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An integrated solution for superficial water resources management based on complex distributed models and innovative web technologies

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Abstract. Action plans to reduce water pollution is a strategic task of European Countries (2000/60/CE) where water demand is steadily increasing, while water resources are limited. Action plans for water resource protection include monitoring activities, programming, identification of interventions, measures, constraints, and, in general, a variety of integrated actions for a water resource management policy. The advances in web-based technologies, computer simulation and high performance (GRID/CLOUD) computing in recent years have highly extended the possibilities in the environmental sciences, and have changed the ways in which land management systems operate. On this basis SAR, CRS4, ERA Progetti have started a collaboration to design tools, procedures and applications for the environment based on knowledge and easy access to up-to-date data and models for politicians, administrators and citizens. Here we present an innovative application accessible on the Internet, based on the web BASHYT portal (www.eraprogetti.com/bashyt), to simulate and analyze the water cycle.

The integrated software system will be tested to quantify agricultural drought periods for a Sardinian case history (San Sperate, South of Sardinia – Italy) produced with the weather data series of SAR meteorological stations for the period January 1995 - February 2008.

Keywords. SWAT – Water balance – Hydrological models – Sardinia – Drought.

Une solution intégrée pour la gestion des ressources en eau superficielle basée sur des modèles complexes et distribués et des techniologies web innovatives

Résumé. Les plans d'action pour la réduction de la pollution de l'eau constituent une tâche stratégique des pays Européens (2000/60/CE), où la demande augmente systématiquement, alors que les ressources en eau sont limitées. Ces plans d'actions incluent des activités de monitorage, de programmation, d'identification d'interventions, de mesures et de contraintes, et en général, une variété d'actions intégrées pour une politique de gestion de la ressource en eau. Grâce aux possibilités offertes par une plate-forme innovative basée sur le Web (BASHYT) et à la disponibilité de données météorologiques constamment ajournées, des modèles hydrologiques (principalement SWAT et QUAL 2K) et des procédures pour les rapports standardisés s'appliquent afin d'améliorer et d'intégrer la disponibilité d'informations à l'état de l'environnement.

Se basant sur ces hypothèses, SAR, CRS4 et ERA-Progetti ont entamé une collaboration pour créer et mettre à disposition, à l'appui des autorités responsables des ressources hydriques, un service de simulation du bilan hydrologique et des processus reliés (flux sortants ; transport de sédiments, de pesticides et de nutriments provenant des sources ponctuelles et diffuses) jusqu'au niveau de sous-bassin. À titre d'exemple, on a produit une application dans laquelle le contenu hydrique des sols permet d'évaluer l'intensité et la permanence des conditions de sécheresse dans le bassin de San Sperate, au Sud de la Sardaigne, produit avec la série Janvier 1995 - Février 2008 des stations météorologiques SAR.

Mots-clés. *SWAT – Bilan hydrique – Modèles – Sardegne – Sécheresse.*

I – Introduction

The complexity of the interactions between land use, soil, climate, anthropogenic stresses and quality of water in regions predominantly agro-livestock oriented (Sardinia is just one example), requires the use of reliable models to evaluate water resources vulnerability. The use of advanced ICT technologies, such as environmental models, GIS and web based applications, involves major investments, also in terms of acquisition of quality data, and the development of an interdisciplinary approach to the study. Such technologies can provide a significant contribution in the description of the water cycle and phenomena related to it.

The correct characterization of the spatial and temporal distribution of rainfall, of the land use, soil and anthropogenic pressures are strategic to represent the complex dynamic of surface and ground water resources and to design its sustainable use.

On these basis SAR, CRS4 and ERA-projects have started a collaboration by integrating data (in particular daily weather-climatic data), tools and expertise in the field of hydrological modeling, with the aim to organize and make available an operational service for the entire region, constantly updated, balanced and refined, which simulate the hydrological budget and related processes (e.g. sediment, nutrients and pesticides cycle). The objective of the work is to make available though a multi layered user-friendly web portal updated quality data, model outputs, visualization and processing tools to support the analysis and assessment of the water cycle.

II – The BASHYT framework

The latest computer technology offers computing and storage resources, distributed over a wide geographical domain, available from fast and secure networks, providing important services, applications and advanced visualization tools. The new paradigm is based on an integrated and collaborative approach where the complexity of the technology is transparent to the user, and interdisciplinary working groups and skills can be enhanced. On this basis, the development and use of enabling technologies (e.g. RDBMS with spatial extension, AJAX technologies, the GRID / cloud computing, etc..), allows to imagine new approaches for the management and the exploiting of data and physical resources available.

BASHYT (Basin hydrologic Scale Tool - http://www.eraprogetti.com/bashyt) is a web-based Collaboative Working Environment (CWE) for management and quantification of human and natural impacts on water bodies receptors, developed by ERA Progetti srl. The system has a modular structure built around the SWAT and Qual2K models. The portal permits to simulate and analyze the integrated water cycle (water balance and quality status of surface water bodies at different space and time scales), through a carefully rigorous methodology (DPSIR model) and to produce reports on environmental states by means of standardized procedures.

Data objects are natively digested by the CWE environment, allowing Web services to be exposed for data mapping, querying and sharing, processing and output distribution, using secure connections through the Web. The CWE framework can be thought as an easy to use Open development framework for constructing spatially enabled Internet- applications made available through the WEB browser.

The portal supports a WEB based live programming environment making the programming features available to developers with almost-zero learning curve. This increases developer productivity by reducing scaffolding code when developing web, GUI, database, GIS or applications.

III – The hydrological model SWAT

SWAT is a watershed-scale hydrological model, developed by the U.S. Department of Agriculture USDA-ARS and Texas A & M University, which allows to simulate the integrated water cycle and to assess the impact in the medium to long term of point and diffuse pollution. The application of the model requires specific information on weather, soil characteristics, topography, vegetation and land use.

The calculation of the water balance is carried out on Individual units (Hydrologic Response Units, HRUs), representing areas with a combination of land cover, soil type and management practice. From a computational, simulation of large basins also does not require too much investment of time and of computing resources. SWAT is an open source model, its use has further advantages: it's free, editable (it can be adapted to the particular needs), it is used by a large community of users around the world, and this encourages its continuous improvement. The model has been tested successfully in different geographical and climatic conditions.

The simplified equation of the water balance is summarized by the following:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_i - Q_{\sup,i} - ET_i - W_i - Q_{gw,i}) \quad (1)$$

where SW_T is the final soil water content, SW_0 is the initial soil water content, t is the time in days, R_i is precipitation, $Q_{sup,i}$ is run-off, ET_i is real evapotranspiration, W_i is percolation and $Q_{gw,i}$ is baseflow.

Actual evapotranspiration is calculated on the basis of potential evapotranspiration. This can be quantified with the Hargreaves, Penman-Monteith or Priestley-Taylor methods. To calculate runoff SWAT uses both the Green & Ampt infiltration method and the Curve-Number method.

The model also includes additional routines that enable to quantify the outflow and soils moisture content, the sediment, nutrients and pesticides fate, channeled toward the main gages in each sub-basin. The different processes described by the SWAT model can help produce a wide range of information for a given basin, for various operational applications.

Among the various possibilities offered by the SWAT model, in this particular study we will focus on the evaluation of a drought indicator to assess the severity and duration of drought period. The development was carried out for the San Sperate catchment in the south of Sardinia, Italy, using meteorological data for the period January 1995 - February 2008, registered by the SAR stations.

IV – Example of application: an index for agricultural drought

1. The agricultural drought

Drought is a temporary condition of relative scarcity of water resource compared to values that can be considered normal for a period of time and on a region (Rossi, 2000). Regarding with the elements of the hydrological cycle we may distinguish between meteorological, agricultural, hydrological and operational drought. While the meteorological drought is identified on the basis of a deficit of precipitation, the agricultural drought depends on the soil moisture deficit which is dependent on the precipitation regime and weather, the soil characteristics and the evapotranspiration rate. The persistence of agricultural drought condition produces negative effects both on natural vegetation and agriculture. Drought periods have an important impact on water supply system causing water shortage, negatively affecting the economic and social system.

Regional water authorities (e.g. in Emilia Romagna, Piedmont, Calabria, Sicily and Sardinia) have organized operational systems to facilitate the collection, processing and dissemination of hydro-meteorological data to monitor drought periods. Several indexes and methods have been proposed since the Sixties to detect and monitor drought events. The most commonly used are essentially the Standardized Precipitation Index – SPI (McKee *et al.*, 1993), the Palmer index – PDSI (Palmer, 1965) and deciles method (Gibbs, Maher, 1967).

However, some authors have highlighted several shortcomings in the implementation of such indices especially if they are used for drought evaluation on a small spatial scale. To this end, agricultural drought indices may be more accurate to evaluate the water deficit on the basis of the available water on the soil profile. The use of hydrological distributed models can provide reliable estimates of the soil water content and help quantify its deficit taking into account the distributed soil and land use characteristics.

2. The San Sperate basin

The Flumini Mannu of S. Sperate basin is found on the south central part of Sardinia and is delimited by the Sarcidano plateau at north, the Sarrabus relief at east, the last layer of Iglesiente massif at West. The topography is characterized by a significant variation in terms of altitude (from 13 to 972 m a,s.l.). The main river is a tributary of Flumini Mannu of Cagliari river which discharges its waters into the Santa Gilla humid area near the gulf of Cagliari which is among the largest wetlands in Europe.

The climate of the area is Mediterranean with long hot dry breezy summers and short mild rainy winters. Average monthly temperature ranges from 8°C (January and February) to 25°C (July and August). Precipitations are largely confined to the winter months, the rainfall regime is characterized by a peak rainfall in December (83 mm) and a minimum in July (8 mm), with an average value of 591 mm/year. The S. Sperate river is characteristically fast flowing, with a relatively important water volume in winter, reduced to a trickle during the dry season. The monthly water volume is characterized by a minimum peak in August (0,16 mc/s) and a maximum in February (4 mc/s). Land is primarily used to satisfy agricultural needs with large areas destined to crop cultivation (Cereal is predominant – 9091 ha). On the south we find vineyards (1709 ha), olive groves (2383 ha) and orchards 1709 ha) mainly. At East, woods and pastures are mostly found.

The hydrological behavior of soil is related to a number of physical soil properties (USDA & NRCS Soil Survey Division, 1994). To obtain information about these soil properties of the S. Sperate basin, a 1:250 000 soil vector map (Arangino *et al.*, 1986) (Aru *et al.*, 1991) has been used, where each cartographic unit has been associated with one or two delineations corresponding to subgroups of USDA soil taxonomy (Cadeddu *et al.*, 2003). Land cover significantly affects the water cycle. In this study the CORINE Land Cover 1:100.000 vector map (Commissione Europea, Ministero dell'Ambiente, 1996) has been used. It consists of a geographical database describing vegetation and land use in 44 classes, grouped into three nomenclature levels. The CORINE covers the entire spectrum of Europe and gives information on the status and the changes of the environment (Cumer, 1999).

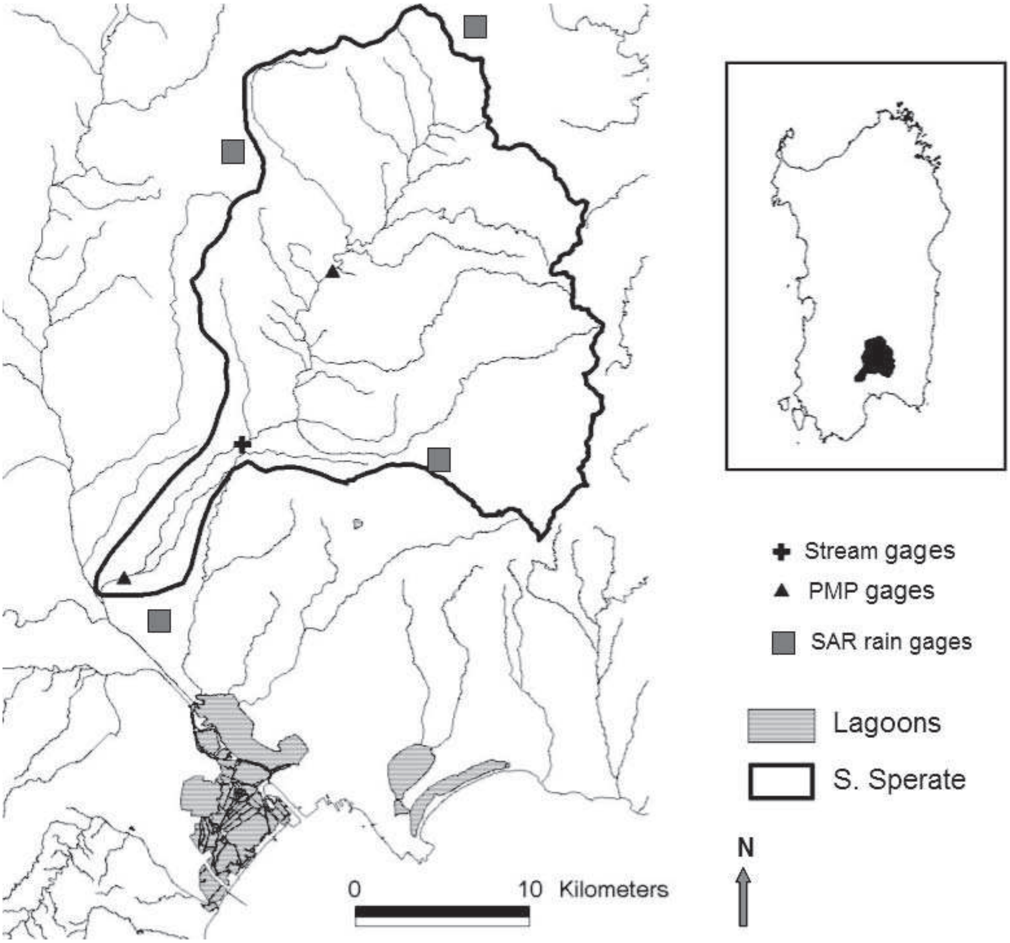

Figure 1. Location of the San Sperate basin.

Based on a 20 m digital elevation model, the 1: 100000 land use and the 1:250000 soil vector map, the S. Sperate has been subdivided in 23 Subbasins made of 444 HRUs.

The model was fed with air temperature and precipitation daily data for the period January 1995 – February 2008 recorded by monitoring network of Regional Agricultural Service for Sardinia (SAR). The climatic stations used for this application are those located in the area or localized in the surroundings: Decimomannu, Dolianova, Guasila, Siurgus-Donigala and Villasalto. Figure 1 shows the area of this study and the location of weather stations.

The model calibration/validation process followed a regional scale approach (Cau *et al.*, 2005). Monthly streamflows and reservoir water level historical records were used as control values. The soil and land cover parameterizations are not restricted to a single watershed, as similar soil and land cover types are found in different basins of the region. The parameters (Available Water Capacity, Curve Number, etc.) controlling the partitioning between baseflow, runoff, percolation, and evapotranspiration, as well as the transport of sediments, nutrients, and pesticides were changed within ranges suggested in the literature and according to the their uncertainty. Changes to the values of these parameters were accepted only if an overall improvement in streamflow was achieved compared to observed data. This was determined using as objective function the Nash-Sutcliffe index. The best-fit parameter values for our model implementation at a regional scale scored a Nash-Sutcliffe index of 0.77, suggesting a reasonably good match between simulated and observed streamflow rates.

3. The drought index

The daily-step run of the SWAT model allowed to estimate the various components of the hydrological balance for each HRU (potential evapotranspiration, actual evapotranspiration, runoff, soil water content, etc..). The SMD (Soil Moistures Deficit) agricultural drought index, a variation of the approach proposed by Narasimhan (Narasimhan, *et al.* 2002), has been calculated on a monthly basis as proposed in the formula (2). For the given month the index expresses the ratio between the anomaly of the monthly value compared to the average multi-annual data, and the difference between the maximum and minimum values for the entire time series available (in our case 1995-2008).

The SMD index reads as follows

$$SMD_i = \frac{SW_i - SW_i^{mean}}{SW_i^{\max} - SW_i^{\min}} \qquad (2)$$

SMD_i - deficit of soil water content for the months *i*

SW_i - monthly average soil water content for the month *i*

SW mean $_i$ – long-term average monthly soil water content for the month *i*

SW max $_i$ – long-term maximum soil water content for the month *i*

SW min $_i$ - long-term minimum soil water content for the month *i*

The index can be positive and negative, indicating for a given month a surplus and a deficit of water content respectively for a given soil (BASHYT automatically quantify the anomaly magnitude observed on a given month and to weigh it with respect to the variability of long-term estimated values to evaluate the SMD drought index).

V – The environmental reporting for the Case Study

The components of the hydrological balance, obtained on daily time step for each elementary territorial units (HRU), obtained by the SWAT model, were subsequently integrated and analyzed on sub-basin spatial scale and on a monthly time step, by means of the post-processing tools of the BASHYT portal. These outputs are then produced and presented on time series and spatial representations by means of dedicated interactive web pages within the portal. Figure 2 shows the hydrological balance for the whole basin.

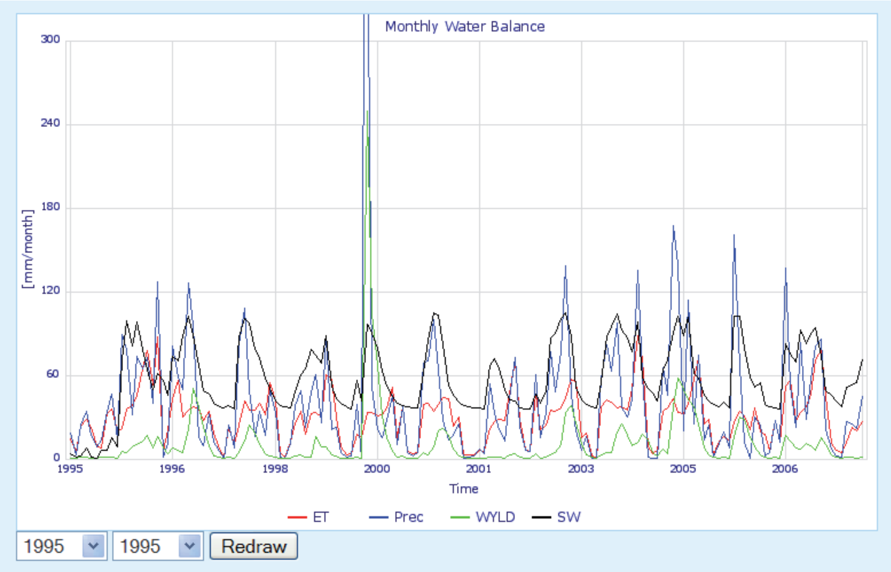

Figure 2. Prec - rainfall, ET - actual evapotranspiration, SW – soil water content, Wyld – water yield for the San Sperate basin, viewed on the BASHYT web portal.

Figure 3 shows the SMD index spatial distribution for the period Agost 2001 – January 2002, The web application permits to interactively monitor the intensity of the deficit condition and the duration of the drought period. In particular the period September - December 2001 is the longest drought period in the 15 years simulation while December 2007 is the one that showed the most sever intensity of the SMD index.

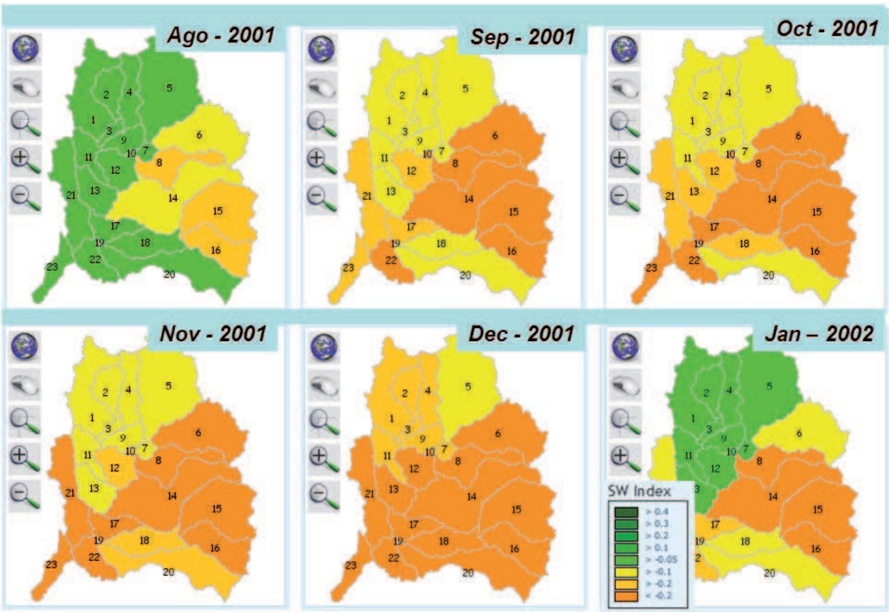

Figure 3. Spatial distribution map of the monthly SMD index (period August 2001 - January 2002).

VI – Conclusion

The proposed procedure for estimating the drought index SMD is based on a complex hydrological balance model which runs on a HRU spatial scale and on a daily time step. This approach has the advantage of examining the hydrological cycle at the correct scales of the hydrological phenomena involved. Subbasin monthly estimates are, as a matter of fact, derived from daily balances at the HRU scale.

Water authorities need to have substantial scientific tools to analyze complex phenomena of interest. BASHYT can represent an important contribution in the field of environmental reporting systems. This environment web-based decision support system is designed to meet the needs of administrations involved in integrating environmental reporting procedures (based primarily on GIS, tables, graphs) and analysis tools.

Finally, the case history briefly presented, although limited to the calculation of SMD on a complex Sardinian basin, allows to appreciate the potential of the proposed system. If extended to the whole region, such system, supplemented also with the assessments of other phenomena of interest (e.g. evaluation of the impact of point and diffuse pollution on water resources, etc..) offer operational tools highly useful for the management of water resources.

References

Arangino, F., Aru A., Baldaccini, P., Vacca, S., 1986. *I suoli delle aree irrigabili della Sardegna. Piano Generale delle Acque*. Cagliari: Regione Autonoma della Sardegna.

Aru, A., Baldaccini, P., Vacca, A., 1991. *Nota illustrativa alla carta dei suoli della Sardegna, con carta illustrata 1:250.000*. Cagliari: Regione Autonoma della Sardegna.

Cadeddu, A., Lecca, G. (2003). *Sistema Informativo dei Suoli della Sardegna da interfacciare al modello idrologico SWAT*. Cagliari, Italy : CRS4, Center for Advanced Studies, Research and Development in Sardinia. (Technical report, 09/03).

Cau, P., Cadeddu, A., Gallo, C. , Lecca, G., Marrocu, M., 2005. Estimating the water balance of the Sardinian island using the SWAT model. *L'Acqua*, 5. pp. 29-38.

Cumer, A., 1999. Le evoluzioni del Land Cover CORINE in Italia. *MondoGIS,* 16.

Gibbs, W.J., Maher, J.V., 1967. *Rainfull deciles as drought indicators*.. Melbourne : Commonwealth of Australia. (Bureau of meteorology bulletin, 48).

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. Preprints. In: *8th Conference on Applied Climatology, 17-22 January, Anaheim. CA*. Amer. Meteor. Soc. pp. 179-184.

Narasimhan, B., Srinivasan, R., 2002. Development of a soil moisture index for agricultural drought monitoring using a hydrologic model (SWAT), GIS and remote sensing. *Texas water monitoring congress. September 9-11, 2002. Austin, TX*.

Palmer, W.C. 1965. *Meteorological drought*. Washington, D.C.: U.S. Department of Commerce Weather Bureau. 58 pp. (Research paper, 45).

Rossi, G., 2000. Drought mitigation measures: a comprehensive framework. In: Vogt, J.V., Somma, F. (eds.). *Drought and drought mitigation*. Kluwer Academic Publishers. pp. 233-246.