A distributed package for sustainable water management: a case study in the Arno basin

FABIO CASTELLI[1], GIOVANNI MENDUNI[2] & BERNARDO MAZZANTI[2]

1 *Department of Civil and Environmental Engineering, University of Firenze, Firenze, Italy*
fabio@dicea.unifi.it

2 *Arno Basin Authority, Firenze, Italy*

Abstract MOBIDIC (MOdello di Bilancio Idrologico DIstribuito e Continuo) is a distributed hydrological modelling package for various applications. The main innovations concern: (a) the coupling of the water balance in the soil and vegetation with the surface energy balance, to the benefit of evapotranspiration computation and the use of remotely-sensed maps for calibration and validation; (b) the interaction between groundwater and surface water bodies, (c) the capability of easily managing data on withdrawals of water, reservoir operation and environmental flow. MOBIDIC-WRM can be used as an effective tool for the evaluation of basin scenarios (e.g. effects of changes in land cover/deforestation and irrigation strategies, exploitation policies for groundwater). It provides a reliable hydrological base for the assessment of crisis indicators such as vegetation stress and lack of environmental flow. In this work we present an application in the Arno basin, central Italy. The outcome of applying the package in order to determine the water budget management strategies is discussed.

Key words water resources monitoring and control; distributed hydrological models; remote-sensing; soil-atmosphere fluxes; environmental flow

INTRODUCTION

Many water resources management applications, such as the development of policies for the sustainable allocation of resources, require the estimation of the water balance for large basins and on minor branches of the hydrographic network, together with the assessment of the interactions between groundwater, surface water and ecosystems. Conventional approaches to water balance computations are usually supply-oriented and focused on major rivers, and lack in flexibility in accounting for spatially variable issues concerning environmental flow, simulation of withdrawals and reservoir operations. A distributed approach, where the basin is represented as discrete cells with assigned geomorphological and hydraulic properties and the river network, can be modelled in separate elementary branches at a very fine level of detail. This approach appears to be a much more suitable tool for water resources management at the basin scale.

The Basin Authority of the Arno River, has set up a modelling framework for the estimation of the water balance using the distributed package MOBIDIC (MOdello di Bilancio Idrologico DIstribuito e Continuo). More specifically, the MOBIDIC-WRM (Water Resources Management) tool is a physically-based model that allows the estimation of the components of the hydrological balance in the subsurface layer, the soil–vegetation system, and in surface water bodies. In the representation of physical processes, the main innovations with respect to existing models concern the coupling of the water balance in the soil and vegetation with the surface energy balance to the benefit of evapotranspiration computation. This tool also makes use of remotely-sensed maps of land surface temperature for calibration and validation and the detailed interaction between groundwater and surface water bodies. Geographical input data, both in raster and vector form, can be supplied to the model in most common GIS formats or as raw binary or ASCII data. Meteorological inputs and data on withdrawals, artificial releases and reservoir operation are fed into the model in DBF or text tables.

A pre-processing step of the model (MOBIDIC-BUILDGIS) is devoted to consolidate the input geographical and time-series data, and to establish the mutual spatial and topological relationships between topography, river network, reservoirs and withdrawal/release points. The hydrological balance can then be run with MOBIDIC-WRM with the desired spatial and temporal resolution. The output of the simulation includes time series of modelled discharges for each branch of the hydrographic network and related statistics (e.g. flow duration curves) and maps of hydrological components (evapotranspiration, runoff, precipitation). The output of the hydrological balance can then be linked with information on environmental flow and water consumption, and the water balance can be computed for each branch of the hydrographic network.

In the application for the Arno basin, the hydrological simulation has been performed on a daily time scale for the period 1992–2006. The geomorphology of the basin and related hillslope processes have been modelled using a Digital Elevation Model with 10-m square cells. Information on land cover, geology and soil hydraulic properties have been retrieved from existing maps and remote sensing data. Both natural (where no withdrawals or artificial releases have been considered) and "anthropic" scenarios have been simulated. The results include modelled discharge time series for nearly 20 000 river branches and more than 22 000 withdrawal sites, flow duration curves, and maps of hydrological components over the basin area (soil moisture, evapotranspiration, infiltration).

MOBIDIC: ALGORITHMS

In MOBIDIC-WRM, the spatial domain for the computation of the hydrological processes is represented by a horizontal discretization of the basin in square cells with arbitrary size and a vertical separation into five layers: (1) vegetation, (2) surface reservoirs (rivers and basins), (3) gravitational soil, (4) capillary soil, and (5) groundwater. With respect to previous versions of the model (Campo *et al.*, 2006), the new formulation includes river and reservoir routing, surface energy balance and groundwater simulation.

The soil–vegetation–atmosphere system

Evapotranspiration is computed from the energy balance between the land surface and the atmosphere. The energy balance is approached by solving the heat diffusion equation in multiple layers in the soil–vegetation system.

The computation of fluxes can be approached either with a "two-source" formulation (contributions from soil and vegetation are computed separately) or with a "combined source" formulation, where soil and vegetation are treated as a single medium with assigned equivalent thermal properties (Caparrini *et al.*, 2005). In the first case, maps of vegetation fraction and Leaf Area Index are needed as additional inputs. The second (combined source) approach is more parsimonious and does not require any ancillary information on vegetation cover. It can be used when there is no particular necessity for discriminating between soil evaporation and transpiration from leaves. In the application presented here, a combined source approach was used. Latent and sensible heat fluxes from the earth surface (soil + vegetation) are computed following a "bulk" heat transfer formulation in terms of the temperature and humidity gradients between the land surface (subscript *s*) and the atmosphere (subscript *a*):

$$\begin{aligned} H &= \rho c_p C_H U (T_s - T_a) \\ L \cdot E &= \rho L C_H U (q_s - q_a) \end{aligned} \tag{1}$$

where U is windspeed and c_p and L are thermodynamic properties (air specific heat and latent heat of vaporisation). The dimensionless parameter C_H is the bulk transfer coefficient for heat and includes the effects of both land surface characteristics (roughness, surface geometry) and atmospheric stability (Van Den Hurk & Holstlag, 1997).

Surface hydrology

The mass balance in the soil layer is approached with a conceptual subdivision of the soil of each cell into two distinct reservoirs: the capillary one (smaller size pores) and the gravitational one (larger size pores). The subdivision between these reservoirs is based on the definition of a threshold pore size, here assumed equal to 60 μm (Busoni *et al.*, 1983). Volumes of water (per unit area) W_g and W_c are limited by maximum capacity values $W_{g\max}$ and $W_{c\max}$, and their evolution in time is governed by the following mass balance equations:

$$\frac{\mathrm{d}W_g}{\mathrm{d}t} = I_{nf} - S_{per} - Q_d - S_{as} \tag{2}$$

$$\frac{\mathrm{d}W_c}{\mathrm{d}t} = S_{as} - E_T \tag{3}$$

where I_{nf} is infiltration rate, S_{per} is percolation, Q_d is hypodermic flow, S_{as} is adsorption from the gravitational to the capillary soil reservoir and E_t is evapotranspiration. The adsorption S_{as} is assumed to be a linear irreversible process, proportional to a "bulk suction head" through an absorption parameter κ:

$$S_{as} = \kappa\left(1 - \frac{W_c}{W_{c\max}}\right) \tag{4}$$

Evapotranspiration E_T is fed by water in the capillary reservoir only, e.g. root uptake is considered to be dominant with respect to direct soil evaporation, and it is maintained at its potential value $E_{T\mathrm{pot}}$ (estimated from surface energy balance) until the soil eventually dries out.

With this conceptualization, the storage capacities $W_{g\max}$ and $W_{c\max}$ may be defined, respectively, as the maximum water content above the field capacity and the maximum water content between field capacity and the wilting point. Water in the gravitational reservoir feeds the percolation flux S_{per} towards the groundwater and the hypodermic flow Q_d towards downhill cells. Both these fluxes are considered to be linearly related to the gravitational water content, with the definition of a percolation parameter γ and a hypodermic flow parameter β:

$$S_{per} = \gamma W_g \tag{5}$$

$$Q_d = \beta W_g \tag{6}$$

The two parameters depend on the saturation hydraulic conductivity K_s and the horizontal spacing determined by computation cell size Δx and can be written as:

$$\beta = \beta^* \frac{K_s}{\Delta x} \tag{7}$$

$$\gamma = \gamma^*\left(\frac{K_s}{\Delta x} + C^*\right) \tag{8}$$

where β^*, γ^* and C^* are lumped coefficients determined by calibration. The infiltration rate I_{nf} to the soil is limited through the saturation hydraulic conductivity K_s and accumulation is limited through the soil gravitational capacity $W_{g\max}$. If P is the precipitation rate on the cell and $(Q_d, R_h, R_d)_{up}$ are the hypodermic flow, Horton runoff and Dunne runoff contributions from upstream cells, infiltration is estimated as:

$$I_{nf} = \begin{cases} \left[P + (Q_d + R_h + R_d)_{up}\right]\left[1 - \exp\left(\dfrac{-K_s}{P + (Q_d + R_h + R_d)_{up}}\right)\right] & if \quad W_g < W_{g\max} \\ 0 & if \quad W_g = W_{g\max} \end{cases} \tag{9}$$

Routing of hypodermic flow follows the same downhill directions of surface flow, and its velocity is given by the product of the pixel size and the parameter β, i.e. it is proportional to the saturation hydraulic conductivity (equation (7)). Downhill routing of surface runoff is performed through a linear filter representing the effect of water storage in the hillslope W_s:

$$\frac{\mathrm{d}W_s}{\mathrm{d}t} = -\alpha_s W_s + R_H + R_D + q_{up} \tag{10}$$

where q_{up} is runoff from uphill that reaches the cell through hillslope routing. The parameter α_s that controls downhill routing is still defined at cell-scale with empirical relations such as:

$$\alpha_s = \frac{\alpha_0}{\Delta x}\sqrt{Ai} \tag{11}$$

where A is the contributing area to each cell, i is topographic slope and α_0 a lumped coefficient to be calibrated. When surface runoff reaches the hydrographic network, it is transferred to it and then propagated through river flow routing.

River and reservoir routing

The hydrographic network is represented in vector form and composed of cylindrical channels where the flow routing can be calculated by different methods (lag, linear reservoirs, Muskingum-Cunge). The network topology is built in the pre-processing phase, starting from a polyline representation of the rivers. A minimum stream order may be set for computation (i.e. river processes can be calculated only from a certain order upwards to save computation time). The interaction of the river network with hillslope processes, groundwater, withdrawals and reservoirs is also spatially structured in the pre-processing phase on the basis of the DTM, together with aquifer location and position of intake/discharge points. Additional attributes of the river network, if required, are geometry of cross sections, stage–discharge relationships, roughness coefficients. The balance equation in each branch is given by:

$$\frac{\partial Q}{\partial t} + c\frac{\partial Q}{\partial x} = \mu\frac{\partial^2 Q}{\partial x^2} + c\left(q_L + q_D + q_W\right) \tag{12}$$

where q_L is lateral inflow (from surface and hypodermic) flow, q_D is base flow (from groundwater) and q_W are withdrawals and/or releases in the branch. The routing parameters are: c, celerity of flood wave and μ, diffusivity. The latter parameter is required only when diffusive schemes are adopted (e.g. Muskingum-Cunge).

Surface reservoirs (either natural or artificial) are schematized with storage and outflow laws connected to the hydrographic network. The geometry of the reservoir is schematised by means of volume–elevation curves that are computed for each reservoir on the basis of available data on dam elevation with the topography of the storage basin retrieved from the DTM. The mass balance is then computed considering the inflow from rivers, groundwater surface and hypodermic flow, and the outflow from outlets and spillways.

The groundwater balance

The groundwater balance can be considered to be a linear reservoir, or with a detailed representation of subsurface processes using the Dupuit approximation. In this case, the groundwater domain is discretized with its own grid (that may have different spatial domains and a horizontal resolution with respect to the one used for surface processes). Both freatic and confined aquifers can be simulated with proper algorithms. A grid of aquifer definition and spatial extent is used in the preprocessing MOBIDIC-BUILDGIS phase in order to establish the interactions between groundwater, soil hydrology and the river network.

Compared to the simple linear reservoir scheme, this approach is more physically sound and can greatly improve the estimation of base flow. However, the detailed simulation of groundwater processes requires additional data on permeability and bedrock depth that in most cases are not available with the exception of limited areas where detailed surveys have been carried out. In the applications presented here, the simplified scheme has been used.

APPLICATION: HYDROLOGICAL BALANCE OF THE ARNO BASIN

MOBIDIC-WRM has been used for the computation of the water balance in of the Arno basin by the Arno River Basin Authority (Fig. 1). The Arno basin has a total area of approx. 8000 km^2 and is bounded by the Apennine Mountains in an arc from north to east with an average elevation of 1000 m above sea level, with a maximum of about 2000 m. The geomorphology of the basin and related hillslope processes have been modelled using a Digital Elevation Model with 10-m square cells. Information on land cover, geology and soil hydraulic properties have been retrieved from existing maps and from remote sensing data. Furthermore, estimations of Environmental Flow and the Base Flow Index were available from previous studies (Manciola *et al.*, 1991).

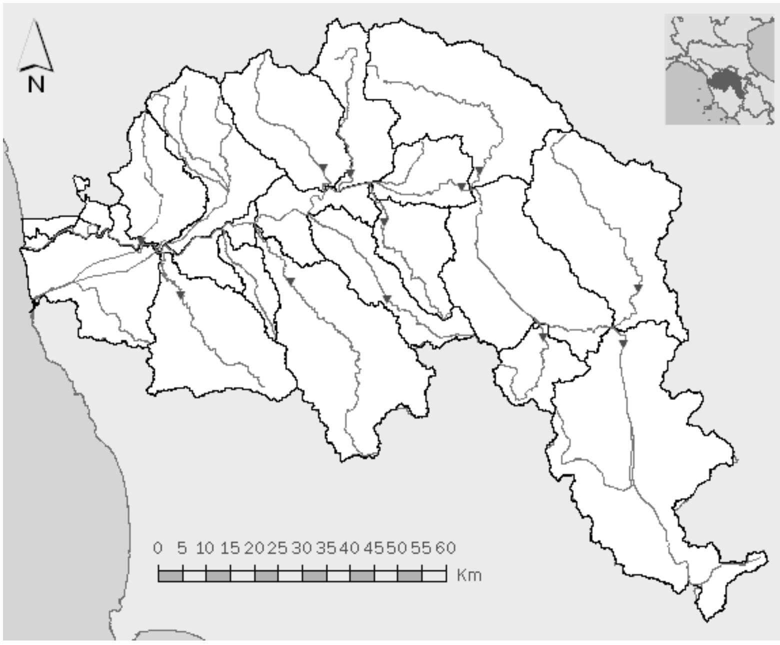

Fig. 1 Territory of the Arno River Basin Authority showing the river gauging stations used for calibration and/or validation, and the sub-basins taken as the main simulation units.

The water balance has been computed on a daily time scale for a 15 year period (1992–2006). The cell size adopted for calculation in 15 sub-basins is 200 m. Groundwater modelling was approached in the simplified form (linear reservoir), due to the scarcity of data on aquifers over the whole territory. Data on withdrawals were provided from the database of the Arno River Basin Authority (more than 22 000 records).

Meteorological data were obtained from the regional hydrometeorological monitoring network. Also, water level measurements for a set of stations and stage–discharge relationships for at least a few years during the period of study were used for calibration and validation purposes (Fig. 1).

Calibration

The estimation of the required parameters was approached with the following constraints in mind: minimization of the differences between simulated and measured flow duration curves; maximization of the numbers of constant model parameters over the whole basin, i.e. assuming the same standard value for every sub-basin. The phase calibration of the model focused on 15 sub-basins over the period 1993–1998; this period was chosen because it contained an adequate number of stations, each with a homogeneous time series.

Some of the lumped parameters aggregates of the entire sub-basin were calibrated, in particular the soil saturation hydraulic conductivitiy K_s and two aquifers parameter: a “Global Loss” parameter (with values between 0 and 20%), and K_f parameter (coefficient of filtration in aquifers, 1.0×10^{-7} and 2.0×10^{-6} m/s). These were left unchanged and equal for all sub-basins (Table 1).

Table 1 Lumped parameters assumed as constant values for all sub-basins.

Parameter	Description	Unit	Value
α_0	Multiplier of downhill routing parameter	[–]	2.0×10^{-5}
$\gamma*$	Multiplier of percolation parameter	[–]	2.0×10^{-7}
$\beta*$	Multiplier of hypodermic flow parameter	[–]	2.0×10^{-6}
κ	Absorption parameter	[s^{-1}]	3.0×10^{-6}

RESULTS

The output of MOBIDIC-WRM provides time series of modelled discharge in all branches of the hydrographic network (here selected from Strahler stream order 3 upwards), together with related statistics, including flow duration curves, drought persistence, etc. Furthermore, maps of the components of hydrological balance (evapotranspiration, runoff, cummulated precipitation) and other environmental states (soil temperature, evaporative fraction) are provided for each day and with the desired temporal aggregation (annual/monthly averages, peak values).

Figure 2 shows the flow duration curves for the period of simulation (1992–2006) from measured data, for selected stations that had water level and stage discharge relationships for the

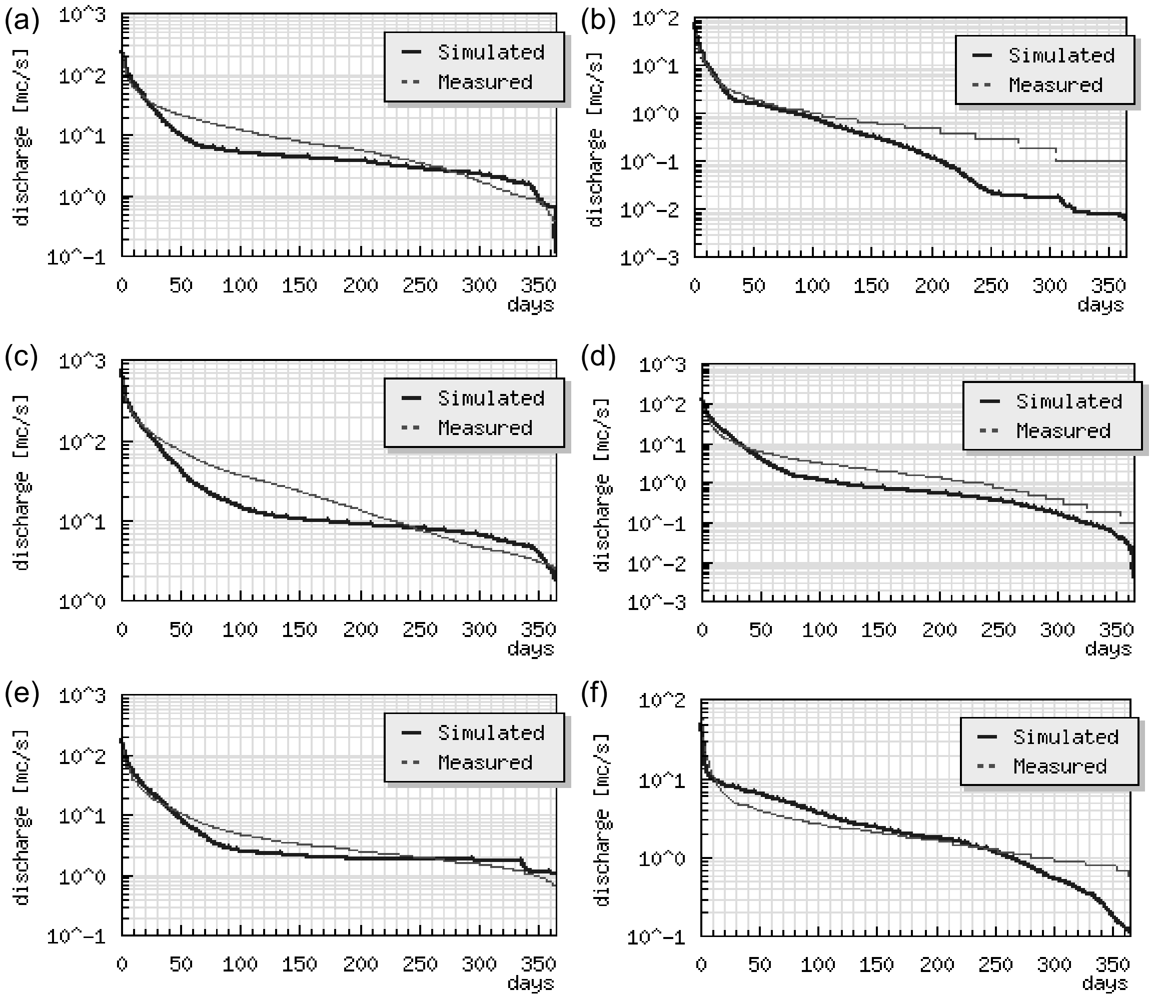

Fig. 2 Flow duration curves from measured data (thicker line) and estimated by MOBIDIC for the simulation period 1992–2006. (a) Fornacina (SIEVE, 831 km²), (b) Bucine (AMBRA, 171 km²), (c) Nave di Rosano (ARNO, 4083 km²), (d) S. Piero a Ponti (BISENZIO, 246 km²), (e) Poggio a Caiano (OMBRONE, 435 km²), (f) Castelfiorentino (ELSA, 806 km²)

whole period, and modelled by MOBIDIC-WRM. The results show a good agreement of measured and modelled flow duration curves on most stations. Poor results are encountered for stations in which groundwater dynamics most probably require a more detailed representation that is not captured with a lumped approach.

Figure 3 shows a comparison between 1 year of measured and modelled time series of mean daily discharge at a river section on an Arno tributary, showing that both peaks and low base flow values are estimated with varying accuracy, and that the temporal dynamics is correctly assessed.

As an example of distributed results, Fig. 4 shows the maps of monthly evapotranspiration over the basin in four selected months, together with specific Q_{355} (discharge with 355 days duration divided by the area of the upstream basin).

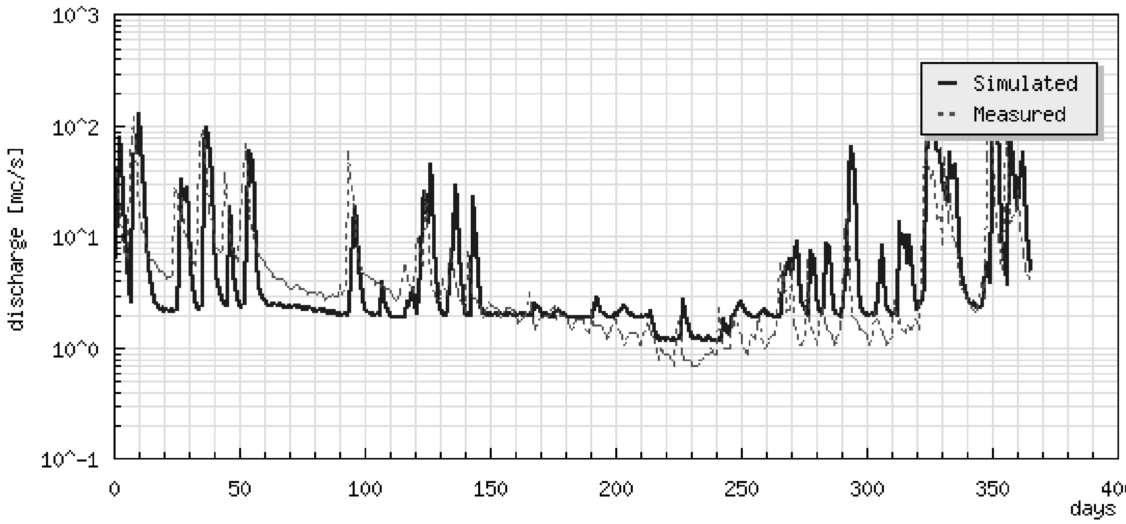

Fig. 3 Example of modelled and measured daily discharge (year 1996) for the Ombrone tributary.

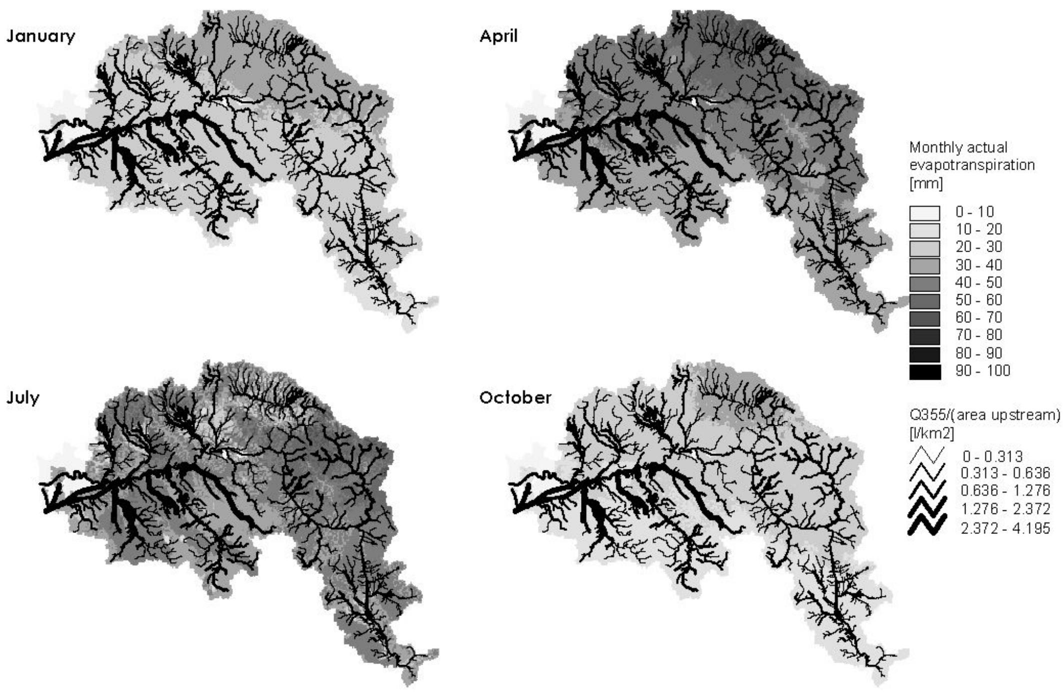

Fig. 4 Monthly evapotranspiration in the basin and specific Q_{355} discharge (defined as Q_{355} divided by the upstream area, in litres per square km).

WATER BUDGET MANAGEMENT AT BASIN SCALE

The hydrological simulation of the whole Arno basin at a 200 m resolution represents the scientific basis on which multi-year strategies and water budget management actions are based. In this framework, the hydrological model results support the strategies and plans for the control of water resources, monitoring the volume and level or rate of flow to maintain and improve the ecological status. This is the main goal of the Arno River Water Management Plan, approved in April 2008 (Autorità di Bacino del Fiume Arno, 2008).

The water balance budget was summarized by subdividing the river network into significant reaches and sub-basins. From these, 44 river sections were selected as closure of sub-basins with distinct hydrological features.

The water budget results were compared with a key parameter, namely a minimum flow index or index of environmental flow (EF), necessary to maintain the hydrological, morphological, biological, and environmental features of the rivers. So, for each river branch, the water balance was computed, according to the 2004 directive of the Italian Ministry of Environment 29/07/04 (Ministero dell'Ambiente, 2004), as natural discharge (Q) minus withdrawal (W) and Environmental Flow (EF):

$$WB = Q - EF - W \tag{13}$$

WB represents the "residual flow", i.e. the flow actually available for further utilization, or, by contrast, the possible deficit. Drafting the basic terms of the budget entails identifying the proper and significant time periods which relate to the various terms.

The water budget was drafted, according the MOBIDIC-WRM results, in terms of daily series focused on the temporal interval on which more critical conditions can occur. Owing to the marked torrential features of the water courses in the basin, including the reaches of major hierarchical rank, such a period fits the months of June, July, August, and September. The model application, as described above, provided a synthetic discharge series for the time period from 1993 to 2006; the results are expressed, for each significant section, in terms of an annual duration curve, with similar duration curves for the dry season (June–September). With the goal to establish (and quantify) the conditions of river reaches, in terms of maintenance of sustainable discharge values, the environmental flow was identified, by hydrologic criteria, as $Q_{7,2}$, i.e. the minimum 7 days-average flow with 2 years recurrence interval.

The term concerning the utilization of water (W), which includes the various withdrawing modalities, relates to the period from June to September. Furthermore, the discharges from the wastewater treatment plants were taken into account. Therefore, the term for the average summer withdrawals takes the following form:

$$W = Q_{srf} + Q_{spr} + Q_{wll} - Q_{wst} \tag{14}$$

where the first three terms on the right hand side are withdrawals from surface water bodies, springs and dug wells, respectively, and the fourth term is wastewater returned to the river network. The resulting residual flow WB may assume, in the significant river sections, either negative or positive values. The negative values point to a severe water deficit in the period, with flows lower than the Minimum Flow Index for more than 60 days in the summer period. The positive values represent the average flow available for further withdrawals. The Arno and its tributaries are characterized by a strongly variable regime, closely linked to the precipitation distribution in space and time. This determines that the more critical conditions are concentrated during the summer, when high temperatures increase evapotranspiration losses and river ecosystems are most stressed. Hence this study was concentrated on the results of simulations for the four summer months, in which all factors influencing the water budget reach a critical phase. To synthesize this into one single stress indicator, the analysis was finally focused on the number of days when the average daily flow rates fall below the site-specific EF value. This number of days is derived from simulated (modelled) flow duration curves. Critical values were aggregated into four classes as in Table 2, in which the criticality map (Fig. 5) is also based.

Table 2 Water deficit level classes, applied for the sub-basins of the Arno basin.

Class	Water deficit level	Number of days with negative values of WB
4	Extreme	> 60 dd
3	Severe	30 ÷ 60 dd
2	Moderate	1 ÷ 30 dd
1	Null	0 dd

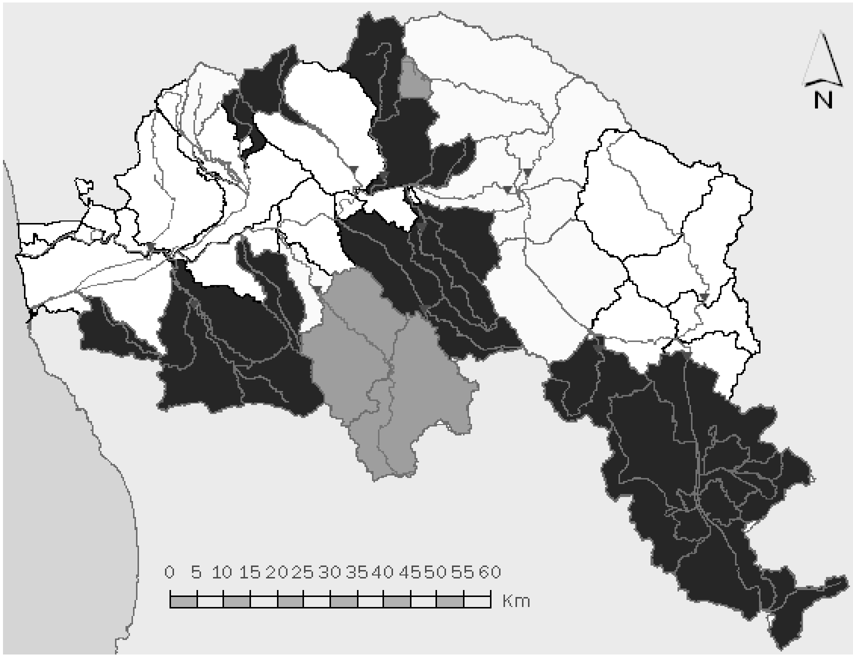

Fig. 5 Sub-basin classification based on water deficit level for the Arno Basin. In black, the areas where the deficit is defined as "extreme"; in grey, the areas where the deficit is defined as "severe".

A different critical level corresponds to different government requirements and monitoring actions, e.g. constraints on new withdrawal permissions, as specified in the Water Budget Management Plan. The critical areas (Fig. 5) are concentrated in the southern portion of the basin, which is mainly the tributaries: Chiana, Ambra, Greve, Pesa, Egola and Era. The upper Ombrone basin and the entire basin of the Bisenzio are also critical areas.

CONCLUSIONS

This paper presents an application of the distributed hydrological model MOBIDIC-WRM for the computation of water balance in the basin of the Arno. Given its characteristics, MOBIDIC-WRM can be used as an effective tool for the evaluation of different scenarios (e.g. effects of changes in land cover/deforestation and irrigation strategies on surface water and energy balance/evapotranspiration regimes, exploitation policies for groundwater). It then provides a reliable hydrological basis for the assessment of crisis indicators such as vegetation stress and lack of environmental flow. The structure of the model also allows the extension of its functionality to other applications including pollutant diffusion in the hydrographic network.

The results on the Arno basin as a whole and for sub-basins were used as the basis for the Water Management Budget Plan of the Arno River. The capabilities of MOBIDIC-WRM to simulate the major seasonal runoff characteristic and to represent temporal and spatial variability, allows the portrayal of water deficit status, and the flexible application of government strategies.

REFERENCES

Autorità di Bacino del Fiume Arno (2008) Adozione del Progetto di Piano di Bacino del Fiume Arno, stralcio Bilancio Idrico, e delle relative misure di salvaguardia. *Gazzetta Ufficiale italiana*, n. 78.

Busoni, E., Costantini, E., Desideri, A., Dimase, A. C. & Sanesi, G. (1983) Risultati sperimentali per la valutazione dei suoli agricoli e forestali in Toscana. CNR Firenze, Italy.

Campo, L., Caparrini, F. & Castelli, F. (2006) Use of multi-platform, multi-temporal, remote sensing data for calibration of a distributed hydrological model: an application in the Arno basin, Italy. *Hydrol. Processes* **20**(13), 2693–2712.

Caparrini, F., Castelli, F. & Entekhabi, D. (2005) Variational estimation of soil and vegetation turbulent transfer and heat flux parameters from sequences of multisensor imagery. *Water Resour. Res.* **41**, WR003358.

Manciola, P. & Casadei, S. (1991) Low flow index and hydrogeological characteristics. In: *ASCE Proc. National Conf. on Hydraulic Engineering*. Nashville, Tennesee, USA, 930–936.

Ministero dell'Ambiente e della Tutela del Territorio (2004) Decreto 28 luglio 2004: Linee guida per la predisposizione del bilancio idrico di bacino, comprensive dei criteri per il censimento delle utilizzazioni in atto e per la definizione del minimo deflusso vitale, di cui all'articolo 22, comma 4, del decreto legislativo 11 maggio 1999, n. 152. *Gazzetta Ufficiale italiana*, n. 268.

Van den Hurk, B. J. J. M. & Holtslag, A. A. M. (1997) On the bulk parameterisation of surface fluxes for various conditions and parameter ranges. *Boun. Layer Met.* **82**, 119–134.