A Decision Support System based on the SWAT model for the Sardinian Water Authorities.

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ABSTRACT

Sardinian Regional Authorities, such as *Assessorato della Difesa dell'Ambiente*, have the demanding problem of water management and protection. Targeted to their specific needs they use alternative applications and models for their specific tasks. Black box models, in the past, have been the most commonly used approach to describe the hydrological cycle. Despite their wide use, these models have shown severe limitations to take into account land use and climate changes. Physically based models can make better prediction when different combination of soil and land use, within the basin, have a significant effect on the hydrological cycle. The variety and complexity of alternative environmental problems found in the island, which vary from the impact of the agro-zootechnical to the industrial compartment, have suggested that empirical models are less suitable to predict the environmental dynamics at the catchment's scale. Regional Authorities enact Regional Directives to enforce different European Directives, and no absolute limits can be drawn to separate their alternative field of application. The *Piano di Tutela delle Acque* Regional Directives aim to enforce water policy in terms of definition on where and how water resources must be used and what water protection actions need to be taken to improve water quality of rivers, lagoons, groundwater, lakes etc.. In this context, the hydrological physically based SWAT model has been chosen and applied to estimate both the water balance of the main catchments of the island and the impact of land management practices on downstream water bodies. The performance of the model has been evaluated on several stream flow monitoring gages against registered data.

INTRODUCTION

Action plans to reduce diffuse and point water pollution is a big challenge to policy makers and presents an ever increasing complexity. The issue of water management, in fact, interrelates water with broader policy questions associated with social and economical development. A cross disciplinary, multisectoral approach must be adopted to collect and link together information that ranges from environmental models to imprecise background data in order to form an overview of the problem at hand. A multisectoral approach is needed to truly integrate river basin management through consideration of socio-economic and environmental aspects, through the use of modeling techniques with GIS functions, and multi-criteria decision aids [Giupponi et al., (2001)].
The management of water resources is an important environmental problem in Sardinia, where water demand is steadily increasing, while water resources are scarce (availability of water is a critical issue in this region, where summer water shortages are a perennial problem). Nutrients that enter water are mostly from the zoothechnical compartment and agricultural land, being in general the industrial compartment still limited. Nitrate and phosphorous levels in water bodies, both ground and surface waters, are found to be increasing and local and regional authorities are now facing this awkward environmental problem. The European Directives require Member States to identify areas that are thought to be at risk of contamination and to establish Action Programmes in order to reduce and prevent further contamination. Consideration of the physical processes associated with water movement, crop growth, and nutrient cycling can be important to evaluate the gradual build up of pollutants due to different land management practices on downstream water bodies (e.g. coastal lagoons). In this framework models can give support to identify indicators at each scale that reflect critical ecosystem processes or state variables related to the integrity and sustainability of those ecosystems.

DESCRIPTION OF THE DSS

In 2002 a Consortium made up of CRS4, TEI srl, PROGEMISA and NAUTILUS has been created for the three year project "*Piano di Tutela delle Acque*" (PTA). One of the main topic of the project is the development of a multisectoral, integrated and operational Decision Support System (DSS) for Sustainable Use of Water resources at the catchment's scale.

The project has three main objectives:

1. to collect all available information (driving forces, natural and anthropogenic pressures on the water systems, historical water quality information of the main water bodies, etc.) and to design a two years monitoring campaign and gather water quality indicators of the main water systems of the island;
2. to design and implement an operational decision support system for the management of water resources that is based on hydrologic modeling, multi-disciplinary indicators and a multi-criteria evaluation criteria;
3. to identify those protection actions to preserve the water quality standards of the water bodies of the island, and for those polluted, to plan actions to reduce contamination below the limits drawn by the National water directives.

As a result of the project, the "*Piano di Tutela*" (PTA) regional water directives will be enacted.
A series of aspects has differentiated what was actually realized during the course of the project and what was thought at the beginning. It is, now, clearly stated that a primary goal is to build relationships between local stakeholders and end users. It was actually the collaboration with the end users that lead us to an ever increasing consideration for the relationship between water management authorities and local communities, and to structuring their contribution in the decision process.

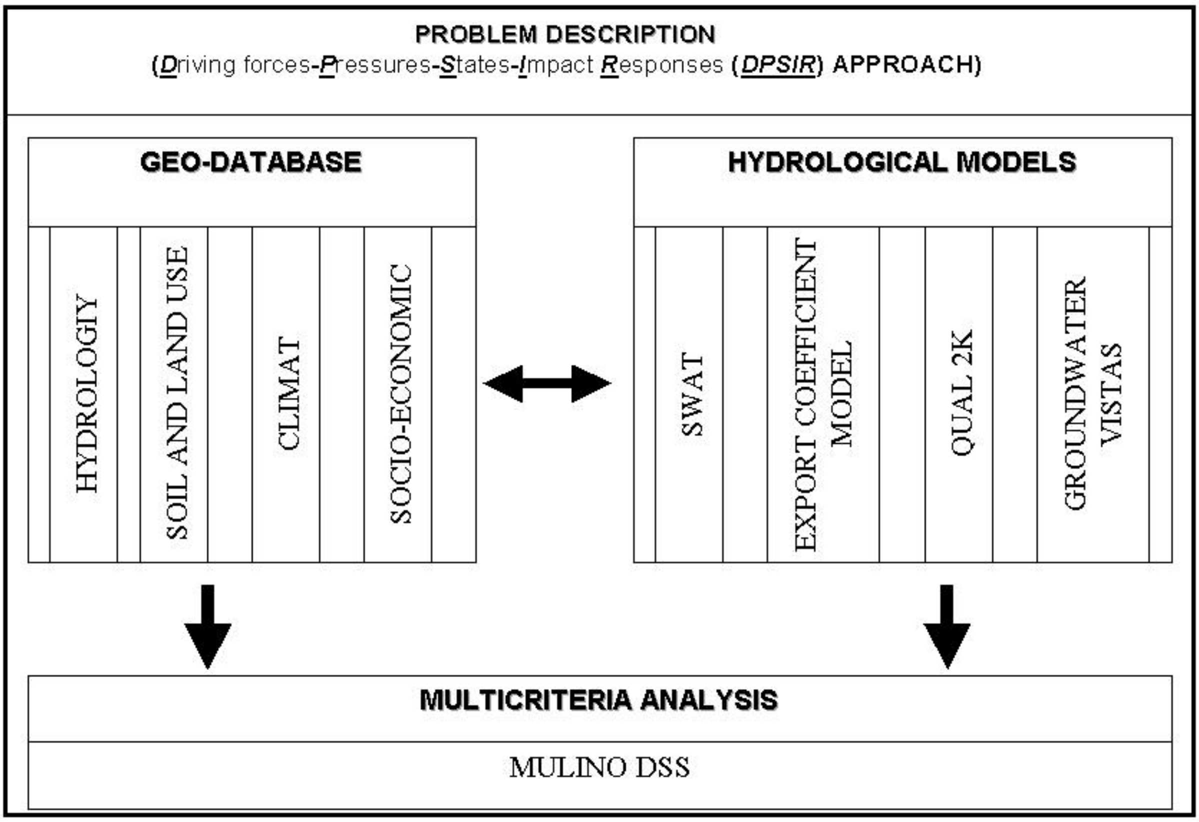

Figure 1. The DPSIR approach can be useful for organizing information that emphasizes cause-effect relationships designed for environmental problem solving. This methodological framework summarizes key information from different sectors (field data, models, socio economic analysis). 4 alternative hydrological models and the multicriteria decision support system (Mulino DSS) are the main modules of the system.

Specific aims of the DSS are improving the quality of decision making and seeking to achieve a truly integrated approach to river basin management. Although the integration of socio economic and environmental modeling techniques with GIS functions and multi criteria decision aids is a specific requirement of the DSS, the informatics architecture has been developed to be modular. The DSS has been designed with stand alone tools to solve alternative problems. With half way passed, the PTA project is undergoing a transition period in which the main modules, that have been chosen, developed and/or integrated with a high level of communication, but essentially with a high degree of independence, are beginning to be used in an integrated way.
The DPSIR conceptual framework has been adopted to structure decision problems by linking Drivers - Pressures – State – Impacts – Responses, thus representing a systemic and dynamic view of the

decision context. The hydrological models are used to explore interactions between pressures and states. Four alternative hydrological models have been chosen: SWAT, the Export Coefficient Model, QUAL 2K, Groundwater Vistas. The first two models (both are catchment's scale models and evaluate the impact of diffuse and point source pollution) differ in approach, time resolution of the input-output, and space discretization criteria. QUAL2K is a comprehensive and versatile stream water quality model. The Groundwater Vistas is a Windows graphical user interface for 3-D groundwater flow & transport modeling. This is a package of different groundwater models (MODFLOW,MT3DMS, etc.).
Theoretically the problem structuring requires three phases:

1. the pressures and the state of the environment are investigated and the causal links identified. In this phase models can give support to identify the cause effect relationship;
2. alternative options for the environmental problem are defined and investigated. In this phase the decisional indicators with the use of local networks analysis, model outputs, economic analysis, etc. are chosen; model results can be read directly in the multicriteria decision support system (Mulino DSS [Giupponi et al., 2001]).
3. a decisional criteria is chosen.

DESCRIPTION OF THE ISLAND

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. Precipitations are 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 typical Mediterranean, characterized by a peak rainfall in December, and a minimum in July, with an average value of about 780 mm/year. A north-westerly wind blows over the island in all seasons, particularly sweeping the west side. 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 found 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 one of the largest island in the Mediterranean Sea (24,089 km^2). 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 up thrust from the sea, later severely affected by late Paleozoic orogenesis. The Sardinian mountains are a chaotic series of deeply eroded ranges, groups, plateaux and uplands, scattered in apparent disarray. 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. Catchments range in size, topography, climate, socio-economic and cultural context.
The 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 and reservoirs (more then 50).
The most important lagoons are located in the humid areas near Cagliari (S. Gilla) and Oristano (S. Giusta, Mistras etc.), 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 island is little populated, its population density is about of 68 p/km^2, slightly higher than a third of the Italian national average. The industrial compartment is limited to a few areas of the Island. Agriculture is usually extensive with the cultivation of cereal, wheat, olives, etc.. The zootechnical compartment is predominant, mostly cows and sheep. Rivers, lakes, and groundwater have been classified in homogeneous groups according to the concentration of contaminants of the waters with regards to the quality limits drawn by the national water directives (152/99). The export coefficient model has been then applied on a regional scale to highlight the cause effect relationship between pressures and states.
The main problems found in the island are associated with an irregular precipitation regime and water scarcity, that effect the availability of supply to the main users. 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.

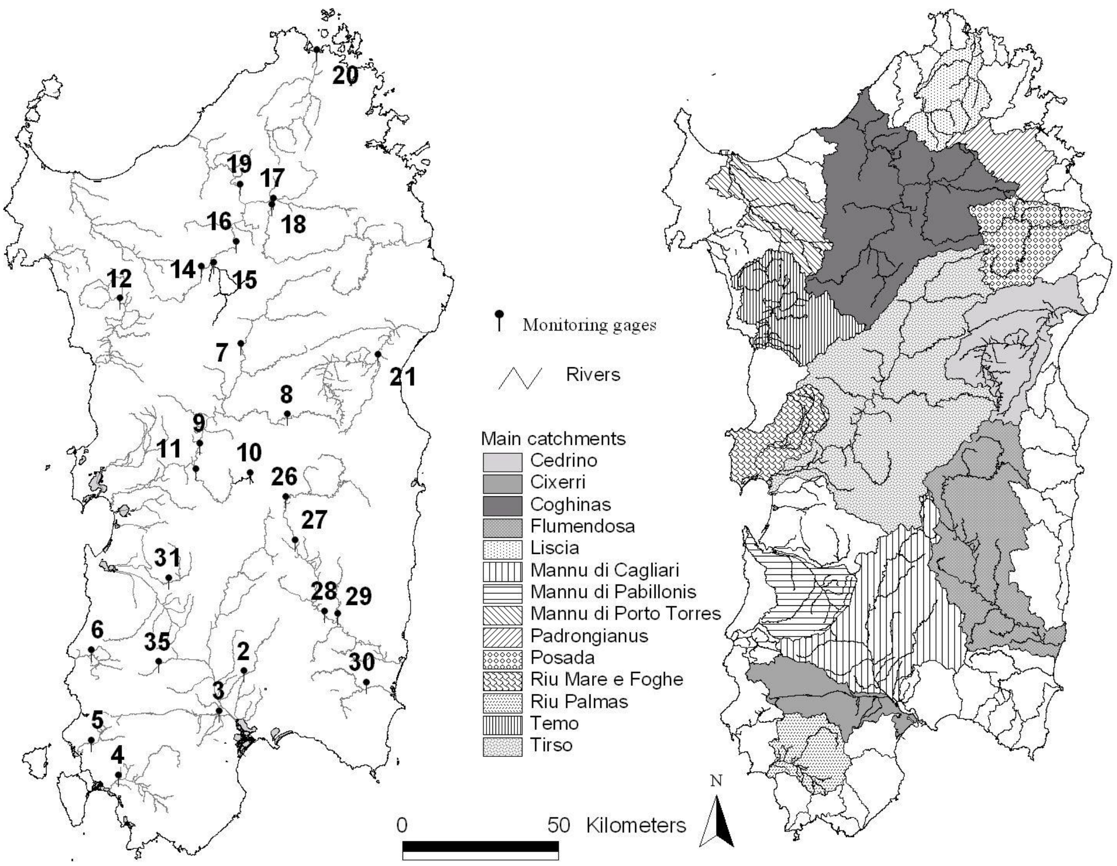

Figure 2. Main rivers, stream flow monitoring gages and main catchments of the island.

DATA AVAILABILITY AND CLIMATE, SOIL AND LAND COVER CHARACTERIZATION

A large effort has been put to collect the available information about the soil, the land cover, the land use and the climate of the island. Rather then organizing the information necessary to SWAT on a catchment's scale, a regional scale approach has been followed. In this context we set up a geographical information system formatted in the SWAT fashion The developed system greatly reduces GIS initializations and offers the possibility to simply rely on a regional framework database without being an expert user of the SWAT model.

For the characterization of the geo-pedologic facies of the region we referred to the soil vector map of Sardinia [Aru et al.,1991] and the land classification for irrigation of Sardinia [Arangino et al., 1986]. 40 representative soil profiles have been described and classified according to the USDA and FAO guidelines. Classical pedotransfer functions have been used to calculate dependent variables (field capacity, permanent wilting point, available water capacity, saturated hydraulic conductivity) from the three independent variables: sand, silt and clay content [Saxton et al., 1986]. 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 for the entire region formatted for the SWAT model [Cau et al, 2003; Cadeddu & Lecca, 2003].

The influence the land use exerts on the water cycle is a function of the density of plant cover, the morphology of the plant species, etc.. The CORINE Land Cover 1:100.000 vector map (www.centrointerregionale.it) has been used. 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 [Cadeddu et al., 2003].

The available rainfall and climatic databases are on a monthly time resolution [Cao et al. 1998]. For this reason a statistical analysis to describe the climate of the island has been carried out using the available, but incomplete, daily records. For each month, average daily maximum air temperature (ºC), average daily minimum air temperature, standard deviation for daily maximum and minimum air temperature (ºC), average daily solar radiation, etc. have been assessed and cast in the *userwgn* database. For the rainfall characterization a stochastic time generator has been developed on the basis of the rainfall statistical characteristics of Sardinia [Cau et al., 2003]. By means of the Markov chain procedure, the time distribution of wet days was determined and then a skewed distribution was 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 was scaled to match the monthly registered rainfall for each station. The Sardinian rain gages have been grouped in two different homogeneous classes, referred in this study as East and West rain gages 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. Finally all the rainfall series were formatted for the SWAT model [Cau et. al., 2003].

CALIBRATION OF THE STREAM FLOW COMPONENT

31 monitoring gages are found scattered along the main rivers of the island. In the present work we have often referred to previous studies to compare results, show limitations and plan future work. Water budget calculations have been performed, using the SWAT model [Neitsch et al., 2001; Di Luzio et al., 2001], for 15 Sardinian catchments, having different climatic and hydrologic conditions. 27 monitoring gages are found within the basins under investigation.

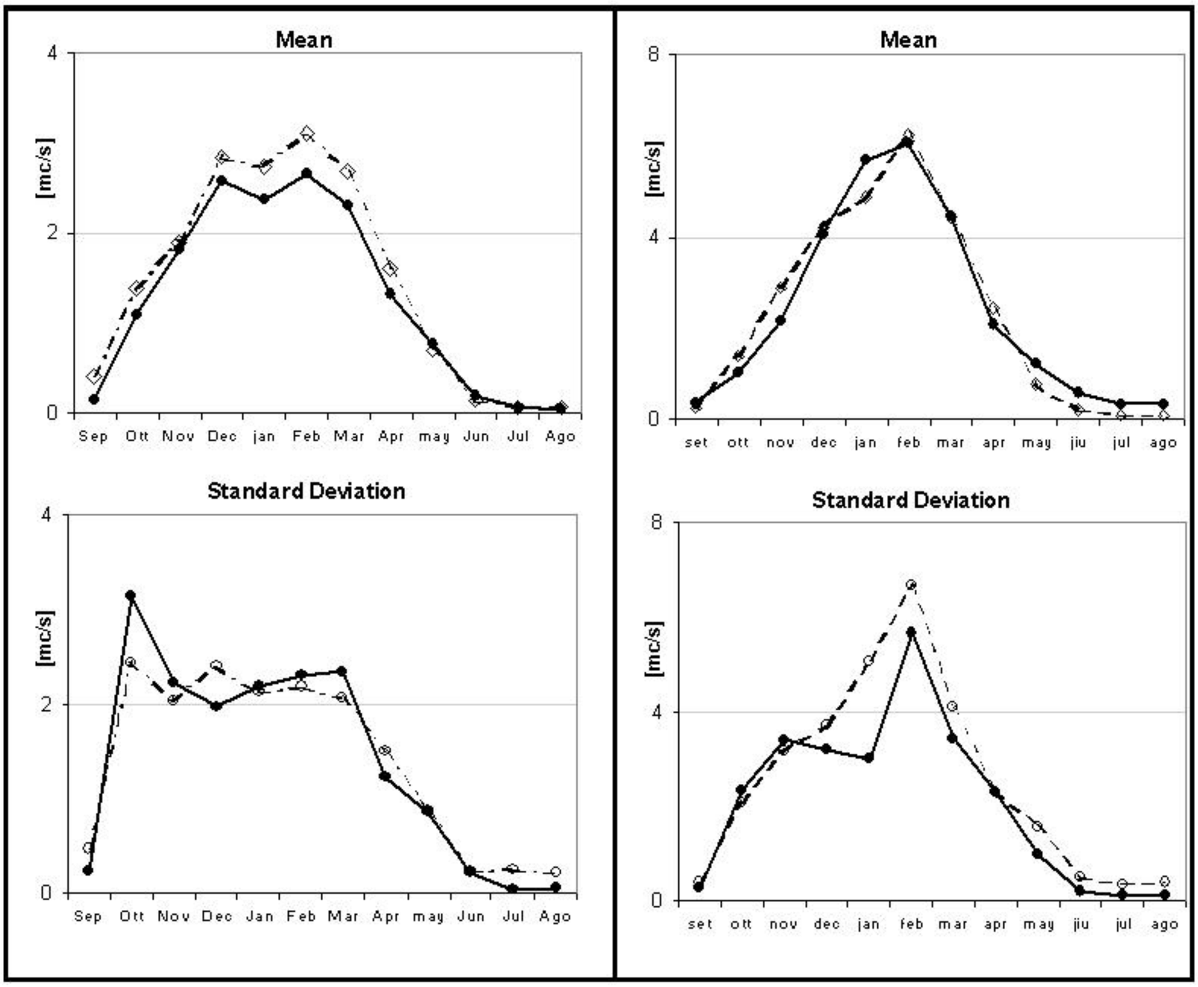

Figura 3. Gage N. 30 (left) and Gage N. 4 (right). Comparison between observed (continuous line) and simulated (dotted line) flow rates after calibration. It is shown the mean (above) and the standard deviation (below) on a monthly basis.

Before calibration, the stream flow component showed to be always over estimated, while the evapotranspiration was highly under estimated. Calibration of the stream flow component has been first done for average annual conditions. Once the stream flow component was calibrated for average annual conditions, we shifted to monthly records to fine-tune the calibration (figure 3). When calibrating a watershed with multiple stream gages, streamflow was tuned first for the gage furthest upstream. Once that gage was calibrated, we moved to the downstream gages. The parameters that have been modified in the calibration procedure have been ESCO, GW-QMN, GWREVAP and CN2. The case studies have been 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 (1922-1992).

RESULTS

Calibration of the stream flow component, performed for the main catchments of the island, is the first step for investigating the effect of all complementary phenomena related to the water cycle (e.g. nutrients and pesticides fate). The quantification of the performance of the model is therefore essential to evaluate the model results. The performance of the model has been assessed through the following ensemble statistical indicators:

1) $$K_{Nash-Sutcliffe} = 1 - \left(\frac{\sum_{i=1}^{N} (Q_{1,i} - Q_{2,i})^2}{\sum_{i=1}^{N} (Q_{1,i} - \overline{Q}_1)^2} \right)$$ (the Nash-Sutcliffe index)

2) $$\overline{Er} = \frac{\sum_{i=1}^{N} \left| \frac{Q_{1,i} - Q_{2,i}}{Q_{1,i}} \right|}{N}$$ (the average error)

Where N represents the years of registered stream flow data, $Q_{1,i}$ is the registered stream flow at time i, $Q_{2,i}$ is the correspondent simulated stream flow. The Nash-Sutcliffe index ranges between $-\infty$ and 1. When $Q_{1,i} = Q_{2,i}$, $K_{Nash-Sutcliffe} = 1$. In our case Nash-Sutcliffe index is 0.77, while the estimated average error is 13%, showing good match between the simulated and the observed stream flow rates.

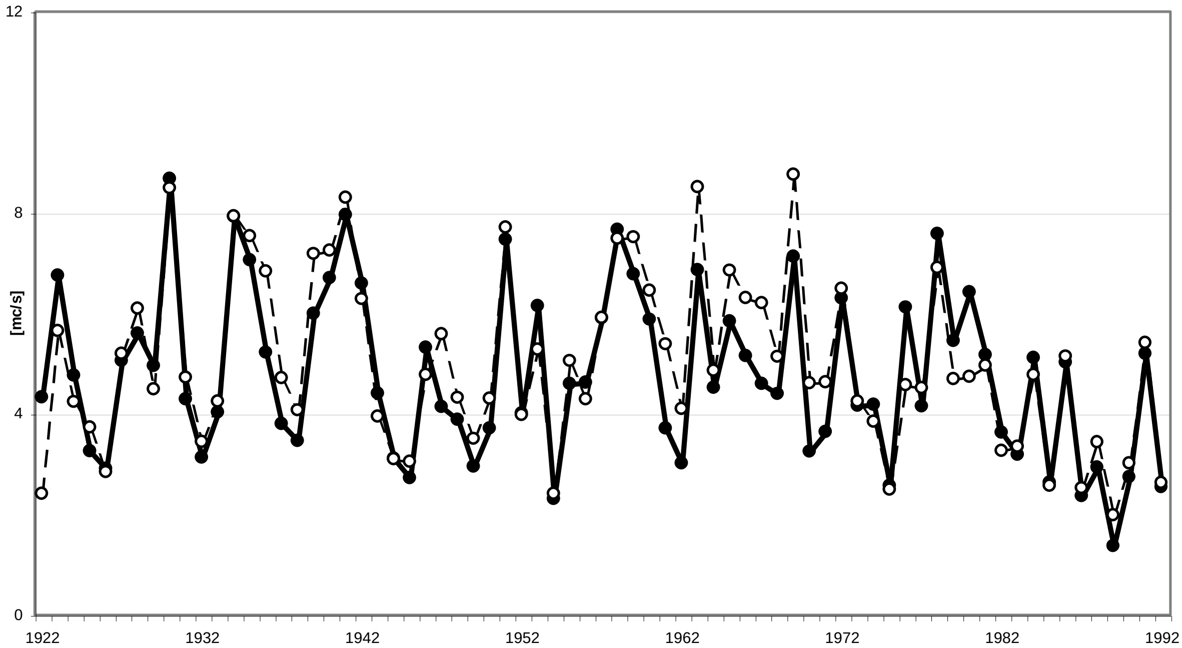

Figure 4. Comparison between registered (continuous line) and simulated (dotted line) annual flow rate (1922-1992).

The model reasonably simulates monthly water flow over a seventy-year period and accurately captures the timing and magnitude of seasonal water yields under current land use/land cover conditions. These results have been accomplished with very little "tuning" of free parameters. Figure 4 shows the comparison between registered and simulated annual flow rate (1922-1992) assembling all the contribution of the basins under investigation. Due to less permeable soils, steeper slopes and different rainfall distribution, the water yields of the East basins are higher then the West basins' ones

(Figure 5). The yearly average number of wet days of the west rain gages, in fact, is 80 (70 between September and April and 10 in the period May-August) with a yearly precipitation value of 687, while the yearly average number of wet days of the East rain gages is 74 (64 between September and April and 10 in the period May-August) with a yearly precipitation value of 828 mm.

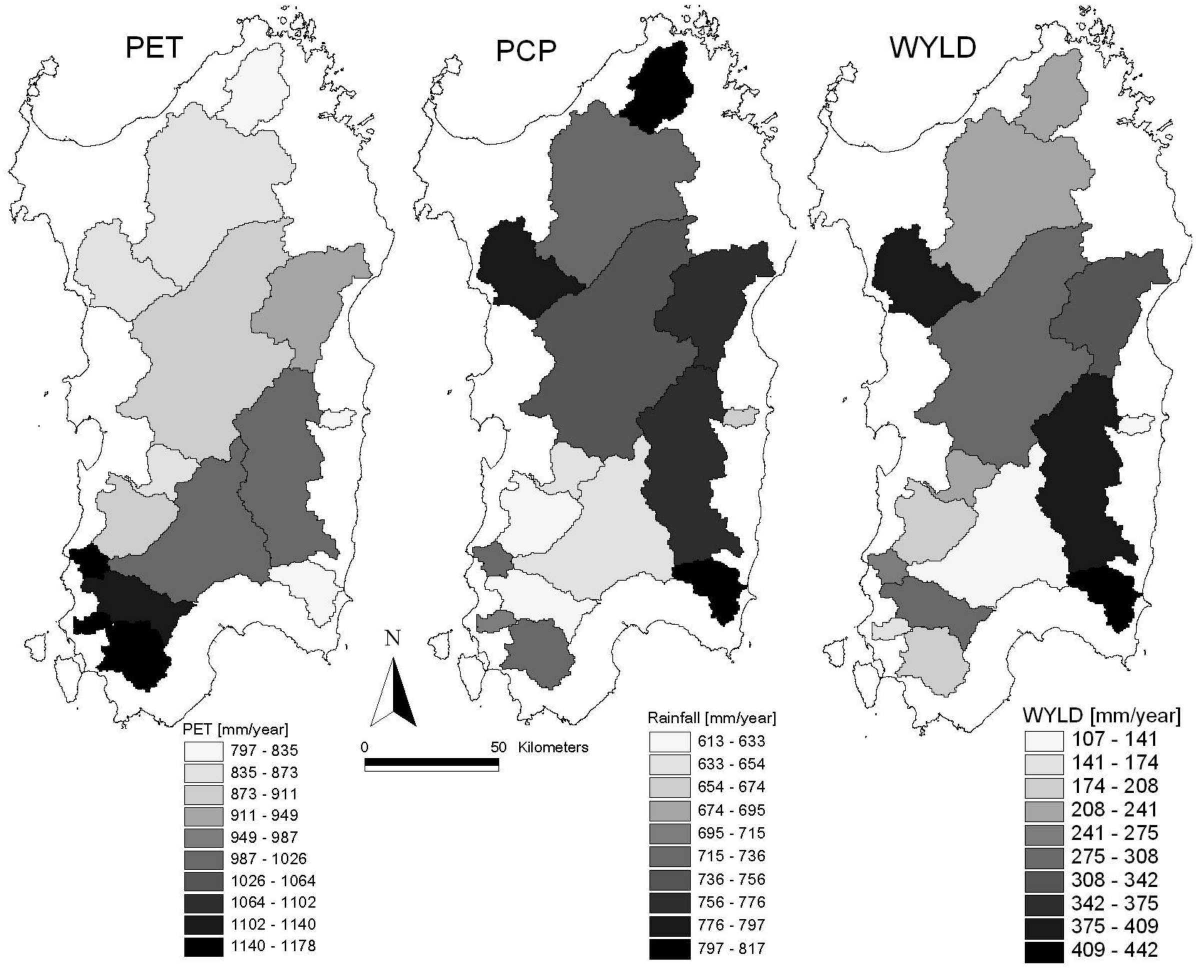

Figure 5. The Multi-catch.avx extension (for more details see "*A user firendly multi-catchments tool for the SWAT model*") has been used to map the spatial distribution of the average (1922-1992) precipitation, potential evapotranspiration and water yield on a yearly basis.

CONCLUSION AND FUTURE DEVELOPMENTS

Land use changes and irrigation schemes need to be managed so as to minimize the risk of water and soil contamination. Water resources management is a complex task when the lack of data and information on the system have an important role in policy design. The complexity of the problems found in the island has shown that a multidisciplinary approach must be adopted to have an overview of the problem at hand. The use of hydrological models at a catchments' scale, such as SWAT, can be important to reproduce the water cycle and to evaluate the impact of land management practices on downstream water bodies. Models can give a contribution to identify indicators at each scale that reflect critical ecosystem processes or state variables related to the integrity and sustainability of those ecosystems. Moreover models can give support to identify the cause effect relationship, highlighting the causal links between human activities, the pressures, and the state of the environment. With half project passed, SWAT has been mainly used to estimate the water budget for the main watersheds of the island. In this context, a regional scale approach has been followed to assess the geographical information. This offers the possibility to simply rely on databases about soil, land cover, climate and precipitation on a regional wide level scale. Model results have shown that SWAT reasonably simulates monthly water flow and accurately captures the timing and magnitude of seasonal water yields under current land cover, soil and climate conditions. Next step is to investigate those situations, where waters are highly contaminated.

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REFERENCES

1. Arangino, F., A. Aru, P. Baldaccini, & S. Vacca. *I suoli delle aree irrigabili della Sardegna* (Piano Generale delle Acque, Regione Autonoma della Sardegna), Cagliari, 1986.
2. Aru, A., Baldaccini, P. Vacca, A. *Nota illustrativa alla carta dei suoli della Sardegna, con carta illustrata 1:250.000*. Regione Autonoma della Sardegna, 1991.
3. Box, G. E. P.& G. M. Jenkins, Time series Analysis: Forecasting and Control, Holden-Day, 1976.
4. Cadeddu A., P. Cau, C. Gallo, G. Lecca, M. Marrocu, and M. Sulis. Implementazione di una procedura per la stima delle componenti del bilancio idrologico a scala di bacino per la Regione Sardegna. Technical Report 03/82. CRS4, Italy, Aprile 2003. Progetto MURST nr. 30 Cluster 11, workpackage 4).
5. Cadeddu A. & G. Lecca Sistema Informativo dei Suoli della Sardegna da interfacciare al modello idrologico SWAT. Report interno del CRS4 - Centro di Ricerca Sviluppo e Studi Superiori in Sardegna (2003)
6. Cau P., Cadeddu A., Gallo C., Lecca G. & M. Marrocu. Estimating available water resources of the Sardinian island using the SWAT model. Proceedings of the Second International SWAT conference, Bari, Italy, pag. 64 - 70, Luglio 2003.
7. Di Luzio M., M. Srinivasan & J. Arnold. *ARCVIEW interface for SWAT2000 – User's Guide*, USDA Agricultural Research Service, Temple, Texas, 2001.
8. Cao Pinna, C., A. Petruso, R. Silvano, A. Fadda, F. Buffa, N. Orrù (eds.), *Studio dell'Idrologia Superficiale della Sardegna (SISS)*, Ente Autonomo del Flumendosa (EAF), Cagliari, Italy, 1998.
9. Giupponi, C., Mysiak, J., Fassio, A., and Cogan, V., MULINO: *Multi-sectoral, Integrated and Operational Decision Support System for Sustainable Use of Water Resources at the Catchment Scale*. In F. Ghassemi et al. (Eds) (Ed). Proceedings of MODSIM 2001 - International Congress on Modelling and Simulation. MSSA-NZ, 1183-1188, 2001.
10. Neitsch, S. L., J. G. Arnold, J. R. Kiniry & J. R. Williams. *Soil and Water Assessment Tool (SWAT) – Theoretical Documentation* (version 2000), USDA Agricultural Research Service, Temple, Texas, 2001.
11. Nicks, A.D. *Stochastic generation of the occurrence, pattern and location of maximum amount of daily rainfall*. p. 154-171. In Proc. Symp. Statistical Hydrology, Tucson, AZ. Aug.-Sept. 1971. USDA Misc. Publ. 1275. U.S. Gov. Print. Office, Washington, DC, 1974.
12. Saxton K. E., W.J. Rawls, J.S. Romberger, and R. I. Papendick. *Estimating generalized soil-water characteristics from texture*. Soil Science Society of America Journal 50(4) , 1986, pag. 1031-1036.
13. USDA & NRCS Soil Survey Division. State Soil Geographic (STATSG0) Data Base - Data use information. Miscellaneous Publication Number 1492, 1994.