European Water 3/4: 3-8, 2003.

Space - time analysis of water deficit

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Abstract: The paper describes the main characteristics of an integrated system aimed to predict space-time variations of water deficit occurring in southern Italy. The system has been developed within the European INTERREG IIC Programme. It, using GIS technologies integrated with tele-metering network, hydrological databases and distributed water balance models, allows to analyse different aspects of the wider drought phenomenon. The integrated system herein proposed represents both an original methodological approach and a suitable tool to determine the critical areas characterised by water deficit that for the analysed region they appear more frequent and wider.

Keywords: Drought, GIS, Water Balance

1. INTRODUCTION

In the last decades water deficit problems rise in different areas of the world, and many of these have become by now extremely intense, reaching situations of dramatic crisis. This scenery seems to be worsened by the progressive increase of drought observed in various southern Europe areas. In this context, numerous initiatives have been promoted by the European Community to face the effects induced by drought on the member States. Among these, the main initiative is the INTERREG IIC Programme, which has permitted the actuation of several transnational planning programmes, and includes among its objectives the development of a strategy for the prevention and co-operation in facing the reduction of water resources due to drought. Specifically, within the sub-programme "Analysis of the hydrological cycle" the southern Italian regions have been analysed in detail because of their meta-stable climatic regime characterised by strong intermittences of the water balance. For these regions, an integrated monitoring system for the analysis and the forecast of the effects produced by prolonged water deficit periods has been realised. The system is made up of a commercial GIS (Arc-View) connected with a Data Acquisition System which stores real time data recorded by the National tele-metering hydro-meteorological network managed by the Servizio Idrografico Mareografico Nazionale (SIMN). The system is running since the beginning of the year 2000 and the tele-metering data are constantly updated and returned according to the input required by the simulation models. These models allow the estimate of spatially distributed hydrological quantities, such as solar radiation, potential evapotranspiration, water deficit.

The paper, after a brief analysis of the main criteria used for developing the integrated monitoring system, describes the theoretical structure of the spatially distributed water balance models, presents the analyses carried out for parameter estimation, and discusses some results obtained through the simulation of water balance in southern Italy during the last five years.

2. INTEGRATED MONITORING SYSTEM

The integrated system developed in southern Italy for the analysis of the prolonged water deficit effects is based on a GIS-embedded water balance modeling, directly linked with a Data Acquisition System aimed to store real time data recorded by the National tele-metering hydro-meteorological network managed by the SIMN (Mendicino and Versace, 1999; Mendicino, 2001). This network has been strengthened with a great number of stations, most of which are aimed to measure specific quantities to be directly used for the estimate of water balance of the southern Italy regions.

For the whole southern Italy, all the geographic information has been stored within the Arc-View GIS according to two data structures, respectively vector and raster. All the spatially distributed hydrological quantities are elaborated, managed and stored using a raster data structure characterised by a 250 m square grid spatial resolution equal to the one utilised for the southern Italy Digital Terrain Model.

Hydrological coverages are directly obtained by linking the GIS with the hydrological databases. Specifically, hydro-meteorological information is managed considering two different data types. The first is based on daily hydro-meteorological values recorded by all gauge stations (historic DB) starting from 1925. The latter is based on real time data recorded by tele-metering stations with a 20-minute time step (real time DB). The hydrological databases have been developed using Microsoft® SQL Server™ software with the aim of making easy the data management and updating. The interaction with databases has been improved realising some Windows-based software applications capable of guaranteeing a more simple and flexible data query, and allowing the user to extract synthetic graphs and reports. These interfaces user-DB can work both autonomously and directly inside the GIS by simple graphical selections on the gauge stations. These additional functionalities are directly embedded within the GIS through a set of Avenue scripts. Specifically, they allow to dynamically query the different station types available in the databases, showing the results obtained inside the GIS.

3. SIMULATION MODELS

On the examined region, water deficit is evaluated on a monthly basis using a spatially distributed water balance model. This model follows the original approach suggested by Thornthwaite and Mather (1955) and simulates soil moisture variations, evapotranspiration and runoff on single 5 km regular grid cells using data sets that include climatic drivers, vegetation and soil properties (Fig. 1). This model does not consider horizontal motion of water on the land surface, or in the soil. The governing equation is based on a simplified mass balance:

$$P = S + E + \Delta W \tag{1}$$

where P is precipitation, E is evapotranspiration, S is water surplus, and ΔW is the change in soil moisture storage. All the quantities are evaluated in millimeters per month. Equation (1) does not differentiate between surface runoff and groundwater runoff, it allows to determine water surplus S as the water which does not evaporate or remain in soil storage and is available to generate surface and subsurface runoff.

The procedure schematises the soil column through a reservoir whose maximum capacity is given by the soil-water holding capacity WHC. The state variable representing the soil moisture at the end of the month i is defined W_i and depends on the difference between precipitation P_i and potential evapotranspiration PE_i values. If $P_i \geq PE_i$ then:

$$W_i = \min\left[W_{i-1} + (P_i - PE_i)\ ,\ WHC\right] \tag{2}$$

and soil moisture is recharged up to the maximum value WHC. When W_i is equal to WHC, further positive values (P_i - PE_i) are considered as surplus S_i. Negative values of (P_i - PE_i) indicate the amount by which precipitation fails to supply PEi requirements. In this case water will be withdrawn from the soil moisture, resulting in an exponential soil moisture depletion, and the actual evapotranspiration E_i is less than PE_i. Actual evapotranspiration E_i equals PE_i when $P_i > PE_i$, otherwise it is equal to the precipitation P_i plus the change in soil moisture storage ΔW_i during the month i. When $E_i < PE_i$, then the difference (PE_i - E_i) represents the water deficit D_i or the amount of water that would be supplied by irrigation to the soil during the month i.

Surplus S_i is hypothesised to be subdivided into two quantities, $\mu_i S_i$ and $(1-\mu_i)S_i$ respectively. The former quantity $\mu_i S_i$ represents the monthly surface runoff, whereas the latter $(1-\mu_i)S_i$ describes the groundwater recharge. A monthly runoff coefficient μ_i is locally determined starting from the Curve Number method suggested by the Soil Conservation Service (1968), and modifying it to account for antecedent soil moisture conditions (Heatwole et al., 1987).

Groundwater recharge $(1-\mu_i)S_i$ is used to determine the runoff delay caused by water transport through groundwater before it enters river channels. If a linear groundwater reservoir is assumed, then its monthly runoff detention Dr_i (mm) can be expressed as follows:

$$\frac{Dr_i - Dr_{i-1}}{\Delta t} = S_i(1-\mu_i) - \frac{Dr_{i-1}}{\beta} \tag{3}$$

where β is the linear reservoir constant and Dr_i-1/β is the groundwater runoff. Groundwater runoff plus surface runoff $\mu_i S_i$ determine the monthly river runoff Q_i.

Potential evapotranspiration PE in the soil-water balance procedure is estimated considering the Penman equation (1948), modified by Monteith (1965):

$$PE = \frac{1}{\lambda}\left[\frac{\Delta(R_n - G) + 86.4\,\rho c_p (e_a - e_d)/r_a}{\Delta + \gamma(1 + r_c/r_a)}\right] \tag{4}$$

where PE is the evapotranspiration rate (mm d^{-1}), 86.4 is a conversion factor, γ is the psychrometric constant (kPa $°C^{-1}$), λ is the latent heat of vaporisation (MJ kg^{-1}), Δ is the vapour pressure gradient with temperature (kPa $°C^{-1}$), Rn is the net radiation (MJ m^{-2} d^{-1}), G is the soil heat flux (MJ $m^{-2}d^{-1}$), ρ is the atmospheric density (kg/m^{-3}), e_a is the saturated vapour pressure at air temperature (kPa), and e_d is the actual vapour pressure (kPa), c_p is the specific heat moist air (kJ kg^{-1} $°C^{-1}$), r_a is the aerodynamic resistance (s m^{-1}) and, r_c is the crop canopy resistance (s m^{-1}). Spatial distributions of this last resistance have been obtained considering Leaf Area Index (LAI) coverages derived from monthly Normalised Difference Vegetation Index images. Penman-Monteith equation requires a great amount of observed data that is not always available on the whole region and for long time periods. A simplified equation for the estimate of potential evapotranspiration in southern Italy has been obtained as follows (Mendicino et al., 2002):

$$PE = a'PE_{RAD} + b'T + c'LAI + d' \tag{5}$$

where PERAD (mm d^{-1}) is the radiation term of equation (4), T is the monthly air temperature (°C), a' (-) is a constant equal to 0.63, b' (mm d^{-1} $°C^{-1}$), c' (mm d^{-1}) and d' (mm d^{-1}) are seasonal parameters shown in Table 1.

Using observed data, equation (5) has shown good performances equal to those obtained through Penman-Monteith equation. Furthermore, the simplified equation has allowed to extend the simulation period also in the past years where only precipitation and temperature data was available.

Table 1. Monthly values of parameters b', c' and d'

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
b' (mm d^{-1} $°C^{-1}$)	0.08	0.08	0.10	0.13	0.16	0.18	0.19	0.17	0.14	0.10	0.08	0.08
c' (mm d^{-1})	0.14	0.23	0.35	0.47	0.55	0.59	0.56	0.48	0.36	0.24	0.15	0.11
d' (mm d^{-1})	-0.27	-0.21	-0.61	-1.32	-2.11	-2.70	-2.88	-2.60	-1.94	-1.14	-0.48	-0.18

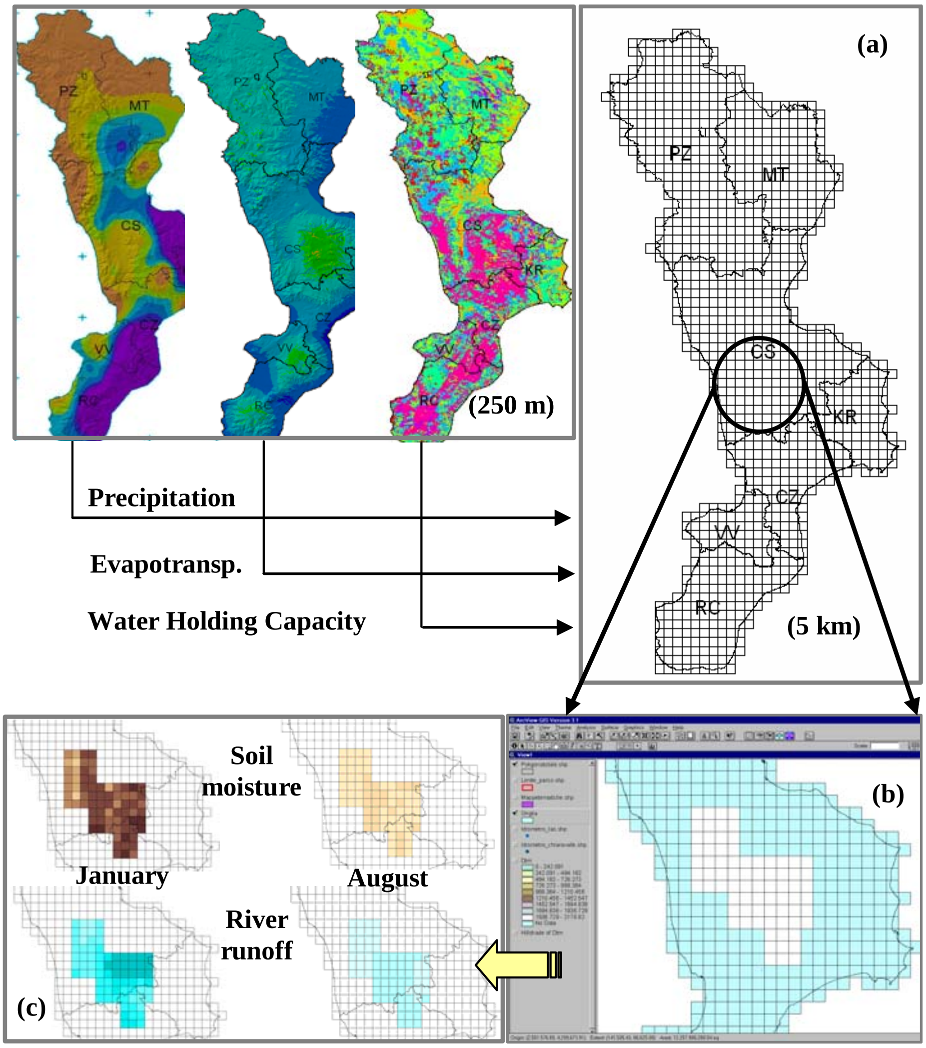

Figure 1. a) Southern Italy grid (5 x 5 km) used for water balance simulations; b) Example of user-selected areas where monthly GIS-water balance procedure is activated; c) Output data mapped by GIS

4. WATER DEFICIT

Model performance has been verified on few experimental basins in southern Italy before proceeding to the analysis of the regional water balance. Further analyses have been carried out varying some characteristic parameters (β, WHC, Dr_0) and observing model sensitivity.

Comparison between model-simulated and observed monthly river flows pointed out that groundwater initial detention Dr0 did not appreciably weigh on simulations; then, it was hypothesised as uniformly distributed on the whole southern Italy and fixed equal to 100 mm. Soil-reservoir constant β was determined considering different classes of values. Results based on the minimisation of root mean square errors and sum of mass discrepancies involved the use of three optimum values (5, 10 and 20 months) depending on soil permeability. These values mean that groundwater runoff in the present month is assumed to be equal to 20% of groundwater detention observed in the previous month for moderate rate of water transmission, equal to 10% for slow rate of water transmission and equal to 5% for very slow rate of water transmission. Changes in soil-water holding capacity did not produce appreciable differences in simulated river runoff with the exception of months characterised by very extreme precipitation events.

Results obtained at basin scale have been extended to the whole southern Italy and the corresponding water balance has been developed by considering historic monthly mean data first (for the period 1925-2001), and then monthly values observed during the years 1997-2001. Simulations carried out on actual data, offer useful information about hydrological characteristics of the examined region, in absolute terms, but can be subjected to criticisms because of the simplifications introduced into the water balance procedure. Differently, their comparison with historic mean quantities univocally defines the critical areas monthly interested by water deficit.

Figures 2a, b and c show the comparison between actual and historic monthly values obtained averaging the spatially distributed water balance quantities on the whole southern Italy. The same figures point out a net reduction in the actual precipitation data that involves a more evident reduction in river runoff. Critical water deficit values are mainly observed during the summer months, with a maximum in August 2000. For the observed period, October 2001 shows the highest critical water deficit characterised by a 80 mm difference from the corresponding historic mean value (Fig. 2c). For these months GIS-embedded modeling allow to automatically determine critical areas whose water deficit values appear to be substantially different from the corresponding historic mean (Fig. 2d).

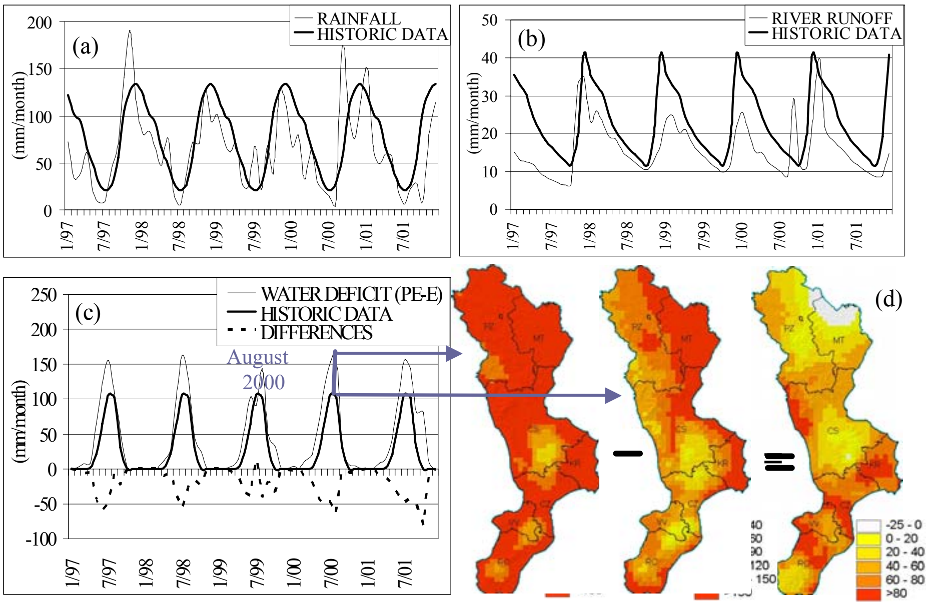

Figure 2. Comparison between actual and historic monthly water balance quantities in southern Italy. a) Spatially-averaged rainfall values; b) Spatially-averaged river runoff values; c) Spatially-averaged water deficit values; d) Example of spatially distributed water deficit differences for the critical August 2000

5. CONCLUSION

An integrated GIS-Web monitoring system aimed to analyse, control and map water deficit periods occurring in southern Italy has been described in this paper.

Real time hydro-meteorological data are stored in databases, which are directly linked to a GIS-embedded water balance modeling. GIS is able to spatially determine critical areas whose water deficit values appear to be different from the corresponding historic means. This is realised on a monthly basis comparing historic mean quantities with actual observed values. Analyses carried out during the years 1997-2001 have shown a diffuse drought phenomenon characterized by an increasing water deficit trend. Specifically, this trend is more evident along the Ionian zones.

The innovative aspect of the proposed system is its GIS-Web architecture, through which all tele-metering recorded data and spatially distributed water balance analyses are available, both as tables and maps, via World Wide Web at http://www.camilab.unical.it.

Future developments will be addressed to two main directions: the first aimed to improve the water balance procedure, especially for what concerns soil properties and the correct definition of groundwater volume; the other regarding the introduction into the water balance of quantities related to irrigation and water supplies.

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