Impact of climate change on hydrological regimes and water resources in TRUST (LIFE + 2007) project

M. FERRI[1], D. NORBIATO[1], M. MONEGO[1], A. GALLI[2], S. GUALDI[3], E. BUCCHIGNANI [3] & F. BARUFFI[1]

1 *Autorità di bacino dei Fiumi dell'Alto Adriatico, Dorsoduro 3593, 30123 Venezia, Italy*
michele.ferri@adbve.it

2 *SGI Studio Galli Ingegneria S.p.a, Via della Provvidenza 15, 35030 Sarmeola di Rubano, Italy*

3 *CMCC Centro Euro-Mediterraneo per i Cambiamenti Climatici, viale A. Moro 44, 40127 Bologna, Italy*

Abstract The River Basin Authority Alto Adriatico is responsible for the management of rivers flowing into the Northern Adriatic Sea. With the purpose of contributing to the general theme of "Water policy", this paper summarizes the experience gained in the European project TRUST - Tool for Regional – scale assessment of groUndwater Storage improvement in adaptation to climaTe change (LIFE + Environment Policy and Governance 2007) - that focuses on adapting measures to preserve the groundwater of the Italian Northern East plain from possible adverse impacts of future climate change. To achieve the aims of the project an innovative catchment scale hydrological model has been implemented and combined with a specific global climate circulation model.
For the production of future climate projections, we used the CMCC-MED model driven by the IPCC's greenhouse gas emissions scenarios. This is a high-resolution global Atmosphere-Ocean and Sea-Ice model (AOGCM) coupled with an interactive model of the Mediterranean Sea. The basin hydrological response is estimated using a semi-distributed, continuous, hydrological model based on a Geomorphoclimatic theory, relating the shape and scale of the catchment transfer function to stream network topology, channel characteristics and climate. Snow accumulation and melt are represented by using a distributed version of the UEB model, while the soil water balance is formulated towards a realistic description of the temporal dynamics of soil moisture, with a phisically based parameterisation which allows the use of vegetation coverage, soil texture and local slope data. The model captures the essential physics of the relevant processes, rather than merely reproducing a correspondence between inputs and outputs within a finite set of observations. Predictive capabilities and robustness of the model were tested by comparing simulation results with 9 years (2000-2008) of quality-controlled hourly data.
According to the climatic scenarios relative to the 21st century, the hydrological model was used to reproduce the variation of the hydrological regimes in the North-East Italian river basins in terms of monthly and annual water balance components. This long-term investigation, based on the previous climatological hypothesis, highlights a general reduction in annual runoff that will lead to a worsening of the groundwater status in the region. The development of appropriate drought mitigation strategies based on reservoir storage operations is analysed and presented.

Keywords hydrological response, modeling, water balance, climatic change.

INTRODUCTION

The main objective of the European project TRUST is to provide, and consequently mitigate, the possible impacts on groundwater resources produced on the Veneto and

Friuli Plain from current and future climate change. The Upper Plain of these regions is in fact home to a major aquifer system, that has been exploited over decades for waterworks, agricultural and industrial uses. In recent years, aquifers, affected by growing water demand, have shown a significant lowering of groundwater levels and artesian depressurisation. Moreover, due to climate change, variations are expected in the extension of snow and in the rainfall distribution and intensity, which will have an impact on the regime of groundwater resources, and in particular on the response of mountain basins that feeds irrigation networks. To estimate these effects an innovative hydrological model was developed on the basin scale, coupled with a global circulation climate model, that can provide plausible scenarios of future water availability. For the prediction of future climate the model CMCC-MED has been used, fed by two different IPCC scenarios of greenhouse gas emissions (A1B and A2). To achieve the spatial resolution required by this study, a downscaling procedure was applied to the atmospheric component of global projections, using a limited area model with a resolution of 8 km (COSMO-CLM).

The hydrological response of the basin is assessed by using a distributed model and by adopting a geomorphoclimatic approach, that involves the transfer function of rainfall-runoff characteristics of the basin to the topology of its river network, and therefore to its geomorphology and climate characteristics. The model reproduces the processes of snow accumulation and melting and the processes of rainfall-runoff separation, solving the water balance in a volume of hydrological active soil (vadose zone), through a realistic description of the temporal dynamics of water content and adopting a physically based parameterization of processes that takes into account the vegetation cover, the soil texture and its slope. The hydrological model implemented, fed by appropriate projections from the climate model, reproduces the potential effects of climate on the hydrological cycle of the investigated basins. Based on the results, possible adaptation strategies will be proposed to mitigate expected changes of the water resource.

STUDY AREA DESCRIPTION

The area of interest covers a surface of fifteen thousands km^2, which includes territories of the Veneto, Friuli and Trentino regions. The area, bounded on the west by Lessini and Berici hills, is shown in Figure 1. The territory is crossed by numerous rivers which are part of the Eastern Alps hydrographic district and flow into the Adriatic Sea; among them, the most important are (from west to east): Bacchiglione, Brenta, Piave, Livenza, Tagliamento and Torre. A unique characteristic of this area is the extraordinary wealth of water, which is a combination of two factors: its particularly favorable geological formation, and a very close relationship between surface water and groundwater, which effectively refills existing aquifers. It is important in this context to assess the contribution of surface water to groundwater recharge.

The creation of a Technical Board involved in decisions, and composed of various institutions (regional and provincial institutions, Environmental Agencies, and stakeholders in general) was at the base of this project. Specific climatic and hydrological measures (acquired hourly from thermometric, anemometric, hygrometric, nivometric, hydrometric gauges) were collected for a detailed weather-climatic characterization of the examined area, as well as geological and soil usage maps for the characterization of soils. The data collected, spatially distributed over the

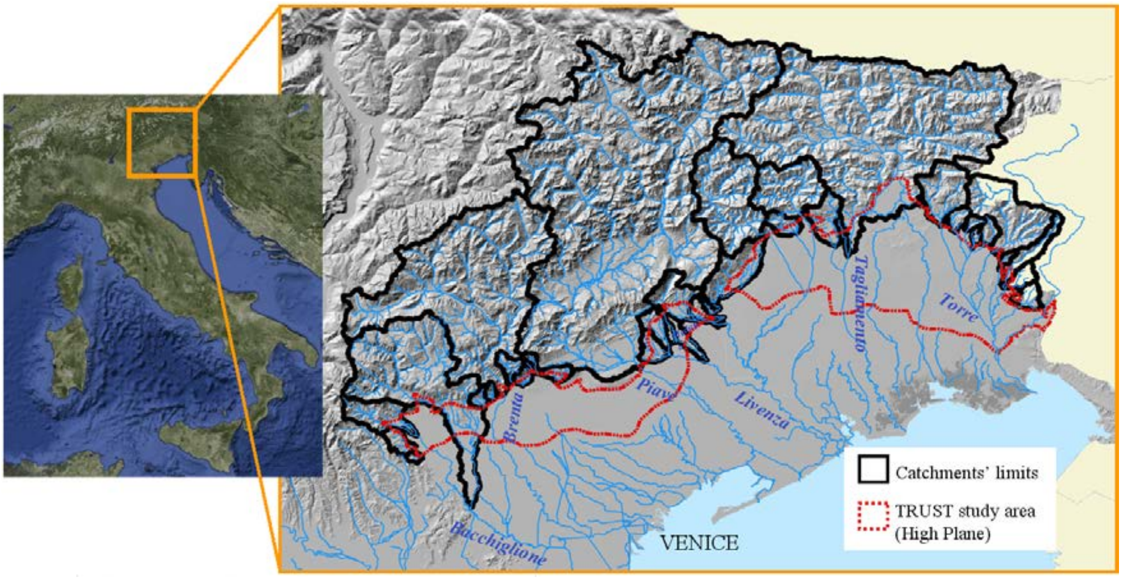

Fig. 1 Study area.

entire area, refer to 250 meteorological stations, 21 nivometric stations and 60 hydrometric stations, and draw on a period of 9 years from 01/01/2000 to 12/31/2008. The data were then homogenized and organized into a geodatabase structure, which formed the basis for model simulations and for their validation.

THE GEOMORPHOCLIMATIC MODEL

Climatic model

The models used to perform the TRUST climate change projections represent a truly innovative set of climate models (Fig.2). A global ocean-atmosphere coupled climate model (AOGCM) coupled with a high-resolution Mediterranean Sea model has been used to produce a set of present and future climate simulations. Therefore, the climate change projections provided by these simulations are performed for the first time with a realistic representation of the Mediterranean Sea. Furthermore, the output of the global model simulations are used as boundary conditions for high-resolution simulations performed with a limited area model (LAM) implemented with a domain that includes the TRUST area. The dynamical downscaling performed with the LAM increases substantially the spatial resolution of the climate change projections and their suitability for climate change impact studies.

The global high-resolution climate model is the CMCC model, which is an AOGCM composed by ECHAM5.4 (Roeckner *et al*., 2003) as atmospheric component and OPA8.2 (Madec *et al*., 1998) as oceanic component. The atmospheric model is implemented with 31 vertical levels and a horizontal resolution of about 80 Km. The global ocean has horizontal resolution of about 2° with a grid refinement (0.5°) in the equatorial region and 31 vertical levels. The oceanic component also includes a dynamical model of the sea ice (LIM, Fichefet & Goosse, 1999). The Mediterranean Sea model is implemented with horizontal resolution 1/16°, 72 non-uniform vertical z levels with partial steps and implicit free surface (Oddo *et al*., 2009).

The coupling between the atmospheric and the ocean components (global ocean and Mediterranean Sea) of the coupled model is performed by means of the coupler OASIS.3 (Valcke, 2006). The atmospheric model exchanges the surface fluxes with the two models independently, then the Mediterranean sea-surface temperature (SST) are overwritten on the SST produced by the global model for the same region. The coupling is performed at a frequency suitable to solve the diurnal cycle. The communication between global ocean and Mediterranean Sea occurs every 8 hours as follows: the Mediterranean model receives the information from the global ocean by means of an Atlantic box with three lateral open boundaries, where fields and fluxes are exchanged. The outflow from the Mediterranean Sea into the Atlantic Ocean, on the other hand, is treated as a river outflow (on the oceanic vertical column) at the Gibraltar Strait. Importantly, the river discharge to the ocean are interactively computed from the surface scheme of the atmospheric model for all the main rivers of the Earth and of the Mediterranean basin. A more detailed description of the CMCC model and a discussion of its ability to reproduce the observed climate is given in Gualdi *et al*. (2010).

The limited area (regional) climate models (COSMO-CLM, Rockel *et al*., 2008) is a non-hydrostatic limited area atmospheric prediction model, that has been developed by the COSMO consortium for weather forecast services and updated by the CLM-Community, in order to develop climatic applications. Compared to the global models, the high horizontal resolution of COSMO-CLM allows a better description of orography and, thus, an improved representation of small-scale physical processes

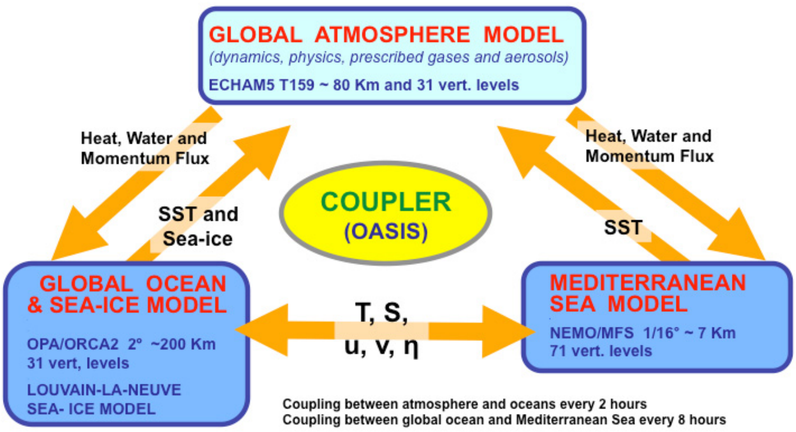

Fig. 2 Schematic of the global coupled climate model composed by the global atmosphere, global ocean and Mediterranean Sea model. The atmospheric model is coupled with both the global ocean and the Mediterranean Sea models. Atmosphere and ocean exchange SST, heat, water and momentum fluxes every two hours. The global ocean and the Mediterranean Sea are coupled at the Gibraltar Strait, exchanging information on temperature, salinity meridional and zonal velocity and dynamical sea-level height every 8 hours.

related to terrain height and land sea-contrast. The model has been implemented on the domain 2-20°E, 40-52°N, with horizontal resolution of about 8 Km and 40 vertical levels and receives the boundary conditions every 6 hours from the global simulation.

The models described above have been integrated to produce climate simulations of the 2nd part of the 20th Century (1951-2000) and projections for the 21st Century (2001-2100). During the 20th Century period of the simulations the distribution and concentration of the atmospheric greenhouse gases (GHGs) and aerosol (anthropogenic sulfate only) have been prescribed from observations. During the 21st Century period, two scenario simulations have been performed, where the GHGs and anthropogenic aerosol have been specified according to the A2 and A1B IPCC-SRES respectively.

Hydrological model

The hydrological response of the catchment is estimated using an integrated model capable of reproducing the processes of snow accumulation and the processes of evapotranspiration and runoff production and propagation. The processes of snow accumulation and melt were modeled by implementing a wrapper-scale distributed computing algorithm UEB - Utah Energy Balance Model (Tarboton *et al*., 1996), while the processes of runoff generation were summarized according to a lumped and physically based conceptual approach, taking into account the vegetation cover, the soil texture and its slope. The water content in a representative control volume of hydrological active soil *S(t)* is updated at each calculation step *dt* by the following balance equation:

$$S(t+dt) = S(t) + I(t) - R_{sub}(t) - L(t) - ET(t) \qquad (1)$$

depending on infiltration (*I*), hypodermic runoff (R_{sub}), deep percolation (*L*), and evapotranspiration (*ET*) components. In the general calculation interval dt, the amount of infiltration is calculated as the difference between the melting snow level *P(t)* (mm) (equal to the liquid precipitation in the absence of snow) and the surface runoff *R(t).* The runoff component is expressed by equation (2), proposed by De Smedt *et al*. (2000), based on a critical threshold (due to the attainment of the soil saturation), above which a Dunnian infiltration mechanism prevails:

$$R(t) = \begin{cases} C\left(\dfrac{S(t)}{S_{\max}}\right)P(t) \Rightarrow P(t) \le f = \dfrac{S_{\max}(S_{\max} - S(t))}{(S_{\max} - CS(t))} \\ P(t) - (S_{\max} - S(t)) \Rightarrow P(t) > f \end{cases} \qquad (2)$$

where *C* is a runoff coefficient at soil saturation, which depends on slope, type of soil and land use (Liu *et al*., 2004), and S_{max}, the water content at saturation, which depends on the nature of land use and soil. Its rating was reduced to the parameter Curve Number *CN* (SCS, 1972), assessed by reference to a condition of dry initial moisture to obtain the maximum values of the specific saturation volume S_{max}. The sub-surface flow is considered proportional to the difference between the water content *S(t)* at time *t* and the field capacity S_c by equation

$$R_{sub}(t) = c(S(t) - S_c) \qquad (3)$$

where $R_{sub}(t)$ is the sub-surface runoff at time *t*, and *c* is an empirical coefficient, depending on the speed with which the flow moves in the sub-surface soil and obtained from calibration. The estimated loss to leaching in groundwater is evaluated according to the expression proposed by Laio *et al.* (2001):

$$L(t) = \frac{K_s}{e^{\beta\left(1-\frac{S_c}{S_{\max}}\right)} - 1}\left(e^{\beta\left(\frac{S(t)-S_c}{S_{\max}}\right)} - 1\right) \tag{4}$$

where K_s is the effective hydraulic permeability of soil in saturated conditions, β is a dimensionless exponent, characteristic of the size and distribution of pores in the soil. The reference values for these parameters can be found in literature, and in particular in the studies of Cosby *et al*. (1984), Dingman (2002) and Lai & Katul (2000). The estimated actual evapotranspiration is performed assuming that it is a function of water content in soil and potential evapotranspiration (calculated by the formulation of Hargreaves & Samani (1985))

$$ET(t) = ETP(t) \cdot w \Rightarrow S(t) > S_{pwp} \tag{5}$$

where S_{pwp} (permanent wilting point) is the minimum water content needed for the initiation of the evapotranspiration phenomena, and w is a evapotranspiration coefficient $w = S(t) / S_{max}$.

The transfer function of the outflows is developed according to the geomorphological theory of hydrological response which links the distributions of residence time in the possible paths within the basin to the basin instantaneous unit hydrograph (Rodriguez-Iturbe & Rinaldo, 1997). In the single sub-basin the surface and subsurface contributions were propagated to the closing section adopting an exponential residence time distribution for the hill state

$$f(t) = ke^{(-kt)} \tag{6}$$

and an inverse Gaussian residence time distribution for the channel state, derived from the diffusive-convective transport theory (Rinaldo, 1991). The constant *k* of equation (6), which is just the inverse of residence time in the hill state, can be calculated as

$$k = v / \overline{L} \tag{7}$$

where *v* is a hill state characteristic velocity, spatially uniform at the sub-basin scale (parameter from calibration), which differs by the different transport processes in place (surface or subsurface runoff), while $\overline{L}$ is an average hill state length calculated as follows: 1) the length of the path in the direction of maximum slope to reach the first channelized cell is calculated for each cell in the hill state, and 2) these lengths are mediated on the sub-basin. In the implemented model, for the surface runoff a geomorphoclimatic approach was adopted, i.e. the surface runoff characteristic velocity is dependent on meteorological event entity, and therefore on the intensity of precipitation. For this purpose, to calculate the transfer of runoff the kinematic theory was introduced, according to which, for each hill state cell, the following equation is applicable:

$$\frac{R_{\sup}(t) \cdot A_{dren}}{B} = q(t) \tag{8}$$

where $R_{sup}(t)$ is the rainfall-runoff component in the calculation step *dt*, A_{dren} is the upstream drained area of the generic cell, B the cell size, $q(t)$ is the specific discharge crossing through the cell. Expressing velocity in the generic cell as

$$v = k_s \sqrt{S}\, y^{2/3} \tag{9}$$

where k_s is the roughness coefficient and S is the slope relative to the cell, the height of water in the cell is obtained according to (8) and (9):

$$y = (q/(k_s y \sqrt{S}))^{3/2} \tag{10}$$

Substituting (10) into (9) the velocity of surface runoff can be calculated for each calculation step dt as a function of rainfall-runoff $R_{sup}(t)$, average in the sub-basin. Note the hill state velocity spatial distribution in the sub-basin and the length of the route to the first channelled cell along the direction of maximum slope, the residence time on the path of the i-th cell can be calculated based on:

$$t_{\sup_i} = \sum_{j=1}^{m} \frac{B}{v_{\sup_j}} \tag{11}$$

where m is the number of cells of the route, each characterized by velocity $v_{sup\ j}$. The constant k can then be calculated according to the average of the characteristic times (11) of all possible paths equally likely inside the sub-basin. The propagation of surface runoff to the closing section of the sub-basin is related to a geomorphoclimatic instantaneous unit hydrograph which assumes a different form for each calculation step dt as a function of the runoff component (Fig. 3).
Propagation of deep drainage at the closing section of the sub-basin is modeled according to the conceptual framework of the linear reservoir:

$$Q_p = k_p V_p \tag{12}$$

where k_p (t^{-1}) is a decay constant determined by exponential regression analysis of the measured hydrographs.

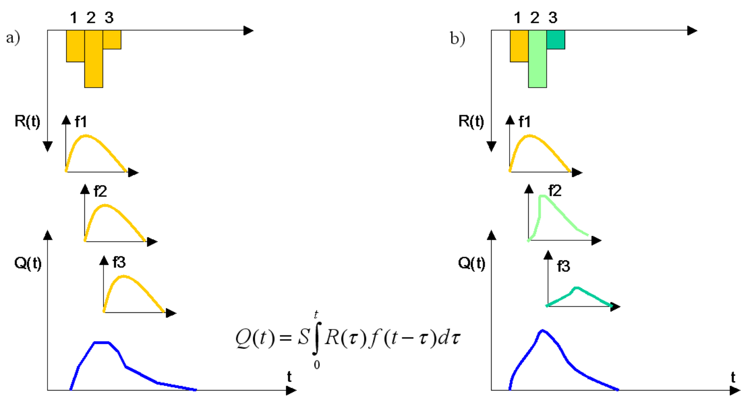

Fig. 3 Convolution integral: a) classic geomorphological approach, b) geomorphoclimatic approach.

APPLICATIONS AND RESULTS

Climate scenarios for the 21st Century in the TRUST project area

The climatic model exhibits some skill in reproducing the major features of the observed climate. The main bias in the global sea-surface temperature (SST) is similar to the systematic error shown by most of the state-of-the-art global coupled models. A slight warm bias of about 1°C affects the upwelling areas of the tropical oceans, whereas a more pronounced cold error (4-5°C) is visible in the north-western part of the Northern Hemisphere oceans, especially the northern Atlantic (not shown).
In the Euro-Mediterranean region, many aspects of the simulated climate appear to be in good agreement with the observations. As shown and discussed in detail in Gualdi *et al.* (2010), the model seems to capture considerably well the observed seasonal features of surface temperature and precipitation (not shown). The orographic precipitation especially appears to be improved in this high-resolution model compared with state-of-the-art AOGCMs as those, for example, used in the CMIP3

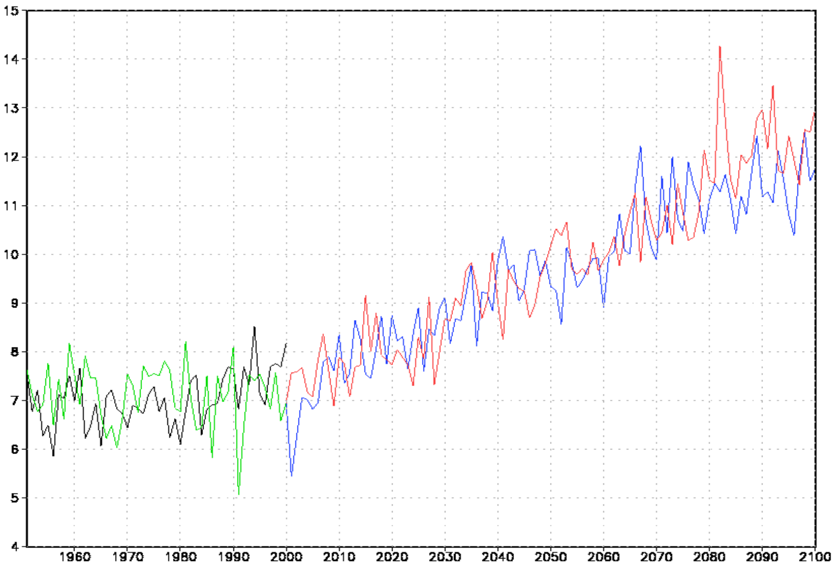

Fig. 4 Time series of the annual mean value of the 2-metre temperature averaged over the TRUST area (11-13.5ºE; 45-46.5ºN) as obtained from the observations (black curve) from the model simulation (green curve) for the period 1951to 2000; from the model projections for the period 2001-2100. The blue curve is obtained from the model integrated with the A1B IPCC-SRES, whereas the red curve is obtained from the A2 IPCC-SRES. The observed data are land temperature analysis from the Climatic Research Unit (Mitchell and Jones, 2005). Units of temperature (y-axis) are °C, whereas on the x-axis is time (years).

programme (Meehl *et al.*, 2007).

The results obtained from the scenario simulations (A2 and A1B) indicate that the Euro-Mediterranean region will be possibly affected by a warming of a few degrees by the end of the 21st Century. In particular, the Mediterranean Sea SST might increase about 2°C in the next decades (2041-2070), while in-land the warming might be even larger (locally up to 5°C and larger), especially during the summer season.

Also precipitation patterns and values over Europe and the Mediterranean area might change quite substantially in the next few decades (not shown). Specifically, precipitation appears to increase over northern Europe and to decrease over the Mediterranean region. These results are well consistent with most of the previous climate change projections (e.g., Giorgi & Lionello, 2008).

Figure 4 shows the evolution of the annual mean 2-metre temperature (*T2m*) averaged over the TRUST region (here defined as the domain 11-13.5ºE; 45-46.5ºN). The near-surface temperature is shown as obtained from the observations (black curve) and from the model simulations for the period 1951-2100. The green curve shows the evolution of the *T2m* value simulated by the model for the period 1951-2000, which, thus, can be compared with the observations (black line). This comparison indicates that the model reproduced well the annual value of *T2m* over the TRUST region and also it captures well the main statistical features of the observed parameter, such as, for example, the amplited of the interannual variability.

The blue and red curves represent the evolution of *T2m*, over the TRUST area, during the 21st Century as obtained from the model projections according to the A1B and A2 scenarios respectively. In both scenarios, at the end of the century, the

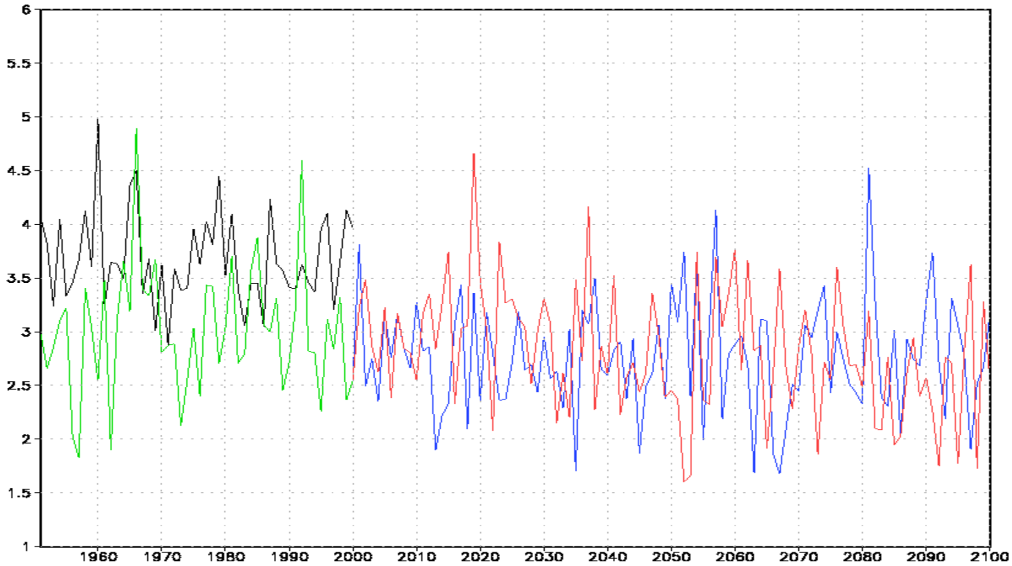

Fig. 5 Time series of the annual mean value of total precipitation averaged over the TRUST area (11-13.5ºE ; 45-46.5ºN) as obtained from the observations (black curve) from the model simulation (green curve) for the period 1951to 2000; from the model projections for the period 2001-2100. The blue curve is obtained from the model integrated with the A1B IPCC-SRES, whereas the red curve is obtained from the A2 IPCC-SRES.. The observed data are land temperature analysis from the Climatic Research Unit (Mitchell and Jones, 2005). Units of precipitation (y-axis) are mm/day, whereas on the x-axis is time (years).

warming of the area is of about 5°C. The results form the two scenarios, at least in terms of annual mean temperature in the region of interest, do not show any substantial difference, even if during the last 20 years the A2 scenario appears to be slightly warmer than the A1B. This is consistent with the fact that the radiative forcing corresponding to the A2 scenario is generally larger than the one assumed in the A1B scenario, particularly in the last part of the 21st Century.

The evolution of the annual mean precipitation averaged over the TRUST region is shown in Figure 5, where (as in Figure 4), the black curve shows the observed annual mean precipitation, the green curve the model rainfall during the observations period, the blue and red curves the 21st Century projections according to the A1B and A2 scenario simulations respectively. As shown in Figure 5, the model appears to slightly underestimate the mean precipitation over the area in the period 1951-2000. The model precipitation deficit comes mainly from an underestimation of the summer precipitation over the region (not shown), whereas the winter rainfall appears to be well reproduced by the simulation. Interestingly, the model (green curve) appears also to slightly overestimate the interannual oscillation of the rainfall.

The results obtained from the scenario simulations (Figure 5, red and blue curves)

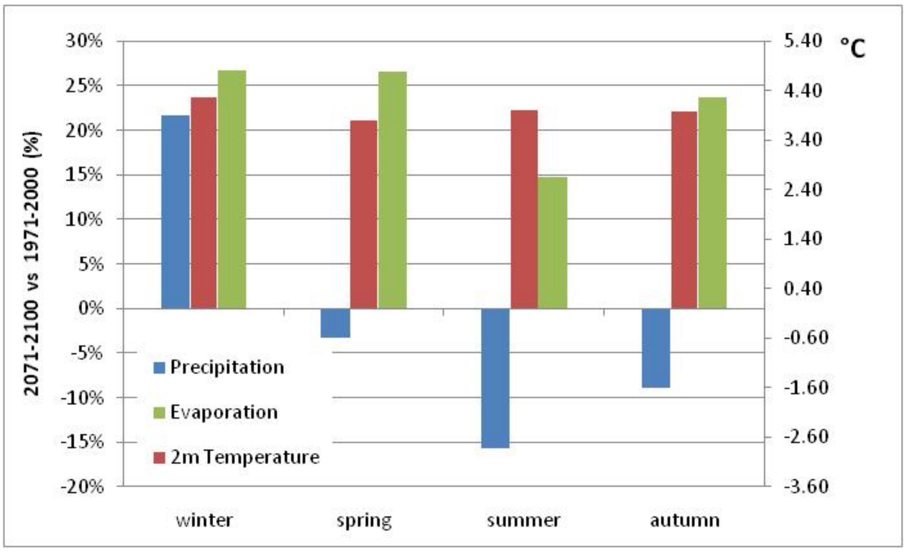

Fig. 6 Change in evaporation (green bar), 2-metre temperature (red) and precipitation (blue) seasonal means averaged over the TRUST area (11-13.5ºE; 45-46.5ºN) obtained from the 20th century and the A1B scenario simulation. The values shown are differences between the 2071-2100 seasonal means and the 1971-2000 seasonal means. Changes in evaporation and precipitation are expressed in percentage terms on the left y-axis, whereas changes in 2-metre temperature are expressed in °C on the right y-axis. Seasons (x-axis) are defined as follows: winter, December-January-February; spring, March-April-May, summer, June-July-August and autumn, September-October-November.

seem to suggest that, in the "TRUST region", changes in rainfall might occur in the form of a relatively moderate negative trend. A slight reduction of precipitation (about -0.5 mm day^{-1} toward the end of the century), in fact, appears to characterize the region. The negative trend is visible and of the same amplitude during both summer and winter seasons (not shown).

The possible (though slight) decrease in precipitation and the marked increase in surface temperature suggested by the future climate projections might lead to some substantial change in the future hydrological cycle. Higher surface temperatures, in fact, may lead to increased evaporation, that in combination with reduced rainfall might impact the water resources and availability in the TRUST region.

Figure 6 shows the changes in the simulated evaporation, *T2m* and precipitation as obtained at the end of the 21st Century (2071-2100) in the A1B scenario simulation with respect to the mean value obtained from the simulation of the reference period (1971-2000), in the TRUST region. For evaporation and *T2m*, the changes appear to have the same sign throughout the year. In particular, the near surface temperature (red bars, left y-axis) shows a rather uniform increase in all seasons of about 4°C.

Consistent with the increased temperature, the mean evaporation increases in the last decades of the scenario simulation (green bars, right x-axis). In this case, the increase appears to be larger in winter, when the model produces almost 26% more evaporation over the TRUST area, whereas in summer the increase of the simulated evaporation is about 15% .

Interestingly, in our simulations, precipitation (blue bars, left y-axis) exhibits a different behaviour in the different seasons. According to the model climate change projection and in particular to the A1B scenario simulation, during winter, mean precipitation averaged over the TRUST area appears to increase of about 0.5 mm day^{-1} during 2071-2100 period compared to the reference period. This corresponds to an increase of more than 20% of rainfall in the winter season over the area of interest. In contrast, during spring, summer and autumn, the simulated precipitation appears to decrease. Especially the mean summer precipitation in the 2071-2100 period appears to be weaker by about 15% with respect to the reference period.

The results obtained from the 20th Century and from the 21st Century A1B scenario simulations performed with our model and shown in Figure 6 are consistent with the results obtained by Lautenschlager *et al*. (2008) and shown in EEA (2009).

The Hydrological Response to Climate Change

According to the climatic scenarios relative to 21st century, given by the CMCC-Med model, the geomorphoclimatic model was used to reproduce the variation on the hydrological regimes of the North-East Italian river basins (Fig. 1).

The topography of these basins is in general rather complex and snow-related processes are important elements for characterisation of the seasonal hydrological balance. It has been decided therefore to include dynamics of snow accumulation and melt in the modeling strategy and estimates of basin-averaged precipitation were obtained by using a Kriging technique based on rain gauge stations' data.

The regime of these river systems is altered by management activities, such as artificial reservoirs and diversions properly introduced in the adopted approach.

The Shuffled Complex Evolution optimization method (Duan *et al*., 1992) was used in combination with a manual calibration to estimate the hydrological model parameters over each basin at the hydrometric stations where historical data were collected. The Nash & Sutcliffe (1970) coefficient of efficiency was used as an objective function during the optimization process.

The calibrated model was then adopted to investigate, for each basin, the flow rate mutation due to future climate scenarios and especially to precipitation and temperature perturbations. This analysis focused in particular on the definition of the worst projection in 21st century in terms of future water availability.

For the sake of brevity the following discussion is focused on a subset of the studied watersheds, selected as examples to show the shifts in timing and magnitude for runoff deriving from the future climate: the Astico river basin closed at Pedescala (137 km^2) and the Cordevole river basin closed at Saviner (109 km^2). Figure 7a shows the location of the two basins while Table 1 reports the relative parameterization obtained both from calibration and literature (based on physical characteristics of river and soils).

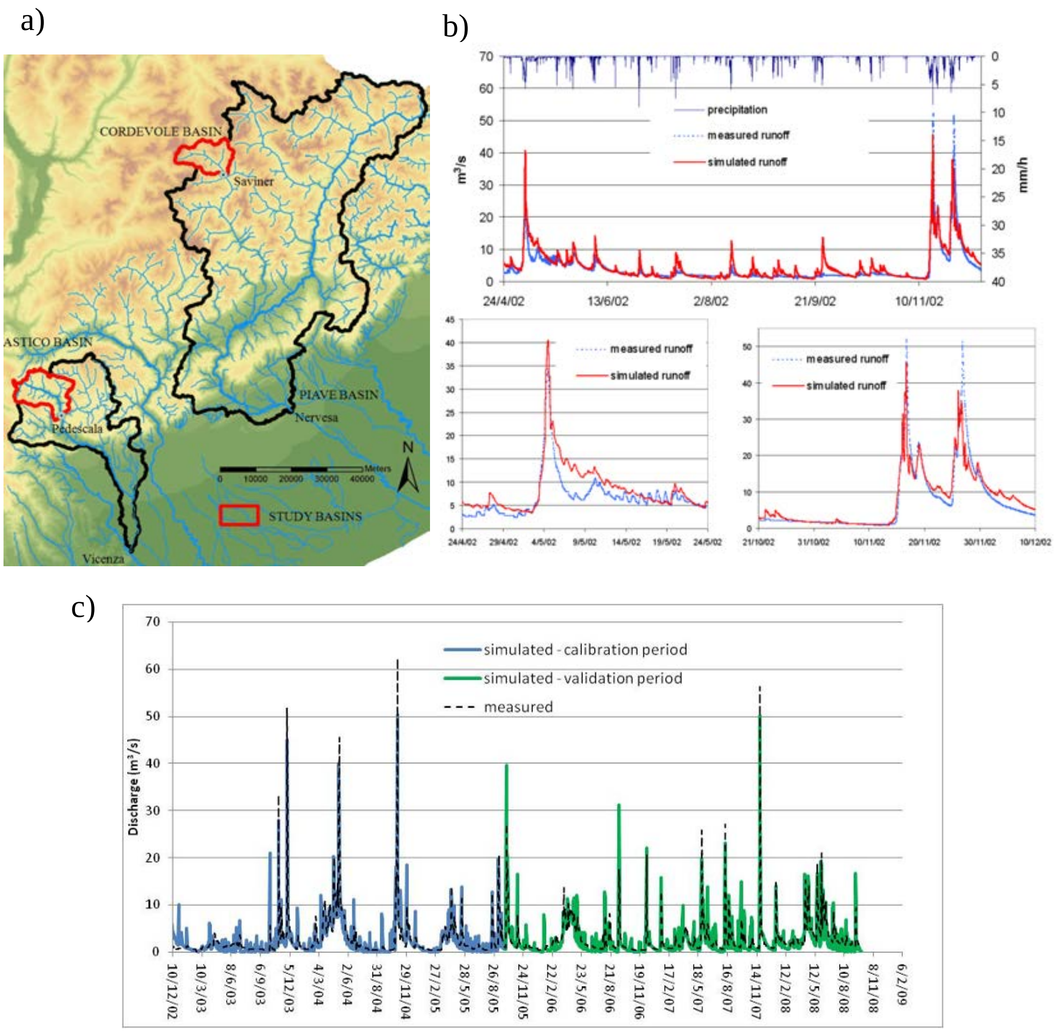

Fig. 7 a) Study basins and their location in Italy; b) application of the implemented model to Cordevole basin closed at Saviner; c) application of the implemented model to Astico basin closed at Pedescala.

Simulation results are reported in Figure 7 and Table 2 considering the division among calibration and validation periods (Fig 7c). Efficiency values in calibration are larger than 0.7 for both the basins and when moving from calibration to validation the efficiency slightly decreases, even though the results are acceptable considering that predictions are particularly difficult to make in alpine regions where data are sparse and the spatial variability of both precipitation and physical controls on runoff generation is enormous. The simulations carried out have shown the importance of the new geomorphoclimatic approach adopted, which is able to reproduce the evolution of the observed outflows even in correspondence of significant meteorological events (Fig. 7b).

Table 1 Parameters used (mean values) in the simulations using the geomorphoclimatic hydrological model.

Basin	C (-)	c (-)	S_{max} (cm)	n (%)	K_s (m h^{-1})	θ_c (%)	θ_{pwp} (%)	β (-)	v_{sub} (m s^{-1})	k_p (h^{-1})	k_s (m$^{1/3}$s^{-1})
Cordevole	0.3	0.3	27	42	0.03	24	12	13	0.003	0.0015	8
Astico	0.8	0.1	39	42	0.05	20	10	12	0.005	0.003	10

Table 2 Model validation and calibration results.

Basin	Area (km^2)	Elevation range (m.a.s.l.)	Mean Annual Precipitation (mm)	Calibration period	E_{NS}	Validation period	E_{NS}
Astico at Pedescala	137	310-1960	1300	1/12/2002-1/10/2005	0.78	1/10/2005-1/10/2008	0.68
Cordevole at Saviner	109	1025-3200	1100	1/10/2000-1/10/2004	0.75	1/10/2004-1/10/2008	0.66

E_{NS}= Nash&Sutcliffe Efficiency.

The calibrated model was run using as input the climate data produced by the CMCC-Med model in order to investigate the hydrological response to climate change until 2100.

Comparisons were made between past, present-day and future hydrology. In the case of the Astico River (Fig. 8) the simulation results show an increase in the future (2071-2100) of the mean monthly runoff in winter, due to an increase in rainfall and in temperature (change in the rain-to-snow-ratio). The runoff based on these climate projections slightly decreases in total volume. With respect to the historical data (1950-1965), the simulation results confirm and emphasize a significant decrease in runoff from April to August (spring and summer seasons), already in place at present-day.

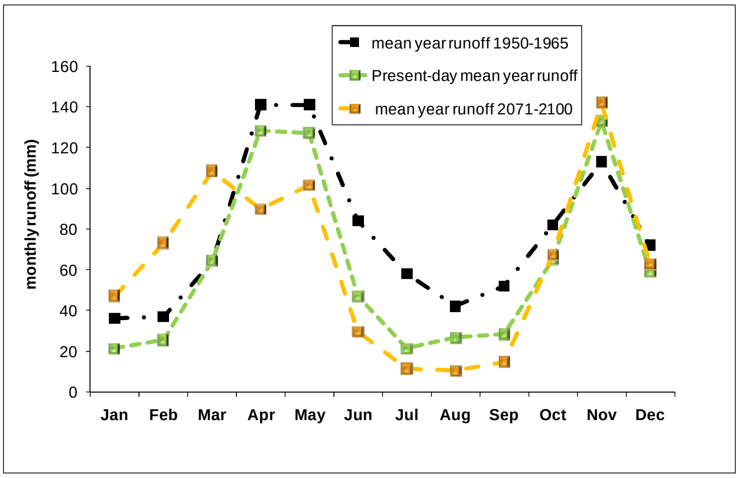

Fig. 8. Monthly runoff for the Astico River (basin closed at Pedescala) for 1950-1965, present day, and 2071-2100 (this latest one is produced by coupling the model with IPCC A1B climate scenarios).

In general, under the studied scenarios, the first peak streamflow in the snowmelt runoff watersheds occurs earlier and summer season flow decreases.

In Figure 9 (a,b) is reported the evolution of monthly runoff of present-day hydrology for an average year (green), and for the driest (red) and the wettest (blue) years (in terms of total annual runoff volume) for the period 2071-2100. For the Astico River (Fig.9a) the great difference between the monthly runoff of the future driest year

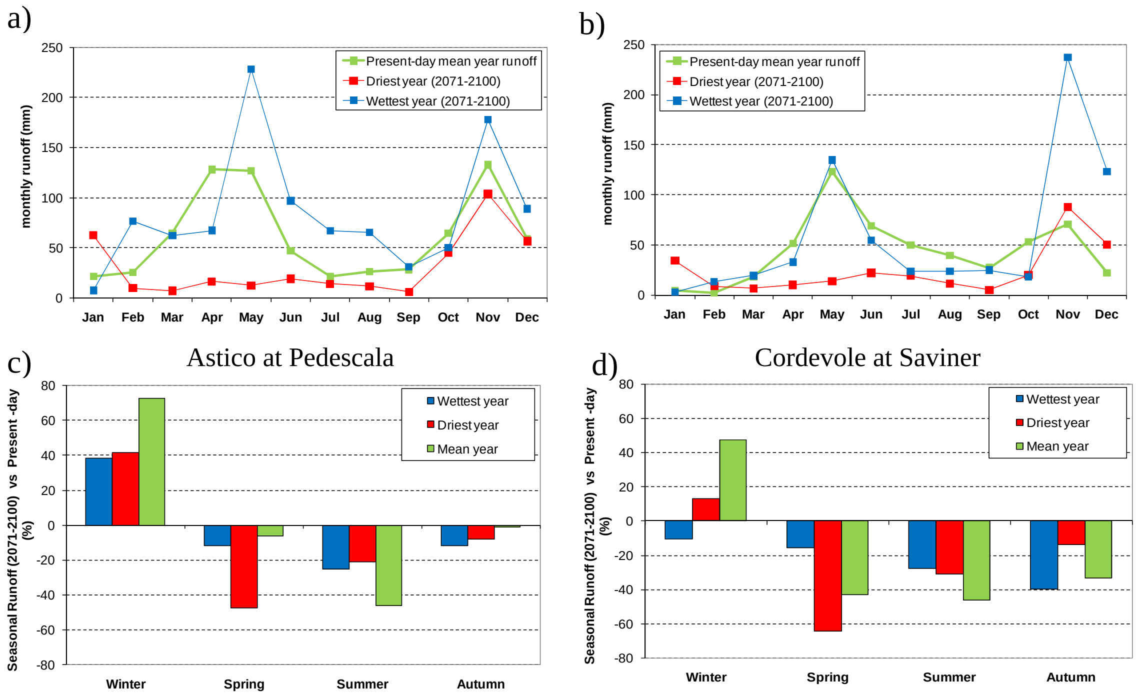

Fig. 9 Monthly runoff for present day, the driest year and the wettest year (in terms of total annual runoff volume) for the period 2071-2100, for: a) the Astico River (basin closed at Pedescala), b) the Cordevole River (basin closed at Saviner). Change in runoff seasonal means obtained from the present day and the A1B scenario simulation for: c) the Astico River (basin closed at Pedescala), d) the Cordevole River (basin closed at Saviner). The values shown are differences between the 2071-2100 seasonal means and the present day means, for the mean year runoff (green bar), the wettest year (blue bar) and the driest year (red bar). Changes are expressed in percentages. Seasons (x-axis) are defined as follows: winter, December-January-February; spring, March-April-May, summer, June-July-August and autumn, September-October-November.

with respect to the present-day mean monthly runoff can be noticed. In the case of the Cordevole River basin (Fig.9b), we can see that the monthly runoff of the future wettest year is comparable to the present-day mean monthly runoff, with the exception of the autumn season, in which high streamflow days, that may result in floods, can occur.

In the conducted simulations, runoff exhibits a different behaviour in the different seasons (Fig. 9c,d). According to the model climate change projection and in particular to the A1B scenario simulation, during winter, mean runoff for the Astico River basin (Fig.9c) appears to increase by more than 60% during 2071-2100 period compared to the present-day. In contrast, during spring, summer and autumn, the simulated runoff appears to decrease. Especially the mean summer runoff in the 2071-2100 period appears to be weaker by about 40% with respect to the present-day. A similar evolution has been registered by analysing the runoff of the wettest and driest years (in terms of total runoff volume) in the period 2071-2100 with respect to the present-day wettest and driest years: the spring runoff of the driest year appears to be weaker by about 45%. Also, for the reported case of the Cordevole River basin (Fig.9d) during winter, mean runoff appears to increase by more than 40% and in contrast, during spring, summer and autumn, the simulated runoff appears to decrease.

From a water resources perspective, the most significant finding common to all the basins in the project area (Fig. 1) is a general decrease in total snow and runoff by 2100. Such reduction in available surface water will impact agricultural water use, especially in the dry season. In fact, the TRUST Area is characterized by a close link between surface water and groundwater, that allows aquifers to recharge. The general reduction in annual runoff will probably lead to a worsening of groundwater status in the region, that will be evaluated by coupling the hydrological model with a groundwater balance model, in order to simulate the exchange between rivers and groundwater and to estimate the water balance terms' mutation rate. About this point, experimental measures are in place with the aim to increase knowledge about the hydro-geological balance and the aquifer recharge modification from permeable river beds and irrigation channels over the entire area. Based on results of measures and simulations , a methodology to identify the extent and location of areas suitable for the development of appropriate drought mitigation strategies (based on water banking techniques) is being implemented.

Drought mitigation strategies in the TRUST project area

In the TRUST Project some concrete experiences of groundwater recharge have been already activated in the Upper Plain with an innovative method which promotes environmental enhancement: the forest areas of infiltration.

The first experimental field (located in Vicenza Province, close to the Brenta River), was equipped with 200 meters long ditches, 100 cm wide and 70 deep, so the infiltrating area of the ditch system is equal to 1200 m^2, 12% of the total experimental area (1 hectar) (Fig. 10).

Trees were planted along the ditches; three possible species are investigated and Paulownia was chosen as the more suitable, as it allows a cycle of rapid growth and it doesn't require available groundwater at very low depth.

From measures made during the experiment the dispersion capacity rate in the

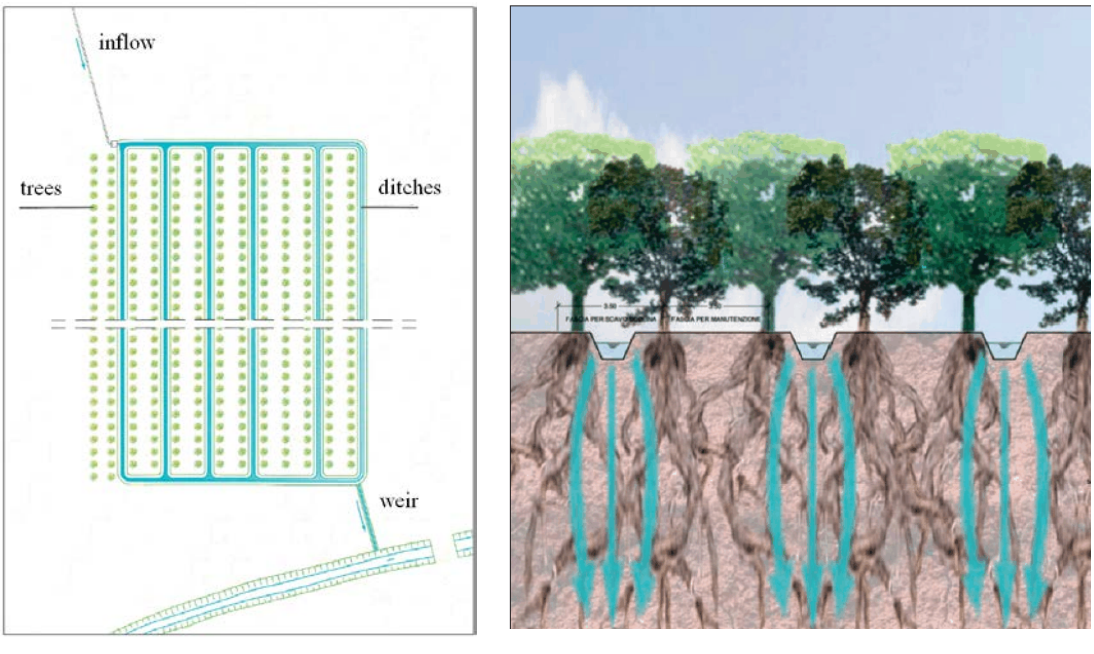

Fig. 10 Scheme of a forest area of infiltration (Dal Prà *et al.*, 2010).

ditch has been variably estimated in the range 0.015-0.04 l s^{-1} m^{-1}. The experimental area is characterized by the presence of very permeable soils (gravels), and less permeable materials.

Based on the above data, we can calculate the area needed to obtain a total infiltration flow of 3 m^3 s^{-1}, i.e. the transport capacity of the local irrigation consortium infrastructure. So we can consider that an area of approximately 100 hectares could easily ensure this charge. The experiment shows interesting values of water leakage and encourages extending the initiative to a larger area. In fact an area of about 100 hectares could infiltrate into groundwater a water volume of about 50 million cubic meters per year, a very significant value.

The method, besides mitigating drought, has the added advantage of enhancing the environment and economic benefits.

CONCLUSIONS

The results presented show the reliability of the geomorphoclimatic model implemented as a tool for evaluating the magnitude of river runoff. It is evidenced in this context that only the synergy taking place between agencies and institutions involved in water resource management, which resulted in the formation of the TRUST Technical Board, made possible the development of a hydrological response model validated on a regional scale.

The hydrological model, coupled with the climate model (CMCC-Med) at high resolution, is able to provide plausible scenarios of future water availability (up to 2100) and to reproduce the potential effects of climate on the hydrological cycle of the investigated basins, and consequently on the regime of groundwater resources, which are mainly fed by dispersion from permeable river beds. The hydrological scenarios, in fact, will be used as input for a more general integrated hydro-geological balance model, capable of analysing the water balance on a macro-scale (the entire TRUST project area) and of evaluating the measures of artificial recharge and the impact of these measures on groundwater and on the users of surface water (irrigation authorities). In fact various adaptation strategies will be proposed on the basis of expected changes in water balance (eg: changes in the management of reservoirs, interventions of artificial recharge that take advantage of the excess surface water) in order to mitigate any effects of drought and water scarcity, and finally propose adaptation strategies and agricultural planning that enable sustainable development of water resources. The objectives of the project, aimed to advance an organized management of surface water and groundwater, are also in line with European Directive 2000/60/EC on water. This model will serve as a predictive tool to support public institutions to promote measures to protect and preserve water resources.

The implementation of a methodology capable to predict the future hydrologic response and provide policies with this information, along with climate change information, and to guide planning to develop efficacy water management techniques remains a topic of intense interest, as well as understanding the mechanisms of large-scale atmospheric dynamics and its local impact.

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