	-24	816
15	242	625	36	184	764	14	0	-93756	-36	820
30	0	587	0	261	704	12	0	-72015	-8	257

Table 1. Annuals system indicators

Most of the indexes show a decreasing trend, revealing a production deintensification process induced by the pricing policy. At WP 15 cent €/m^3 water savings are about 80%, and maize is not irrigated since the marginal value of water for this crop is only 10 cent €/m^3. The high WP shifts the system to rain fed agriculture. The impact on NI is negative -20% and -25% respectively, only in minimal part caused by a transfer to water agency, mostly caused by the different crop mix and production process adopted. Subsidy (SU) first decreases, since the per hectare value is much lower for wheat than for maize; the final increase is due to the substitution of sugar beet, not supported by CAP, with cereals. GDP contribution always decreases –18% and -24%. Also employment, completely linked to family labor (LF) decreases –13% and -25%. Environmental indicators show an articulated pattern: energy balance (ENE) improves by 36% and 51%; nitrates balance (NIT) first shows a better performance 50% for the presence of soybean in the crop mix, then the index reverses since only cereals require more nitrates than the original crop mix. Pesticides (PES) do not vary at a medium WP but present a strong decline in consumption –70% in the extensive final combination.

The study conducted shows that a water pricing policy could be very effective to save water, reducing water consumption in the annual crop system characterized by maize and sugar beets. But the same policy has also others impacts on the socio-economic and environmental dimensions which should be carefully addressed. A trade-off among conflicting objectives emerges which the analysis can quantify leaving to the political process the final decision.

<u>The fruit system</u>

In the Po Basin the fruit system is relevant for added value and employment. External markets represent an important destination for this production which is concentrated in the eastern region, where climate conditions are more favorable for the sea proximity. Figure 3 presents the impact of a pricing policy.

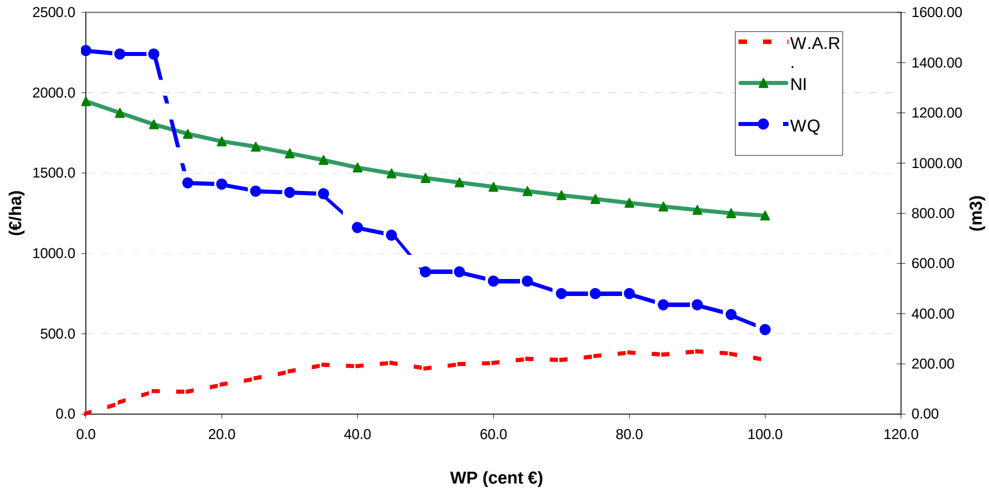

Figure 3. Water pricing on fruit system

The curves present a similar pattern but are very different in magnitude. Water demand for low WP, below 10 cent €/m^3, is stable at about 1400 m^3/ha; irrigation on annual crops is profitable. Increasing WP irrigation on annual crops is abandoned and the curve shows a sharp decline to about 900 m^3/ha. This volume is kept in the range 15-35 euro cent/m3. A relatively elastic area follows: irrigation is abandoned on less profitable crops, such as grapes, apricot and some nectarines. The curve becomes again quite inelastic up to 1 euro/m3, where irrigation is still profitable on kiwi, pear and plumb. The curve has been cut here because higher prices have no real interest since they will never be implemented.

NI and WAR show opposite trends. NI from nearly 2000 euro/ha at zero WP declines quite linearly to 1350 euro/ha at the maximum WP. WAR shows a constant increase up to a WP of 90 cent €/m^3 where it reaches a maximum of about 400 euro/ha. It should be noted that the level of these curves is much higher than the one observed in the annuals cropping system.

Other important differences emerge in Table 2 presenting the fruit system indicators for the WP levels previously identified.

WP	WQ	NI	W.A.R.	SUB	GDP	LF	LE	ENE	NIT	PES
0	1448	1948	0	98	2831	198	7	-36348	65	28630
15	921	1744	138	98	2614	193	7	-31816	66	28592
30	882	1622	265	95	2489	191	7	-30590	66	24885

Table 2. Fruit system indicators

A pricing policy also in this case determines articulated impacts, some positive and some negative; the conflict among environmental, social and economical objectives require trade-offs which the DS can quantify supporting the policy process.

The WP increase from zero to 30 cent €/m^3 determines the following effects: WQ decreases by 39% which is a positive effect, NI declines –17%, this represents the price paid by farmers as reduced family income, only in little part transferred to the Water Authority. SUB increases +3% since annuals crops cover higher extension due to the extensivation process, while GDP declines -12%. Impact on employment is negative, family labor LF –4%. Environmental indicators show a mixed pattern: a decrease in ENE –16% and PES –13%, NIT are stable +1%.

The aggregate results are quite different when compared with the annual crop system, at the high WP water demand is now about 900 m^3/ha while before it was null, in fact the marginal water value in fruit is in fact much higher and this is strictly linked to a much higher labor requirement LF (200 and about 12 h/ha respectively) and NI (1600 and 600 euro/ha). These figures not only confirm that fruit is a more intensive activity which takes greater advantage of water, but also quantify the value of the resource for the system. Fruit systems may cause stronger pressure on the environment for PES and ENE, but NIT is not a problem.

Conclusions

DSIRR is an innovative program which permits users to support water management in agriculture, integrating micro-analysis at farm level with macro analysis at catchment scale.

Among the main characteristics of the DS are:

- a Graphical User Interface which permits a direct control of the simulation by the user;
- integration of agronomic, engineering and economic aspects;
- farmer’s preferences consideration via a multicriterial approach;
- incorporation of the decision makers and stakeholders own insights;
- flexibility in model definition;
- transparent and replicable processes;
- richness of information produced covering socio-economic and environmental aspects;
- reduction of costs, time and effort to generate shared information;
- a modular approach enabling a continuous development of the program which can be easily linked to other models and software.

In brief, DSIRR is not a generic overall system but a very specific tool to analyze water use and policy in agriculture with great attention to local situations in a macro context.

The DS is currently used in the context of the EU WADI project to study the impact of

WFD on irrigated agriculture in Italy (Bazzani et al., 2002 and 2003b). The research points out that relevant differences exist among cropping systems coexisting in the Po Basin. In fact, while the annual crops are quite sensible to a water price increase, fruit exhibits a much more inelastic response. The implementation of a pricing policy could have strong effects in terms of water saving in annual crops but is quite ineffective in fruit where it would mainly reduce farm income and deteriorate the market competivity of the system. But even when economically sound, a pricing policy is seldom technically feasible in the Po Basin since the existing network is mainly represented by open channels[3], therefore it is difficult to meter consumption which is a necessary condition to volumetric pricing. Rationing the resource could in this context represent a feasible alternative but this could increase water table extraction with negative environmental impacts. Transaction costs involved with this policy for monitoring and enforcing should not be neglected and studies conducted show that they are high. A feasible policy seems to require the adoption of a mix of policy instruments with strong attention to local specificity. Technological innovation in irrigation and the adoption of less water demanding crop varieties represent promising solutions which anyhow require research and technical assistance in agriculture. The diffusion of water saving technology could be largely favored by some form of incentive which could be made dependent on the adoption of soft agricultural processes, i.e. forms of agriculture characterized by a reduced use of chemicals and operations. At this regard the CAP reform opens interesting opportunities decoupling subsidies from production and introducing eco-sussidiarity. The support coming from DSIRR to analyze these alternative scenarios can be effective and this will be objective of future research.

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Benchmarking Models for the Water Framework Directive: Evaluation of SWAT for Use in the Ythan catchment, UK

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Abstract

The principle objective of the EU project Benchmark Models for the Water Framework Directive (BMW) is the establishment of a set of benchmark criteria to assess appropriateness of models for use in implementation of the Water Framework Directive (WFD). With regard to diffuse pollution, models are required to determine links between pollution delivery from land to surface water bodies, downstream processes and in-stream ecological impacts. A hierarchical series of benchmark criteria, to be applied on a case specific basis, have been developed for selection of diffuse pollution models. The criteria have been applied to the Soil Water Assessment Tool (SWAT) to evaluate the suitability of the model code for use in the Ythan catchment, UK. Nitrates thought to originate from agricultural fertilisers have been identified as the main pressure within the Ythan watershed, which was designated as a Nitrate Vulnerable Zone in 2000. SWAT performed successfully within the benchmarking process. The model operates at an appropriate spatial and temporal scale resolution to adequately simulate nutrient transformation and transportation in the Ythan catchment. With respect to the WFD, SWAT provides information that is appropriate to the needs of water managers for development of river basin management plans. As such, SWAT is believed suitable for use in this case.

Introduction

Mathematical models provide a practical technique for examination of pollutant transport and transformation at the river basin scale. Many model codes have been developed that simulate different processes in different water bodies. These model codes range in complexity. Each model possesses a unique set of characteristics, for example, processes simulated, spatial and temporal scales of operation and data requirements. Selection of an appropriate model code to meet the requirements of a specific modelling application can therefore be a difficult task for which assistance may be required.

The EU project Benchmark Models for the Water Framework Directive (BMW) aims to provide guidance to aid selection of model codes for use in the field of water management, specifically in the context of the Water Framework Directive (WFD). This guidance is to be provided through the development of model benchmarking techniques. Benchmarking is the process of comparing performance against an accepted standard, best practice, or the performance of others. It is intended that the benchmarking processes will also help model developers improve computer codes to better suit water management purposes. The benchmarking process, as developed within BMW, consists of two main stages, evaluation of model codes in relation to qualitative benchmark criteria and assessment of model performance relative to other simple models.

This paper describes an application of the benchmark criteria to the Soil Water Assessment Tool (SWAT). The model is evaluated to determine suitability for use in the Ythan catchment, UK, an area where diffuse nutrient pollution, specifically nitrates from agricultural fertilisers, has been identified as a main pressure on water quality (Edwards et al., in press;

Edwards et al., 1990; Raffaelli et al., 1989). In particular the benchmark criteria were applied to determine the suitability of SWAT for:

(1) Identifying and quantifying nutrient source areas within the Ythan catchment;

(2) Investigating nutrient delivery from land to surface water;

(3) Assessing the effectiveness of potential management scenarios for reducing in-stream nutrient loading in the catchment.

Methodology

The benchmark criteria are divided into two main categories: generic (for application to all models), and domain specific (for application within individual modelling domain such as diffuse pollution, rivers and groundwater). The criteria are applied on a case specific basis, i.e. with a particular application in mind. Hence, it is the model application not the model code that is benchmarked. Given the modelling objective for the Ythan catchment, the diffuse pollution criteria have been selected to assess SWAT's suitability for use. The generic benchmark criteria, also used in the assessment, are not included within this paper.

The diffuse pollution benchmark criteria are hierarchical in structure. The criteria are divided into seven categories: model suitability for use, data availability, modelling objectives and requirements of the WFD, spatial and temporal scale resolution, transformation and transportation processes, data processing, and model output and model integration (Figure 1). A series of questions are asked under each category. The questions are answered by selecting the most appropriate statement from three options. This should be done with the modelling objective in mind. The statements classify the model application as good, ok or poor with regard to a particular criterion. Selection of certain statements results in the model code being ‘not recommended’ for use (Table 1). The number of criteria falling into each class provides the assessor with an indication of model suitability for use. Considerable research is required to accurately assess the suitability of a model code that is previously unknown to the evaluator.

Results and Discussion

Given the modelling objective detailed above SWAT performed successfully when evaluated against the qualitative diffuse pollution benchmark criteria. The model achieved a ‘good’ classification for 70% of the questions asked and at no point during the assessment was it ‘not recommended’ for use. Initial investigations indicate therefore that SWAT is suitable for application within the Ythan catchment.

As it was developed for application at the river basin scale, SWAT operates at an appropriate spatial extent for use in the Ythan catchment (680ha). The model meets the requirement of the WFD to assess receiving waters in the context of their respective river basins. SWAT accounts for regional climatic (e.g. precipitation and air temperature) and catchment (e.g. topography, land use and soil type) characteristics and as such is considered capable of capturing the nature of the Ythan region. Importantly, there is a good balance between the model data requirements and data availability for the Ythan. Where necessary, field measurements can be supplemented by derived data or values taken from literature. It is believed that all necessary data can be provided with a reasonable degree of accuracy. SWAT has been successfully applied in Europe and the UK (Boorman, 2003; Bouraoui, 2002). The most recent work conducted within the UK has however, focused on evaluating the impact of climate change on water quality.

SWAT includes inputs for the main nutrient sources in the Ythan catchment. It delineates catchments and sub-catchments into hydrological response units, a scale that is considered to provide sufficient information regarding spatial heterogeneity to effectively model nutrient flux in the Ythan region. Although not fully distributed, the model is believed to provide an adequate level of differentiation to enable key nutrient source areas to be identified. Sufficient information is provided to examine the relationship between land use and water quality at the sub-catchment level. As it is capable of long-term simulation (>10years) at a daily resolution, SWAT can be applied to identify and quantify both inter- and intra-annual variation separating natural from management related changes. The capacity of the river basin to store nutrients in soil, vegetation and groundwater dictates that it can take some time to assess changes in anthropogenic activities that may have an impact on water quality. Long-term simulation enables the extent of any potential changes to be determined.

Theoretical documentation indicates that SWAT effectively simulates the key bio-geo-chemical processes and interactions governing the fate of nutrients in the catchment system. It accounts for the main factors influencing nutrient transport and transportation (e.g. soil temperature and moisture content). Driven by a comprehensive hydrological model SWAT simulates the main pathways for nutrient transport from land to water in addition to routing water and nutrients through the river system. However, the suitability of the Universal Soil Loss Equation (USLE) for use in Scotland has been queried as the equation fails to deal with soils where organic matter contents are greater than 4%. Most Scottish soils have organic matter contents in excess of this threshold (Lilly et al., 2002).

Prediction of nutrient fluxes at the catchment scale requires consideration of river, groundwater and land-based processes. SWAT is a good general-purpose model that includes both groundwater and river components and as such is considered to be comprehensive and stand-alone. Output from SWAT has been used to provide sub-catchment level nutrient loadings as an input to QUESTOR, a specialised river model (Boorman, 2003). If necessary, SWAT will be coupled with a dedicated river model during the Ythan application.

The WFD mandates the development of river basin management plans detailing how Member States will prevent further deterioration and protect and enhance the ecological status of receiving waters. These management plans will specify pollution control strategies based on best management practices. To achieve this aim, water managers must assess the implications of potential management scenarios on water quality. The facilities developed within SWAT to enable the assessment of long-term implications of various management strategies make it a suitable tool for evaluation of a variety of scenarios of relevance to the Ythan catchment. These include good agricultural practice (e.g. timing and amount of fertiliser applications), the effects of buffer strips and land use change.

Conclusion

SWAT performed successfully when evaluated against qualitative diffuse pollution benchmark criteria and is therefore believed suitable for use in the Ythan catchment. The model code is considered to meet the requirements of the modeling objective, detailed above, in addition to providing information required by water managers for the development of a river basin management plan for the area. The evaluation of the model has highlighted the USLE as a potential problem with regard to application of SWAT within Scotland.

Following application of SWAT within the Ythan catchment the second quantitative stage of the benchmarking process, an assessment of model performance, will be undertaken.

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Table 1. An example of a benchmark question indicating the three possible answers.

Data requirement versus data availability	
Good	Sufficient field data available to calibrate, validate and apply model.
OK	Good balance between data requirement and availability. Where necessary data can be derived or taken from literature to supplement field data. Any assumptions made must be robust.
Not recommended	Insufficient data to reliably run the model.

Figure 1. Structure of the qualitative diffuse pollution benchmark criteria.

Hierarchy of qualitative benchmark criteria

1.0 Model Suitability for use

2.0 Data availability

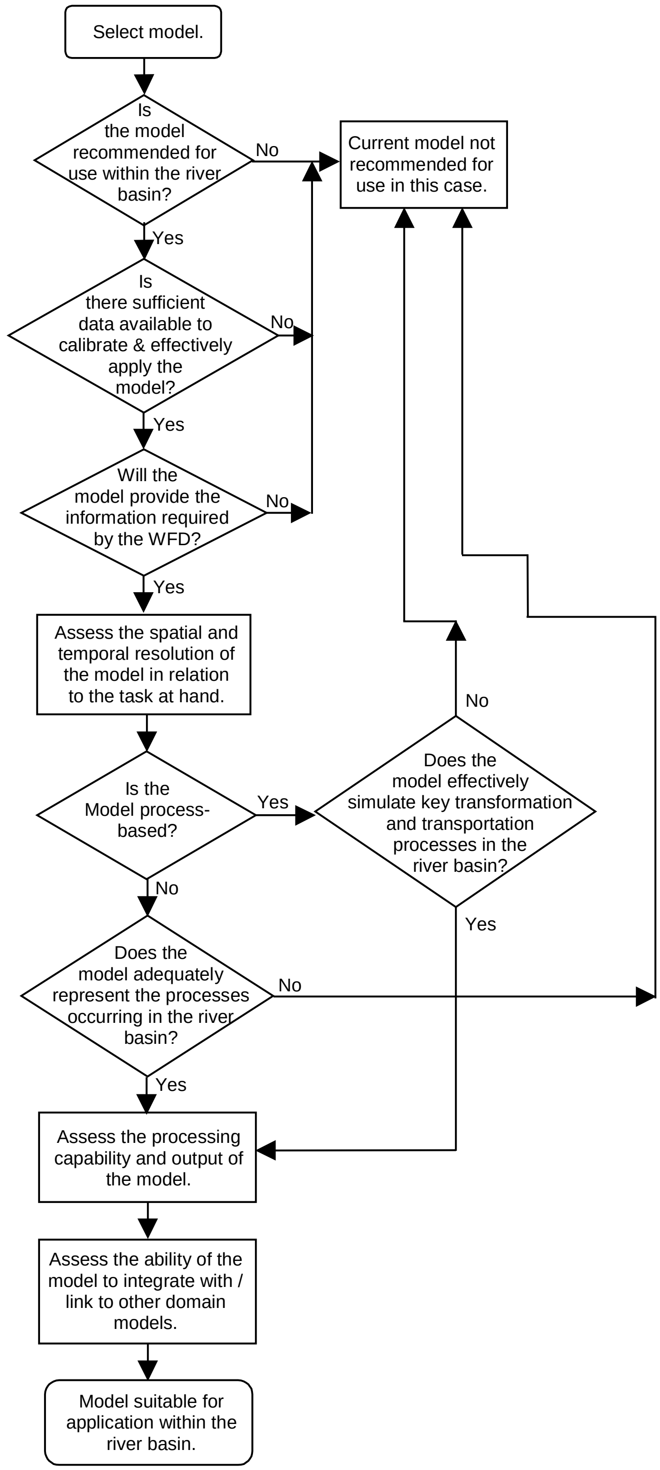
3.0 Modelling objective / requirements of the WFD

4.0 Spatial and temporal scale / resolution

5.0 Transformation and transportation processes

6.0 Data processing and model output

7.0 Model integration



The Significance of the Differences in Soil Phosphorus Representation and Transport Procedures in the SWAT and HSPF Models and a Comparison of Their Performance in Estimating Phosphorus Loss from an Agriculture Catchment in Ireland

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Abstract

Phosphorus transported from agriculture land has been identified as a major source of water pollution in a large number of Irish catchments. Models of this process are required in order to design and assess management measures. This paper reports on the comparison and assessment of two of the most promising physically-based distributed models, SWAT and HSPF, with particular emphasis on their suitability for Irish conditions. The representation of the overall soil phosphorus cycle is similar in both models but there is a significant difference in the level of detail in describing the chemical and biochemical processes in each model. There are differences in modeling the mechanisms by which phosphorus is removed from the soil column and transported in dissolved form with the runoff water or in particulate form attached to eroded or detached sediment. These differences could have a significant influence on performance when using either of the models to simulate phosphorus loss from any catchment. Both models are applied to estimating the phosphorus concentration at the outlet of the Clarianna catchment in north Tiperrary (Ireland). This catchment is small ($23km^2$) and the land use is mainly pasture on grey brown podozolic soils. The results of model calibration are presented along with an assessment of the usefulness of the model outputs as a water quality management tool.

Introduction

Removal of phosphorus (P) from the soil is influenced by various physical and chemical parameters. While the physical parameters control the generation of water fluxes which represent the deriving force for P removal, the chemical parameters affect the chemical transformations occurring to the different P forms in the soil and water. Any model to account for P loss from soil should have a structure incorporating a simulation of both the flow generation and the P transformations in order to utilize them in the estimation of P removal. The Soil Water Assessment Tool (SWAT) model and the Hydrological Simulation Program – FORTRAN (HSPF) model both have the required structure to deal with flow and phosphorus components, though their methods differ. The two models have been used in a study within the European Water Framework Directive (WFD) to quantify the amount of phosphorus transported from an agriculture catchment in Ireland.

Eutrophication in water bodies has been identified as a major threat to water quality in Ireland due, in most cases, to excess phosphorous inputs from agricultural land (McGarrigle et al., 2002, pp. 28). The Clarianna catchment is one of many catchments where the phosphorus levels in its rivers has markedly increased in recent years. The catchment area is approximately $23km^2$ and it is located in the middle of Ireland in an area principally occupied by pasture where agriculture and animal rearing practices are dominant. The main soil type in this catchment is grey brown podozolic characterized by a structure allowing good drainage of water in the subsurface layers which in turn enhances the leaching of phosphorus downwards. A limestone aquifer lies beneath the soils.

This paper first describes the main equations used in the SWAT and HSPF models to simulate the soil phosphorus transformations and removal. Moreover, the significance of these equations on the overall estimation of the phosphorus loss simulation is assessed based on the results of the application of both models on the Clarianna catchment to predict the flow and total phosphorus concentration variables. In this assessment the predicted values of the two variables are compared with the available observed data at the outlet location of the catchment for the period between 1/12/2001 and 07/29/2003.

Phosphorus Component in the SWAT Model

SWAT monitors six different pools of phosphorus in the soil. Three pools are inorganic forms of phosphorus whereas the other three pools are organic forms. Fresh organic P is associated with crop residue and microbial biomass, while the active and stable organic P pools are associated with soil humus. The organic phosphorus associated with humus is partitioned into two pools to account for the variation in availability of humic substances to mineralization. Soil inorganic P is divided into solution, active, and stable pools. The solution pool is in rapid equilibrium (several days or weeks) with the active pool, while the stable pool is in slow equilibrium with the active pool. Furthermore, the model assumes that the runoff water removes the P in solution from the top 10 cm layer of the soil while the eroded sediment transports the organic and inorganic phosphorus are attached to the soil particles. The mathematical relations used by the model to describe the chemical transformations occurring between the various soil phosphorus variables and the removal of phosphorus from soil are presented below.

Mineralization/immobilization of active organic P (P_{min})

$$P_{min} = 1.4 \times \beta \times \sqrt{\gamma_{tmp} \times \gamma_{sw}} \times P_{acor} \qquad (1) \qquad \Rightarrow \begin{cases} P_{acor} : \text{storage of active organic P} \\ \beta : \text{rate coefficient of mineralization} \\ \gamma_{tmp} : \text{nutrient cycle temperature factor} \\ \gamma_{sw} : \text{nutrient cycle water factor} \end{cases}$$

Decaying of fresh organic P (P_{dec})

$$P_{dec} = \delta_{ntr} \times P_{fresh} \qquad (2) \qquad \Rightarrow \begin{cases} P_{fresh} : \text{storage of fresh organic P} \\ \delta_{ntr} : \text{residue decay constant} \end{cases}$$

Adsorption/desorption between the solution P and the active inorganic P ($(P_{ads/des})_{sol<->act}$)

$$P_{(ads/des)_{sol \leftrightarrow act}} = P_{sol} - P_{actads} \times \left(\frac{pai}{1 - pai} \right) \qquad (3) \qquad \Rightarrow \begin{cases} P_{sol} : \text{storage of soluble mineral inorganic P} \\ P_{actads} : \text{active adsorbed inorganic P} \\ pai : \text{phosphorus availability index} \end{cases}$$

Adsorption/desorption between the active inorganic P and the stable inorganic P ($(P_{ads/des})_{act<->sta}$)

$$P_{(ads/des)_{sol \leftrightarrow act}} = \beta_{eq} \times \left(4 \times P_{actads} - P_{stads} \right) \qquad (4) \qquad \Rightarrow \begin{cases} P_{actads} : \text{storage of active adsorbed inorganic P} \\ P_{stads} : \text{stable adsorbed inorganic P} \\ \beta_{eq} : \text{slow equilibrium rate} \end{cases}$$

Solution P removed in runoff water (P_Q)

$$P_Q = \left(\frac{P_{sol}}{\rho_b \times D \times k_d} \right) \times Q \qquad (5) \qquad \Rightarrow \begin{cases} P_{sol} : \text{storage of soluble P in the top layer} \\ \rho_b : \text{bulk density of the soil} \\ D : \text{depth of the top soil layer} \\ k_d : \text{soil P partitioning coefficent} \end{cases}$$

Removal of P forms associated with the eroded material (P_{sed})

$$P_{sed} = P_{att} \times \left(\frac{SY}{A} \times \varepsilon \right) \qquad (6)$$

P_{att} : storage of certain P form to be removed with sediment
SY : sediment yield
A : Area of the land
ε : P enrichment ratio

Phosphorus Component in the HSFP Model

In the HSPF model, the phosphorus material is assumed to exist in the surface, upper, lower, and groundwater storages. The surface storage receives external phosphorus inputs and releases organic and inorganic adsorbed phosphorus attached to the eroded material and soluble phosphorus dissolved in the runoff water. All the storages contain three forms of phosphorus--soluble inorganic phosphorus, adsorbed inorganic phosphorus, and organic phosphorus. Only the soluble phosphorus moves from one storage regime to the other with the aid of the flow flux (infiltration, percolation, interflow, and base flow) and it can also be taken up by plant roots. The mineralisation, immobilisation, adsorption and desorption processes can be simulated with a first order kinetic model which has a general form but with different parameter values for each process. The amount of soluble phosphorus dissolved in the surface runoff is calculated as a fraction of the phosphorus storage in the surface layer. The fraction corresponds to the ratio of the runoff rate to the amount of water stored in the surface layer. Likewise, the attached inorganic and organic phosphorus removed with the sediment material are calculated as fraction of the storages of both phosphorus forms in the surface layer. The fraction in this case is the ratio of the amount of sediment eroded to the amount in the parent material. The mathematical equations related to the phosphorus simulation in the HSPF model are as follows.

<u>General form of the first order kinetics equation for simulating the adsorption, desorption, mineralization and immobilization fluxes</u> (P_{flux})

$$P_{flux} = P_{stor} \times K \times \theta^{(T-35)} \qquad (7) \qquad \Rightarrow \begin{cases} P_{stor}: \text{ storage of phosphorus} \\ K: \text{first order rate parameter for the process} \\ \theta: \text{temperature correction factor for the process} \\ T: \text{soil temperature} \end{cases}$$

<u>Solution P removed in runoff water</u> (P_Q)

$$P_Q = P_{sol} \times FSO \qquad (8) \qquad \Rightarrow \begin{cases} P_{sol}: \text{ storage of soluble P in the surface layer} \\ FSO: \text{fraction of soluble P that transported} \end{cases}$$

<u>Removal of P forms associated with the eroded material</u> (P_{sed})

$$P_{sed} = P_{att} \times \left(\frac{SY}{A} \times \varepsilon\right) \qquad (9) \qquad \Rightarrow \begin{cases} P_{att}: \text{storage of P to be removed with sediment} \\ P_{surf}: \text{storage of P in the surface layer} \\ Ratio: \text{ ratio of sediment eroded to that exist in the surface layer} \end{cases}$$

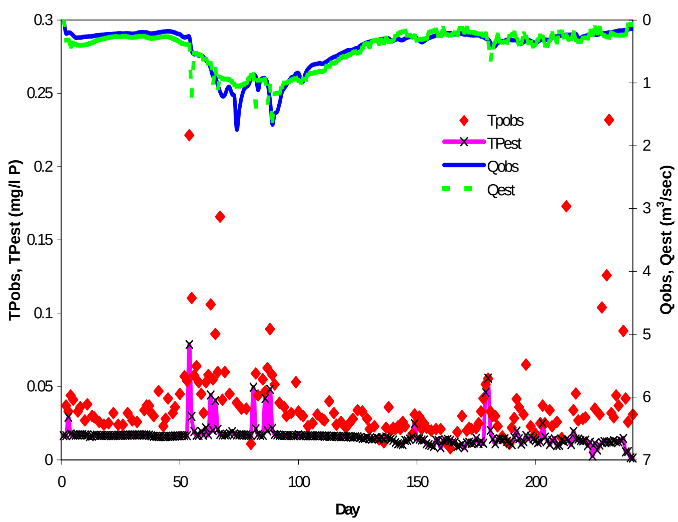
Results

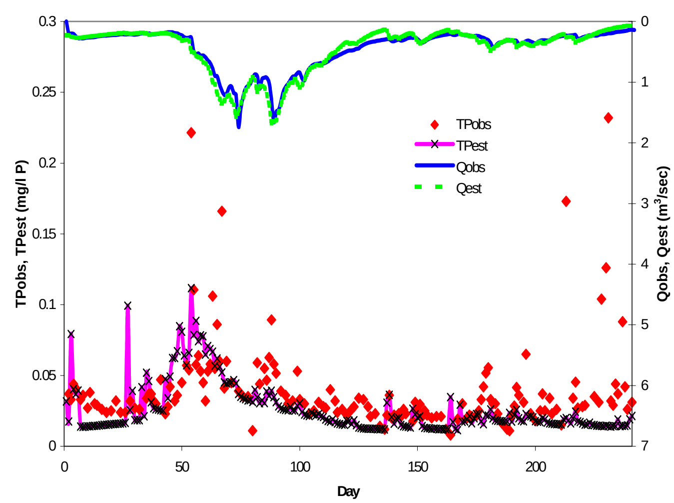
First, the flow discharge estimation with the two models (SWAT and HSPF) at the catchment outlet has been calibrated throughout the period of the simulation. This was accomplished by changing the values of the model parameters which have significant effect on the flow generation of each model. After achieving a satisfactory flow simulation the parameters of the best flow calibration were used in all the phosphorus calibration cases. In each of those cases, different sets of parameters controlling the soil phosphorus transformations and removal for both models were used until acceptable results were obtained. To facilitate an easy comparison among the performance of the two models in predicting the total phosphorus (TP) concentrations only the best results for the flow and the phosphorus concentrations from the two models are presented. Figures (1) and (2) show the results of the flow and the TP using SWAT and HSPF models respectively. In each figure, the observed flow (Qobs) and the estimated flow (Qest) hydrographs were plotted at the top while the observed TP (TPobs) and the estimated TP (TPest) graphs were put at the bottom.

Discussion

Generally, the simulated flow hydrograph from SWAT is not in good agreement with the measured values and is worse than what is obtained from the HSPF model. The general trend in TP prediction with SWAT is that there was nearly constant low TP base values associated with the base flow while there were high TP values taking place during the runoff storms. The constant low TP base values could be the result of the assumption of a constant phosphorus concentration in the base flow, resulting in an inaccurate estimate of the P load contributed by the base flow. Essentially, this means that the model ignores the soil phosphorus movement in the lateral dimension and considers it in the vertical direction only. In addition to the inadequate simulation of the TP values associated with the low flows, all of the high TP values fall below the observed values which could reflect the general tendency of the model to under predict at high flows. There are few high TP values appearing near to the end of the low period. These values are difficult to relate to any of the surface hydrological mechanisms which transport the phosphorus and they were not expected. Despite the fact that simulated flow values were significantly comparable to the observed in the case of HSPF model, the estimation of the TP values was not as good as the flow. Alternatively the model produced high TP values during the initial period which does not match any observed value. Moreover, apart from one point, all the other points with high TP values were under estimated by the model. Similar to SWAT, the model did not reproduce the high TP values associated with low flows at the end of the simulation period.

The total phosphorus concentrations were calculated from both models by summing the average daily loads of the phosphorus delivered with the runoff water (soluble P) and the eroded sediment (attached inorganic P and organic P) divided by the average daily flow discharge at the outlet location. The amount of P delivered with the sediment is always the most important in the calculation of the phosphorus loss since the phosphorus solubility is limited. Therefore, the chemical transformations which occur to the various phosphorus forms in the soil, especially those affecting the storages of the organic phosphorus and attached inorganic phosphorus, have great influence in the phosphorus removal. The equation in SWAT used to account for the mineralisation process depends on both the temperature and moisture content of the soil. In contrast, the corresponding equation in the HSPF model depends only on moisture content, neglecting the effect of temperature. Likewise, the adsorption and desorption processes are temperature dependant in the HSPF model while in SWAT they only depend on a rate coefficient. The difference in the way of describing the chemical transformations in the two models in addition to the flow prediction might impact the phosphorus removal and hence produce the difference in results.





Conclusion

The SWAT and HSPF models were applied to the Clarianna catchment in Ireland to estimate the phosphorus loss to the channel reach. Different simulations for the flow and total phosphorus resulted from the two models. The difference in the mathematical representation of the chemical transformations between the soil phosphorus variables in addition to flow prediction could be the main cause of the difference in the phosphorus simulation with the two models

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A Comparison between SWAT and a Distributed Hydrologic and Water Quality Model for the Camastra Basin (Southern Italy)

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Abstract

Over the last 20 years, the contribution of diffuse pollution sources to surface waters has increased, despite several decades of research on agricultural management practices to minimize water pollution. The main purpose of this research is to make a comparison between the Soil Water Assessment Tool (SWAT) and a distributed hydrologic rainfall-runoff model applied to the Camastra river basin.

The hydrologic and water quality distributed model, based upon a spatial discretization of the territory into elementary square cells, schematises the main hydrological processes of degradation and transport of nutrients, performed on a control volume built on the single cell. For the evaluation of the local generation of surface, sub-surface- and ground-water runoff, a modified version of the WetSpa (Yongbo and De Smedt, 2000) distributed hydrologic model, coupled with a procedure for the nitrogen alteration and transport assessment. Pre-processing and following visualization of outputs has been carried out using geographic information system (GIS) software.

The study area is the 350 km^2 Camastra lake basin (Southern Italy). The water quality data used for the model calibration have been collected in a monitoring campaign performed by the ARPAB (Basilicata Region Environmental Protection Agency). Two simulations over the identical time period have been conducted in the same region by using the developed model and the SWAT model. The comparison shows the difficultly of SWAT to provide good simulations of the stream flows and reservoir balances, which complicates the use of the SWAT model to model the water balance and water quality in the study region.
KEYWORDS. Distributed, hydrological, water quality, modelling, SWAT, comparison.

Introduction

Over the last 20 years, due to the enactment of the Merli law (1976) and recently due to the d.lgs. 152/99 in Italy, the construction of more and better wastewater treatment plants has resulted in a significant reduction of point source emissions. However, the organic river matter and nutrient loads still exceed the threshold values fixed by the legislation. Meanwhile the contribution of diffuse sources has increased, despite several decades of research on agricultural management practices to minimize water pollution.

The development of environmental models, in order to simulate pollutant source effects, and water resources management is one of the research activities carried out at the DIFA Department, (Department of Engineering and Physics of Environment) at the University of Basilicata.

Hydrological and water quality modelling of the generation and movement of water and its pollution content from the source area to the receiving waters provides useful knowledge for water resources management. There are many simulation models in use; the skill is in selection the right model, balancing data requirements against the cost of model implementation.

In order to asses the applicability of hydrological models to small watersheds of the southern part of Italy, it has been choose to make a comparison between the SWAT model and a distributed hydrologic model, which is a modification of a WETSPA model (Yongbo and De Smedt, 2000).

Materials and methods

Study area

The study area is the Camastra River, the major tributary of the Basento River, located in the Basilicata Region, in the southern part of Italy. The watershed area amounts to 350 km^2 with an elevation range from 524 m to 1832 m above seal level (asl)., with a mean elevation of 970 m asl. The watershed is mostly covered (63% of the total area surface) by forests and semi-natural areas, while the remaining part is represented by agricultural areas (35%) and water bodies and artificial surfaces (2%), and includes four municipal wastewater treatment plants. At the final outlet, a dam has been constructed that creates a reservoir of about 40.000.000 cubic meters. The overall course of Camastra is an example of high environmental sensitivity due to the stream regime and the multiple uses (agricultural, industrial, and drinking water) of the lake waters. The Camastra is a typical humid basin of Eastern Basilicata, with a mean annual rainfall depth of *h=1003 mm*. Water discharge was measured daily at the outlet by the authority that manages the lake water resource. Water quality parameters measures were conducted for the lake waters by the Basilicata Region Environmental Protection Agency. The monitoring program obtained samples six times per year.

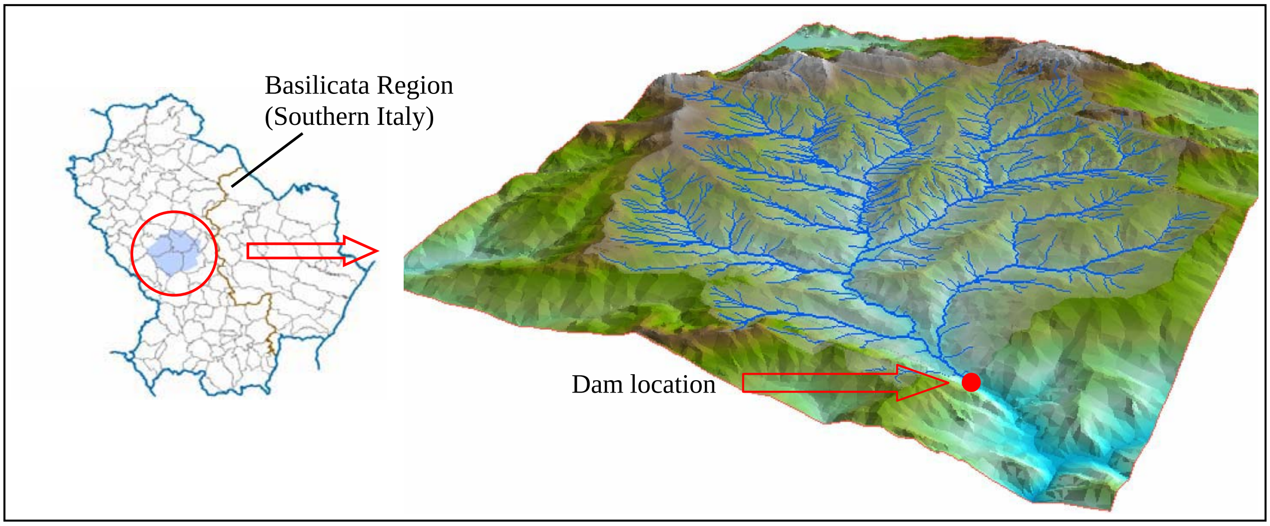

Figure 1. Camastra river basin location, Digital Elevation Model and digitized river network.

The distributed hydrologic model: theory

The hydrologic and water quality distributed model, based upon a spatial discretization of the territory into elementary square cells (cell size 240 m), schematises the main hydrological processes of degradation and transport of nutrients, performed on a control volume built on the single cell.

Surface runoff is proportional to the saturation coefficient, and is locally evaluated. The hydrological processes are simulated in a grid schematization of a river basin. The computation of the runoff for each cell of the grid is carried out by the following equation:

$$Q_S = CP\frac{(\vartheta_t - \vartheta_0)}{(\vartheta_s - \vartheta_0)} \qquad (1)$$

where: Q_s is the amount of surface runoff [L], P is the net precipitation (rainfall minus interception) [L], ϑ_t is the soil moisture content, ϑ_s is the saturated soil moisture content, ϑ_0 is the residual soil moisture and C is defined as default runoff coefficient, which depends upon slope, land use and soil typology. Figure 2 shows the Camastra river basin default runoff coefficient.

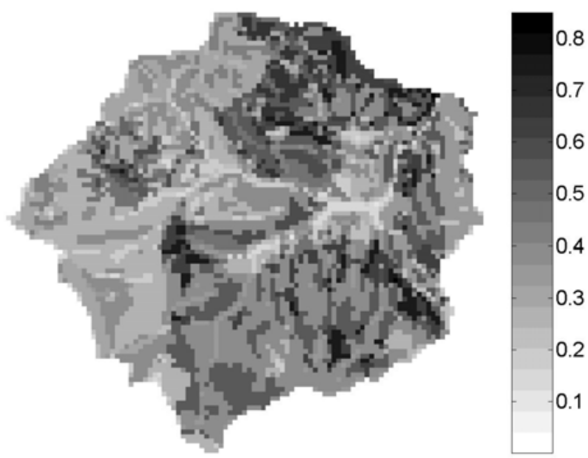

Figure 2. Camastra river basin default runoff coefficient (cell size 240m × 240m).

The soil has been simulated by a bucket (see Figure 3) with variable depth, depending on the land use class. The bucket is the control volume for the elaborations. In the model, soil moisture storage varies continuously depending on rainfall, evapotranspiration, interflow and groundwater recharge. The soil moisture storage has been evaluated by using the following water balance equation, for each grid cell:

$$S_{t+\Delta t} = S_t + F_t - E_t - RI_t - RG_t \qquad (2)$$

Where: $S_{t+\Delta t}$ represents the total water content in the soil profile at time t+Δt [L], S_t is the total soil water content at time t [L], F_t is the infiltration amount into the soil during the time Δt [L], E_t is the actual evapotranspiration from the soil during the time Δt [L], RI_t is the lateral out subsurface flow during Δt [L], and RG_t is the groundwater recharge during Δt [L].

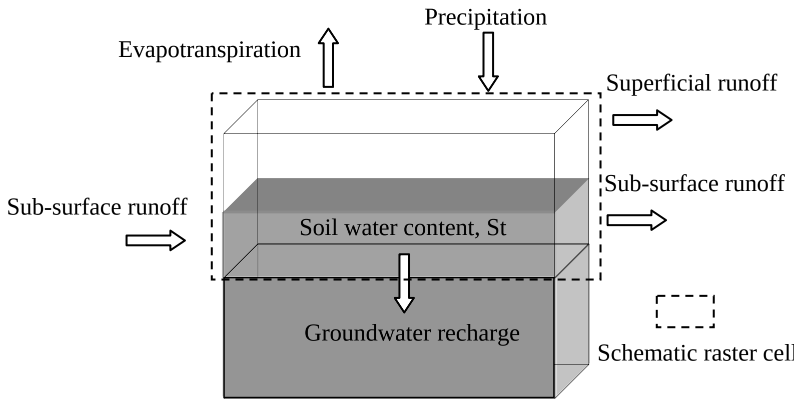

Figure 3. Input and output fluxes in a single cell.

The subsurface flow starts when the soil water content exceeds the field capacity:

$$RI_t = \max\left(0, c_i(S_t - S_c)\right) \tag{3}$$

where RI_t is the lateral in and out subsurface flow of the soil during time t [L], S_t is the total soil water content at t time, S_C the soil moisture storage at the field capacity, and c_i the shallow subsurface runoff coefficient.

The percentage of water that comes into the saturated zone can be derived by the use of the Darcy law:

$$RG = -q = K\,grad(h) \tag{4}$$

where: RG is the groundwater recharge [L/T], K the hydraulic conductivity [L/T], *grad(h)* the hydraulic gradient. The Irmay equation has been used in this study to calculate the groundwater recharge flow of the single cell:

$$RG_t = K_t \Delta t = K_s \left(\frac{\theta_t - \theta_0}{n - \theta_0}\right)^{\alpha} \Delta t = K_s \left(\frac{S_t}{S_S}\right)^{\alpha} \Delta t \tag{5}$$

where: RG_t is the groundwater recharge at time t [L], K_t the hydraulic soil conductivity at t time, K_s the saturated hydraulic conductivity, α an index characterizing dimension and distribution of soil porosity, n the porosity.

The potential evapotranspiration has been determined by the Blanney-Criddle equation, and the actual evapotranspiration has been evaluated by using the equation proposed by *Davies ed Allen* (1973):

$$ET_t = (1 - e^{-b\,(\vartheta t - \vartheta o)/(\vartheta c - \vartheta o)})\,ET_0 \tag{6}$$

where: ET_t represents the actual evapotranspiration [L], ET_0 is the potential evapotranspiration at time t [L], $b = 10.56$ is an empiric value to calculate actual evapotranspiration, θ_t is the soil moisture content at t time, θ_0 is the residual soil moisture content, θ_C is the soil moisture content at the field capacity.

Input data to the distributed model

For the distributed model, a schematization of the territory into elementary cells has been created. All the maps have been converted into raster images with a resolution of 240m × 240m that provides 94 rows and 102 columns. A land use raster map was obtained from the CORINE-Land Cover Project (3rd level) cartography. Figure 3 shows the land use map used in this study for the distributed hydrological model.

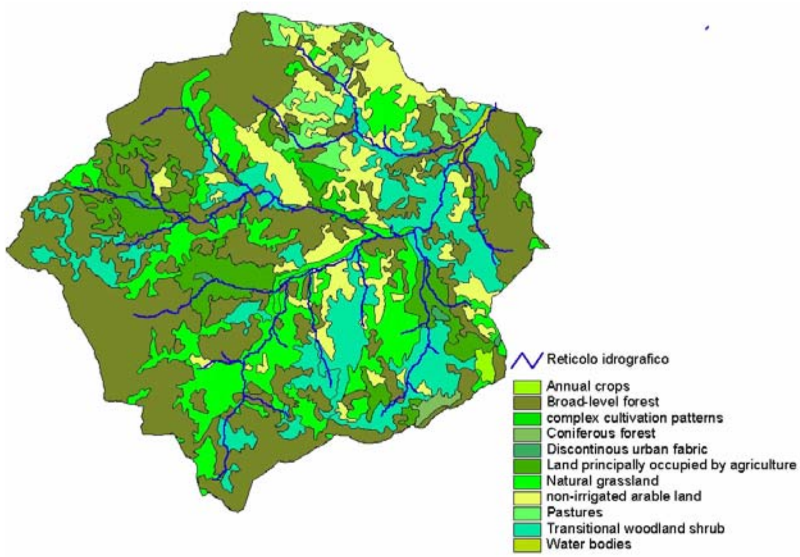

Figure 3. Camastra river basin CORINE-Land Cover (3rd level).

Using a 1:100,000 scale cartography, 12 lithological units were created in the Camastra river basin (Table 1).

Table 1. Lithological formations of the Camastra river basin.

Lithological formation	*Area (km^2)*	*Area (%)*	*Permeability (mm/s)*
Alluvial deposits	10.74	3.1	5×10^{-4}
Flinty limestone	17.98	5.3	5×10^{-4}
Complex “varicolori” clay	129.69	37.9	1×10^{-8}
Internal carbonatic platform	4.12	1.2	1×10^{-3}
Detritic complex	0.77	0.2	1×10^{-4}
“Numidic Flysch”	0.02	0.0	1×10^{-4}
Formation of Schist Siliceous	18.37	5.4	1×10^{-4}
Formation of “Galestrino”	49.76	14.6	1×10^{-6}
Formation of “Gorgoglione”	31.66	9.3	1×10^{-5}
Formation of “Monte Facito”	5.39	1.6	1×10^{-5}
Formation of “Serra Palazzo”	36.47	10.7	1×10^{-5}
Sands and conglomerates	36.82	10.8	1×10^{-3}

The Digital Elevation Model (DEM), available in raster format, was used for the distributed model. It is characterized by a 240m mesh grid (see Figure 4).

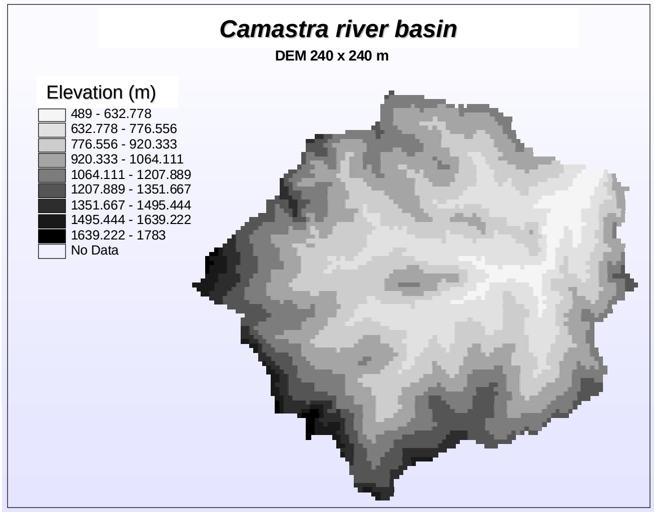

Figure 4. Camastra river basin Digital Elevation Model (cell size 240m×240m) and streams.

Meteorological data was available at tree different stations distributed inside and outside the watershed, consisting of daily precipitation and temperature series from 1997 to 2000.

The SWAT model: theory

The SWAT model (Neitsch *et al.*, 2001) is a semi-distributed and continuous time model that operates on a daily time step to estimate the effects of water management and pollutant releases in stream systems. SWAT allows modelling the entire process of the hydrological cycle, including rainfall, evapotranspiration, water withdrawals, and groundwater recharge. The model allows the division of watersheds into smaller subwatersheds, which are then subdivided into multiple hydrologic response units (HRUs) that create separate, unique combinations of soil and land cover properties in subbasins.

In the SWAT model, surface runoff occurs whenever the rate of water application to the ground surface exceeds the rate of infiltration. SWAT allows estimating of surface runoff with the SCS curve number procedure (SCS, 1972). The SCS runoff procedure is an empirical model that can be schematized with the following equation:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)}$$

where *Qsurf* is the accumulated runoff or rainfall excess [L], *Rday* is the rainfall depth for the day [L], *Ia* is the initial abstractions which includes surface storage, interception and infiltration prior to runoff [L], and *S* is the retention parameter [L]. The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content.

Input data to the SWAT model

Input data required to setup a SWAT run are topography, soil, land use, weather, and management data. For the SWAT model application more detailed spatial data have been used. Particularly, a raster DEM map, with a cell size of 20m × 20m, has been used. A detailed river network layer derived from the GIS Laboratory of the Department of Engineering and Physics of Environment (University of Basilicata) is shown in Figure 5.

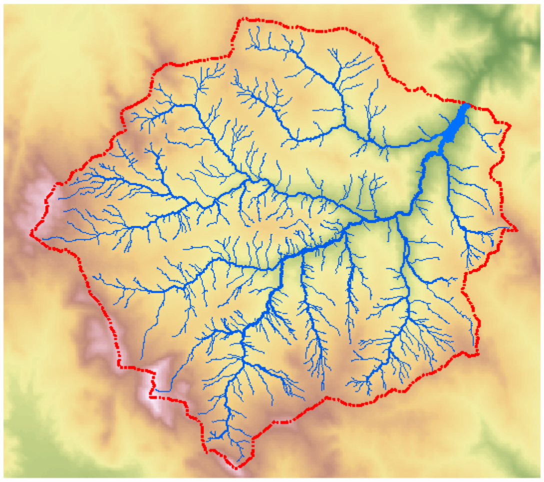

Figure 5. Camastra river basin Digital Elevation Model (cell size: 20m×20m) and streams.

The land use map was provided by the Sigria project (INEA, 2003) cartography, and integrated with the CORINE-Land Cover Project (3rd level) map. A soil map has been obtained by integrating three different soil type maps with an acquisition scale of 1:50.000. Meteorological data was available at three different gages (consisting of daily precipitation and temperature series from 1997 to 2000), and at six different stations (consisting of daily solar radiation, and wind velocity series from 1997 to 2000). Measured flow, total nitrogen and phosphorus series from 1997 to 2000 at the final outlet of the watershed were also available.

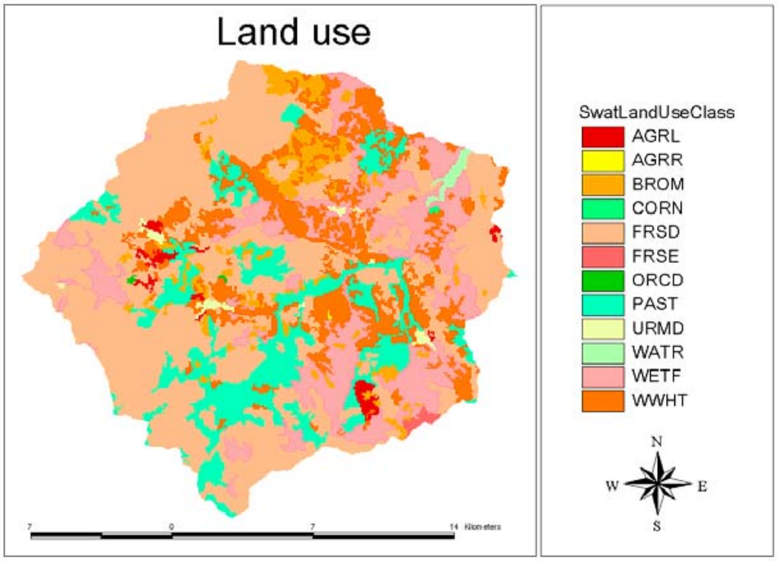

Figure 6. Camastra river basin land use map (SWAT model land use typologies).

Management data have been obtained from the literature and information supplied by several experts.

Results and Discussion

Measured discharge data of 1997 were used for the calibration of both models. Results show that, for the calibration period, the distributed and the SWAT models give correlation coefficients of R^2=0.77 and R^2=0.53 respectively. Results are shown in Figure 7 and 8.

Figure 9 shows the daily comparisons of measured and predicted discharges for 2000, the last year of the validation period (1998-2000). During the validation process, both models were run without changing the input parameters. The statistical analysis of simulated discharges yielded an R^2 of 0.6 for the distributed model results and R^2=0.42 for the SWAT model.

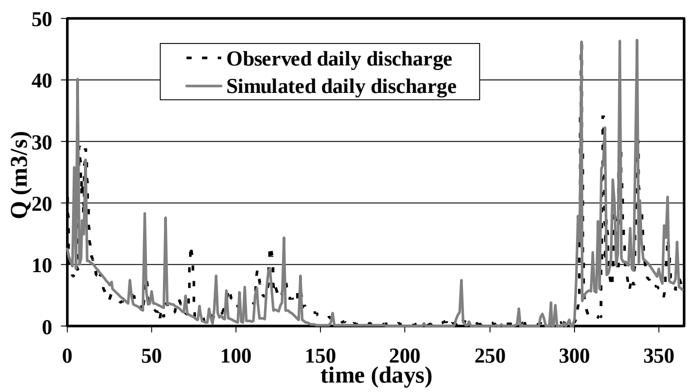

Figure 7. Comparison of observed and simulated with distributed model daily discharge for the calibration period (1997).

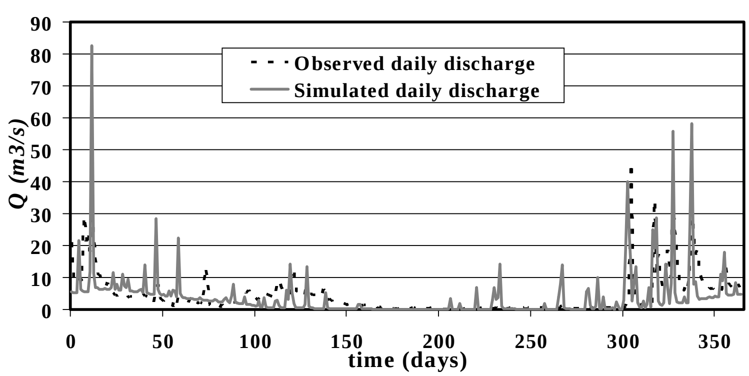

Figure 8. Comparison of observed and simulated with SWAT model daily discharge for the calibration period (1997).

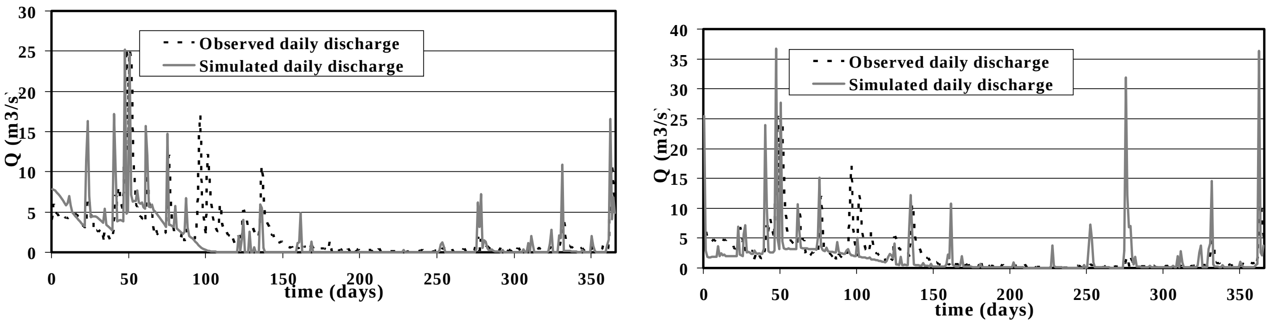

Figure 9. Comparison of observed and simulated, with distributed model (left) and with SWAT model (right) daily discharge for the last year of the validation period (2000).

It can be seen that the SWAT model does not show a good agreement between calculated and observed daily discharge, and shows a worse behaviour than the distributed model. Particularly, for the SWAT model, the peaks are too high and the recessions are too low. Given the difficulty in predicting daily discharge, it was not possible to perform a calibration for pollutant components. Probably, the major difficulty can be found in the unavailability of data required from the SWAT model, such as detailed soil parameters, and such meteorological data as potential evapotranspiration, and relative humidity.

Conclusion

The SWAT model and a distributed model have been tested for the Camastra River basin, to evaluate the applicability of such models to the Basilicata region. Evaluation of both models results with measured discharge at the final outlet allows comparison of the accuracy and the applicability of distributed and semi-distributed models. In particular, the different approach to the spatial division of the watershed, and the lack of meteorological and soils data could be the main causes of the difference in the two models simulations. Further studies will concern the better understanding and the overcoming of the difficulties found in the SWAT model running.

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Propagation of Uncertainty in Large Scale Ecohydrological Modeling

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Introduction

The need for sophisticated validation methods including comprehensive sensitivity and uncertainty analyses has often been pointed out. This study presents an example where the hydrological processes of the SWIM ecohydrological model (the Soil and Water Integrated Model) (Krysanova et al., 1998, 2000) are thoroughly analysed. The SWIM model was developed on the basis of two previously developed models, SWAT (Arnold et al., 1993) and MATSALU (Krysanova et al., 1989) in order to provide a comprehensive tool to investigate the impacts of land use and climate changes at the regional scale.

The modeling in meso- (100-10,000 km^2) to macroscale (>10,000 km^2) catchments implies various sources of uncertainty. One source of uncertainty is the model itself (as a simplification of the reality). This concerns also the process-based models like SWIM and SWAT, which combine physically-based mathematical descriptions and conceptual formulations. Another source of uncertainty is model parametrisation, because some parameters can be identified only as ranges and have to be calibrated. A third source of uncertainty is input data, as the available data usually have a rough resolution in time (e.g. climate data) and space (maps of soils and land use) and have to be interpolated to cover the entire region. This paper describes the analysis of uncertainty in model parametrisation.

The level of uncertainty often increases if the model integrates processes of hydrology, agriculture, and geomorphology, where different data sampling protocols may apply. But there is also a chance to reduce uncertainty by modelling different but physically related processes (e.g. plant growth and changes in soil moisture), because a certain parameter combination, physically possible to describe one process, might result in unreliable results for another. This additional information can serve as criteria to reduce the parameter space and the uncertainty in the model results. An important issue is therefore the determination of the model sensitivity to the input data and model parameters and the quantification of uncertainty in the simulation of the hydrological processes in order to assess the reliability and robustness of the model results. Then a comprehensive model validation will help to reduce the uncertainty of the model results and improve the reliability of the model applications.

The Basin Under Study and Data

The total Elbe basin has an area of 148,268 km^2. The German part of the Elbe, where the model was applied, covers 2/3 of the drainage basin area from the Czech border to Neu Darchau, the lowest gauge station not influenced by tidal processes. The total length of the Elbe is 1092 km. Climatically, the Elbe basin is one of the driest regions in Germany, with the long-term mean annual precipitation of 659 mm, and the long-term mean discharge at the estuary of 877 m^3 s^{-1} with an average inflow from the Czech Republic of 315 m^3 s^{-1}. Hydrologically the drainage area is subdivided into three subregions:

(1) the mountainous area in the south, ≈ 20% of the total area,
(2) the hilly mountain foreland, predominantly covered by loess soils, and
(3) the undulating northern lowlands, ≈ 52% of the total area.

All spatial information (the digital elevation model or DEM, soils, land uses, and water table contour maps) was stored on a grid format with 250 m resolution. Subbasin boundaries were provided by the German Federal Environmental Office (UBA) and partly subdivided, using the DEM and the GRASS geographic information system (GIS). The whole Elbe basin was subdivided into 226 subbasins. The land use map was created using the European CORINE land cover map. The original 44 land use classes were reclassified into 15 classes.

Soil parameterization was taken from the soil map of the Federal Republic of Germany (scale 1:1,000,000). The map distinguishes between 72 different soil types. Each soil type is characterized via the "leading profile" with up to 8 different layers. Together with the soil map, physical parameters for each layer such as texture classes, porosity, bulk density, humus, and organic nitrogen content are provided. Saturated conductivity was estimated for each soil layer using pedotransfer functions.

In the study the external drift kriging technique was used to interpolate temperature (with the DEM as additional information), and the ordinary kriging method was used to interpolate radiation and precipitation.

Methods

Three subbasins of the Elbe, the upper Saale (mountains, 1013 km^2), the Mulde (mountains / loess area, 2091 km^2), the Löcknitz (lowlands, 447 km^2), and the total Elbe basin were selected to investigate the sensitivity and uncertainty. The selected subbasins are representative for three Elbe subregions. The intention of the analysis was to investigate the extent that results of hydrological validation are robust and reliable. One objective was to illustrate the sensitivity of the model results to changes in the basic input parameters. Another goal was to investigate the uncertainty of the model results when applying the model to catchments without observed data in different regions of the Elbe river basin or under similar conditions elsewhere.

The following parameters were chosen (after intensive preliminary study of the model sensitivity) for the sensitivity and uncertainty analyses:

- Three major calibration factors: *sccor* for saturated soil conductivity, *rcor* for river routing, and *alpha* for groundwater return flow and water table depth,
- The parameter *slope* and *crad* show the model sensitivity to input data in order to analyse the influence of topography and incoming solar radiation,
- Two tabulated parameters *be* (to analyse the effect of the biomass-energy ratio), and *cnum*, (to analyse the influence of the curve number),
- The parameter *clai* used as a factor to correct the leaf area index simulated by the model (to investigate the sensitivity of the water cycle to vegetation growth).

The calibration factors were sampled randomly, within physically meaningful limits, whereby the parameter limits are site-specific and set, based on information gained during the nested model validation. The parameters *be*, *crad, slope*, and *cnum* were sampled from a normal distribution with a mean of 1, and the values were multiplied with the input data of the biomass energy ratio, slope and radiation, in order to assess the sensitivity of the model results to higher or lower input parameters. The parameter *clai* was sampled randomly from a normal distribution with a mean of 0. The parameters sccor and alpha were sampled from an equal distribution, and the parameter rcor was sampled from a triangle distribution.

300 parameter sets were generated for each of the four basins using the Latin Hypercupe method in order to restrict the number of simulations (Richter et al., 1996). Each parameter set was the input for a four-year simulation run. Two model criteria were considered in the analysis: the difference in water discharge balance, DIF, and the efficiency criteria developed by Nash & Sutcliffe (1970), EFF.

Sensitivity Analysis The sensitivity of model results to the parameters was estimated using the partial correlation coefficients of the rank transformed data (the simulation results, Tarantola 2001). For a sequence of observations, the correlation between the specific input variable X_j (model parameter) and the model output Y (the difference in discharge balance or the efficiency) was calculated and considered as a measure of linear relationship between X_j and Y.

In all cases, the parameters *crad* and *clai* had the highest correlation with DIF, followed by *sccor,* while the other parameters had practically no influence. This confirms the well-known fact that a correct reproduction of evapotranspiration dominates the quality of the simulated water balance.

The correlation of the parameters to the model efficiency was not uniform in different subbasins. In the mountainous catchment, the routing correction factor had the highest influence, whereas the other catchments showed a high sensitivity to changes in the saturated conductivity. In lowlands, the percolation of water through the soil layers is more important than in mountains. Apparently, routing is the most important process in areas with high relief intensity, whereas in lowland and loess catchments the correct simulation of soil processes and evapotranspiration have a prevailing influence on the quality of model results. The model is very sensitive to changes in *lai* (especially in lowland), although this parameter was not used as a calibration factor. This indicates the importance of dynamic and interactive representation of vegetation in hydrological models. The efficiency criteria developed by Nash and Sutcliffe is used to analyse whether the model is able to reproduce water fluxes dynamically (e.g. seasonality of water flows and flow regime). The high correlation of efficiency to *lai* underlines the importance of a correct reproduction of plant growth.

Uncertainty Analysis

The uncertainty was investigated using histograms of the DIF and EFF criteria based on the 300 simulations for every basin. Figure 1 shows eight histograms demonstrating the results of the uncertainty analysis. The distribution of the model criteria DIF is plotted in the upper part, and the lower part illustrates the distribution of EFF. Each part has four histograms, three for the subbasins, and one for the total Elbe basin.

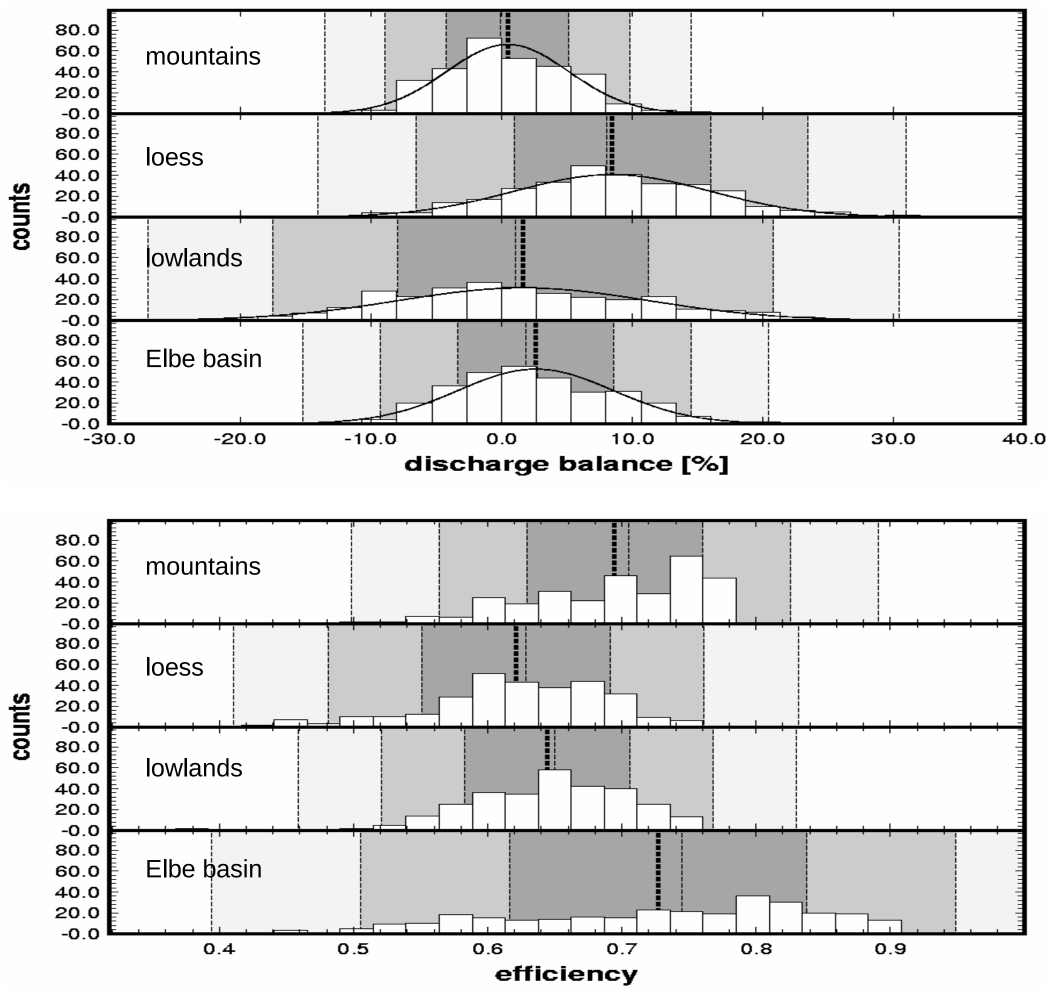

Figure 1. The results of the uncertainty analysis. Upper plot: distributions of the model criterion DIF based on 300 Monte Carlo simulations, for subbasins from the mountains, the lowlands, the loess area, and the total basin. Lower plot: distributions of the model criterion EFF for the same basins.

The model shows a good reproduction of the water balance, the mean value of 300 simulations is around 0 for all catchments except those in the loess area, where the model tends to overestimate discharge slightly. It is known that the hydraulic parameterization of loess soils involves a lot of uncertainties when the parameters are transferred from lab measurements to the basin scale, so that the inherent heterogeneity of the soils (cracks, macropores, and textural characters) cannot be well represented in macroscale polygon covers.

All efficiency values on the lower histograms are above 0.3, and mean values are above 0.6. The conclusion is that also taking into account the uncertainty in the parameter input, the model reproduces satisfactory the dynamic flow pattern of the river discharge in different basins even if the parameters are taken as random values. The model shows the best performance with the highest efficiencies in the mountainous catchment. The lower efficiencies, with higher standard deviation, were obtained for the loess and lowland catchments. This result agrees with the outcome of the model validation, where the nested lowland catchments produced the poorest results, while the validation of the hydrological processes in catchments from the mountains produced the best results. In lowland catchments the hydrological conditions are often unclear (groundwater flow, ponds, wetlands and the drainage network), and it is impossible to reproduce water discharge with high accuracy without detailed information.

The DIF and EFF distributions for the total Elbe basin are a composite of the results for sub-catchments. The simulated discharge is slightly overestimated. The average of the efficiency distribution is better than those for subcatchments, but has a higher dispersion.

The overall result of the uncertainty analysis is that, in macroscale applications of SWIM, 90% of the simulations had efficiency above 0.53 and the absolute deviation between the observed and simulated river discharge was lower then 9.9 %. The uncertainty in simulation of the hydrological processes for lowland and loess sub-areas is higher, while the results in mountainous parts of the basin show a robust and stable performance, and are not very sensitive to changes in the model parameters.

Summary

The sensitivity and uncertainty analyses show that the model results were robust but more stable in mountainous catchments than in lowland and loess parts of the model area. The overall conclusion of the study is that model applications on the macroscale should always include additional investigations in mesoscale subbasins to analyse the special characteristics of the subregions. Different processes play a dominant role in different areas of the basin, and the implementation of additional observations (like groundwater table records) in the validation procedure could help to improve the model performance.

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The i_SWAT Software Package:
A Tool for Supporting SWAT Watershed Applications

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Introduction

The Mississippi River Watershed covers 3.2 million km^2 across parts or all of 31 U.S. states (Figure 1) and two Canadian provinces. Excess nitrogen, phosphorus, and sediment loadings have resulted in water quality degradation within the Mississippi and its tributaries. The nitrate load discharged from the mouth of the Mississippi River has also been implicated as the primary cause of the seasonal oxygen-depleted hypoxic zone that occurs in the Gulf of Mexico, which covered nearly 20,000 km^2 in 1999 (Rabalais et al., 2002). Approximately 90% of the nitrate load to the Gulf is attributed to nonpoint sources; 56% of this nonpoint source load is estimated to come from above the confluence of the Ohio and Mississippi Rivers (CENR, 2000). The Upper Mississippi River Basin (UMRB), which covers a region of about 480,000 km^2 (Figure 1), is the major source of the nitrate load that originates upstream from the Ohio River. Cropland and pasture are the dominant land uses, which together account for about 67% of the total UMRB area (http://www.umbsn.org/news/documents/chg_face.pdf). Nutrient inputs via fertilizer and/or livestock manure on cropland and pasture areas are the primary sources of diffuse nutrient pollution to the UMRB stream system.

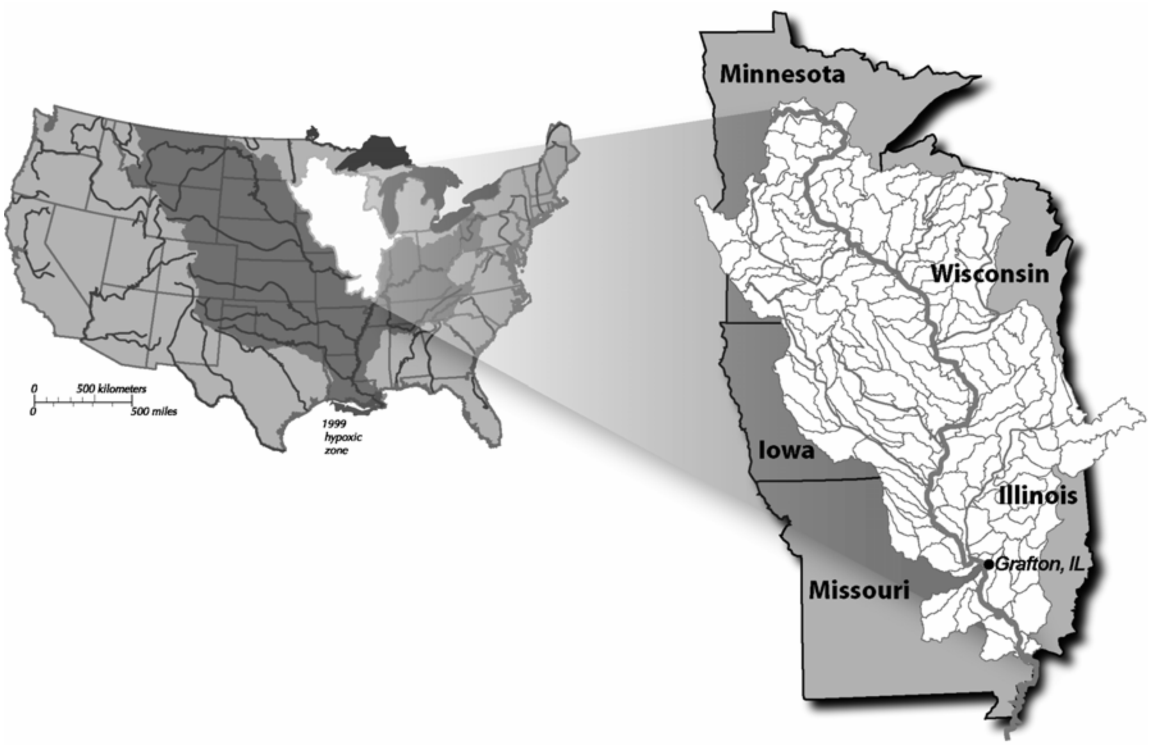

Figure 1. Location of the Upper Mississippi River Basin (UMRB) within the Mississippi River Basin, the 131 8-digit watersheds located within the UMRB, and the location of Grafton, IL.

A simulation study using the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) has been initiated to assess current and alternative nutrient, cropping, and management practices in the URMB, to support efforts to solve water quality problems in the Mississippi River and its tributaries. The ArcView SWAT (AVSWAT) interface (http://www.brc.tamus.edu/swat/swat2000doc.html) could not be used for this application because the key land use dataset was not available in a Geographic Systems Information (GIS) format. Thus the interactive SWAT (i_SWAT) Windows® software package was constructed to manage the input and output data for the UMRB SWAT simulations, and the execution of the model for each scenario. Overviews are provided here of: (1) i_SWAT, (2) input data and using i_SWAT for the UMRB application, and (3) initial SWAT UMRB flow results.

Overview of I_SWAT

The i_SWAT system is currently designed to support applications of SWAT2000 (SWAT). A single Access® database is used to manage both the input and output data of a SWAT simulations within i_SWAT. This requires the user to convert all existing input data from ASCII files and other file formats into Access. A general schematic of the data flows for the i_SWAT system is shown in Figure 2. An initial preprocessing step is required to fill the Access database tables. Once the input data have been constructed, the SWAT simulation can be executed within i_SWAT. Output data for each simulation is scanned from standard SWAT output files and also stored in the database.

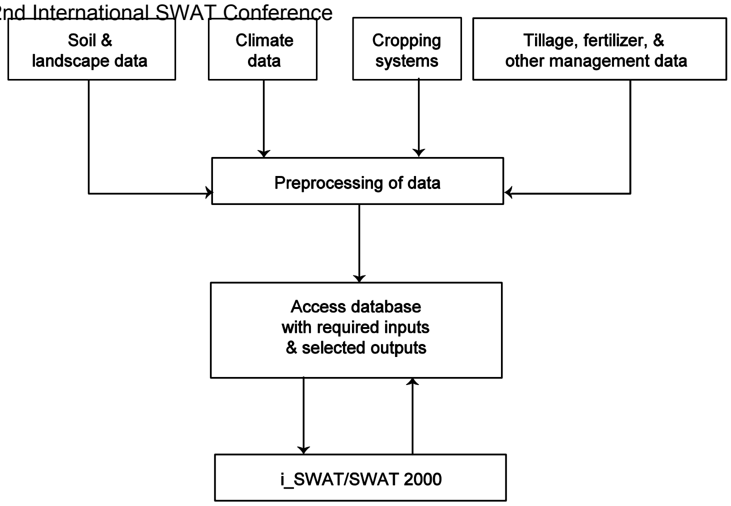

Figure 2. Schematic of i_SWAT system data flows

The i_SWAT software is accessible at http://www.public.iastate.edu/~elvis by clicking on i_SWAT (similar software can also be obtained for the Century and EPIC models). A download is provided for an empty Access database (empty.mdb) that contains the required tables and data columns needed for i_SWAT. Documentation is provided on the website for the structure of the data tables, including the names used in the ACCESS tables for each variable, the equivalent SWAT variable name, the units (if applicable), variable types (integer, etc.), and variable descriptions.

Table 1 lists the data tables that are currently included in an Access database for i_SWAT, and the corresponding descriptions and SWAT input or output files. The input data stored in the Access database are translated into the ASCII files required for SWAT when i_SWAT is executed. The file.cio is also created by i_SWAT, based on the other input files that are created for the SWAT simulation. Several input files are currently not supported by i_SWAT (see Table 1 footnote) because they are not needed for the UMRB application. Thus these files must be constructed outside of i_SWAT if they are required for a specific SWAT simulation (they may eventually be included in i_SWAT as part of future developments). At present, i_SWAT extracts selected daily, monthly, or annual flow, sediment, and nutrient indicators from the SWAT.rch output file and stores them in the OUTPUT REACH table in the Access database. Options for extracting output at the hydrologic response unit (HRU) level are under development; other outputs may also be included in future developments.

Storage of the data in Access allows the i_SWAT user to change input parameters using queries or macros within the database, rather than having to make modifications in individual ASCII files. Some input editing can also be performed within i_SWAT, including the data within the standard SWAT fertilizer, pesticide, crop, and tillage files. Other i_SWAT features include imports of existing SWAT (version 2000 only) datasets, print and print preview options of management system lists, charts of output by subbasins or HRUs, and subbasin routing structure maps. The empty.mdb, or other database with the correct structure, must be opened in i_SWAT before importing an existing SWAT dataset. Input files that are not supported by i_SWAT must be copied into the directory where the SWAT simulation is being executed if the files are needed for the specific SWAT application.

Table 1. List of tables currently Access database used by i_SWAT

Database table	Description	SWAT files[a]
Input data		
Control Records	Input control codes and basin-level parameters	.cod, .bsn
Crop	Crop/plant growth parameters	Crop.dat
Fertilizer	Fertilizer and manure nutrient contents	fert.dat
HRU	Characteristics for each HRU	.hru, .gw
Management	Management data for each HRU	.mgt
Pesticides	Degradation and other pesticide characteristics	pest.dat
Point Sources	Point source loading data by subbasin	.pcs
Pond	Pond and wetland data by subbasin	.pnd
Reservoir	Reservoir characteristics by subbasin	.res
Routing	Contains data for the watershed configuration file	.fig
Soil layers	Soil layer data required by HRU	.sol
Soils	Soil name; misc. soil data by HRU	.sol
Stream Water Quality	Initial in-stream water quality data by subbasin	.swq
Sub-basins	Subbasin area, channel, and related data	.sub, .rte
Tillage	Residue mixing depth, etc. for tillage equipment	Till.dat
Urban	Urban build-up/wash-off of solids data	urban.dat
Water Use	Consumptive water use data by subbasin	.wus
Weather by Month	Monthly weather and wind statistics	.wgn
Weather Historical	Daily historical precipitation and temperature data	.pcp, .tmp
Weather Stations	Weather station coordinates and elevations	.wgn
Output data		
Output HRU Annual	HRU outputs (under development)	.sbs
Output Reach	Daily, monthly, or annual outputs at subbasin outlets	.rch
Miscellaneous		
Help Text	i_SWAT variable descriptions (under development)	-

[a]The input files are created from the corresponding Access tables; the Access output tables are filled from the corresponding SWAT output files. The file.cio is created by i_SWAT when a SWAT run is executed; the .slr, .wnd, .hmd, .pet, .wwq, .chm, .lwq, recday.dat, recmon.dat, and reccnst.dat files are currently not supported by i_SWAT and must be constructed by the user.

The charting functions can be invoked after a successful completion of a SWAT simulation; charting options are accessed by right clicking on the specific chart template. Both a latitude and longitude must be entered in the database Sub-basin table for each subbasin in order to create a routing map (the longitude variable is not used by SWAT).

Input Data and I SWAT Application for the UMRB Study

The key data source for the URMB study is the U.S. Department of Agriculture National Resources Inventory (NRI) database (http://www.nrcs.usda.gov/technical/NRI), which contains extensive cropping history, conservation practice, and other land use information for one million "points" across the United States based on a statistical survey taken every five years from 1982-1997. Each point typically represents several hundred to several thousand ha, that consist of homogeneous soil, land use, and other characteristics. Crop rotation and management practices derived from the NRI and/or other data sources were used to configure SWAT for baseline conditions; and the same process will also be used for the alternative cropping and management scenarios.

To perform the SWAT baseline simulation, the UMRB was subdivided into 131 subwatersheds (Figure 1) that coincide with the boundaries of U.S. Geological Survey 8-digit hydrologic cataloging unit watersheds (http://water.usgs.gov/GIS/huc.html). The HRUs were then created by aggregating NRI points together within a given 8-digit watershed, that possessed common land use, soil, and management characteristics. A total of 15,498 HRUs were created for the UMRB for the initial SWAT baseline simulation, with the greatest HRU densities in the areas dominated by intensive agriculture.

The HRU and subbasin data were loaded into an Access database with the structure outlined in Table 1. The SWAT baseline simulation was then executed using i_SWAT, which also extracted the flow and other relevant data at the subbasin level and stored it in the Access database. Several iterations of the process have been performed to accommodate debugging and calibration of SWAT inputs.

Preliminary Flow Results

Flow comparisons between simulated and measured flows are being performed at USGS stream gauge 05587450 located on the Mississippi River at Grafton, Illinois (Figure 1), just above the confluence of the Mississippi and Missouri Rivers. The gauge at Grafton captures flow from 119 of the 131 8-digit watersheds, which is assumed representative of the entire UMRB. An initial SWAT UMRB study was performed (Jha et al., 2003) using AVSWAT in which topographic, land use, and soil data were obtained from the U.S. Environmental Protection Agency BASINS version 3 software and data package (http://www.epa.gov/ost/BASINS/). Calibration and validation of SWAT were both performed for this study (30-year simulation period), resulting in a good agreement between the predicted and measured cumulative monthly flows (r^2=.79 for the 1989-96 validation period shown in Figure 3). Preliminary cumulative monthly flows obtained with limited calibration are also shown in Figure 3 for the NRI-based 20-year SWAT baseline simulation. These results for 1989-96 also tracked the measured data reasonably well (r^2=.53); but further calibration is required to obtain more accurate results.

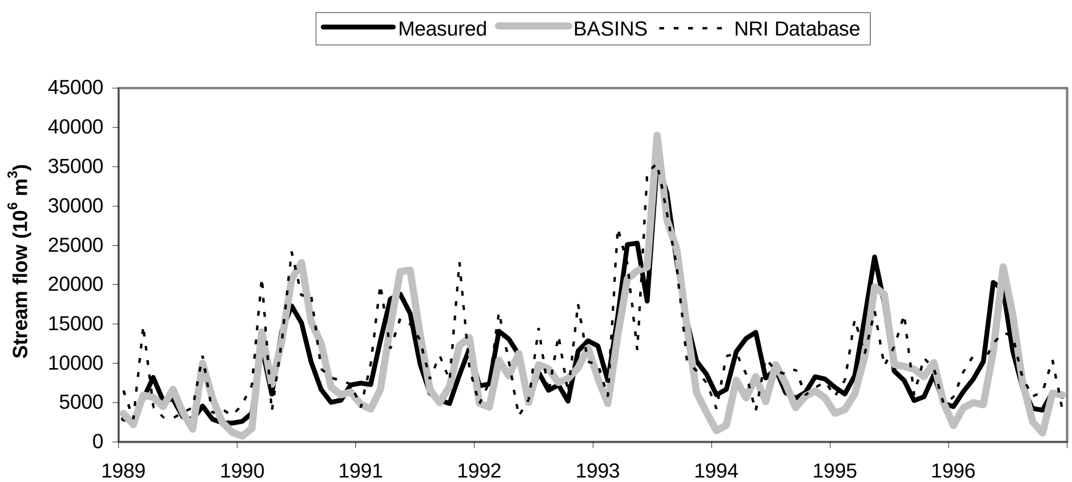

Figure 3. Measured versus predicted cumulative monthly stream flows during 1989-96 for the UMRB as represented by the Mississippi stream flow gauge at Grafton, Illinois.

Conclusions

The i_SWAT software package is proving to be a robust tool in supporting the application of SWAT for the UMRB. The i_swat approach can also be used for other watersheds, providing the user fills the Access database tables with the required data. Both improvement of current options and addition of new options will be part of future i_SWAT enhancements. The initial NRI-based UMRB SWAT results are encouraging; but further calibration and validation of SWAT is required for improved results. Further sensitivity analyses will also be performed to determine what the optimal number of HRUs is for the URMB simulations. The total number of HRUs may be reduced, especially in the agricultural areas.

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V. Model Integration

The Model Concept in the Project FLUMAGIS: Scales, Simulation and Integration

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Abstract

In order to reach the environmental targets of the European Community (EC) water framework directive on different scales, a concept for the scale-specific simulation of water-bound fluxes in the FLUMAGIS project is presented. According to the interdisciplinary relevance, scale levels have been defined which comprises the micro-, meso- and macroscale. Thus, for the description of the water balance and matter fluxes within the landscape the models NASIM (microscale), ArcEGMO (micro- to macroscale), ABIMO and SWAT (meso- to macroscale) have been selected. The usage of all these models aims to examine the transferability and applicability of the simulation results to the next higher or lower scale, as well as holding the system open for other models. The scale transition and thus the information exchange between the models are scale-specific depending on the application and compilation of existing parameters and indicators. During the first working phase, the behaviour and sensitivity of the models on different frame conditions and factors is checked out and possibly adapted by using artificial areas. Despite the different model concepts and the temporal differentiation of the input parameters, the results show an acceptable accordance. The simulation results of SWAT and ArcEGMO mostly show only small differences, whereas the results of ABIMO and NASIM show greater differences. In general, these differences are caused by different temporal resolutions and parametrization options of the models. As a first step towards the consideration of the whole area, the ABIMO conceptual model was found suitable for estimating the mean runoff for the Upper Ems River Basin.
KEYWORDS. EC water framework directive, scale-specific simulation, parameter and indicator system, artificial areas.

Introduction

The Water Framework Directive (WFD, established in 2000 (EC 2000) forms a framework for the measures of the European Community (EC) in the field of water policy. The directive defines the environmental targets for surface and groundwater for the European Union. Management plans for whole river basins shall serve as the main instrument for the implementation of the directive. Additionally, the participation of all concerned authorities and surveys is required (EC 2000). The FLUMAGIS project[2] (www.flumagis.de) contributes to an improved implementation of participation approaches on the management processes. The project is focused on the development of an interactive tool for the assessment and three-dimensional visualization of the hydrological and ecological conditions in river basins. The simulation of the impact of land use on the water balance fluxes in the landscape is an essential basis for the establishment of a knowledge base for this system. A lot of problems exist regarding the implementation of the directive. Examples are deficiencies in the spatial differentiation of environmental quality targets, planning and measure levels, and the lack of a common and homogeneous database for several scale levels. However, planning for water protection measures requires the designation of further scale levels due to the different regional conditions. Thus, the open scale problems and the regional relationship of management measures made it necessary for us to develop a concept for the scale-specific simulation of the water balance and the matter fluxes.

Study Areas

The studies are carried out in the mainly flat Upper Ems river basin in Northwestern Germany, which covers an area of 3,740 km^2. The hydrological processes in the Upper Ems basin are characterized by increasing precipitation amounts from the Northwest and Central basin (700 mm/a) to the Southeast (1.200 mm/a) but also by the widespread permeable sandy soils. The runoff dynamics are closely related to precipitation patterns. The Ems River has its sources at the foothills of the Teutoburger Wald mountains (altitudes reach only about 360 m above sea level or asl) on the Eastern border of the Upper Ems river basin. The Ems River flows through the North German Lowlands to the North Sea. Detailed investigations will be carried out in three subbasins. The selected subbasins cover areas between 160 km^2 and 350 km^2. The Ems floodplain, between Telgte and Greven (13.5 km^2), represents another study area for investigations with a high spatial-temporal resolution. Figure 1 shows the location of the study areas and its land use pattern (green – forests, red – settlements, light yellow – agricultural land use).

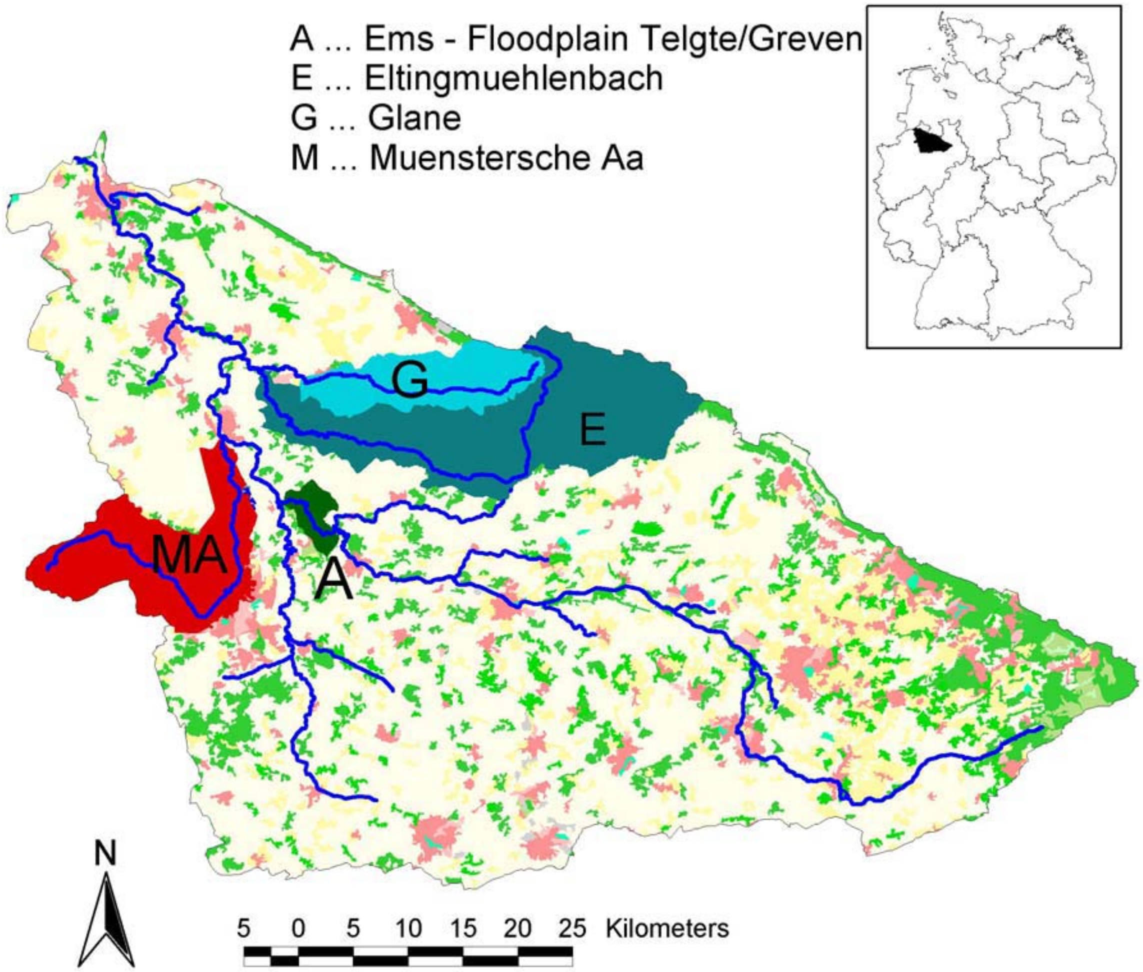

Figure 1. Location of the study areas in Germany and land use pattern of the region. Agriculture (bright colour) is the dominating land use type.

The River Basin is dominated by agriculture and is one of the most intensively used agrarian regions in Europe. Agricultural land (arable land, pasture and heterogeneous agricultural use) covers 81% of the total area, followed by forests (11%) and settlements, industry and infrastructure (9%). Figure 2 gives more detailed information about the land use of the area.

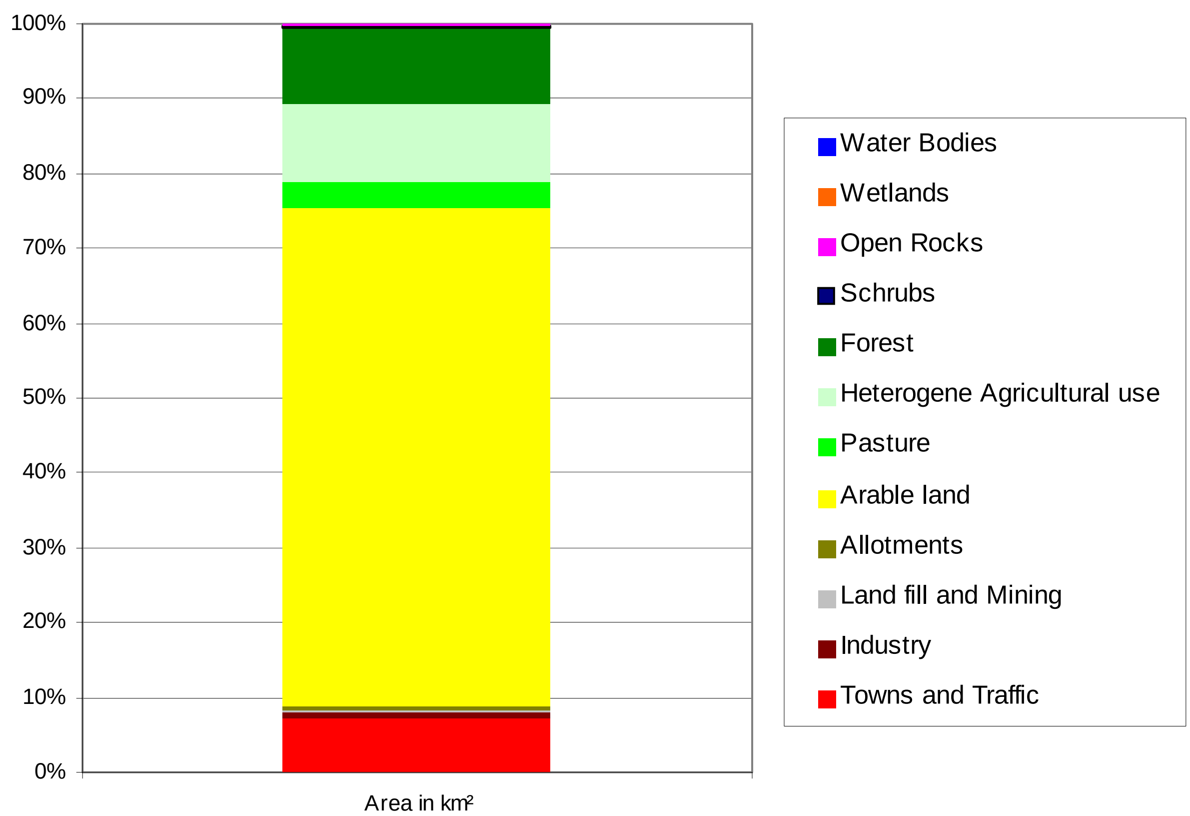

Figure 2. Proportion of the land use types on the area of the Upper Ems River Basin in the year 1997 (CORINE Land Cover)

A detailed analysis shows that arable land dominates the land use structure with approximately 65%. Such a high percentage of arable land in an area with mostly poor soils is caused by the cultivation of forage crops for stock farming. Several environmental problems and land use conflicts are the consequence.

A concept for Scale-Specific modelling

The main objective of FLUMAGIS is the development of an assessment and visualization tool for integrated river basin management. Specific scale definitions of the WFD (report scale, measure scale, etc.) require the use of scale-specific tools for the investigation and visualization of the ecological situation in river basins and the effects of water protection measures. The use of scale-specific methods and tools must be based on a data transfer between these tools. The transfer could be realized by specific indicators resulting from a simulation process for a certain scale level or as input data for another model simulation on another scale.

The scale transition and information exchange between the models should be realized by a selection of existing indicators at the outlets – under consideration of variability and uncertainty (comparison of aggregation levels). An essential basis is the development of a regional- and scale-specific indicator system for the investigation of the water balance and matter fluxes (Schmidt et al. 2003). Thus, existing indicator systems are examined on their suitability for ecological assessments due to the requirements of the WFD. The so-called Indicators of

Hydrological Alteration (IHA) have been proven suitable for the characterization of the runoff dynamics in surface waters (Richter et al. 1996, Ehlert & Van den Boom 1999, Zepp 2002). Further hydrological indicators result from the BWK-instructions (BWK 2001). They play an important role for rivers in urban areas with special impairments by sewage and stormwater discharge. Information which is extracted from existing concepts has to fulfill several requirements to meet the aims of the WFD. This is caused by the required participation, the considered scale levels, and the model selection and application. After passing through this filter, the resulting indicator pool will be examined according to how well it represents a certain scale level (Table 1).

Table 1. Scale matrix for the identification of the scale-specific representiveness of indicators.

Indicator / Scale level	Indicator A	Indicator B	Indicator C
MICROSCALE 1:5,000-1,000	+	-	+
MESOSCALE 1:25,000-10,000	+	+	-
MACROSCALE 1:500,000	+	-	-

The indicators form the basis for scale transition between the models and help to prove the quality of the simulation results. The procedure is a combination of “top down” and ‘bottom up” approaches (Volk & Steinhardt 2000) and the investigation of processes and conditions on different levels. As a result, knowledge about the efficiency of detailed management measures (microscale) for the whole area is obtained. The macroscale investigations enable a spatial differentiation of the landscape and a designation of regions with environmental risks and land use conflicts. More detailed model systems can be focused on these areas to get exact information about water quality and quantity and the water-bound material fluxes. A “calculation knot” (outlet) forms the central interface of the scale transition. This technique presumes that the applied model systems generate mutually comparable results about the concerned parameters. This is especially necessary regarding the use of quantitative indicators for the investigation of hydrologic and environmental conditions. The method aims to examine the transferability and applicability of the simulation results to the next higher or lower scale level, as well as holding the systems open for other model systems.

Simulation Models and Artificial Areas

According to the textual and scale-specific requirements of the project, several conceptual and physically based simulation models are selected: NASIM 3.10 (Hydrotec 2001), ArcEGMO 2.3 (Pfuetzner et al. 2001), SWAT 2000 (Arnold et al. 1993, 1998, Neitsch et al. 2001) and ABIMO 2.1 (Glugla & Pfuertig 1997, Rachimov 1996). The selection was determined by the scale-specific applicability of the models, the data availability, and the experiences of the working team. The specific approach, and different structures of the simulation models and the spatial-temporal resolution and parametrization requires comparing calculations to detect potential variations (Table 2). At first, a relative comparison of the models with different scale-specifics is carried out on the basis of artificial areas with variable differentiation levels. This method provides information about the model specifics and variations of the results. During the first phase of the relative model comparison, the artificial areas are distinguished by a few homogeneous parameters. This is advantageous because the resulting datasets are concise and manageable and the calculation times are reduced. The spectrum of the properties for each parameter is determined by the given landscape characteristics of the study area (the Ems River Basin). Homogeneous relief and soil parameters (one layer) have been selected, and land use is represented by different scenarios (Table 2). The simple artificial catchment covers an area of 10 km². The catchment is divided by a river into two similar slopes (2.5 km x 2 km).

Table 2. Structure of the artificial area.

Soil	Land use	Relief	Climate
• B1 – Gleyic posdol from sandy river sediments • B2 – Loess soil	• Forest (deciduous) • Pasture • Arable land • Surface sealing	• 5º Slope angle • 1% river channel incline	• Precipitation and PET data: 1970 – 1993

During the phase of creating a simple artificial catchment, 12 scenarios were created. Table 3 shows the main parameters, describing the soil and land use conditions of the scenarios. The parameters of the selected typical soil represent their magnitude in the Upper Ems River basin.

Table3. Main Soil and Land use Parameters of the artificial areas.

Nr.	Soil	Saturated water conductivity [mm/h]	Available water capacity [mm/m]	Land Use	Root depth [cm]	Interception [mm]
1	GLEYIC PODSOL	23.75	139	Forest	150	8
2	GLEYIC PODSOL	23.75	139	Pasture	100	4
3	GLEYIC PODSOL	23.75	139	Arable land	100	3
4	Loess soil	5.42	325,5	Forest	150	8
5	Loess soil	5.42	325,5	Pasture	100	4
6	Loess soil	5.42	325,5	Arable land	100	3
7	GLEYIC PODSOL	23.75	139	F30/P10/A50/S10 1)	150/100/100/0	8/4/3/2 2)
8	GLEYIC PODSOL	23.75	139	F10/P5/A75/S10	150/100/100/0	8/4/3/2
9	GLEYIC PODSOL	23.75	139	F10/P20/A50/S20	150/100/100/0	8/4/3/2
10	Loess soil	5.42	325,5	F30/P10/A50/S10	150/100/100/0	8/4/3/2
11	Loess soil	5.42	325,5	F10/P5/A75/S10	150/100/100/0	8/4/3/2
12	Loess soil	5.42	325,5	F10/P20/A50/S20	150/100/100/0	8/4/3/2

1) F – Forest; P – Pasture; A – Arable land; S – Surface sealing; the number shows the relative part of each Land use of the whole artificial area

2) Interception of sealed surfaces

Differentiated climate data series are used according to the model specifications (Table 4).

Table 4. Model types and temporal resolution of the used data.

Model	**NASIM**	**ABIMO**	**SWAT**	**ArcEGMO**
Type	Physic. based with conceptual parts	conceptional	Physic. based with conceptual parts	Physic. based with conceptual parts
Precipitation	6 min	Long-term mean annual values	Daily values	Daily values
Temperature	Daily values	-	Daily values	Daily values
Evapotranspiration	Daily values	Long-term mean annual values	Daily values	Daily values

This method enables the evaluation of sensitive operating input parameters. Therewith, the requirements on the spatio-temporal discretization of the input data sets can be described more precise. Phase 2 and 3 of the sensitivity analysis are focused on the design of more complex artificial areas (more soil layers, differentiated land use). On the base of the increasing complexity of the artificial watersheds, the simulations will be advanced to the usage of "real" data. The comparison of the simulation results for the artificial areas and the derived parameter is the basis for the identification of the scale-specific relevance of parameters.

First results

<u>First results of the relative model comparison</u>

Selected hydrological parameters (mean, minimum and maximum runoff, mean monthly runoff, etc.) have been used for the first relative model simulation comparison. The method allows users to identify the indicators which could be used later for data transfer between different scales in FLUMAGIS. Figure 3 shows the first simulation results, calculated with datasets of simple artificial areas.

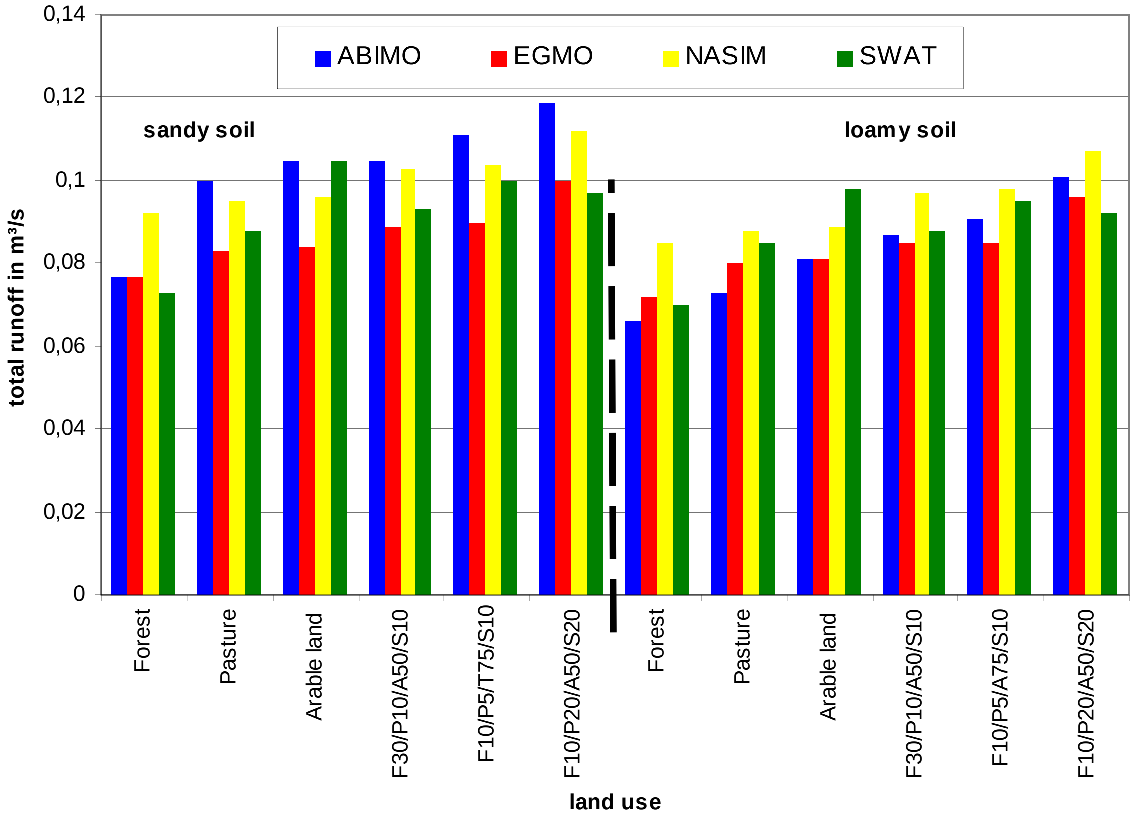

Figure 3. Comparison of simulated mean runoff in a artificial area, calculated with ABIMO, ArcEGMO, NASIM and SWAT (F – Forest, P – Pasture, A – Arable land, S – Surface sealing)

These simulations show similar results for all models: As expected, the highest values of runoff are observed under sandy soil. Under a loamy soil, the values are obviously smaller. The total runoff increases with an increased proportion of surface sealing. The simulation results of SWAT and ArcEGMO show only small differences in most cases. The differences of the simulated mean runoff are, in general, less than 10%. Only for the scenarios "arable land" do the differences rise up to 20%. This is caused by the different parametrization possibilities of the models for the agricultural characteristics. SWAT has the most options to describe agricultural cultivation practices by parameters. In order to enable a comparison to the other model systems, we had to simplify that land use type in which fertilization is controlling plant growth and seasonal evapotranspiration. More detailed parametrization would lead here to more precise results.

The simulation results of ABIMO and NASIM show greater differences (up to 30%), which are mainly caused by the different temporal resolution of the precipitation and evapotranspiration data (Table 2). The simulation results differ more widely at the other indicators like mean runoff (i.e., runoff statistics, mean monthly discharges). Those results are the first step for determining the expected variations and uncertainties of the simulation.

The next steps of the work with artificial catchments include simulations with vertically differentiated soils and a larger semi–artificial catchment. Semi-artificial means that we use a digital elevation model (DEM), a river system, and the soils of a real catchment, but the land use scenarios are created in a synthetic way. This method should enable us to get better information about the effects of input parameters on the simulation results in terms of a sensitivity analysis. Additionally, the method is used as a stepwise approach of the simulations to the more complex scenarios with the study areas.

First simulation of the whole study area using the ABIMO model

The total runoff for the whole study area of about 3,500 km^2 has been calculated with ABIMO as a first step towards a first area-wide differentiation. Due to the characteristics of the ABIMO conceptual model (Table 5), the results are long-term mean annual values of the total runoff. The model best fits flat loose rock areas (Herzog et al. 2001, Volk et al. 2001) which are found in most of the study area. Thus, it can be assumed that most of the precipitation seeps away more or less vertically and the simulated total runoff corresponds approximately with the groundwater recharge of the study area.

Table 5. Input data for the ABIMO calculation

Climate	Soil	Land use	Groundwater level classes	Degree of canalization
Long-term mean annual values of precipitation and Potential Evapo-transpiration (1960-1990, Raster data (Data source: German Weather Service DWD)	Digital soil map 1:1,000,000 (BGR. 1995) - Available water capacity - Soil types sub-divided in Sand, Silt, Clay, Loam and organic	CORINE Land Cover 1:100,000 (Statistisches Bundesamt 1994). - Land use types subdivided in arable, forest (deciduous and evergreen), gardens, sealed surfaces, water, yield classes	Derived from the Digital soil map 1:1,000,000 (BGR 1995)	Derived from Glugla & Fuertig (1996), Kuntze (1998) and CORINE

Figure 4 shows the results for the study area. According to the prevailing sandy soils with a high permeability, the values are relatively homogeneous. The floodplains with a surface-near groundwater levels have a higher evaporation and thus show the lowest runoff. The highest total runoff values are calculated for the hilly regions of the Teutoburger Wald with high precipitation amounts. The results give us a first estimation of the conditions for the whole area. The mean annual runoff of the area amounts to 368 mm/m² (area-weighted) which are relatively high in comparison to other lowland regions in Germany. The specific runoff reaches 11.7 l/s/km².

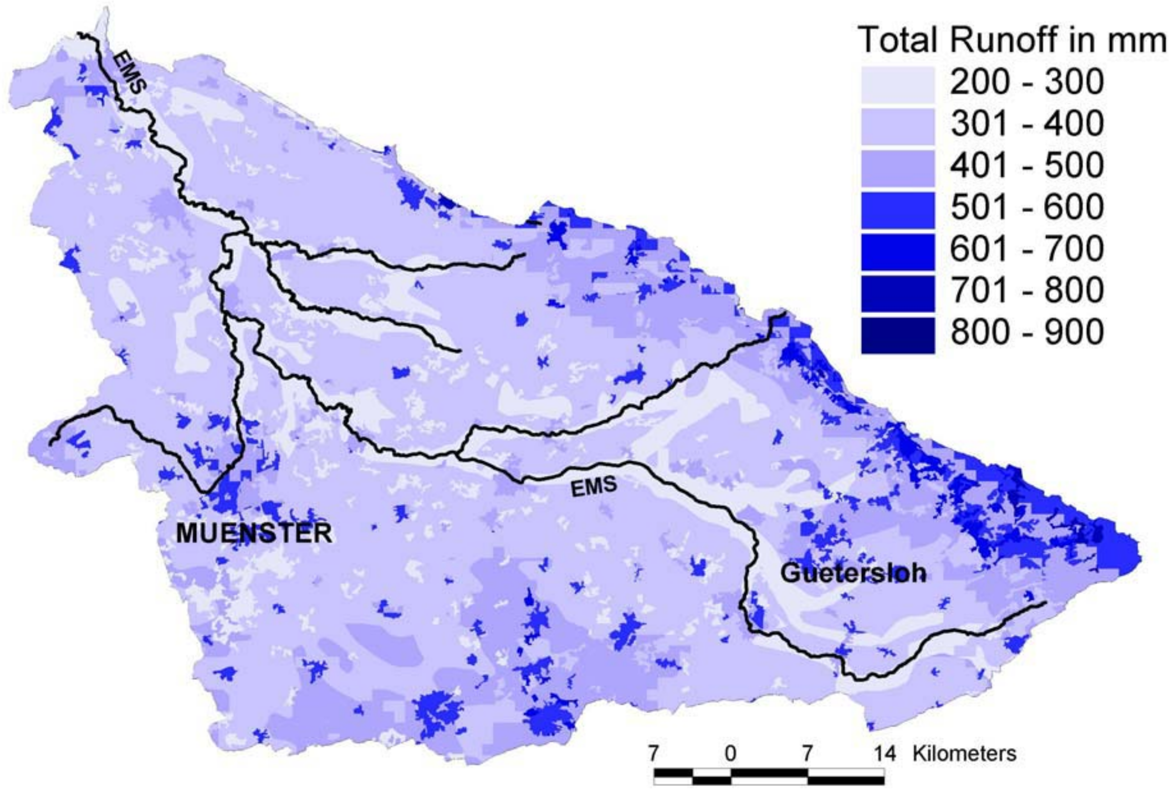

Figure 4. Total runoff for the study area simulated with the conceptual model ABIMO.

For a first validation of the received results, the streamflow data from five gauges at the Ems River were averaged and area-weighted. The daily streamflow data were passed through a digital base flow filter. The method is based on automated base flow separation and recession analysis techniques and is described in Arnold and Allen (1999) and Arnold et al. 1995). One of the results of the filter is the calculation of baseflow fractions (the percentage of baseflow contribution to the streamflow). By relating the baseflow fraction to these converted values, this results in an estimation of the baseflow contribution and a groundwater-recharge rate. This basic hydrologic information is important for river basin management, which is one goal of our project. Values about groundwater recharge and baseflow contributions help track the paths of nutrient inputs in the river system. The results are an important contribution to develop detailed and effective measures for reducing eutrophication processes in the area. Table 6 shows the comparison of the simulated runoff using ABIMO, area-weighted streamflow data and calculated baseflow fractions.

Table 6. Comparison of the ABIMO simulations, area-weighted streamflow data and baseflow calculations.

Gauge	River	Subbasin area [km2]	Mean streamflow [m^3/s]	Mean total runoff (area weighted) [mm/a]	Result of ABIMO simulation [mm/a]	Diff. [%]	Rate of baseflow contribution * [%]	Baseflow contribution (area-weighted) [mm/a]
Einen	Ems	1486	15.93	338.12	379.1	10,8	68.0	229.92
H. Langen	Ems	1616	17.49	341.31	375.6	9,1	69.5	237.21
Haskenau	Ems	1845	18.97	324.25	373.0	13,1	68.0	220.49
Greven	Ems	2842	27.77	308.15	375.1	17,8	63.0	194.13
Rheine-U.	Ems	3740	36.16	304.90	368.6	17,3	65.5	199.71

* This is an average of the first two baseflow filter passages (Fraction 1 and Fraction 2)

The area-related runoff values (converted streamflow data) show relatively small differences regarding the large areas of the gauge-related subbasins of the Ems River. As mentioned before, this is mainly caused by the relatively homogeneous soil and precipitation conditions as well as the dominant agricultural use of the study area. This is confirmed by the slight storage behavior of the river basin (a small amplitude of total runoff and baseflow contributions). The small differences between the measured and the calculated total runoff data are caused by a number of difficulties of the input information used in this study. The main problem is that the area of the given gauged basins differs from the GIS-based approximation. Additionally, the measured and calculated periods are not identically at every gauge. The input data for climate used for the water balance simulation with ABIMO covers 1961 to 1990. Some of the average streamflow data from the gauging stations are generated in longer (1950 to 2000) or shorter (1977 to 2000) time periods. A lot of environmental investigations for large areas over long time periods that use several data sets face this problem. Serious interpretation of results has to point out these uncertainties.

The results received by the ABIMO simulation could be used for the assessment of landscape functions (i.e. groundwater recharge and availability) for water protection projects on larger scales. In connection with land use information, we try to localize hot spots and potential risk zones of eutrophication of ground- and surface- water. This will be done also in more detail by the use of the model systems like SWAT, ArcEGMO and NASIM. This “top down” method enables the further focus on areas with the highest need for the implementation of management measures.

Conclusion

Despite the basically different model concepts and the temporal differentiation of the input parameters, the results show an acceptable accordance for the simple artificial areas. The simulation results of SWAT and ArcEGMO show mostly only small differences, whereas the results of ABIMO and NASIM show greater differences. In general, differences are caused by different temporal resolutions and parametrization options of the models. As a first step towards the consideration of the whole area, the conceptual model ABIMO was found suitable for estimating the indicator mean runoff for the Upper Ems River Basin.

The next phases of the relative model comparison are focused on the further development and differentiation of the artificial areas. The enhanced model comparison (all indicators, higher differentiated artificial areas) shall be the basis for the determination of the scale-specific application of indicators. Additionally, it is seen as the basis of plausible forecasts of the effects of management measures on the water balance and matter fluxes in landscapes. Another important point is the development of links from the model to the developing working platform of FLUMAGIS. It has to be examined if the derivation of parameters and indicators for the assessment of the environmental conditions is transferable to other regions. Thus, cooperation with other projects of the "River Basin Management" research program is aspired.

Acknowledgements

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Modelling Diffuse Pollution on Watersheds Using a GIS-linked Basin Scale Hydrologic/Water Quality Model

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Abstract

Over the last twenty years, regulations in matters of water resourses have become more effective at tackling point source pollution to ground and surface water systems. However, to meet the current requirements of the European Union (EU) Water Framework Directive (WFD), diffuse sources also need to be quantified and controlled. Diffuse pollutants are generally estimated by area- and pollutant- specific emission factors, which is a function of land use. However the comparison of instream direct measurements with the results of these indirect emission estimates often causes misleading results. The aim of this study is to combine a water quality simulation model, (USEPA-QUAL2E), run on a regional scale and an average annual temporal basis, with the GIS-linked physical-based Soil and Water Assessment Tool (SWAT) model. For this study, the SWAT model was modified to comply with Italian data sets to simulate the factors driving diffuse pollution in large and complex watersheds. Two watersheds were considered for this analysis: the Cherio River basin and the Mantova domain agricultural watershed. In these two areas, QUAL2E simulations (run with a discharge corresponding to a direct quality measurements) enabled the quantification and integration of the effect of point and non point sources over the measured instream total load. The integration of QUAL2E and SWAT simulations enables users to quantify overestimations of the diffuse load contributions and to adjust the source apportionment of point and non point source contributions to the instream total load within the SWAT model. SWAT predictions were much more accurate than the indirect emission estimates for both the studied watersheds.

KEYWORDS: non point and point source pollution, water quality models, integrated monitoring, nutrients, catchment management.

Introduction

Diffuse pollution enters the environment through a multitude of pathways. Even when anthropogenic, diffuse pollutants generally reach the surface water systems mediated by the environment itself. Over the last twenty years, legislation and regulations have become more effective at handling point sources to ground and surface water systems. However, to meet the current requirements of the EU legislation (Water Framework Directive 60/2000), diffuse sources of water pollution need to be identified, quantified and controlled. The extent of diffuse pollution is generally indirectly estimated by using area- and pollutant- specific emission factors, which are a function of land use (arable, grasslands, etc.). However, in many cases, the comparison of instream direct measurements with the mass balance results derived from these indirect emission estimates, has lead to misleading results (Zessner and Kroiss, 1999; Svendsen and Kronvang, 1993, Arheimer and Brandt, 1998, Azzellino et al., 2003). However, in spite of the difficulty of deriving direct measures of the apportionment of point and non point contributions to the instream total load, direct measurement is probably the only approach that can guarantee the validation of diffuse pollution assumptions. Therefore the aim of this study was to combine the use of a water quality simulation model, (USEPA-QUAL2E, Barnwell and Brown, 1987), run on a regional scale and an average annual temporal basis, with a GIS-linked physical-based model USDA SWAT (Arnold and Allen,1992). The model was modified to comply with Italian data sets to simulate the factors driving diffuse pollution (i.e. weather, soil properties, topography, vegetation, and land management practices) occurring in large and complex watersheds. This approach is already used in the project "Modeling Wister Lake Watershed using a GIS-linked Basin Scale Hydrologic/Water Quality Model" of the USEPA (Srinivasan et al. 1995)

Methodology

Two watersheds were considered for this analysis: the Cherio River basin (Drainage area: 150 km^2) and the Mantova domain agricultural watershed (310 km^2). Both of these watersheds are typical of many areas of the Po River valley. The Cherio River basin covers, in approximately equal proportions, both the mountainous and plains zones typical of the topography and vegetation of Northern Italy. The Mantovano area, within the Po and Mincio River Basins, is a plain zone dominated by intensive agricultural land use (Figure 1).

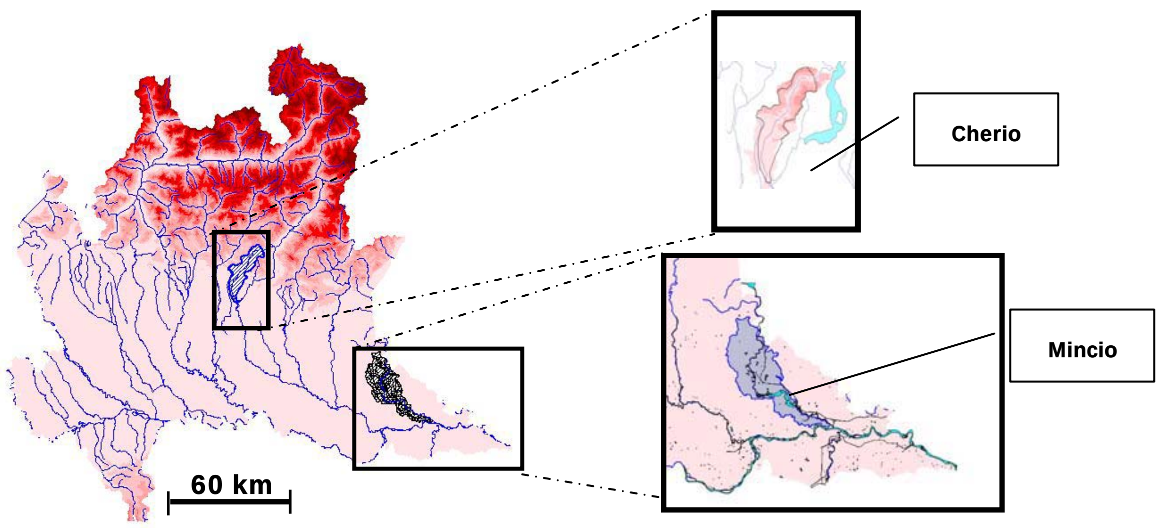

Figure 1. Study Area (Darkness scale is proportional to the elevation)

QUAL2E simulations relied on indirect estimations of the input loads, either for point sources, where population equivalent (PE) specific emission factors and average treatment removals were used (Table 1), or for non point sources, for which land use area specific emission factors were used (Table 2). Industrial point sources have been estimated on the basis of the industrial typology and the number of employees. These emission factors were substantially the same ones used by most of the Italian watershed management authorities (e.g. Autorità di Bacino del Po, among others). According to the measurements, nitrogen speciation was assumed to be 75% nitrates, 5% ammonia and 20% organic, whereas all of the phosphorous was considered to be dissolved.

Table 1 - Point sources emission factors and average treatment removals used to estimate the domestic wastewater loads.

Pollutant	Emission	Imhoff Removal %	A.S.* Removal %	A.S. + N Removal %	A.S. + N, P Removal %
BOD_5	60 g BOD PE^{-1} d^{-1}	25	90	92	92
COD	129 g COD PE^{-1} d^{-1}	25	85	85	85
Total-N	12.3 g N PE^{-1} d^{-1}	15	35	65	65
Total-P	1.8 g PE^{-1} d^{-1}	20	35	35	85

Table 2 - Diffuse area specific contributions as function of land use.

Pollutant	Arable	Grasslands	Forest	Other
Nitrogen percolation and runoff kg N (ha^{-1} y^{-1})	20 – 30	5 – 7	3 –10	5
Phosphorous erosion and runoff kg P (ha^{-1} y^{-1})	0.5 - 1.3	0.3 – 0.5	0.2 – 0.3	0.2 –0.5

In the same areas the SWAT model was run to simulate the effects of point and non point source loads. As input layers for the AVSWAT2000 a DEM grid at a 40 m spacing and the ERSAF maps on land use and soil characteristics were used. In order to run the AVSWAT routine the ERSAF land use codes were translated into the SWAT land cover classes. The weather database was generated on the basis of site specific average monthly temperature and precipitation parameters (i.e. min, max and standard deviation). Concerning the Mincio Basin which is characterised by a very complex system of irrigation channels that overlay the natural hydrographic network, a pseudo-hydrography was generated by means of the Watershed Delineation tool ("*Burn In*" option) within the SWAT model. Such simplification of the river network reflects the average pathways of the diffuse pollutants to the main stream (Figure 2).

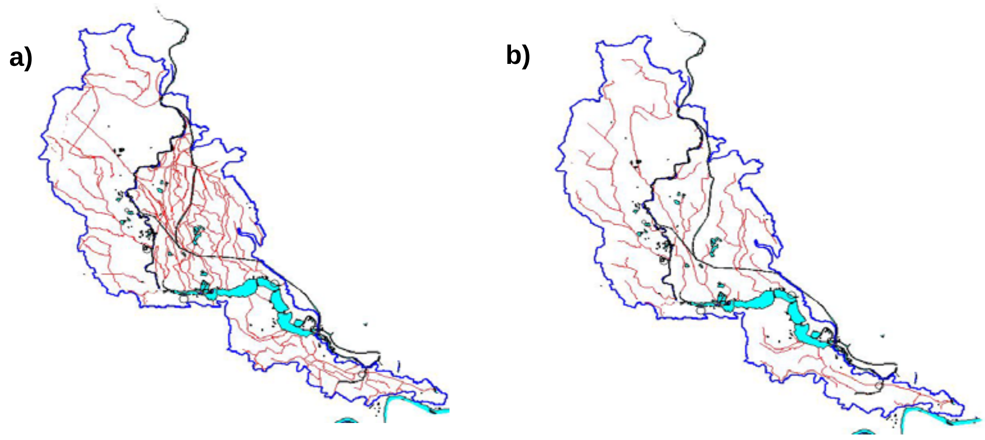

Figure 2. a) Hydrographic network and irrigation channel system of the Mincio Watershed; b) Pseudo-hydrography generated by the SWAT Watershed Delineation tool.

It was necessary to simulate lakes for both of the studied watersheds: two lakes at the headwaters of the Cherio and Mincio Rivers (i.e. Endine and Garda Lakes) and the Mantoa lakes within the Mincio watershed.

Results and Discussion

Both the QUAL2E and SWAT simulations were validated by comparing the simulated point load contribution to the mean annual scenario of the emasurements. This mean annual scenario reflects the impact of point source loads on the river quality. As a matter fact the median of the monthly direct measurements from a three year monitoring campaign (i.e. grab samples of instantaneous concentration and discharge conditions), has been used as a reference value for the model validation. The median was preferred to the mean because of the distribution skewness of the water quality measurements. Qual2E simulations in both cases showed a reasonable match with measured values (errors ± 20%). It should be noted that QUAL2E is much more reliable than the SWAT model for the assessment of the impact of point source loads on the river quality since the models temporal scale is much closer to the actual scale of the direct measurements. Moreover the mean annual scenario approximates the QUAL2E model's general assumptions (i.e. steady-streamflow and constant emissions). On the other hand, the scale and the general assumptions of the SWAT model are less appropriate to simulate dry weather conditions. Point source loads effect on water quality as simulated by the SWAT model were obtained by computing the monthly median of the nutrient simulated values over a three year time span and converting the contribution to an instantaneous load (i.e. spanning the monthly load over 30 days). Therefore, by following this approach, although smoothed by the conversion to the instantaneous values, the non point source load contribution was still present in the median monthly load. In light of these considerations the point source load estimates, validated by the QUAL2E simulation, were applied to the SWAT model. Figure 3 shows the point load contribution resulting from both of the models. Finally, the SWAT model was run for the two basins in order to evaluate the diffuse pattern within each watershed.

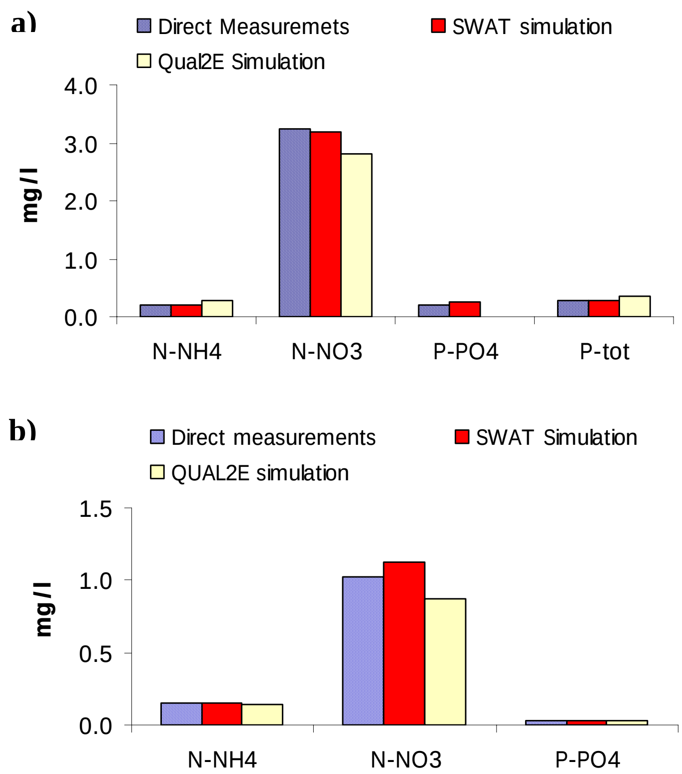

Figure 3. Point load effect on the river quality: comparison of the SWAT/QUAL2E simulations with the mean annual scenario (median of direct measurements). a) Cherio b) Mincio Basins.

As Figure 4 shows, the two model simulations were quite different for the two basins. The diffuse load was much lower for the Cherio catchment than for Mincio River catchment. This is quite reasonable since the Mincio River flows in a plains area dominated by intensive agricultural land use. Also it is interesting to observe that the diffuse load increases downstream within the Cherio basin since the agricultural zone covers just the lowland part of the basin (Figure 4a). The same pattern is only partially visible for the Mincio basin due to the effect of the Mantoa lakes which constitute a barrier for most of the non point source loads (Figure 4b). In order to compare the SWAT simulation results to the most used indirect estimates of diffuse load (i.e. the land-use area specific emission factors by Autorità di Bacino del Po, AdBPo), QUAL2E was used to simulate the water quality corresponding to a streamflow higher than the 75° percentile. Basically the few direct measurements available at a flow higher than such a value were used as reference to highlight overestimations.

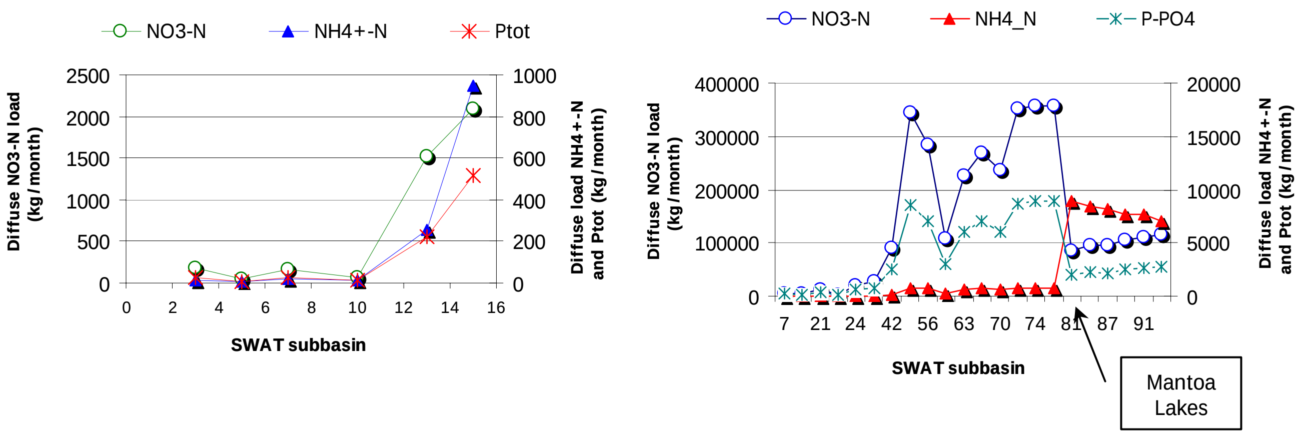

Figure 4. Simulation of the downstream pattern of diffuse loads: a) Cherio b) Mincio rivers.

The assumption was that the river quality during these high flow events was basically the result of both point and non point contributions. For these simulations input point loads were kept constant although diluted by 25%, and diffuse loads were evaluated either on the basis of AdBPo coefficients or by using SWAT predictions. Non point loads within the QUAL2E model were simulated as incremental flow contributions. AdBPo diffuse loads, being evaluated on an annual basis, were distributed following the monthly precipitation trend over the monthly average of rainy days. Similarly the SWAT predictions were distributed over the same interval of rainy days. Figure 5 shows the results of these simulations for the two watersheds, highlighting a remarkable overestimation of the AdBPo coefficients with respect to the direct measurement and the SWAT predictions.

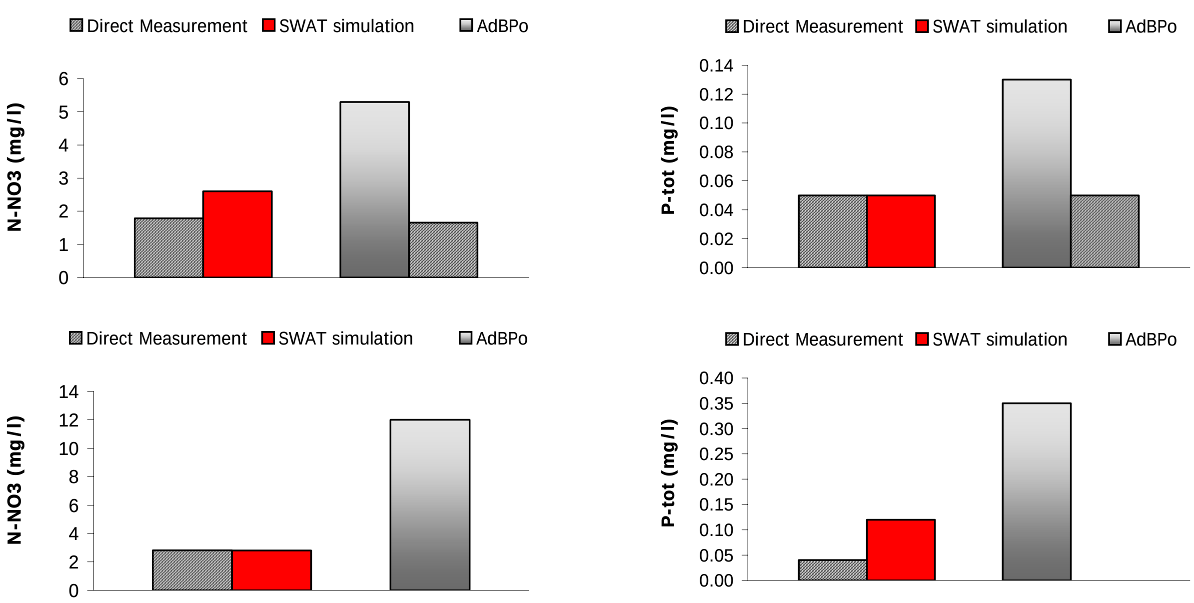

Figure 5 – QUAL2E simulations comparing SWAT predictions, AdBPo estimates and measurements.

Conclusions

Watershed scale diffuse pollution is generally quantified by using area- and pollutant-specific emission factors, which are a function of land use. However from the literature it is well known that these indirect emission estimates may be largely overestimated. The integration of QUAL2E and SWAT simulations would enable users to quantify the overestimation of the diffuse loads contribution and adjust the source apportionment of point and non point contributions to the instream total load within the SWAT model. SWAT predictions were much more accurate than the indirect emission estimates for both the studied watersheds.

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Eco-Hydrologic and Economic Trade-Off Functions in Watershed Management

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Abstract

The evaluation of ecological and economical assets and drawbacks due to changes in land use is a major topic in sustainable landscape management. For example, maintaining biodiversity, water quality and farmers income with changing land use and management is crucial for a successful realization and societal acceptance of political decisions concerning land use. In the Collaborative Research Centre 299, the Soil Water Assessment Tool (SWAT), the agro-economic simulation model ProLand (Prognosis of Land use), and the biodiversity model ANIMO are coupled by a joint geographic information system (GIS) database. Analyses are presented for the Aar catchment, a 60 km^2 sub-catchment of the Dill catchment (693 km^2), located in a low mountain range north of Frankfurt, Germany. Spatially explicit land use scenarios for different land use options are generated by ProLand, which account for different assumptions on the natural, technical, economic and political premises. For a given land use, ProLand predicts the optimal production system for a location (e.g. intensive and extensive rangeland, cropland or forest). Based on these land use scenarios, SWAT quantifies the hydrological balance and nutrient fluxes. ANIMO then predicts ecological indicators of species richness. Subsequent determination of trade-off functions and benefits integrate ecological and economic aspects such as added value, groundwater recharge and biodiversity.

KEYWORDS: Integrated modeling, economic-ecological trade off, land use change, scenario analysis.

Introduction

Integrated model approaches represent a state-of-the-art research tool to analyze landscape services (Antle et al., 2001). A major improvement by these model concepts is the possibility to derive benefits or trade-offs between different landscape services such as biodiversity, employment, water supply or food production. Scenarios of different land use or management options can be used to evaluate the sociological, ecological and economic assets and drawbacks of land use changes. Within the framework of the collaborative research centre SFB 299, an Integrated Tool for Ecological and Economical Modeling (ITE^{2}M) has been developed and is currently being improved. As an example of the prospects of ITE^{2}M various scenarios of land use in the Aar catchment are presented.

Methodology

The Agro-economic model ProLand

ProLand (Prognosis of Land use) assumes that the land use pattern is a function of the natural, economic, and social conditions (Kuhlmann et al., 2002). The main focus is to analyze the consequences on the allocation of agricultural and forestry systems as the general condition change with respect to economic, social and natural/technical influences. Based on small-scale information on the spatial distribution of physical, biological and socio-economic characteristics in a region – data are contained in a common GIS network (25 m x 25 m) – the allocation of land use systems is modeled, assuming land rent maximizing behavior of the land user for any parcel of land. Land rent, in this context, is defined as the sum of monetary yields including all subsidies minus input costs, depreciation, taxes, and opportunity costs for employed capital and labor. As a result two different types of model outputs have to be distinguished. First, a map of the potential spatial distribution of land use systems is generated. Second, the model calculates a set of aggregated key indicators to characterize the economic performance of land use as results of specific scenarios.

The eco-hydrologic model SWAT-G

The modified version of SWAT-G (Eckhardt et al., 2002) is based on SWAT 99.2 and is used to calculate hydrological and matter fluxes within the Aar and Dill catchment. SWAT-G and other versions of SWAT differ in the way of representing the interflow component. An anisotropy factor distinguishes vertical and horizontal saturated conductivity. In addition, during the course of parameterization, the deepest soil horizon is parameterized with a high bulk density and very low available water content to account for the fissured rock aquifer characteristic for the geo-hydrological conditions in the catchment. Prior to model application, SWAT-G was automatically calibrated and successfully validated in the Aar catchment (see Huisman et al., 2003).

The biodiversity model ANIMO

The spatially explicit landscape model ANIMO (Steiner and Köhler, 2003), a cellular automaton, is used to quantify the effects of land use changes on regional diversity. The model assumes that each habitat (land use) has its own species inventory depending on environmental, regional and historical constraints. Main habitats are sampled and in situ species numbers are implemented in the model. For each habitat an intrinsic species pool is determined with its portions of habitat generalists and specialists. Single cells interact with neighboring cells in the way that all habitat generalists of the central cell disperse into the four next surrounding cells. The number of species in a cell (α-diversity) was affected by the species inventory surrounding the cell and this in turn influenced the dissimilarity between habitat cells regarding species inventory (β-diversity) and that again affected the overall diversity of a landscape (γ-diversity). The employed species number per habitat were derived from field investigations (Steiner et al.

2002) and extrapolated to the Aar catchment. For each land use scenario, the within-area diversity (α), measured as the number of species occurring in one cell (Whittaker 1972) and the between-area diversity (β), which measures the average changes in species between two sites (Cody 1993), were calculated and then averaged for the entire landscape. The multiplicative combination of α and β resulted in the overall diversity of a landscape (γ-diversity, Whittaker 1977).

Results and Discussion

Land use scenario: Optimized suckler cow management

ProLand derives land use based on the calculation of an optimal land rent given the current ecological and economic conditions in the area of investigation (Control scenario, Figure 1), comprising forest, cropland, dairy and suckler cow production. As an alternative, the land rent is analyzed for an optimized land use system for peripheral regions such as the Dill catchment, in this case an extensive rangeland management by suckler cows with winter grazing (outwintering). The introduced suckler cow management is realized on the entire agricultural area, whereas forest distribution is fixed as a change is unlikely due German public regulations. The comparison of the control and the optimized suckler cow scenario reveal that maximum improvement of 75 % increase in land rent can be realized in only a small number of raster elements, which is hence nearly equivalent to the control scenario. Further land use scenarios are derived by blending the control scenario with the suckler cow scenario. The >0, 25 and 50 % scenarios define raster elements result in an improved land rent of >0, 25 and 50 % respectively as compared to the control scenario (Figure 1).

Spatial changes in land use for the scenario of outwintering suckler cow management are less pronounced compared to the extended shifts in land use described by Weber et al. (2001). Despite the different objective of modeling land use changes – Weber et al. investigated the influence of different field sizes aggregation on land use distribution – the main difference to their estimation is the fixation of forest distribution in the present scenarios as described above.

The control scenario is characterized by the land use options forest, pasture, and cropland (crop rotation). An alternative land use system for the marginal regions of the area of investigation is outwintering suckler cow management. The maximum improvement of land rent calculated by ProLand of 75 % compared to the control can be achieved on 3 % of the total land cover. 50 % land rent increase by the introduction of suckler cows is marginally higher within 4 % of the land area whereas up to 26 % of the land area shows an overall improvement of land rent larger than 0 % (Figure 1).

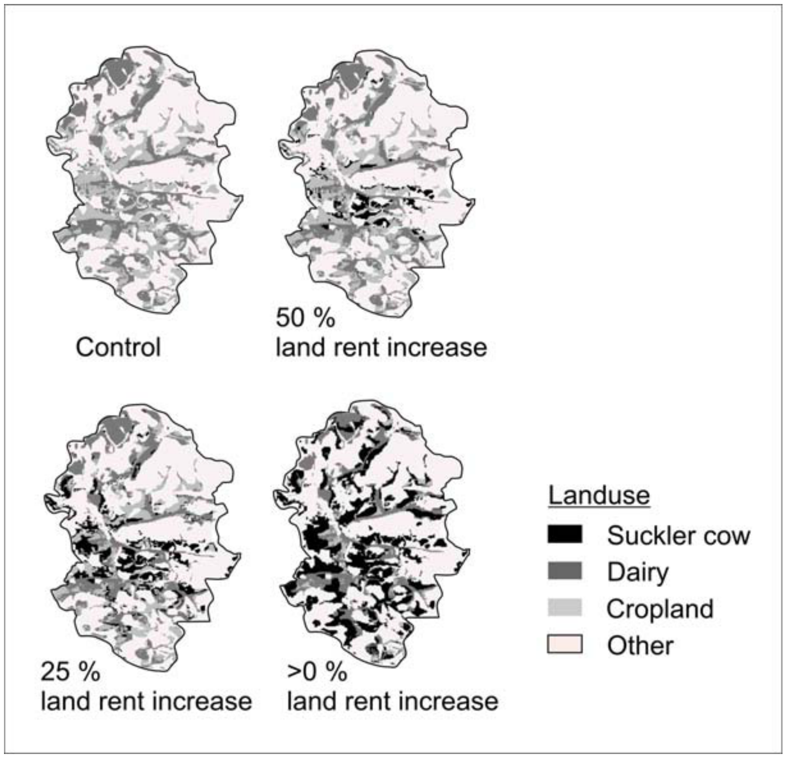

Figure 1. Agricultural land use distribution calculated by ProLand in response to the introduction of suckler cow management and resulting land rent improvement. Land use Other is comprised of forests (50.3 %), water (1.5 %) and settlements (5.3 %).

Economic versus ecological losses, benefits and trade-offs

Land use distribution in response to a required increase of land rent of up to 75 % for the Aar catchment results in an overall improved agricultural value added of up to 4 % (Figure 2). Associated with this higher economic value is a loss in labor input as intensive dairy production is replaced by the less labor intensive outwintering suckler cow management. The slight increase of labor input between 40-70 % land rent increases is the consequence of change of use towards cropland, which is the most extensive land use option of the three agricultural production systems investigated in this study. Floristic γ-diversity peaks at around the 20-30 % land rent scenarios, which is an effect of the high spatial heterogeneity and diversity of the land use systems cropland, dairy and suckler cow (Figure 1). Surface runoff as an indicator for erosion potential is very low and remains constant throughout all land use scenarios at < 30 a^{-1}. A similar behavior is obvious for groundwater recharge (approx. 80-90 mm a^{-1}), an objective commonly connected with drinking water supply. Even though water flux components are fairly constant, overall discharge seems to increase with a reduction of pasture production and a percentage increase of cropland (Figure 1).

An improved economic and ecological land use option for the Aar catchment with a slightly increasing floristic diversity and a constant groundwater recharge can be found at an increase of agricultural value added at around 3.02 Mio. € (Figure 3). This is equivalent to the 25 % scenario or – given in land use percentage – a change of use of dairy pasture (-2.5 %) and cropland (-5.5 %) towards an outwintering suckler cow management on about 8 % of the total land area compared to the control scenario.

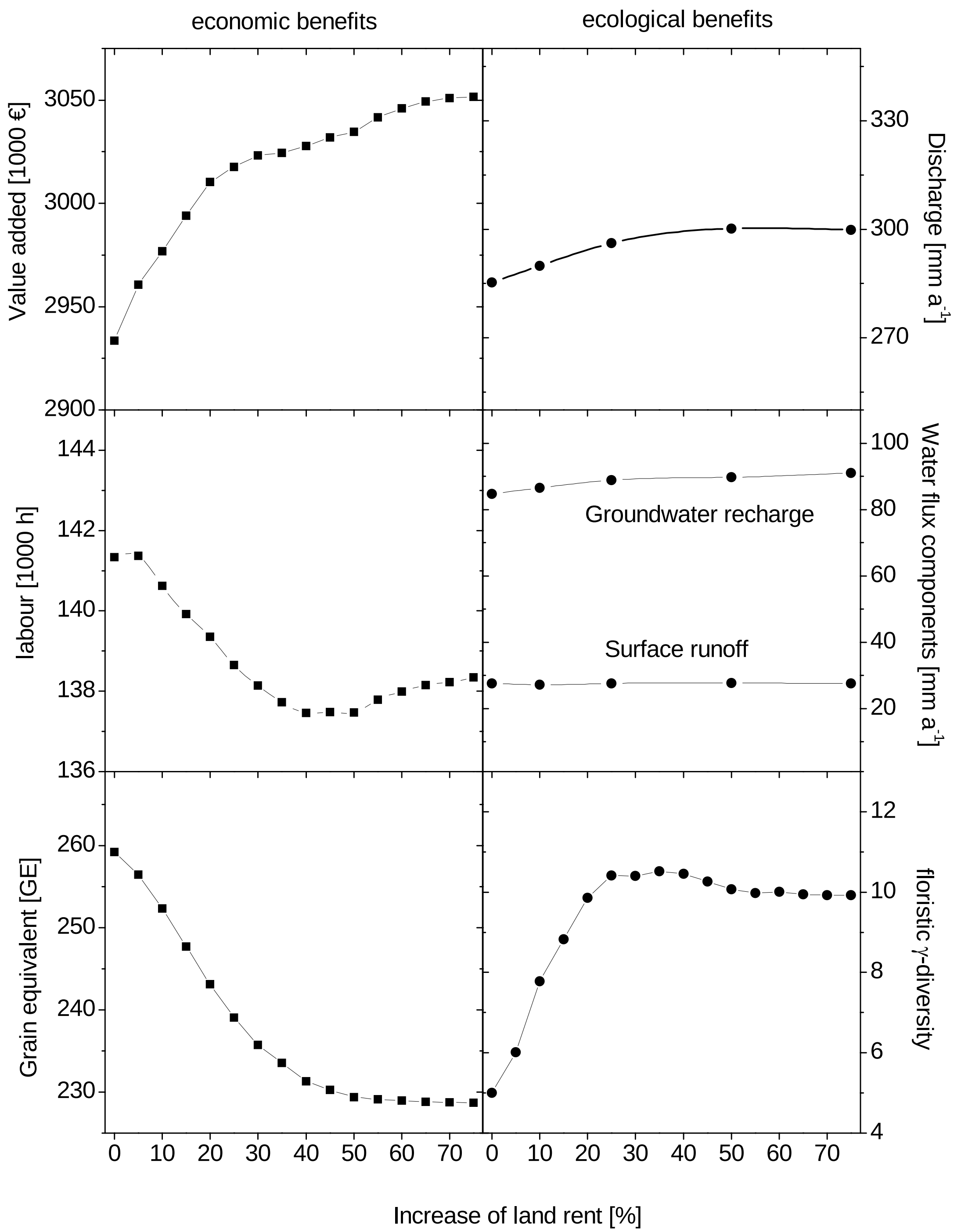

Figure 2. Economic and ecological objectives in view of land use systems. Control: land use types equivalent to conditions in 1994; scenarios: introduction of suckler cow management and areal extent in which land rent improved by >0 %, 25 % and 50 % respectively.

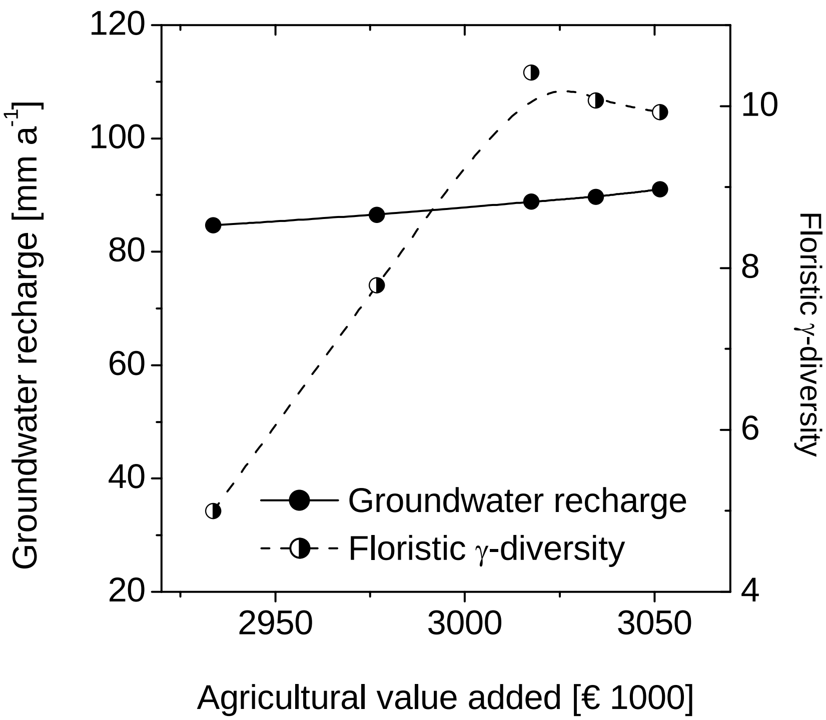

Figure 3. Ecological-economic trade offs for optimized suckler cow management.

Conclusions

Integrated modeling tools such as ITE^{2}M are helpful to investigate and evaluate the losses, benefits and trade-offs of human action with respect to economic and ecological landscape services. Based on a common GIS model network we are able to combine multi-disciplinary research approaches and calculate the proposed changes in hydrological components, biodiversity and economic objectives such as employment rate or farmers income. Regarding the regionally adjusted land use management of suckler cows, an optimized improvement of 25 % in land rent leads to a maximum increase of floral diversity while hydrological components remain nearly constant.

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Integration of In-Stream Water Quality Concepts within SWAT

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Introduction

The European Union (EU) Water Framework Directive of December 2000 imposes a new approach to water management in which reaching the in-stream quality objectives is essential. The directive also imposes an integration of all the water (quality) problems at a river basin scale to reach these objectives. Research in water quality modelling follows this new holistic approach on water quality management. As diffuse pollution sources are increasingly responsible for water quality problems, catchment models are more often used for water quality modelling. Upscaling of agricultural field-scale modelling tools or the inclusion of erosion and nutrient equations in catchment hydrological models has led to a number of tools that enable the calculation of the contributions of water, nutrients and sediments from drained areas.

In integrated river water quality modelling, the in-stream processes form a key role, as it is here that the pollution of different origins are accumulated and transformed to finally determine the water quality. The mathematical translations of the biological and physicochemical processes in rivers can be done in various ways, but two main trends can be distinguished. These are the traditional QUAL2E model (Brown and Barnwell, 1987) and the recently developed RWQM (River Water Quality Model) (Rauch et al., 2001), based on the ASM (Activated Sludge Model) (Henze, 1995). In this view, an evaluation of the weak and strong points of the different concepts is performed and adaptations to the process descriptions are proposed and compared.

VUB-QUAL-BOD

The traditional Qual2E model is based on the phenomenological approach of the Streeter-Phelps equations. The main state variables are the BOD (Biological Oxygen Demand) and DO (Dissolved Oxygen). Later, new state variables and processes have been added, resulting in a three-layer model (Masliev et al. 1995):

- the phenomenological level: the traditional Streeter-Phelps state variables BOD and Dissolved Oxygen (DO);
- the biochemical level: the extended Streeter-Phelps model variables ammonia, nitrate, nitrite and Sediment Oxygen Demand (SOD);
- the ecological level: the algae model variables organic nitrogen, organic phosphorus, dissolved phosphorus and algae biomass (as chlorophyll-a).

Due to these different levels, the mass balances are not always consistent (Masliev et al., 1995, Shanahan et al. 1998). For instance the processes dealing with the sediments are not linked to the river column processes, allowing a higher release by the river bed than what has historically been deposited. Also, using BOD as a measure for organic carbon is not directly fitting in mass balances, as it is not a quantitative mass value but only has a biological meaning. BOD is also harder to estimate than COD (Chemical Oxygen Demand). However, the equations can be transformed to be applicable for slow and fast COD variables.

Qual2E is extended and modified in such a way that the known shortcomings are overcome (Table 1). To close the system at the river bed, new state variables that describe the state of the water bed have been included. In this way, the river bed will only release solutes if there is a source available due to the settling of organic matter in the past. The release rates are considered to be independent of the source.

Although the absence of the biomasses of the pelagic bacteria is known to be a drawback of the model, they were not included. Changes of their population due to changes in the environment by emissions and corresponding lag times for their activity are thus not considered. Masliev et al. (1995) demonstrated that they behave in riverine conditions as “fast variables,” meaning that they adapt relatively quickly to changing conditions and thus can be excluded without causing big errors.

Sessile macrophytes were added to the model in the form of plants, with processes similar to algae. Organic matter can be partitioned in different fractions with different rates for hydrolysis and settlement. This allows to account for different rates when, for instance, organic matter with very high nutrient contents - such as manure - reaches the river. These loads usually behave differently than organic matter of other origin. Minor adaptations include denitrification and phosphate adsorption.

Table 1: Critics on QUAL2E (after Masliev et al., 1995, Shanahan et al. 1998).

1	*Failure to close mass balances involving interaction of the sediments*
2	Pelagic bacteria are not considered
3	Lack of sessile microbiota
4	Different rates for hydrolysis and settlement for the different organic fractions
5	Use of BOD as a measure of organic carbon

***RWQM-integration**

The River Water Quality Model (RWQM) (Reichert et al, 2001) has its roots in the Activated Sludge Model (ASM) for wastewater Treatment Plants (WWTP) (Henze et al, 1995). To take the activated sludge processes as the basis for a river model is quite logical, as both the river and WWTP pollutants undergo common processes such as bio-oxidation, bio-deoxygenation and bio-denitrification. Other processes - such as photosynthesis - occur more typically in rivers and had to be added to the ASM. The ASM is characterised by a high level of complexity in process formulation, state variables and parameters, whereby a consistent mass balance is respected at all levels. In an activated sludge basin, the process of pollutant removal is based and controlled by the presence of microbial organisms and hence is modelled as such in ASM.

The RWQM thus has a strong physical and biological basis. The main problem is that the high complexity leads to a high number of variables and - most of all - parameters (24 variables, 36 kinetic parameters, 6 equilibrium parameters, 13 stoechiometric parameters, and 36 mass fractions) if only the water column is taken into account. The parameter estimation problems seem to be the biggest disadvantage of the model (Marijns and Bauwens, 1997).

In an integrated modelling context, the RWQM is not directly applicable due to the fixed composition of organic matter that is assumed. Within the framework of diffuse pollution it is not possible to have a fixed composition in the organic matter: the contributions of organic P and organic N depend on crop, water, erosion and nutrient processes. Also, the point sources of industries can have the strangest compositions. These different organic fractions have also other rates for hydrolysis. The following modifications were needed:

- Splitting up of the organic components (organic N, organic P and organic C)
- Separate rates of hydrolysis for these components

The RWQM model defines processes and variables for the water column and the river bed, but does not specify the exchange between those phases. Diffusion processes of the soluble components at the sediment/water column interface and deposition/resuspension of the solids had to be worked out and included in the model codes.

ESWAT

ESWAT is an extension of the well known SWAT model (Arnold et al., 1998). The free shared codes of SWAT allowed for the adaptation of the software according to the requirements or needs of the model developers. For integrated modelling, the section on the river simulation needed to be extended. For water quality simulations with urban drainage problems, it is necessary to have a smaller time step than the daily time step of SWAT98. For this purpose, a sub-hourly infiltration model and an hourly river routing were added, allowing for the development of an hourly river water quality module. Point sources are considered with an hourly, daily or monthly frequency.

An automated calibration module is also included in ESWAT. The module uses the shuffled complex evolution algorithm (SCE-UA) (Duan et al., 1992) to minimise the optimisation criterion (van Griensven et al., 2002).

Dender River Case Study

The Dender River is a tributary of the Scheldt River and drains an area of 1384 km². The river reacts quickly to precipitation events. After storms, the flow can rise to over 100 m³/s, while the flows are less than 1 m³/s in summer. Water levels are kept constant by a number of sluices on the main channel to guarantee ship-traffic. The main channel is also partly canalised. The water quality is classified as bad to very bad due to domestic, industrial and agricultural pollution. An ESWAT model has been built for the downstream part of the basin (700 km²) (van Griensven et al., 2002).

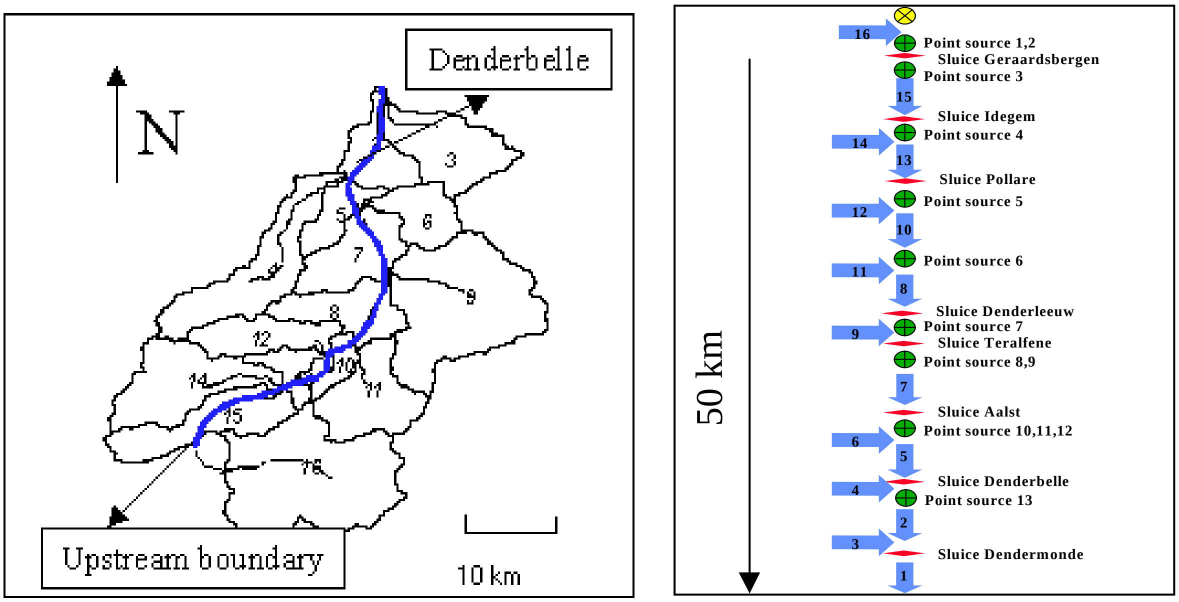

Figure 1: Delineation of the subbasins and the scheme of the main channel.

Calibration

To achieve a more objective comparison, automated calibrations were performed using oxygen and ammonia measurements on the Dender River. Hereto, objective functions are defined by the mean squared error for the oxygen and ammonia observations at Denderbelle, located 10 km upstream of the river mouth. Oxygen and ammonia N are aimed at as a good fit for both models. A trade-off between the objectives is achieved by aggregating both objective functions after transforming them in a probabilistic scale within the range of 0-1 (van Griensven et al., 2002). In this way, an optimisation criterion is defined as the sum of the standardised objective functions (van Griensven et al., 2002).

Applications of QUAL2E to the Dender model are described in Vandenberghe et al. (2001) and van Griensven et al. (2002). In this study, QUAL2E and VUB-QUAL-BOD used nine free parameters while RWQM-integrated used 15 free parameters.

Figure 2 shows the curve fitting for the dissolved oxygen (DO) and ammonia N concentrations for the three concepts. With the limited available measurements, it is not appropriate to decide which concept is performing better by visual comparison of the graphs or by mean squared errors. Nevertheless, there are differences in the shapes of the curves. QUAL2E is showing more sudden changes in the concentrations compared to QUAL-VUB-BOD and certainly to the RWQM-integrated simulations. RWQM-integrated gives much flatter graphs. Apparently, simulating changes in the biomass concentrations results in slower reactions of the oxygen and ammonia N concentrations. The biomasses have to grow first before responding to changes in the organic loads.

Evaluation and Conclusion

All models gave a reasonable fit for oxygen and ammonia. A clear difference between them is the flatter shape of the curves when the RWQM type models are used. This is due to the time needed by the bacteria to adapt to changed organic matter concentrations. Both concepts are able to fit the model outputs to observations and give proof of the ability of the model to describe the dynamics. This is, however, not sufficient as a validation. A true validation should at least also include an evaluation of the model performance on a separate data set that was not used for the calibration in order to detect problems with over-parameterisation. The process description can also be evaluated by getting better understanding on how bacterial biomasses react in riverine conditions. Hereto, the typical observations of water quality variables such as DO, ammonia and the organic fractions are not sufficient. In addition, monitoring and detailed analysis of the bacterial biomasses, their activities and how they react and adapt themselves to a changing environment are necessary.

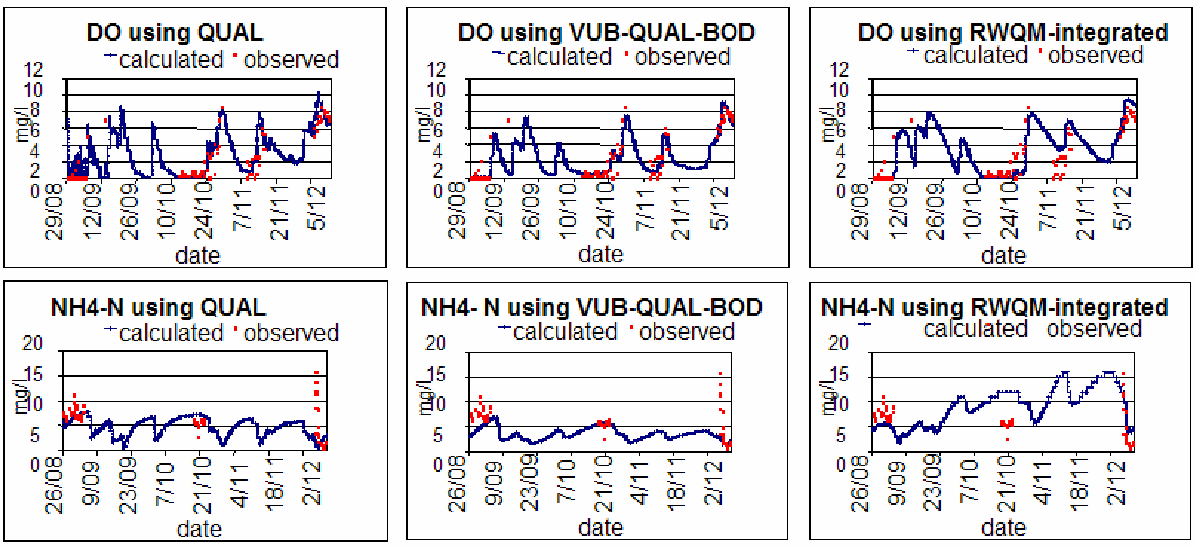

Figure 2: Dissolved oxygen and ammonia N graphs for September-December 1994 at Denderbelle.

Acknowledgements

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VI. Posters

Application of the SWAT Model on Agricultural Catchments in Finland

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Abstract

Agriculture is the main nutrient source to surface waters in Finnish agricultural catchments. Agricultural losses of nutrients are of a diffuse nature, having both temporal and spatial dimensions. These losses can only be assessed by studying the whole catchment area over time. In Finland, catchment-scale nutrient leaching models are tested for this purpose. In order to analyse the prevailing complex hydrological, soil and land use interactions on agricultural catchments in Finland, the SWAT model is applied to Savijoki. It is a small agricultural catchment, which well-represents the intensively cultivated areas in south-western Finland. In Finnish conditions nutrients are mostly transported during snowmelt periods and autumn rains. Successful calibration of flow during these periods is a prerequisite for modelling nutrient loads from the catchments. SWAT is being calibrated to measured time series of flow and nutrient concentrations at the outlet of the Savijoki catchment. The paper describes the hydrological conditions in this quickly responding small scale catchment and presents the land-use characteristics utilized for the SWAT model application. As part of the MicroHARP project, the aim of this model application is to evaluate the applicability of the SWAT for estimation of agricultural nutrient loads and the effects of agricultural management practices on these loads. The applicability of the SWAT model is currently also being tested for Water Framework Directive purposes within the EU project BMW 'Benchmark Models for the Water Framework Directive' in the Yläneenjoki catchment in south-western Finland. The catchment is divided into sub-areas with varying soil types and land use. The water quality in ditch and river water varies accordingly. The SWAT simulation case study consists of two steps: (1) SWAT is calibrated to a measured time series on flow and nutrient concentrations at the outlet of the catchment representing a "normal" monitoring situation in Finnish catchments; (2) the calibration will be performed using 13 additional 10-year monitoring points for water quality scattered within the catchment.

Methodology

The Savijoki catchment is located in south-western Finland (Table 1). It is a sub-catchment of River Aurajoki that discharges to the Baltic Sea. There are no lakes in the catchment. Agricultural fields consist of clayey soils and they cover 39% of the catchment area. The rest is mostly forests growing on thin glacial till layers. Spring cereals are the most common agricultural crops and livestock density is relatively low. Monitoring data on flow (daily values) and nutrient concentration (flow-proportional sampling strategy) was available at the catchment outlet since year 1981.

The Yläneenjoki catchment is situated on the coastal plains of south-western Finland (Table 1). The largest part of the area is covered by forest. The main line of agricultural production is spring cereals. Barley and oats are cultivated on over 50% of the fields. The dominating field soil types are sandy loam and clay. They cover approximately 75% of the agricultural area. Forest is mainly growing on till and organic soils. The range of field slopes is relatively wide (0-10%) but the median field slope is 1%.

Table 1 Variables describing the Savijoki (SAVI) and Yläneenjoki (YLA) catchments.

	SAVI	YLA
average annual air temperature [^oC]	5.2	4.2
annual precipitation sum [mm]	698	719
total catchment area [km^2]	15.4	227
field percentage [%]	39	27

Results

Savijoki catchment

Based on the Digital Elevation Model (DEM), the catchment was divided into 13 sub-basins by SWAT. The original DEM grid data had to be reclassified due to very flat topography on agricultural area. Data on soil types were based on a digital soil map provided by the Geological Survey of Finland. The soil data was further interpreted based on published information on the hydrogeology of Finnish agricultural and till soils. The original land use map (National Land Survey of Finland) for Savijoki consisted of 43 different types of land use, including different classes for forests on organic and mineral soils. In the first model version agricultural area consisted of a single class (field). For the preliminary testing this detailed land use map was re-constructed for model application. A digital stream network was also needed and superimposed onto the DEM. Several combinations of threshold values were tested for HRU delineation. Due to high variability (and also some inaccuracy) in soil types and land-uses, high threshold values (30% for land use and 20% for soil class) were needed for a realistic HRU description. The total number of HRUs was 25 for the preliminary test.

The measured specific runoff was highly variable during years 1981-2000. The mean, minimum and maximum values were 11.7, 0 and 303.5 $l\ s^{-1}\ km^{-2}$, respectively. Accordingly, the measured annual runoff showed a high variation and was correlated to annual precipitation. The mean annual runoff was 369 mm. The highest runoff (616 mm) occurred in 1984, corresponding to the highest precipitation (874 mm, local station) and snow water equivalent (119 mm). This headwater catchment typically responds rapidly to snowmelt and precipitation events. This is mostly due to low groundwater storage in the forested areas and intensive sub-surface drainage on fields. A conceptual understanding of the water pathways and residence times is crucial for flow calibration in these complex hydrological conditions. Especially, in order to calibrate the spring time peak flow, a detailed analysis of measured snow water equivalent and soil frost is needed.

Yläneenjoki catchment

For the SWAT simulations the available data on land use and soil types had to be aggregated. Forests in Finland are classified according to their stage of growth and dominant tree and soil type into approximately 50 classes. Since the parameterisation of all these would be an overwhelming task the classes were regrouped according to their stage of growth: cut and recently planted forests, forests of active growth (biomass<$150m^3ha^{-1}$) and old forests (biomass>$150m^3ha^{-1}$). Similar regrouping was required for coarse soils which show a great variety but only patchwork locations within the catchment: tills, till ridges, eskers, gravel and coarse sand were grouped and parameterised according to till characteristics which are the dominant type. In conclusion, the SWAT parameterisation was performed for seven land use types (water, field, forest cuts & recently planted forest, active forest, old forest, peat bog and sealed areas) and six soil types (open bedrock, till & other coarse soils, silt, clay and turf) (Table 2).

Table 2. Distribution of land use and soil types.

Land use types:	Distribution [%]
- active forest	52
- field	28
- old forest	12
- sealed areas	4
- peat bog	2
- forest cuts & recently planted forest	1
- water	1
Soil types:	**Distribution [%]**
- clay	40
- till & other coarse soils	23
- open bedrock	21
- turf	14
- silt	2

The first classification of the Yläneenjoki catchment resulted in 30 sub-basins. With a threshold value of 20% for land use and soil types the number of HRUs is 91. This meant that land use types were reduced to three and soil types to three as well.

Discussions and Conclusions

These preliminary tests of the SWAT model showed that the available GIS data on soils and land use were suitable for basic model set-up on two agricultural catchments of different sizes. One part of the further application of SWAT is testing the role of forested areas on hydrology and nutrient losses, since forest covers over 50% of both catchment areas. For this purpose detailed information is needed on forest biomass development and typical forest soil properties allowing credible parameterisation of the model. Proper calibration of the snowmelt induced high flow peaks is of great importance. Measured snow water equivalent data will be compared to modelled ones on both catchments.

Acknowledgements

Financial support of the MicroHARP project (No: 15529-1999-12 F1ED ISP FI) through the Commission of the European Communities and of the BMW project (Project Contract No.: EVK1-CT-2001-00093) through the European Union is gratefully acknowledged.

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Homepage of the MicroHARP project: http://www.ymparisto.fi/eng/syke/ird/harp.htm

Homepage of the BMW project: http://www.ymparisto.fi/eng/research/euproj/bmw/homepage.htm

An Integrated Modelling of the Guadiamar Catchment (Spain)

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Abstract

Modelling water resources phenomena is a key step for water managers to ensure a sustainable development. It is particularly important to simultaneously manage surface water and groundwater in terms of both quantity and quality. To this purpose, an integrated model composed of the quasi-distributed catchment model SWAT linked to the fully distributed ground-water model MODFLOW and the reactive multicomponent transport model PHT3D for saturated porous media was developed. This new coupled model was applied to a Mediterranean catchment, the Guadiamar in Spain. The study site was heavily contaminated after a dam failure of a lead-zinc-copper mine in April 1998, which released large amounts of heavy metals in acidic water and toxic mud. The purpose of the study was applying the coupled model to evaluate, after the removal of the polluted soil, the fate of the remaining heavy metals. The model accurately reproduced the variation of the piezometric level, and the exchanges between surface water and groundwater. The fates of cadmium, lead, and zinc were studied to estimate their potential leaching to the aquifer and evaluate if they represented a threat to the groundwater as it was used for human consumption.

Introduction

The dam failure of the Los Frailes lead-zinc-copper mine at Aznalcóllar, in April 1998, released approximately 4 million cubic meters of acidic water and 2 million cubic meters of toxic mud, containing large amounts of heavy metals, into the nearby Agrio river (Grimalt et al., 1999). This area is located in Guadiamar watershed upstream of the Doñana National Park. The resulting flood not only affected river bank vegetation but also agricultural lands and open meadows. Even after the toxic mud was removed and the retained acidic water treated, studies showed that significant contaminants remained in the soil and in the river bed.

The primary objectives of this paper are to present the assessment of the ecological risk to the Guadiamar river basin and the development of tools for watershed integrated management. The current management plan in the Guadiamar river basin is to restore and maintain water quality at high standards to support the ecosystem diversity, to stop and attempt to reverse the ecological degradation resulting from anthropogenic activities. Understanding the hydrology of the Guadiamar watershed by using a hydrological model is an important first step towards a better management of its natural resources: the coupled models SWAT-MODFLOW-PHREEQC2-PHT3D were tested here for this purpose.

Methodology

The Guadiamar watershed covers an area of 1 500 km^2 in Andalusia, in southern Spain. The ground is gently sloping with elevations that range from 0 m to 600 m above sea level. The climate of the region is typically Mediterranean, with an average annual rainfall of 570 mm and an average annual temperature of 17°C. The Guadiamar river flows from north to south for 90 km. Gravel fluvio-deltaic aquifers underlie the sandy alluvial aquifer, and form two aquifer formations. The watershed is characterised by an open-mine upstream and a national park downstream. The Doñana National Park is one of the most important wetlands in Western Europe. The marshes and ponds of the park are the wintering area for a large number of migrating waterfowl species.

The SWAT-MODFLOW-PHREEQC2-PHT3D linkage used SWAT v.99.2 (Arnold et al., 1998), MODFLOW-96 v.3.3 (Harbaugh and McDonald, 1996); Phreeqc-2 (Parkhurst and Appelo, 1999) and PHT3D (Prommer et al., 2001). The methodology is based on modelling of: the general hydrology of the region using SWAT; the groundwater flow using MODFLOW; the fate of heavy metals in the unsaturated zone using Phreeqc-2 and in the saturated porous media using PHT3D

The SWAT model (Soil and Water Assessment Tool) is a semi-distributed watershed model with a geographic information system (GIS) interface that outlines the sub-basins and stream networks from a digital elevation model and calculates daily water balances from meteorological, soil and land-use data. SWAT simulates each sub-basin separately according to the soil water budget equation taking into account daily amounts of precipitation, runoff, transmission losses, percolation from the soil profile, and evapotranspiration.

MODFLOW is a fully distributed model that calculates groundwater flow from aquifer characteristics. It solves the three-dimensional groundwater flow equation using finite-difference approximations. The finite-difference procedure requires that the aquifer be divided into blocks called cells, where the aquifer properties are assumed to be uniform. The unknown head in each cell is calculated at a node at the centre of the cell. The hydrologic terms simulated by SWAT are transformed from cumulative volumes per unit area [L] to flow rates [L3/T] in the system of units specified for MODFLOW's simulation. This volume is given by integrating flow rates over time. Thus hydrologic terms simulated by SWAT for each sub-basin are combined to specify fluxes for MODFLOW's solution in each time step (Perkins and Sophocleous, 2000). These fluxes include groundwater recharge, tributary inflow, and a maximum rate for evaporation from shallow groundwater.

Phreeqc-2 is a computer program for simulating chemical reactions and transport processes in natural or contaminated water. It provides all of the capabilities of a geochemical model, including speciation, batch-reaction, 1D reactive-transport, and inverse modelling. Speciation modelling uses a chemical analysis of a water to calculate the distribution of aqueous species by using an ion-association aqueous model. It is used to simulate the fate of heavy metals in the unsaturated zone using several soil geochemical analysis.

PHT3D is a three-dimensional groundwater contaminant, solute transport and geochemical model that can simulate advection, dispersion, dual domain mass transfer, and chemical reactions of dissolved constituents in groundwater. The code is based on MT3DMS (Zheng and Wang, 1999) or solute transport and on Phreeqc-2 for geochemical reactions (Parkhurst and Appelo, 1999). PHT3D uses the output head and cell-by-cell flow data computed by MODFLOW to establish the groundwater flow field. The concentrations of heavy metal percolation simulated by Phreeqc-2 are used as recharge concentration terms for PHT3D.

Results and Discussion

The coupled models (SWAT-MODFLOW-PHREEQC2-PHT3D) were applied to the Guadiamar watershed for the period 1980-2015. The modelling consisted of a two-step approach. Calibration targets for the models are the available measured monthly stream flows from the outlet gauging station and piezometric levels from three boreholes for the quantitative point of view, for the 1980-1998 period. Model parameters were adjusted by trial and error to reduce the differences between simulated and measured values using the Nash-Sutcliffe coefficient. Then the coupled model was run for 1998-2015 to predict heavy metal concentrations in the groundwater for the water quality point of view.

First, the digital elevation model, with a cell-size of 20 m, was used to discretise the watershed into 92 sub-basins with local dominant soil and land-use. Data of daily precipitation and temperature were available from four meteorological stations for the 1980-2000 period. Meteorology from 2000 to 2015 was considered the same as 1980-1995, and no climate change was taken into account. Each sub-basin was characterized by the amount of rainfall and the temperatures from the nearer meteorological station.

Within MODFLOW, the aquifers were represented as two layers, discretised into a grid of 216 rows and 83 columns. The row and column of the model represented a 200-1000 m wide strip of aquifer. Groundwater limits for the model corresponded to those described by ITGE (Instituto Tecnológico GeoMinero de España, 2000). These boundaries were designated as no-flow cells. Two isotropic layers represented the alluvial and regional aquifer. The calibrated hydraulic conductivities and specific yield of the alluvial and regional aquifers used in the model fell within the range of literature values (Instituto Tecnológico GeoMinero de España, 2000). Recharge was distributed according to SWAT simulation outputs for each month. Stream-aquifer interaction was simulated using a stream-routing package for MODFLOW. Stream flows assigned to the upstream reach of each stream segment were values input from monthly SWAT simulation. The model was calibrated under steady-state conditions by adjusting input data including hydraulic conductivity, and vertical leakage. Calibration under transient conditions also included adjustment of specific yield and evaporation.

Then heavy metals contained in six sandy soils (fluvisol) were modelled by Phreeqc-2. Heavy metal concentration was calculated according to the JRC's sample campaign (Kemper, 2003). Finally the PHT3D model was based on the grid and results of MODFLOW. Distributed heavy metal concentrations calculated by Phreeqc-2 were input for each stress period (month). A simple system was considered {Civ, Ca, Cd, Cl, Na, Pb, Si, Zn, calcite, chalcedony} in order to limit the computational time. Initial element concentrations were interpolated from sampling results presented by Manzano et al. (1999).

Figure 1 shows the measured and simulated monthly discharges at the Aználcazar gauging station. The range of data is 0-80 m3.s-1. Predicted peak flow rate by SWAT-MODFLOW and monthly flow compared favourably with the measured values (despite the lack of measured data during some periods). The Nash-Sutcliffe coefficient for monthly flow is 0.72 for 1980-1998 (corresponding to the period with available data). In most cases, the order of magnitude of the flood peaks and recession curves was in good agreement. The representation of the piezometric levels was adequate even though some discrepancies were noted at the beginning of the simulation probably due to model initialisation. During the period 1984-1994, the coupled model overestimated the water level in the centre of the basin, probably due to illegal ground-water abstraction not considered, since the modelling exercise was carried out using only the official ground-water withdrawal rates.

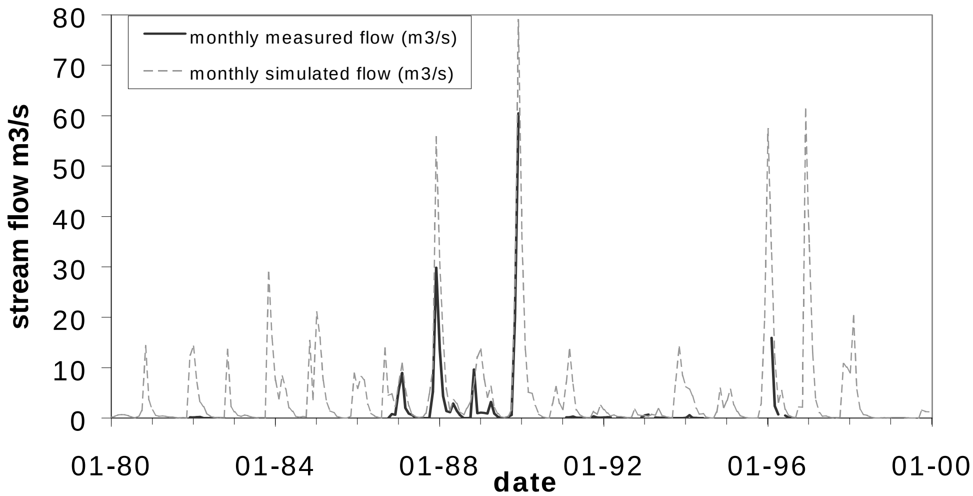

Figure 1. Measured and simulated monthly discharge (m3.s-1) at Aználcazar gauging station.

Concerning the water quality, risk prediction (without validation) for the 1998-2015 period indicated that initial contamination due to flooded boreholes was acute in the alluvial aquifer. Cd and Zn in the soils behaved similarly and reached the alluvial groundwater after three years. The highest concentrations were predicted to occur in the beginning of 2002 (about 5.10-6 mol.L-1 for cadmium and 5.10-3 mol.L-1 for the zinc), then the concentrations decreased. Lead behaved differently: its percolation through the unsaturated zone was slower and it reached the groundwater after 10 years, its predicted concentration was still increasing in 2015. Regional aquifers were contaminated locally. These results were consistent with precedent local observations (Sánchez-Camazano and Sánchez-Martín, 2000). Regional aquifers were contaminated locally. An illustration of the distribution of Cd in the alluvial aquifer is shown in Figure 2.

Conclusions

The proposed methodology for modelling the general hydrology of the region and the fate of heavy metals using the coupled models (SWAT-MODFLOW-PHREEQC2-PHT3D) for the Guadiamar catchment was very appropriate. In particular the water quantity presented very good Nash-Sutcliffe coefficients (0.72 for the monthly water discharge). The risk prediction demonstrated that Cd, Pb and Zn represented a threat to the groundwater as it was used for human consumption.

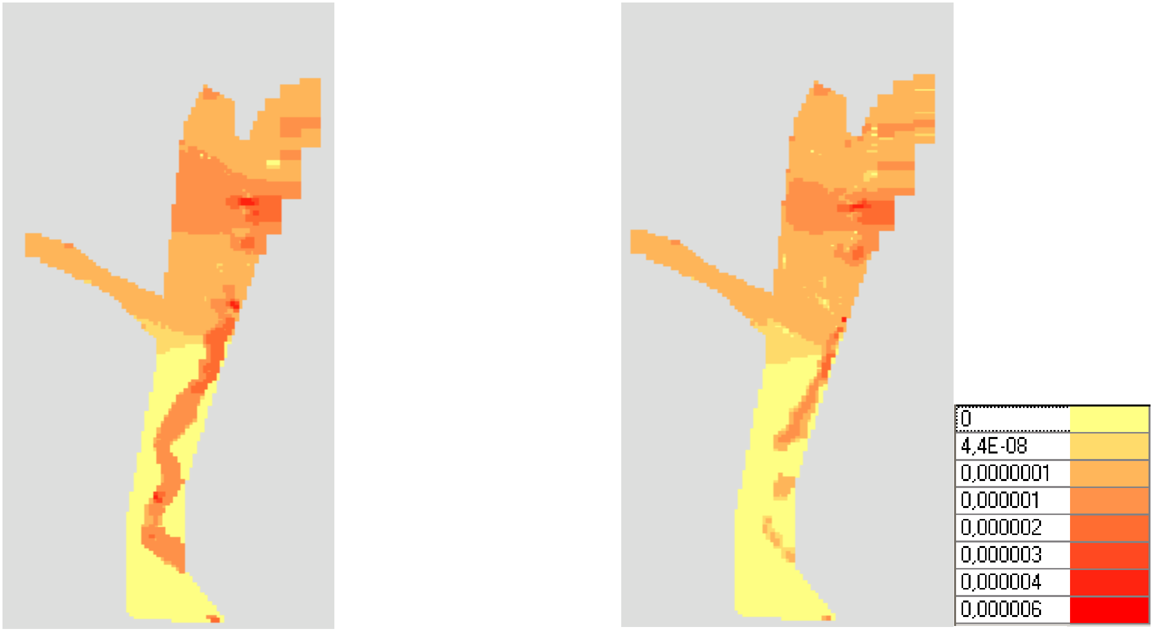

Figure 2. Predicted distribution of Cd (mol L-1) in the alluvial aquifer in January 2003 and 2015.

Acknowledgment

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Validation of a Statistical Model of Source Apportionment of Riverine Nitrogen Loads by the Physical Model SWAT

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Abstract

In this study the Soil Water Assessment Tool (SWAT) model was used to validate a statistical model of source apportionment of riverine nitrogen loads. The SWAT model has been applied to an area (1570 km^2), which partially covers the river basin of Great Ouse, in East Anglia (UK). Water flow and nitrogen load were calibrated using daily measurements from 1995 to 1999. Then SWAT results were compared with the statistical model predictions. SWAT was shown to be an interesting tool to interpret and give a physical meaning to the statistical model parameters.

Introduction

Many European countries face high river nitrogen loads and the scientific community is asked to provide reliable modeling tools to evaluate nitrogen sources contribution to water pollution. A large number of models address the problem of basin nitrogen losses, ranging from physical to statistical approaches. Mechanistic models describe in detail nitrogen fate and transport, allowing a better understanding of the process involved. However data and calibration requirements are important and increase with basin size. Thus, in large scale analysis statistical models were often preferred (Seitzinger et al., 2002; De Wit, 2000, Caracao and Cole, 1999; Smith et al. 1997; Howarth et al., 1996), as their parameterisation is less demanding. However, uncertainties concerning their predictive abilities are high. The objective of this study is to assess the reliability of a statistical model prediction applying the physically-based model SWAT (Arnold et al., 1998).

Methodology

A statistical model of source apportionment of riverine nitrogen loads was developed in a large area (8900 km^2) in East Anglia (UK) (Grizzetti et al., 2003). Then the physically-based model SWAT was applied in a sub-catchment (1570 km^2) in order to validate predictions of the statistical model (Figure 1). The statistical model, inspired by the SPARROW methodology (Smith et al., 1997), consists of a non-linear regression equation, where the river nitrate load is related to the different nitrogen sources, including fertilizer, atmospheric deposition and point discharges, reduced by the retention processes occurring in soils and water. The model considers two steps in nitrogen removal: losses occurring during the transport from land to the river, and losses due to soil denitrification, volatilisation, plants consumption of nitrogen, and soil storage. All these processes are lumped together and modeled using a decreasing exponential function that takes into account rainfall, temperature and basin topography. The losses taking place during river transport are controlled by in-stream denitrification, plants consumption and net sedimentation, and are represented by a decreasing exponential function that takes water flows into account.

The statistical model predicts the annual nitrate loads at different points of the river network according to the characteristics of the drained area. The model allows the estimation of nitrogen removal in soil and water. Even though the statistical model performance was satisfactory both in calibration and in validation (Grizzetti et al., 2003), the approach does not allow the quantification of the processes responsible for nitrogen removal separately. The physically-based SWAT model was applied to the same area to validate the statistical model, by comparing the predicted annual flux of nitrogen through soils and water, and by comparing also the spatial variation of nitrogen removal.

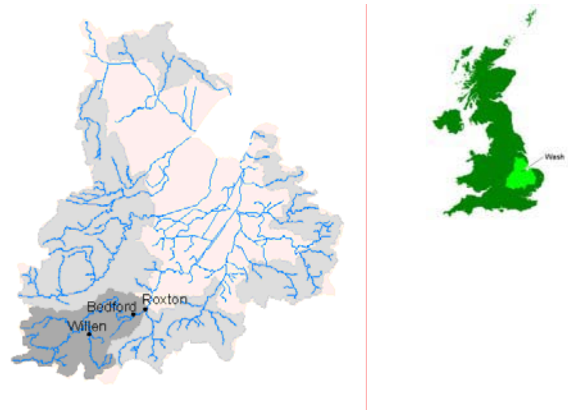


Figure 1. Area of study: the statistical model was applied in area marked in light grey, while the SWAT model was applied in the area marked in dark grey.

The statistical model was developed over an area of 8900 km^2, which partially covers the river basins of Great Ouse, Nene, Welland and Witham, in East Anglia (UK). Then the physically-based model SWAT (Arnold et al., 1998) was applied in the basin of Great Ouse (1570 km^2) (Figure 1).

In this region the average air temperature is 4° C in winter and 17° C in summer. The precipitations range between 547 and 657 mm/yr, increasing with altitude. The area is characterized by rich clay soils. Average flow at the downstream gauging stations is 10 m^3/s and flow peaks occur during the winter season. Arable lands occupy 55% while grasslands represent 35% of the area. Grasslands are more frequent in the west part, where the density of cattle and sheep is higher.

The SWAT ArcView Interface (Di Luzio et al., 2002) was used in order to perform the model parameterization. A digital elevation model of 100x100 m grid size was available for the basin. The digitized stream flow network was imposed, as the down-stream part of the area is flat. The land use map, computed from the agricultural census (1997) of DEFRA (English Department for Environment Food and Rural Affairs), and the European soil map were used in this study. Data of fertilizer application and land use management were taken from DEFRA, while soil physical and hydrological characteristics were estimated from the European soil map database. The average annual load of point discharges was computed for each sub-basin. Concerning the atmospheric deposition, an average value of 10 kg N/ha/y suggested by EMEP (2003) was considered. Two rainfall stations and one meteorological station provided daily measurements. Precipitation and temperature time-series consisted in daily values from 1980 to 1999. Average weather characteristics were estimated from the data provided by the meteorological station. Daily measured data of flow and water quality at three gauging stations were available from 1980 to 1999 (Figure 1). The basin was subdivided into seven sub-basins and 73 HRUs obtained considering a threshold of 20% for soils and 5% for land use. These threshold values provided a spatial representation of the land use and the soils of the basin close to the original maps.

Results

The data at the Bedford gauging station were used for calibration while those of Roxton and Willen were reserved for validation. SWAT modeling performance was evaluated by the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970). Daily water flow was calibrated for a five years period extending from 1995 to 1999 (Figure 2). The efficiency of for the calibration was 0.75. The efficiencies for the validation at Roxton and Willen stations for the period from 1995 to 1999 were 0.67 and 0.37, respectively.

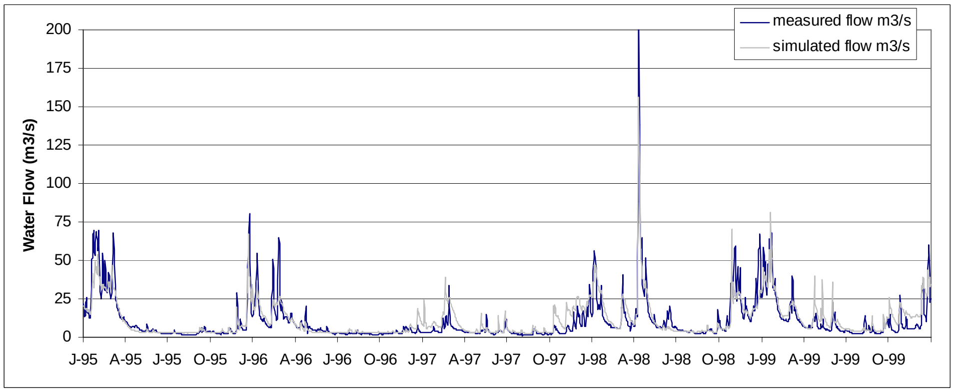


Figure 2. Measured and simulated water flow at the Bedford gauging station.

The daily nitrate load was calibrated at the Bedford station for the period 1995 to 1999, with an efficiency of 0.27 (Figure 3). The average nitrate concentration of the groundwater contribution to the river was estimated considering the average nitrate leaching and the average water percolation from the bottom of soil computed by SWAT.

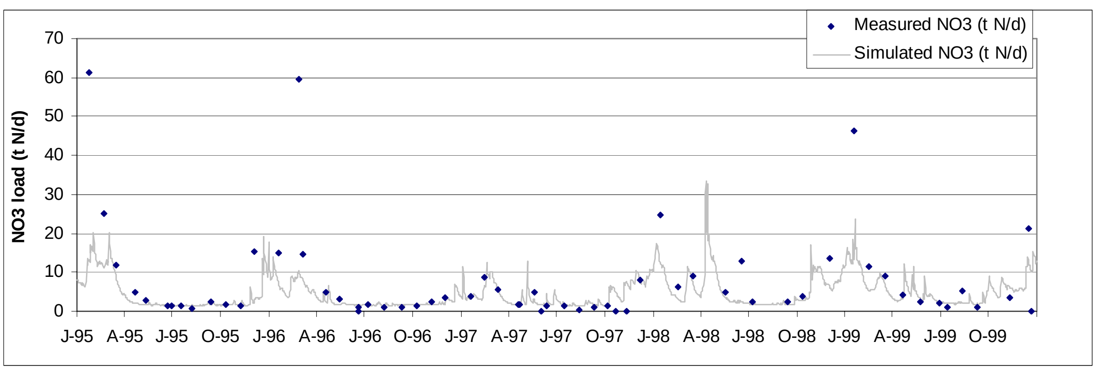
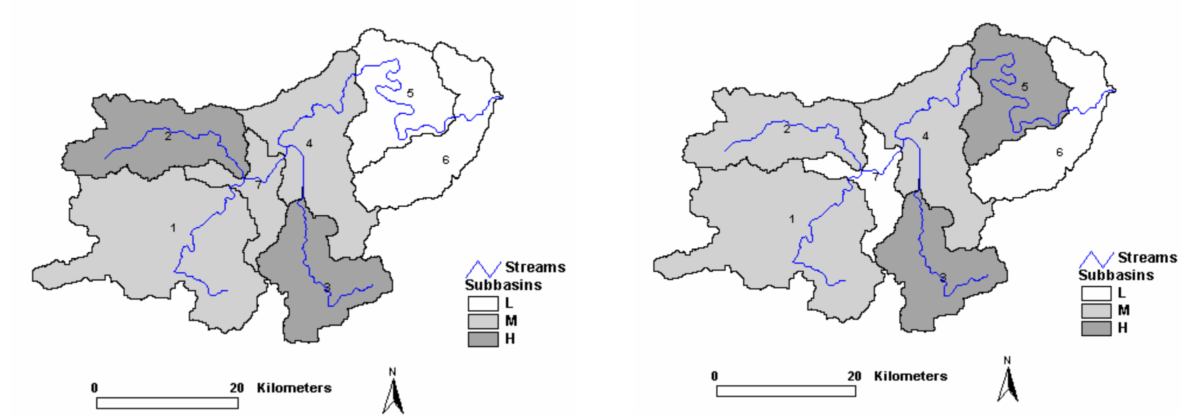


Figure 3. Measured and simulated nitrate load at the Bedford gauging station.

According to SWAT estimation, the nitrogen diffuse emissions from the catchment account for 69% of the in-stream nitrogen load, while the remaining 31% is due to point discharges. Similar values were found by the statistical model, with diffuse emissions (fertilizer and atmospheric deposition) accounting for 70% of the total nitrogen load and point emissions contributing to 30%.

Average values of in-stream nitrogen removal were computed for each sub-basin, and then compared with the values estimated by the statistical method in order to evaluate the spatial distribution of the predicted retentions. The results are shown in Figures 4. SWAT estimated an average river retention of 0.5%, which is lower than the 1.9% predicted by the statistical model.



Percentage of nitrogen removed during the in-stream transport in the 7 sub-basins according to the statistical model (Figure 4, left) and the SWAT model (Figure 5, right). Values refer to 3 classes, L, low, M, medium, and H, high removal.

Discussion

As shown in Figure 3, SWAT underestimated the high peaks of nitrate load, occurring during the winter season. This is due to the model underprediction of groundwater contribution to the total nitrate load in the stream. In fact, in SWAT only an average concentration of nitrate can be specified for the groundwater, while in the studied area the nitrate concentration in sub surface water varies according to the season. This underestimation is acute, because the contribution of the groundwater to the water flow is high, as indicated by the ratio (0.17) between the runoff and the baseflow estimated by the Baseflow Program (Arnold and Allen, 1999). The geology of the area is represented by mudstone, and probably only subsurface flow and local shallow aquifers contribute to the river flow. These waters are more likely to be influenced by the nitrate leaching, contributing to the seasonal variation of nitrogen load, as in this area the nitrate leaching is higher during the winter, when soils are saturated and plants uptake reduced.

The source apportionment of river nitrogen loads obtained by the two methodologies is in good agreement. This indicates that the reduction of nitrogen in soils estimated by the statistical model is coherent with the estimation of SWAT that takes into the physical process occurring in the basin. Concerning the spatial distribution of in-stream nitrogen removal, the major discrepancies are observed for sub-basin 5 and 7 (Figure 4). These two sub-basins present the longest and the shortest river segment, respectively. The river length influences the residence time, affecting the retention. This aspect may be more important in SWAT than in the statistical model. However also the low efficiency in nitrate calibration for SWAT (due to the underestimation of groundwater contribution), may be responsible of the discrepancies between the two models.

Conclusion

In this study the SWAT model was shown to be an interesting tool to explain parameters of the statistical model previously developed, allowing the validation of their physical interpretation. Further improvements in simulation of nitrate concentration in the groundwater contribution to the river flow are required to take into account it seasonal variation.

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SWAT Application to the Yongdam and Bocheong Watersheds in Korea for Daily Stream Flow Estimation

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Abstract

The Soil Water Assessment Tool (SWAT) model was applied to estimate daily stream flow for the Yongdam and Bocheong watersheds in Korea. The model was calibrated and validated for the two watersheds and a new routine was added to analyze runoff processes in paddy fields. As it turns out, the SWAT model is applicable to Korean watersheds, and can simulate more precisely the runoff characteristics in paddy fields using the daily water balance method.

KEYWORDS: SWAT, Paddy fields, Water balance

Introduction

The daily stream flow estimation for water resources planning and management is important in Korea as in other countries, so such continuous rainfall-runoff models as SSARR, NWS-PC, SLURP, and TANK etc., have been applied since the 1980s (Kim et al., 2003).

The TANK model was first introduced in Korea by Han et al. (1976), and many studies have been carried out by Kim et al. (1986), Kim (1988), Lee et al. (1991), Heo et al. (1993), Park (1993), Park et al. (1994), Lee et al. (1995), Eom et al. (1996), Seo (1997), Woo et al. (1998), Lee (1998), and Im (2000). The SSARR model has been applied for analyzing runoff and operating reservoirs in watershed by Ahn et al. (1989), Kang et al. (1998), and Kang (1998). Noh (1991) and Kim et al. (1996) developed a lumped model, DAWAST (DAily WAtershed STreamflow model) that simplifies the soil layers of watershed into two storage layers, and can be applied for designing and operating irrigation reservoirs. In addition, NWS-PC, PRMS, SLURP, TOPMODEL, and USDAHL-74 have been also used to estimate stream flows in Korea. Recently, several applications of HSPF (Chun et al., 2001) and SWAT (Kim, 1998; Kang et al., 2003; Kweon et al., 2003) have been developed for predicting water quantity and water quality by many researchers.

Runoff from paddy fields is varied with drainage outlet heights and ponding depths, and this concept has been adapted in simulating the hydrological processes that occur in irrigated paddy fields in Korea.

SWAT is a semi-distributed model partitioned into a number of subwatersheds or subbasins. Runoff is predicted separately for each hydrologic response unit (HRU) using the curve number (CN) method or the Green-Ampt method, and routed to obtain the total runoff at

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the outlet of watershed (Neitsch et al., 2001). But, these methods cause some error in calculating runoff from irrigated paddy fields in Korea. Hence, in this study, a water balance method considering water movement in paddy fields was suggested, and evaluated by comparing SWAT results with those from CN method.

The purposes of this study are testing the applicability of the SWAT model to Korean watersheds, and evaluating a new water balance method considering runoff processes in paddy fields.

Methodology

Description of the SWAT model

The SWAT model was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land uses and management conditions over long periods of time (Neitsch et al., 2001).

Application to Korean watersheds

General description of the applied watersheds

The Yongdam and Bocheong watersheds were selected for application of SWAT. The Yongdam watershed is located in the upstream mountainous area of the Yongdam multi-purpose dam, and the Bocheong watershed is one of the representative experimental watersheds of the International Hydrological Program and reflects a typical land use pattern in Korea. In Figure 1, the location of each watershed and hydrological and meteorological gauging stations is shown.

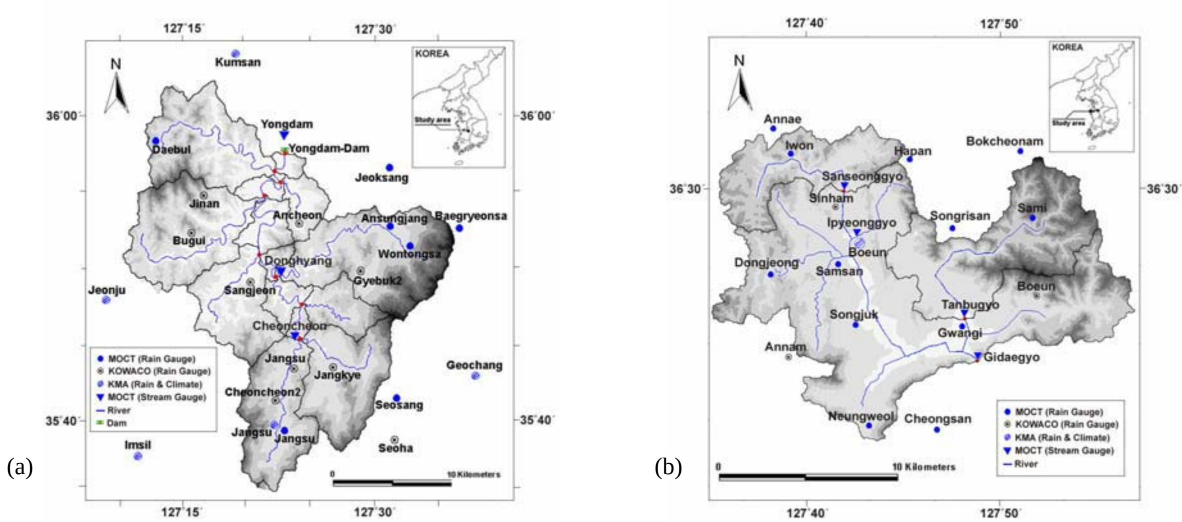


Figure 2. Location map of (a) Yongdam and (b) Bocheong watersheds and gauging stations.

Input data collection and delineation of subbasins and HRUs

Hydrological and meteorological data were collected and compiled including river stages, stage-discharge relations, rainfall, temperature, and humidity etc., on a daily basis. Daily discharges at each watershed's outlet were calculated and checked for data reliability.

A 1" digital elevation model or DEM (prepared by MOE) and digital land use data (1:25,000) from the product of NGIS were used. A detailed soils map (1:25,000) and a generalized soil map (1:50,000) were also selected. The details of each watershed are described in Table 1. As shown in Table 1, the areas of each watershed are 930 km^2 and 348 km^2 respectively, and the dominant land use for both watersheds is forest. The stream flows of the Bocheong watershed are strongly affected by irrigation water use and drainage pattern.

Table 1. Land uses and soil types of the applied watersheds

Watershed	Area (km^2)	Land use (%)				Soil type (%)		
		Forest	Paddy	Upland	Others	Sandy Loam	Clay Loam	Others
Yongdam	930.0	77.0	10.4	7.8	4.8	93.2	-	6.8
Bocheong	348.0	63.1	16.6	10.4	9.9	71.8	18.4	9.8

The number of subbasins and HRUs was determined after some investigation of the scale effect. Figure 2 shows that there are no significant changes on Nash-Sutcliffe's model efficiency and RMSE (root mean square error) by increasing the number of subbasins and HRUs for the Yongdam watershed. The subbasins and HRUs were delineated considering the gauging stations, tributaries, land uses and soil types. The Yongdam watershed is composed of the 15 subbasins and 175 HRUs, and the Bocheong watershed has 3 subbasins and 24 HRUs.

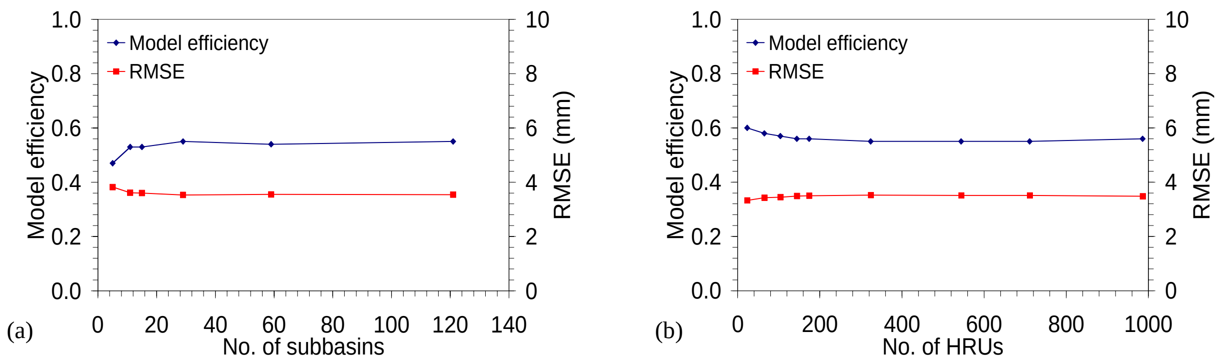


Figure 3. Scale effect of subbasins and HRUs for Yongdam watershed.

Water balance in paddy fields

The runoff characteristics in paddy fields in Korea are shown in Figure 3. It was specified that the drainage and retention were varied with the drainage outlet height and ponding depth. The SWAT model utilizes the CN method or Green-Ampt method for surface runoff calculation, so it cannot consider a specific runoff process in paddy fields. Therefore, the following relationships (Kim et al, 2000; Kang et al., 2003) were suggested;

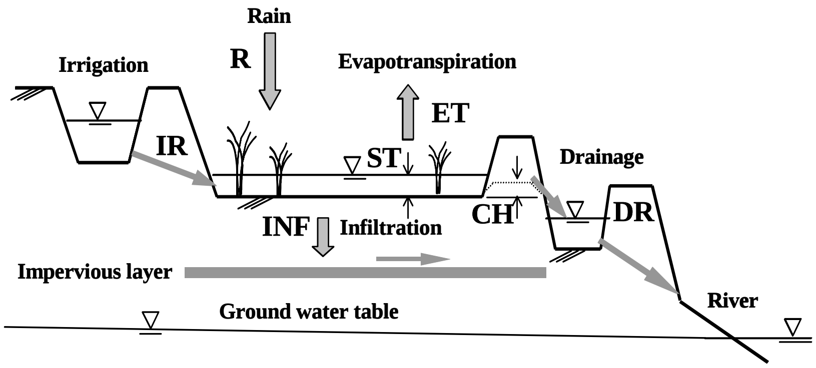


Figure 3. Water balance in paddy fields.

$$DR_t = ST_t - CH \quad \text{if } ST_t > CH \tag{1}$$

$$DR_t = 0 \quad \text{if } ST_t \le CH \tag{2}$$

$$ST_t = ST_{t-1} + IR_t + RAIN_t - INF_t - ET_t - DR_t \tag{3}$$

where DR_t = surface drainage from the paddy (mm), ST_t = ponding depth (mm), ST_{t-1} = ponding depth of the previous day (mm), CH = drainage outlet height (mm), IR_t = irrigated water (mm), $RAIN_t$ = rainfall (mm), INF_t = infiltration (mm), and ET_t = evapotranspiration (mm).

Results

Model calibration and validation

Model calibration and validation were carried out and the criteria for model performance was checked with the Nash-Sutcliffe's model efficiency (NE) and coefficient of determination (R^2), based on the sequence of observed and simulated daily stream flows over the calibration and validation periods as shown in Figure 4. The model efficiencies for each watershed were 0.77 and 0.65 from the calibration results, and 0.76 and 0.50 during the validation period respectively.

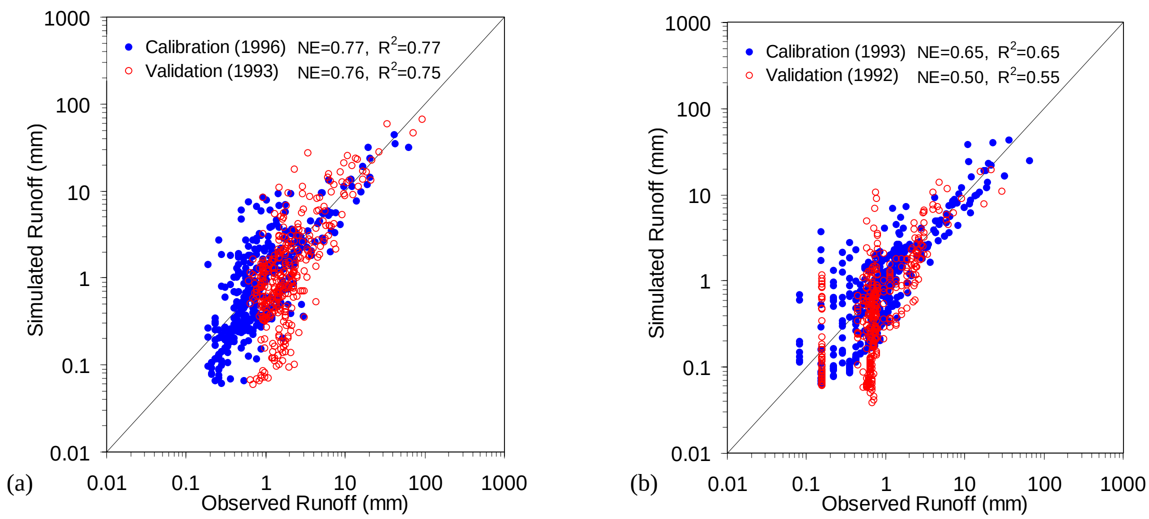
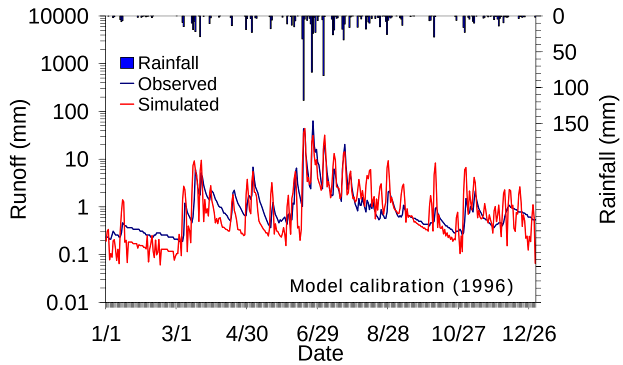


Figure 4. Results of calibration and validation: (a) Yongdam watershed, (b) Bocheong watershed.

Figure 5 provides the comparison of observed and simulated daily stream flows for each watershed. It shows that the SWAT model simulated stream flows successfully except during spring and winter seasons. Snowmelt-related parameters were not calibrated and the observed data during the seasons were unreliable.

(a)



(b)

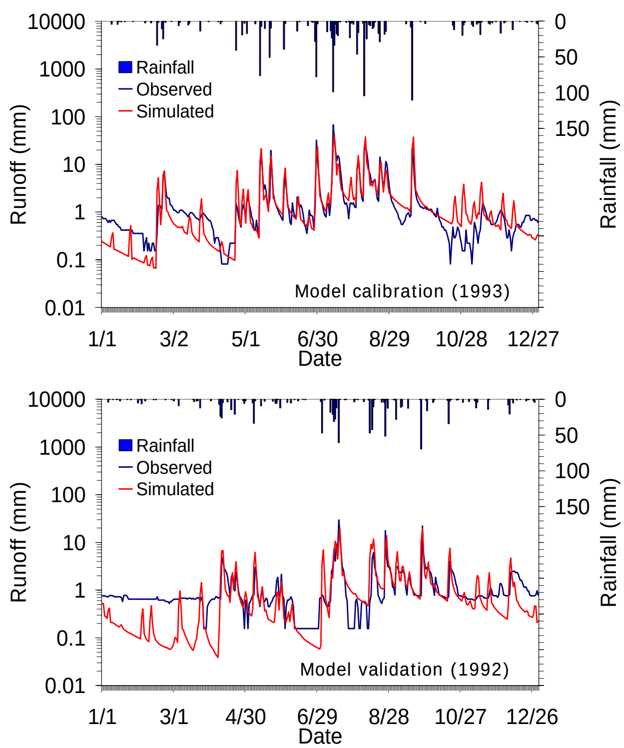


Figure 5. Comparison of observed and simulated runoff: (a) Yongdam watershed, (b) Bocheong watershed.

Water budget estimation

The detailed results of the annual simulation are described in Table 2. The surface flow, lateral flow, and base flow were estimated individually to be about 23%, 54%, and 23% of the total runoff, and the annual deviations varied highly with the amount of rainfall. The annual average evapotranspiration was over 440 mm and equaled to about 40% of the annual rainfall, but the annual variation was not significant.

Figure 6 shows the schematic diagram of estimated water budget for each watershed.

Table 2. Application results of SWAT model.

Watershed	Year	Rainfall (mm)	Surface flow (mm)	Lateral flow (mm)	Base flow (mm)	Percolation (mm)	Evapotrans -piration (mm)	Simulated runoff (mm)	Observed runoff (mm)
Yongdam	1993	1543.4	259.8	566.1	236.4	243.0	453.1	1087.3	1133.2
	1994	686.0	48.3	190.2	58.0	54.0	415.9	296.1	328.1
	1995	1111.3	135.2	361.3	157.8	157.8	447.3	653.6	576.5
	1996	1184.7	161.9	412.4	153.6	154.7	445.4	727.0	705.5
	Mean	1131.4	151.3	382.5	151.5	152.4	440.4	691.0	685.8
Bocheong	1990	1501.2	180.3	477.6	231.9	236.6	564.6	888.9	919.7
	1991	1007.0	83.9	288.2	142.2	144.0	489.9	513.8	621.7
	1992	943.2	75.2	262.4	114.5	114.3	500.2	451.6	479.5
	1993	1342.4	188.1	423.4	207.4	205.6	502.9	818.2	824.9
	1994	765.3	63.7	201.0	83.4	81.2	460.9	347.6	436.3
	1995	983.9	137.0	271.2	94.6	94.1	487.6	502.3	534.4
	1996	1164.0	142.0	328.7	137.0	139.1	527.3	607.2	796.4
	1997	1663.7	343.1	522.2	229.3	237.7	538.9	1094.0	1068.1
	Mean	1171.3	151.7	346.8	155.0	156.6	509.0	653.0	710.1

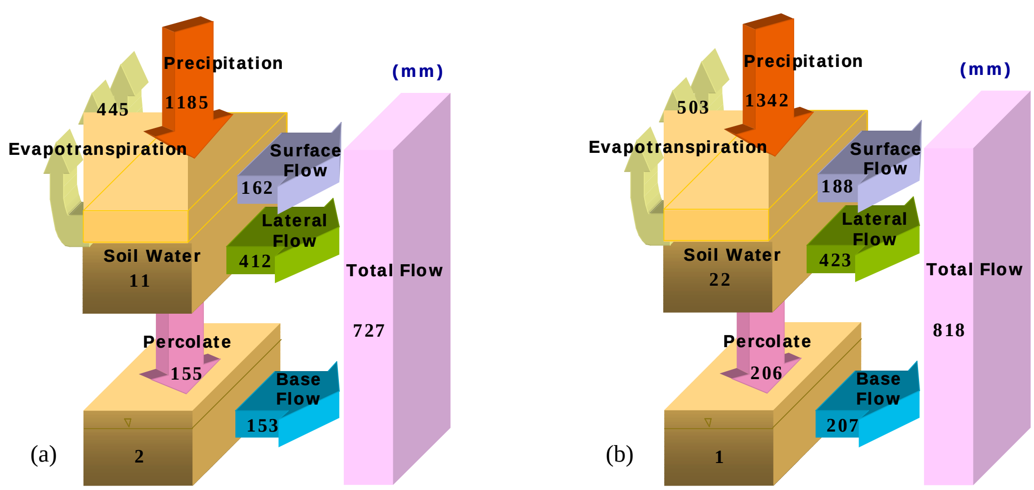


Figure 6. Water budget diagram: (a) Yongdam watershed (1996), (b) Bocheong watershed (1993).

Runoff simulation in paddy fields

The surface runoff from the paddy fields in the Bocheong watershed was simulated by the water balance method and compared with the results from the SWAT model using the CN method during the irrigation periods for 10 years. The compared annual and daily results between the methods from June to September are shown in Figure 7.

The annual surface runoff in paddy fields by the water balance method is higher than that by CN method with a range of 30% to 189%, and an average of difference is about 68%. This trend is more significant during drought period (1994-1995). The water balance method gives better results because it comes closer to the actual irrigation condition in Korea.

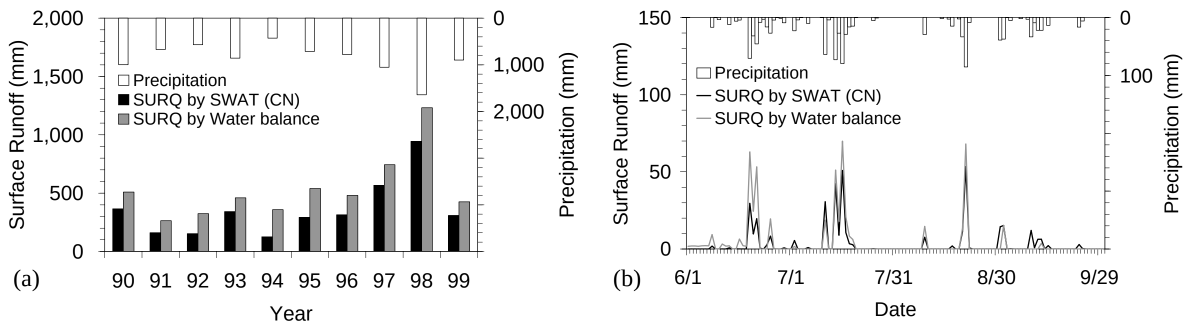


Figure 7. Comparison of surface runoff from the paddy fields between CN method in SWAT and water balance method: (a) annual surface runoff, (b) daily surface runoff (1992).

Discussion and Conclusions

The SWAT model was applied to estimate the daily stream flow for two mountainous and typically agricultural watersheds in Korea. In order to reflect the characteristics of the runoff process in paddy fields, a new routine was added and tested. The calibration and validation results showed a good agreement with the simulated and observed daily stream flow. Even though it was difficult to obtain proper parameters for the SWAT model, the model performed successfully for these Korean watersheds.

In Korea, the drainage outlet height in paddy fields is usually managed seasonally to prevent excesses or shortages of water during the irrigation periods. So, the newly suggested water balance method will be able to simulate the runoff process in paddy fields more precisely.

For the application of the improved SWAT model (SWAT-K), further studies including accurate monitoring and validation of the water balance method in paddy fields are necessary.

Acknowledgement

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A GIS – Linked Hydrology and Water Quality Model: SWAT

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Abstract

In this paper, application of a Geographic Information System (GIS) technology to watershed modelling is presented. The Pusiano Lake watershed is located in North Italy, at southern boundary of the Alps on a prevalently calcareous substratum. The aim of the modelling framework is to model nutrients on a basin-scale and to estimate how loads from the catchment affect water quality.

A preliminary hydrological study was conducted using the HEC-HMS model, which allows users to understand the complex dynamics of the catchment. The Soil and Water Assessment Tool (SWAT) was chosen to study water quality aspects in the watershed. The model requires spatial data on elevation, hydrography, land use, soil characteristics, etc. It leads to implementation of GIS as integral part of databases. The GIS interface for SWAT allows users to examine the available spatial data and provides a strong integrated tool for Lake Pusiano watershed modelling.

Introduction

A river water quality monitoring program is carried out in the Lake Pusiano watershed (Northern Italy), whose main stream is the Lambro River (Figure 1).

Figure 1. Watershed location.

The water quality of the Lambro River is very poor, mainly due to high nutrient concentrations. The aim of the Lake Pusiano project is to develop a basin-scale model of nutrients and other pollutants. The project focuses on establishing a system analysis approach to the study of the entire basin to achieve better watershed characterisation and to improve water quality planning.

The realization of this project requires the support of GIS (Geographical Information System) technology, that allows users to collect, store, manage, analyse and display a large quantity of data associated with a watershed. The Soil and Water Assessment Tool (SWAT), a GIS linked hydrology and water quality model, was chosen to analyze water resource issues in this basin (Santhi et al., 2001). SWAT allows users to determine the loadings of water, sediment and nutrients to the main channel, and it models the transformation of chemicals in the stream and streambed.

Aim

Watershed analysis is carried out in the ArcView GIS platform developed by ESRI. The objectives include several tasks, including simulation of hydrology (the preliminary study was conducted in the 2001 HEC-HMS model) and average pollutant concentrations resulting from catchment activities; estimation of average nutrient loads; and evaluation of how nutrient concentrations can be reduced in the river. This paper presents efforts made in the development of a methodology for water quality modeling using SWAT.

Methodology

To carry out a complete pollution load assessment, data on the extent of the watershed basin, land uses, climate, vegetation, and soil types were collected. SWAT requires a land use and soil map to determine the area and the hydrologic parameters of each land-soil category simulated within each sub-watershed. Land use data describes vegetation, water, natural surface and cultural features on the land surface. The land use map (1:10,000 scale, Figure 2) was developed by the Lombardy Region within the DUSAF (Destination of Use of Agricultural and Forest Grounds) plan. Land use classes in the Pusiano catchment include forests (66.7%), meadows and pastures (7.7%), agricultural lands (3.7%) and water surfaces (6.2 %).

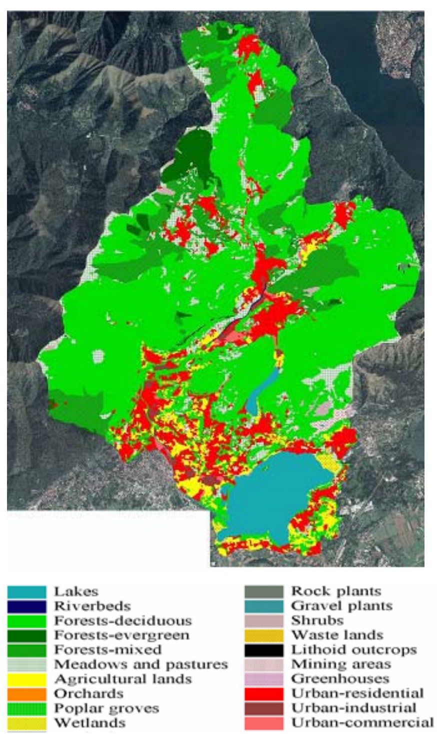


Figure 2. Land Uses.

The DUSAF land use class for urban areas (13.3%) has been further subdivided into 3 sub-classes (residential, industrial and commercial areas) using the colour digital orthophotos of the "IT2000" plan. A soil map is also required to estimate pollutant generation in watershed applications. Since there is not an official soil map for the Pusiano catchment, it was necessary to create one using a GIS. Starting from the lithologic map, as well as the land use and slope, 7 WRB (World Reference Base for Soil Resources – ISSS, ISRIC & FAO,1998), categories were identified. The soil categories which should exist in the catchment include the following: Rendzic Leptosols, Calcaric Leptosols, Skeletic Cambisols, Dystric Cambisols, Eutric Cambisols, Calcaric Regosols and Calcaric Phaeozems. The soil map (Figure 3) has been drawn by implementing an algorithm on the basis of the distributive model that has been worked out. The algorithm has been written using Avenue, the ArcView GIS programming language.

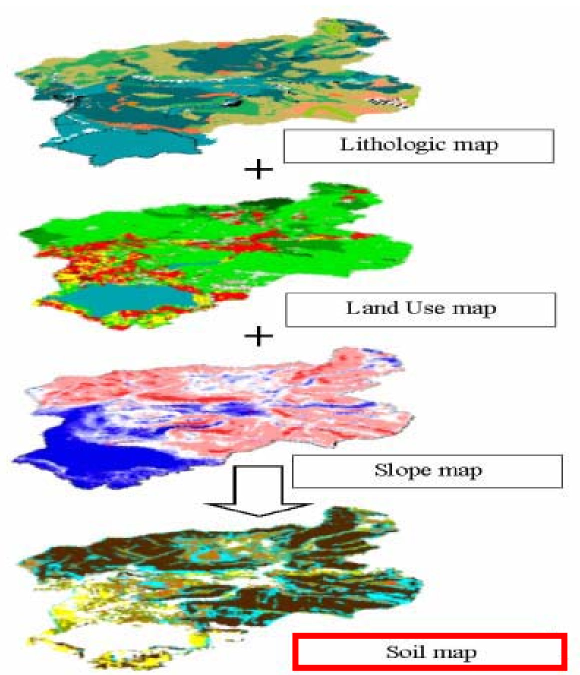
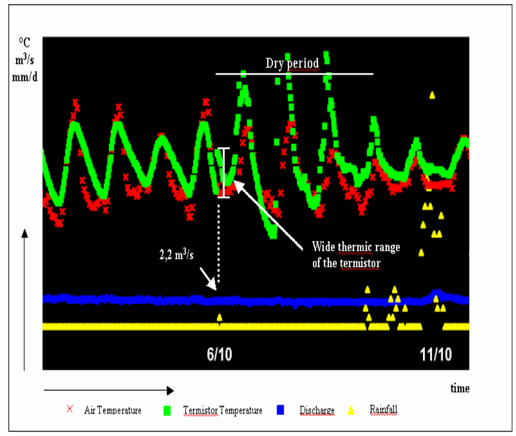
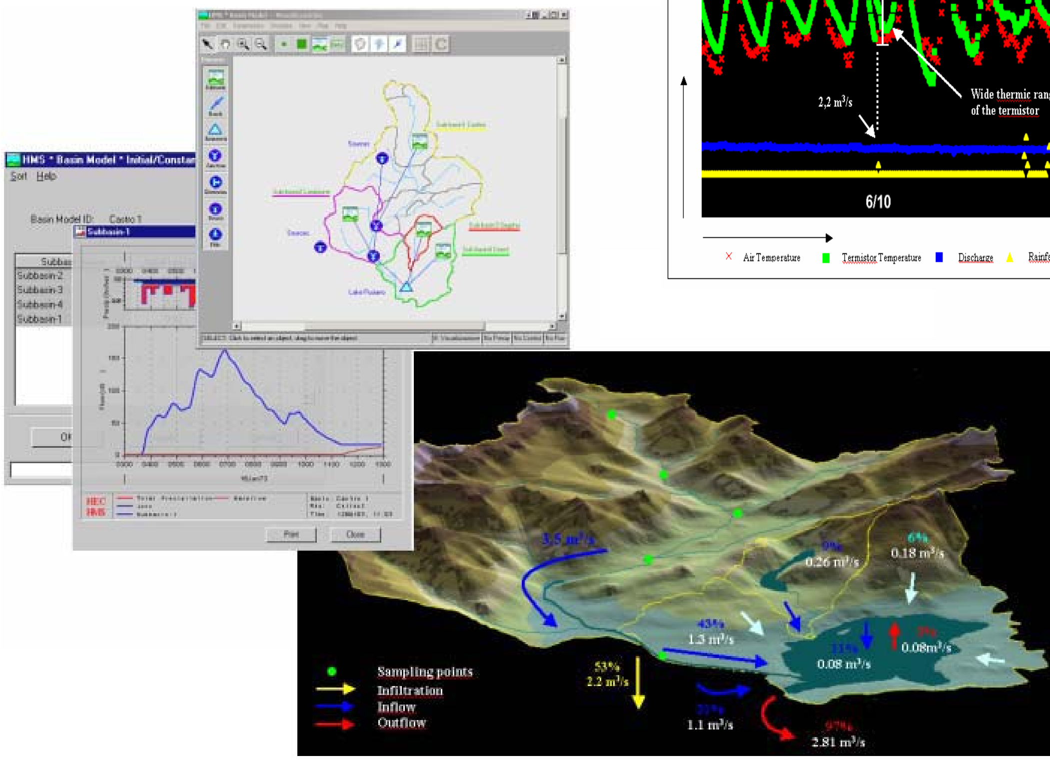


Figure 3. Soil map.

The hydrologic study of the Lake Pusiano catchment showed many difficulties due to intense infiltration phenomena relating with the influent alluvial cone of the Lambro River and the geological substratum, which results show is more then 90% calcareous. A thermostat, measuring temperature every 30 minutes, was installed in the bed of river to study the infiltration problem. A wide range in temperature measurements points out the moment when the river becomes dry (Figure 4).





The corresponding discharge measurement recorded up-river of this point provides an estimate equal to 2.2 m^3/s, or around 53 % of the total discharge. A hydrological model (Fig.5) HEC-HMS (Hydrological Engineering Center - Hydrologic Modeling System, Version 2.1, January 2001, United States Army Corps of Engineers, California. http://www.usace.army.mil/) was used to describe hydrological flows at daily base.

The use of a complete set of climatic data (1970-2002) and hydrometric data led to the following findings: 1) correct evaluation of groundwater flows, that are difficult to compute in other ways; 2) verification on whether or not the meteorological gages in the area are suitable to explain the hydrological processes; 3) compilation of the hydrological balance to know the principal components of the system; 4) an error estimate in the simulation of daily discharges; 5) recovery of missing data; and 6) development of a hypothesis on calibrating strategies to improve the estimates. The model requires spatial and temporal data on land use, soil and hydrology, and extensive water quality information. Water quality data will be collected from five quality measurement points for a period of one year. The location of water quality measurement points and the hydrological balance of Lake Pusiano for January 1, 2002 to November, 11 2002 (subdivided in its principal components) is shown in figure 6. It is desirable to collect the model data sets under condition of low, medium and high flow in order to assess overall water quality conditions. Data about point sources that affect water quality will be obtained from local municipal offices.

Conclusion

Research is still under way, but so far the data collected for this study provides a good foundation for the development of a comprehensive hydrologic system analysis tool to study water quantity and quality issues. The purpose of this study is to define how the various "polluting" activities in the basin (both point sources and diffuse pollution) influence water quality in the lake. In this study, the watershed and lake are considered a unique trophic system that is studied jointly. Analyses of the transport of nutrients in the catchment using SWAT will consist of using input data to model the lacustrine system so it is possible to study the links between the catchment and the lake. Possible changes in the management of the territory in the future will be studied as it relates to variations in lake's chemical cycles. Using SWAT together with a hydrodynamic model, DYRESM (Hamilton et al., 1997), and an ecological model, CAEDYM (Gal et al., 2003), it will be possible to study how these variations can influence biological cycles of phytoplankton and zooplankton populations. The SWAT-DYRESM-CAEDYM modelling will be done in cooperation with the Centre for Water Research in Perth, Western Australia (Fig 7). The results obtained in this research will be used in the restoration plan to recover the ecological quality of the river and the lake.

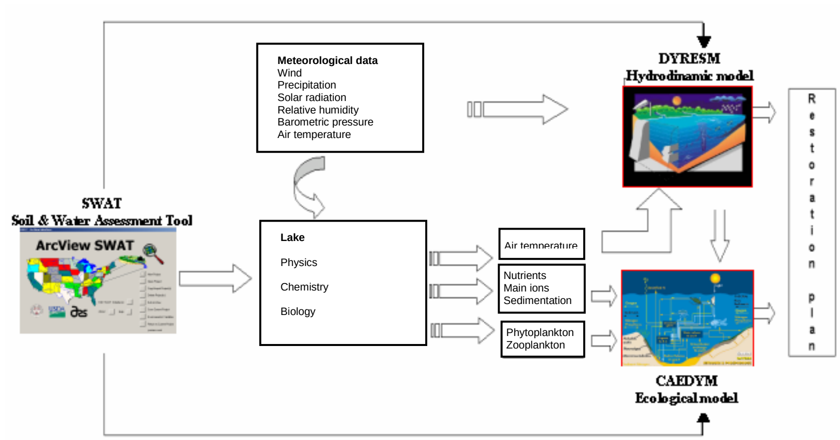


Figure 7. Link to others models and projects.

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Application of SWAT Model to the Piedmont Physiographic Region of Maryland

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[2.] USDA/ARS-Environmental Quality Laboratory, BARC-West, Building 007, Rm-211, Beltsville, Maryland, USA. Email: sadeghiA@ba.ars.usda.gov

Abstract

Existing watershed scale models without proper validation may lead to erroneous predictions and result in some misconceptions about such models. This study used six years of hydrologic and nutrient loading data to calibrate and validate the capability of the SWAT (Soil and Water Assessment Tool) model in assessing hydrologic and water quality response of a 340 ha watershed in the piedmont physiographic region of Maryland. Previous studies have indicated that most existing models only handle subsurface flow bounded by the surface topography, thus neglecting the possible subsurface flow contribution from the outside of watershed. This appears to be a great model deficiency considering the major pathway of pollutant loadings via subsurface flow. Preliminary simulations showed that model underestimated subsurface flow, especially during the wet periods. A water budget analysis therefore was performed to quantify various components of the hydrologic cycle within the watershed. The resulting imbalance in water budget analysis suggested the groundwater contribution from outside the watershed. Adjustments to measured base flow were made to exclude the extra groundwater recharge, thus showing a moderate improvement in model's predictions. However, SWAT seemed to be unable to closely simulate the extreme wet hydrologic conditions. Despite the poor monthly predictions and some extreme events, the model showed a strong agreement between yearly measured and simulated data for nitrate loadings. Overall, SWAT is a reasonable watershed scale model on long-term simulations for management purposes.

Introduction

Nonpoint source pollution of surface and groundwater has become recognized as an important environmental problem associated with agricultural production for any region. Continuous water quality monitoring is expensive and spatially impractical in mixed land use watersheds. Therefore, mathematical watershed scale models are among the best tools available for analyzing water resources (quantity and quality) issues in spatially diverse watersheds. Although existing watershed scale models provide some reasonable guidelines, their application without proper validation has resulted in some misconceptions about such models.

SWAT (Arnold et al., 1998) has been applied to numerous projects and applications have shown some promising results. Peterson and Hamlett (1998) applied SWAT to model the hydrologic response of the Ariel Creek watershed of northeastern Pennsylvania, which contains fragipan soils and wetlands. The report revealed that model calibration yielded Nash-Sutcliffe coefficient (R^2) of 0.04 and 0.14 when comparing daily and monthly flows, respectively. Eckhardt and Arnold (2001) used a stochastic global optimization algorithm to perform the automatic calibration of SWAT simulation on a low mountain range catchment in central

Germany. The results indicated a good agreement of measured and simulated daily stream flow with a R^2 value of 0.70. They concluded that the mean annual stream flow is slightly underestimated by 4%. Saleh et al. (2000) applied the SWAT to assess the effect of dairy production on water quality within Upper North Bosque River Watershed in north central Texas. Model outputs were compared to flow, sediment, and nutrient measurements for 11 stream sites within the watershed for the period of October 1993 to July 1995. Results indicated that SWAT was able to predict the average monthly flow, sediment, and nutrient loadings at 11 stream sites reasonably well with R^2 values ranging from 0.65 to 0.99.

The objective of this study is to evaluate the SWAT model's capability in simulating the hydrologic and water quality response of an agricultural watershed in the piedmont physiographic region of Maryland.

Model Description

SWAT, a physically based model with spatially explicit parameterization, is used in this study. A complete description of the model components is found in Arnold et al. (1998). In brief, SWAT contains hydrology (surface runoff, percolation, lateral subsurface flow, groundwater flow, transmission losses, evapotranspiration, and channel flood routing), nutrient (nitrogen, phosphorous), pesticide, and pathogen components.

Watershed Characteristics and Methodology

The 346-ha Warner watershed located in the Piedmont physiographic region of Maryland was selected for this study (Figure 1). The watershed drains into Little Pipe Creek and then into the Monocacy River. These water bodies are part of the Chesapeake Bay watershed. Most of the upland agricultural soils belong to Penn Silt Loam series with an average slope of 3-8%. Land use in the upper portion of the watershed has a mixture of dairy, beef, pasture, and cropland. The dominant land cover in the upper potion of the watershed (subwatershed 1C) is pasture. The rest of the watershed toward the downstream section (215 ha) is also under dairy, beef, pasture, and cropland. There are about 350 dairy cows in this portion of the watershed.

The watershed was subdivided into 40 subwatersheds based on the similar land use for the SWAT simulation. The land use type and topography of each subwatershed were both extracted from the geographic information system (GIS) database. Soil parameters for the corresponding soil series extracted from a GIS system were obtained from the Soils-5 database. Site-measured daily rainfall data were used for entire watershed simulation. Monthly stream flow measured at the outlet of the watershed (station 2A) for the period of April 1994 through December 1999 was separated into storm flow and base flow, and was used for flow calibration and validation of the model simulations. Also, average pollutant concentrations measured at the outlet of watershed (station 2A), were used to calculate the pollutant loadings leaving the watershed.

For the flow calibration, the runoff curve numbers were adjusted to give good correspondence with the observed storm flow. Because of the high base flow contribution (76% to the total stream flow) in this physiographic region (Shirmohammadi et al., 1997), groundwater in the shallow aquifer was assumed totally to return to stream eventually and no percolation to deep aquifer was considered. The parameter for groundwater delay was also adjusted to obtain the peak and a proper shape for the hydrograph, giving a better match with observed flow. Monthly flow measurements from April 1994 through December 1995 were used for flow calibration. The remaining period of data (1996 through 1999) were used for flow validation.

Graphical methods (time series plot and scattergram), and statistical measures were used to evaluate the model performance.

Results and Conclusions

The model underpredicted base flow, especially for the winter and early spring. A previous study (Chu et al., 2000) indicated that measured base flow at the outlet of watershed included subsurface flow contribution from outside the watershed boundaries, and that the SWAT model has no mechanism to account for it. Therefore, a water balance equation was used to estimate the subsurface flow contribution from outside the watershed. Measured base flow was therefore corrected for the extra subsurface flow contribution from the water balance adjustment. Figures 2 and 3 show that such adjustment made the SWAT simulations match better with the adjusted measured data during both calibration and validation periods except for an extreme wet year 1996. Precipitation in 1996 was almost twice as much as the other years within the study period. Comparisons of statistical measures indicated a strong improvement of model's simulation by excluding 1996 data (Table 1).

All nutrient loadings leaving the watershed have been adjusted to consider the chemical transport via subsurface flow contribution from outside the watershed. Despite the satisfactory results of monthly flow simulations, SWAT performed comparatively poorly in predicting monthly nitrate loadings. However, the model predicted annual nitrate loadings much better. Figure 4 presents time series plot of model's prediction of yearly nitrate loadings compared with the measured data after adjustment.

In conclusion, SWAT is a reasonable watershed scale model on long-term simulations, especially for predicting annul hydrologic and water quality responses. It should be noted that ignoring the subsurface contribution of water and chemicals into the watershed aquifer could cause significant errors in prediction. One should be aware of the subsurface flow contributions from the outside of watershed when applying model in regions with abundant groundwater.

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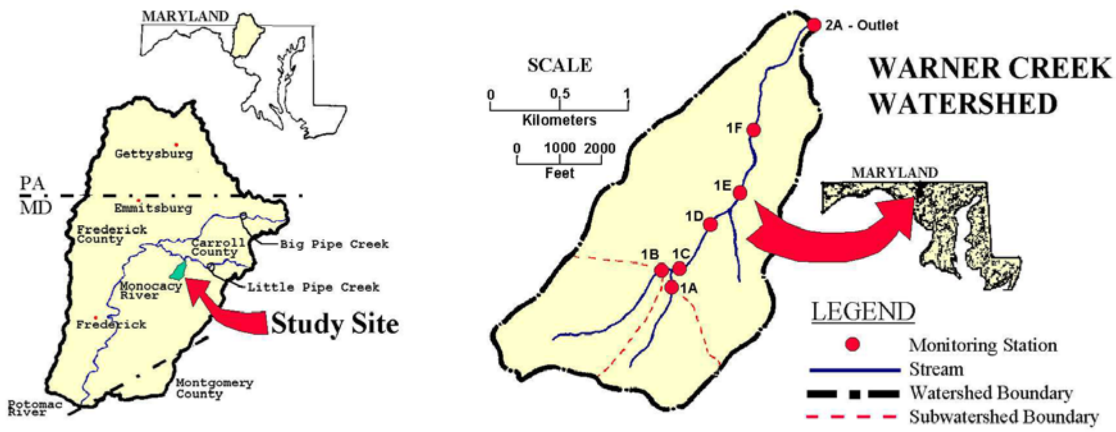

Figure 1. Watershed boundary and monitoring stations.

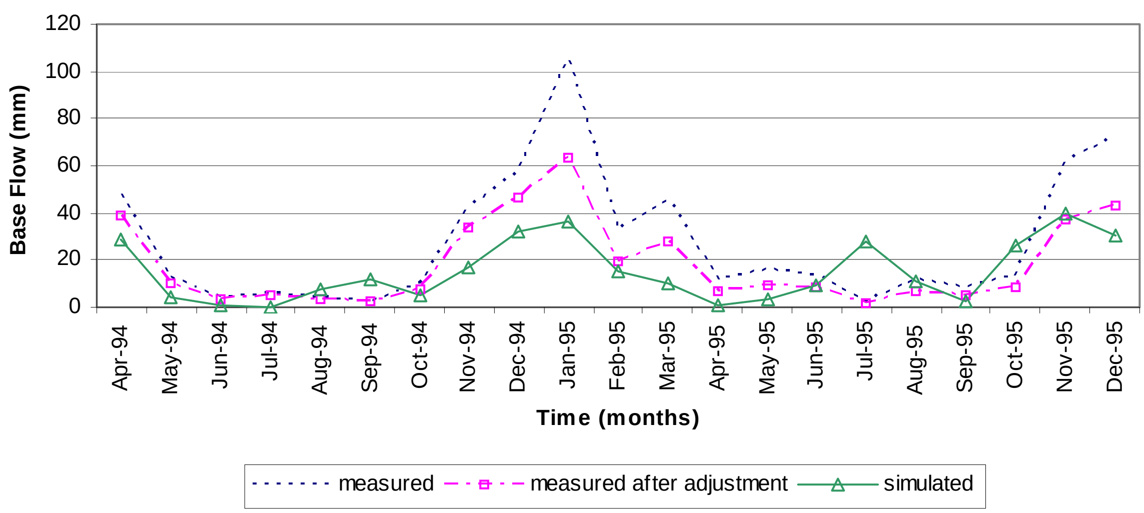

Figure 2. Base Flow at Station 2A (Calibration, 1994-1995).

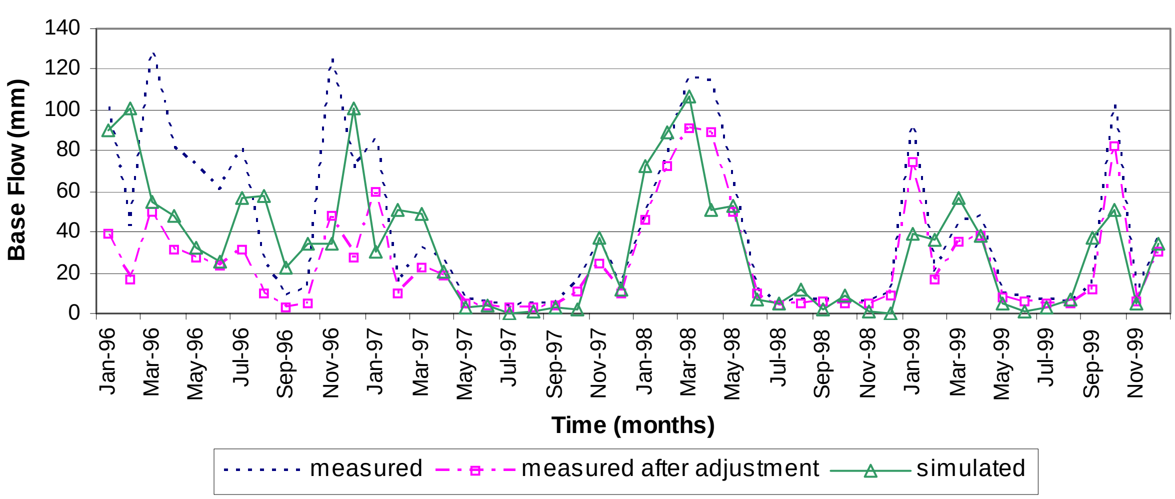

Figure 3. Base Flow at Station 2A (Validation, 1996-1999).

Table 1. Linear regression comparison and Nash-Sutcliffe coefficient for measured flow before and after adjustment versus simulated flow during calibration and validation periods.

	Hydrologic measurements	Intercept	Slope	r2	R2(Nash-Sutcliffe)
Calibration (April, 1994-1995)	Base flow before adjustment	5.62	0.35	0.56	0.27
	Base flow after adjustment	5.27	0.54	0.57	0.53
	Stream flow before adjustment	11.47	0.44	0.66	0.52
	Stream flow after adjustment	10.99	0.59	0.69	0.68
Validation (1996-1999)	Base flow before adjustment	11.67	0.53	0.47	0.42
	Base flow after adjustment	13.63	0.78	0.42	-0.02
	Stream flow before adjustment	11.20	0.61	0.69	0.63
	Stream flow after adjustment	13.24	0.76	0.68	0.67
Validation (1997-1999)	Base flow before adjustment	6.15	0.64	0.62	0.60
	Base flow after adjustment	5.92	0.82	0.66	0.62
	Stream flow before adjustment	5.10	0.67	0.75	0.70
	Stream flow after adjustment	5.35	0.78	0.78	0.78

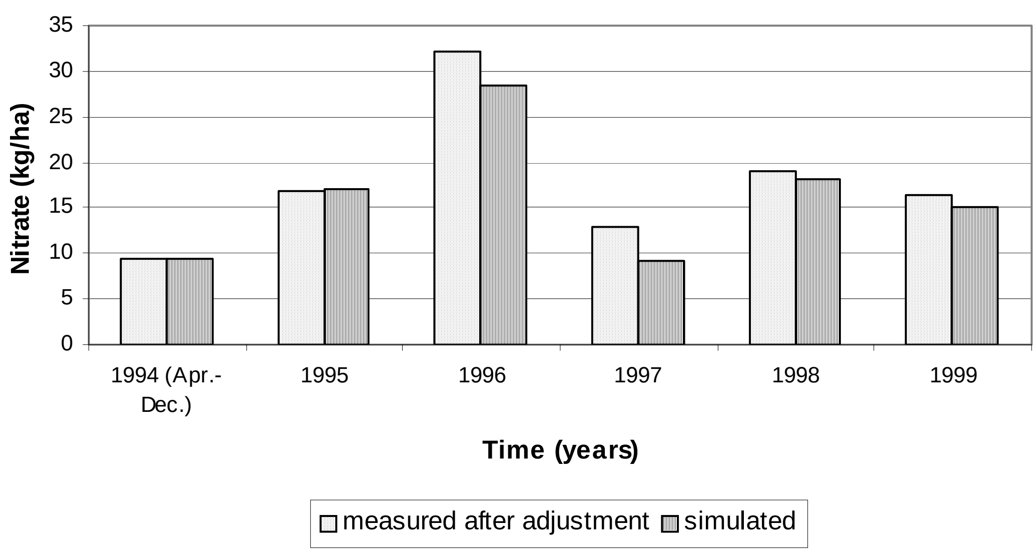

Figure 4. Yearly Nitrate Loadings at Station 2A.

Appendix

IRSA-CNR

Istituto di Ricerca sulle Acque – Water Research Institute
Consiglio Nazionale delle Ricerche – National Research Council

USDA – ARS Research Lab.
Texas Agricultural Experiment Station
Texas A&M University in College Station
Temple - TEXAS

SWAT2003
2nd International SWAT Conference

July 1-4 2003
Bari, Italy

CONFERENCE PROGRAM

Organizing Committee:

Jeff Arnold (USDA ARS, Texas, USA)
Roberto Passino (IRSA-CNR, Italy)
Raghavan Srinivasan (Texas A&M University, Texas USA)
Antonio Lo Porto (IRSA-CNR, Italy)

Tuesday, July 1st, 2003	16.00 – 18.00	Registration and Ice-Breaking Cocktail Party

Wednesday, July 2nd, 2003		**Session A** Convenor Roberto Passino
	9.30 – 10.00	**Welcome** Roberto Passino, Jeff Arnold, Antonio Lo Porto, Local Authorities.
	10.00 – 11.45	**Roundtable** **Directions in Watershed Modelling** Participants: R. Passino (IRSA-CNR, Director, Italy, EURAQUA), A. Jones (Texas A&M University, USA), A. Tilche (European Commission - DG Research), J. Froebrich (Hannover University, Germany, Chairman of the TempQsim EU R&D Project), S. Borgvang (NIVA, Norway, Chairman of the EuroHarp EU R&D Project), G. Bidoglio (EU Joint Research Centre, Italy, Pilot River Basin Network Secretariat), M. Girod (Maison des Sciences de l'Eau - Université de Montpellier 2, Director).
	11.45 – 12.00	Coffee Break
		Session A (continued) Convenor Antonio Lo Porto
	12.00 – 12.20	T. Dillaha (Virginia Polytechnic Institute and State University, USA)
	12.20 – 12.40	M. Fiorentino (Università della Basilicata, Italy, PUB Initiative)
	12.40 – 13.30	R. Srinivasan, M. DiLuzio, J. Arnold *SWAT2003 – New Developments in the Model and AV Interface*

Wednesday, July 2nd, 2003		**Session B** **SWAT Developments** Convenor Nicola Fohrer
	15.00 – 15.20	Claire Baffaut, Jeff G. Arnold, and John S. Schumacher Fecal coliform fate and transport simulation with SWAT
	15.20 – 15.40	Saleh, A., Bing Du., J.G. Arnold, D.B. Jaynes *Enhancement of Tile and Pothole Flow Components in SWAT: Application to the Walnut Creek Watershed, Iowa.*
	15.40 – 16.00	Chaponniere, A; Maisongrande, P.; Hanniche L. *Combining satellite information to SWAT for the modelling of snow runoff in a small semi-arid mountainous watershed in Morocco.*
	16.00 – 16.20	Marlos Jhonny Melo de Souza, Robert E. White and Bill Malcolm *Applying AVS2000 to predict runoff and phosphorus movement from an agricultural catchment to support the modelling of chlorophyll a production.*
	16.20 – 16.50	Coffee Break
		Session C **Model Applications I** Convenor: Faycal Bouraoui
	16.50 – 17.10	Maria Grazia Badas, Mauro Sulis, Roberto Deidda, Enrico Piga, Marino Marrocu and Claudio Paniconi *Evaluation of SWAT streamflow components for the Araxisi Catchment (Sardinia, Italy).*
	17.10 – 17.30	Eugenio Benedini, Flavio Cammillozzi, Angiolo Martinelli *Model SWAT Application on the Alban Hills*
	17.30 – 17.50	Wenzhi Cao, William B. Bowden, Tim Davie, Andrew Fenemor *Application of SWAT in a large mountainous catchment with high spatial variability*
	17.50 – 18.10	Pierluigi Cau, Allessandro Cadeddu, Claudio Gallo, Giuditta Lecca & Marion Marrocu *Estimating available water resource of the Sardinian Island using the SWAT model*
	18.10 – 18.30	Juan Guillermo Martinez, Rodolfo Jasso, Ignacio Sanchez and Jeffrey J. Stone *Runoff volume simulation in a semiarid watershed in northern Mexico using the SWAT model and GIS*

Thursday, July 3rd, 2003		
	Session D **Model Applications II** Convenor Randel Haverkamp	
	9.00 – 9.20	Ruth A. McKeown, Gordon Putz, Jeff Arnold *The application of SWAT to a small, forested watershed on the Canadian boreal plain*
	9.20 – 9.40	Ashok Mishra, Jochen Frobrich, S. Kar *Potentials and Applicability of the SWAT Model in Check Dam Management in Small Watershed*
	9.40 – 10.00	Giuseppe Pappagallo, Antonio Leone, Antonio Lo Porto *Use of management models to study human impact on quality and quality of water resources in the basin of Celone River (Apulia, Italy).*
	10.00 – 10.20	Ekaterini Varanou, Michail Pikounis, Evangelos Baltas and Maria Mimikou *Application of the SWAT model for the sensitivity analysis of runoff to land use change*
	10.20 – 10.40	Brett M. Watson, Selva Selvalingam, Mohammed Ghafouri, Jeff Arnold, Raghavan Srinivisan *Predicting catchment water balance in southern Australia using SWAT.*
	10.40 – 11.00	Vera Munteanu *Trace element levels in the Dubasari reservoir of the Dniester River*
	11.00 – 11.30	Coffee Break
	Session E **Model Applications III** Convenor Jochen Froebrich	
	11.30 – 11.50	Paolo Barsanti, Leonardo Disperati, Pietro Marri and Antonino Mione *Soil erosion evaluation and multitemporal analysis in two Brazilian basins*
	11.50 – 12.10	Kelsi S. Bracmort, Bernard A. Engel and Jane Frankenberger *Modeling the long-term impacts of BMPs in an agricultural watershed*
	12.10 – 12.30	Mauro Sulis, Luis Rodrigues, Claudio Paniconi and Nelson Lourenco *Application of the SWAT Model in a decisional framework for the Caia Catchment, Portugal.*
	12.30 – 12.50	Manoj Jha, P.W. Gassman and R. Gu *Modeling diffuse pollution at a watershed scale using SWAT*
	12.50 – 13.10	Guido Wyseure, Bernard Biesbrouck, Jan Feyen and Jos Van Orschoven *Application of AVSWAT to the Catchment of the Kleine Nete (Flanders; Belgium) for scenario testing as an integrated exercise in hydrological modelling*
	13.10 – 13.30	Narayanan Kannan, Sue White, Fred Worrall and Mick Whelan *Modelling pollutants in runoff from the Colworth experimental Catchment.*

Thursday, July 3rd, 2003	15.00 – 24.00	**Visit to Polignano a Mare and Alberobello towns; social dinner**

Friday, July 4th, 2003		
	Session F **Other Tools/Techniques – Autocalibration, Uncertainity, etc.** Convenor Ann Van Griensven	
	9.00 – 9.20	A. van Griensven and T. Meixner *Sensitivity, optimisation and uncertainty analysis for the model parameters of SWAT*
	9.20 – 9.40	J.A. Huisman, L. Breuer, K. Eckhardt and H-G. Frede *Spatial consistency of automatically calibrated SWAT simulations in the Dill Catchment and three of its sub-catchments*
	9.40 – 10.00	Lo Porto A., De Girolamo A.M., Garnier, M., Passarella G. *Evaluation of the optimal location of monitoring sites based on hydrologic models and GIS technology*
	10.00 – 10.20	Francisco Olivera, Milver Valenzuela and Raghavan Srinivasan *Linkage of the ArcHydro data model with SWAT*
	10.20 – 10.40	Agnieszka A. Romanowicz, Marnik Vanclooster, Mark Rounsvell and Isabelle la Leunesse *Sensitivity of the SWAT model to the soil and land use data parametrization: a case study of the Thyle catchment, Belgium*
	10.40 – 11.00	Sole, A., Caniani D., Mancini I.M. *Swat and remote sensing used to demonstrate the impact of land use changes on hydrology and water quality of the Agri river (Southern Italy)*
	11.00 – 11.30	Coffee Break
	Session G **Other Models and Tools** Convenor Raghavan Srinivasan	
	11.30 – 11.50	Guido M. Bazzani *DSIRR: a DSS for the economic and environmental analysis of irrigation*
	11.50 – 12.10	Caroline F. Dilks, Sarah M. Dunn and Robert C. Ferrier *Benchmarking models for the Water Framework Directive: evaluation of SWAT for use in the Ythan catchment, UK.*
	12.10 – 12.30	Ahmed Nasr, Michael Bruen, Richard Moles, Paul Byrne and Bernadette O'Regan *The significance of the differences in soil phosphorus representation and transport procedures in the SWAT and HSPF models and a comparison of their performance in estimating phosphorus loss from an agriculture catchment in Ireland.*
	12.30 – 12.50	Sole, A., Caniani D., Mancini, I.M. *A comparison between SWAT and a distributed hydrologic and water quality model for the Camastra basin (Southern Italy).*
	12.50 – 13.10	Fred Hattermann and Valentina Krysanova *Propagation of uncertainty in large scale eco-hydrological modelling*
	13.10 – 13.30	P.W. Gassman, Todd Cambell, Silvia Secchi, Manoj Jha and Jeff Arnold *The I_SWAT software package: a tool for supporting SWAT watershed applications*

Friday, July 4th, 2003		
	Session H **Model Integration** Convenor Giuseppe Giuliano	
	15.00 – 15.20	Martin Volk, Gerd Schmidt *The model concept in the project FLUMAGIS: Scales, simulation and integration*
	15.20 – 15.40	Arianna Azzellino, Marco Acutis, Luca Bonoma, Erika Calderara, Roberta Salvetti and Renato Vismara *Modelling diffuse pollution on watersheds using a GIS-linked basin scale Hydrologic/Water Quality Model*
	15.40 – 16.00	L. Breuer, J.A. Huisman, N. Steiner, B. Weinmann and H.-G. Frede *Eco-hydrologic and economic trade-off functions in watershed management*
	16.00 – 16.20	Wael Khairy *Estimating extreme flood events under expected climate change in the next century*
	16.20 – 16.40	A. van Griensven, and W. Bauwens *Integration of in-stream water quality concepts within SWAT*
	16.40 – 17.00	*Coffee Break*
	Session I **SWAT2003 – Future Plans** Convenor Jeff Arnold	
	17.00 – 18.30	Open discussion on future plans with SWAT, ArcView interface and status of current projects.

Posters

Ilona Barlund, and Kirsti Granlund
Application of the SWAT model on agricultural catchments in Finland.

Celine Conan, Faycal Bouraoui
An integrated modelling of the Guadiamar catchment (Spain).

Bruna Grizzetti, F. Bouraoui, G. de Marsity and G. Bidoglio
Validation of a statistical model of source apportionment of riverine nitrogen loads by the physical model SWAT.

Chulgyum Kim, Hyeonjun Kim, Cheolhee Jang, Seongcheol Shin, Namwon Kim
SWAT applications to the Yongdam and Bocheong watersheds in Korea for daily stream flow estimation

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