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## A case study in Italy

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# Climate change will affect hydrological regimes in the Alps

## A case study in Italy

1 Global warming is impacting water resource distribution in temperate regions, tampering water and food security (Barnett *et al*. 2005, Beniston *et al*. 2007, Solomon *et al*. 2007, Bates *et al*. 2008). Changes in precipitation and temperatures as expected under transient climate change conditions will likely have considerable fallout upon stream flow regimes worldwide (Bavay *et al.* 2009, Bocchiola *et al.* 2011), including the impact of modified seasonal snow cover upon hydrology in the Alpine environment (Barnett *et al.* 2005, Groppelli *et al.* 2011b). Snow cover duration and thickness influence freshwater availability during Spring and Summer and regulates hydrological cycle of Alpine basins and future snow cover dynamics is of tremendous interest. Hydrological models are fed with outputs from climate models (Drogue *et al.* 2004) to provide the climatic input for medium and long term impact analysis on water resources (Bultot *et al*. 1992, Boroneant *et al.* 2006). General Circulation Models (hereon, *GCMs*) and Limited Area Models (hereon, *LAMs*) are physically based tools presently used in predicting climate change effects (Bardossy 1997, Bates *et al*. 1998). *GCMs* and *LAMs* perform reasonably well in simulating synoptic atmospheric fields, but they usually reproduce poorly historical records at the spatial scales of interest in impact analyses and proper tailoring is required for local use (Lammering and Dwyer 2000), so downscaling of *GCM*-based data is a key aspect in climatologically driven hydrological simulation (Lammering and Dwyer 2000, Ranzi *et al*., 1999). Here, we investigated prospective (until 2050) hydrology within an Alpine stream of Northern Italy (Serio river closed at Grabiasca, 92 km$^2$ drainage area, average altitude 1900 m a.s.l, main channel length ca. 12 km). Specifically, we want to investigate i) modified climatic regime of the Serio river under potential climate change scenarios, ii) modified hydrological regimes of Serio river at different altitudes, and iii) snow cover dynamics at catchment scale, and its fallout upon hydrology. To do so, we used a minimal hydrological model to mimic the flow series within the catchment. We then used climate scenarios (until 2050) from two *GCMs* (CCSM3, ECHAM5, storylines A1B, A2, B1), properly downscaled for the area, to force the hydrological model and to obtain future projections of hydrological flows. We evaluated seasonal and yearly variation of stream flows, using standard flow descriptors (*e.g.* Groppelli *et al.* 2011b), for different flow sections at different altitudes. The proposed results may be useful for river managers and may provide a template for investigation of future water resources in high altitude Alpine catchments under climate change.

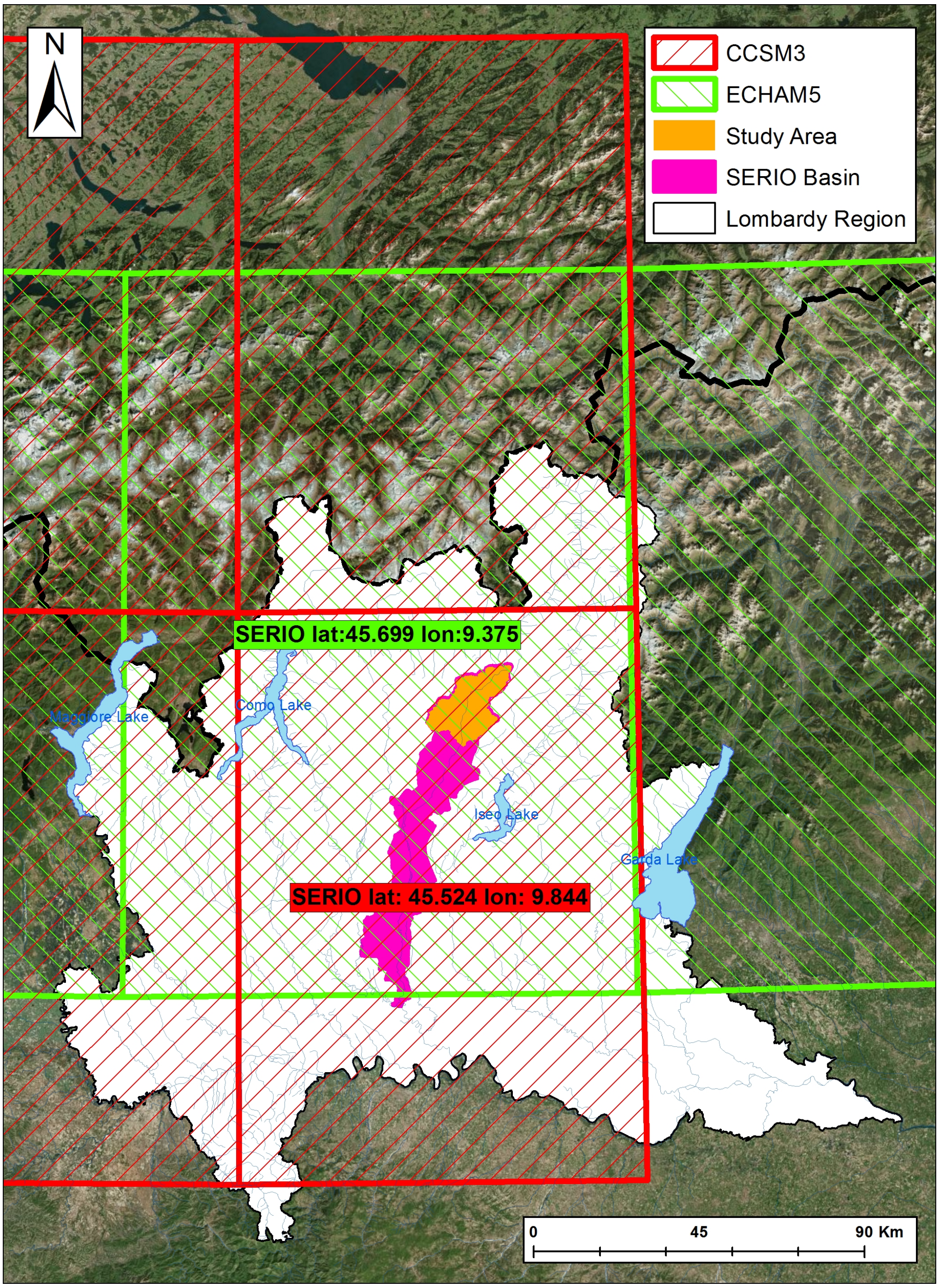
## Case study

### The Serio River

2 The Serio River (figure 1) is 124 km long and drains 1256 Km$^2$ of Lombardy region before joining the Adda river, a tributary of the Po river. It sources at 2129 m a.s.l., nearby the Barbellino lake, between Pizzo Coca and Torena Mountain, and flows in N-S direction. Serio river is exploited for hydropower generation and irrigation and its watershed includes wide urban and industrial areas, producing high polluting loads. In the Alpine valley (approx. until Valbondione, figure 2, Canobbio *et al.* 2010), channel bed is mainly made of cobbles and boulders, while in the mountain and piedmont floodplain (approx. until section 5 here, figure 2) the river is wider and has lower slope, with cobbles, gravels, and occasionally boulders and bedrocks. Investigation of prospective hydrology in the Serio river is important because i) there is a strong demand of water for multipurpose uses and ii) hydrological fluxes control water quality (Canobbio *et al.* 2010) and modified hydrology may decrease suitability for river biota. The outflows of Serio River are affected by regulation occurring at the Barbellino Dam (figure 2). We used observed stage data for the river closed at Grabiasca (738 m a.s.l., 92

km$^2$, figure 2), available for six years during 2005-2010. We studied the river until section 5 in figure 2, where the piedmont part of the river ends. Furthermore downstream this area, and particularly before the next hydrometric station on Cene (figure 2), considerable water withdraw starts (with no or little return), and it is not possible to assume mass conservation within the stream anymore.

**Figure 1. Serio River: geographic area**



## Climatological and hydrological regime

3 The precipitation regime (ca. 1300 mm per year) according to the Köppen-Geiger climate classification belongs to the temperate/cool continental class, with seasonal snow cover above 1000 m a.s.l or so (Bocchiola and Rosso 2007, Bocchiola and Groppelli 2010) and a maximum of precipitation during the end of Summer and Fall and a minimum in Winter. Monthly temperature ranges from 23.8°C in July to -1.5 °C in January and yearly average is 9.4 °C. Average discharge at Grabiasca is estimated into 2.7 m$^3$s$^{-1}$ and flow displays two peaks, one

in spring (May) for snowmelt and one in Fall (November) for rainfall. Driest periods are in Summer (August) and Winter (February). Snowmelt contributes to ca. 20-40% of flows in the five river sections we studied here (1614-2180 m a.s.l, average basin altitude). Hydrology of the Serio river is largely influenced by seasonal snow cover depletion and timing, sustaining in stream flows during Spring and Summer. Several recent studies display climate warming within the Northern Italian Alps, affecting snow covered area and snow water equivalent (hereon, *SWE*) at thaw, and potentially modified hydrological cycle (Barontini *et al.* 2009, Bocchiola and Diolaiuti, 2010; Soncini and Bocchiola 2011, Groppelli *et al.* 2011b, 2011c), potentially affecting Serio river. Expected impact of projected climate change upon Alpine catchments (*e.g.* Bavay *et al.*, 2009) may entail, in short
i) increased discharges in Fall and Winter as due to trading of rainfall for snowfall, and ii) decreased discharges during Spring and Summer, due to lack of snow melt from winter snow pack.

## Historical database

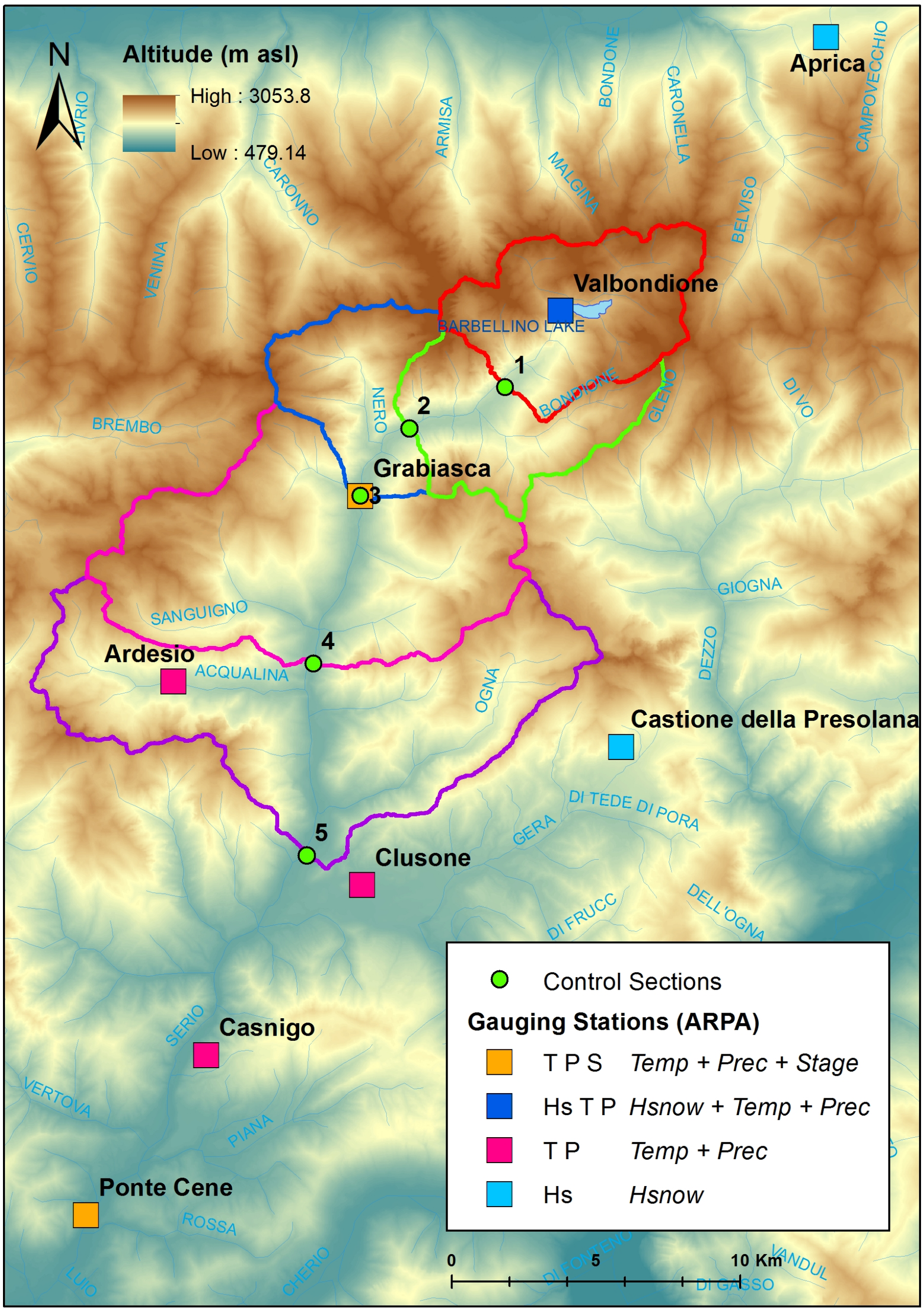
4 We used here a historical database of weather variables (daily temperature and precipitation) provided by the Regional Environmental Protection Authority (ARPA) of Lombardy Region. We used data from 8 most complete AWS stations, measuring temperature and precipitation (6 stations), snow depth (3), and river stage (1 station) in the Serio catchment (figure 2). The main features of the measuring stations are reported in table 1. Discharge data could be estimated during 2005-2011 by way of stage level data at Grabiasca Station (figure 2), using a stage-discharge equation provided by ARPA. Further data used are the DTM (20 m cell size) of the Serio basin, and land use maps from CORINE Land cover, for estimation of maximum soil storage potential $S_{II}$ according to the *SCS-CN* method.

**Table 1. Measuring stations and measured variables during 2000-2011 (discharge *Q* in Grabiasca, 2005-2011**

| Gauge Stations | *A* [m a.s.l] | *T* | *P* | *Hs* | *Q* |
|---|---|---|---|---|---|
| Valbondione | 1802 | x | x | x | - |
| Grabiasca | 738 | x | x | - | x |
| Ardesio | 1002 | x | x | - | - |
| Clusone | 599 | x | x | - | - |
| Casnigo | 501 | x | x | - | - |
| Ponte Cene | 361 | x | x | - | x |
| Castione della Presolana | 1180 | - | - | x | - |
| Aprica | 1950 | - | - | x | - |

*A* is altitude, *T* is temperature, *P* is precipitation, *Hs* is snow depth, and *Q* is discharge.

**Figure 2. Available measuring stations and investigated stream sections**



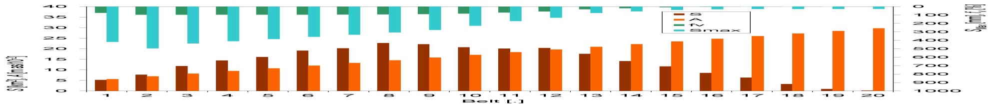
Green dots indicate the chosen river sections for simulation. Golden squares indicate sites featuring temperature, precipitation, and river stage measurements. Blue squares indicate sites featuring snow depth, temperature, and precipitation measurements. Pink squares indicate sites featuring temperature and precipitation measurements. Cyan squares indicate sites featuring snow depth measurements.

# Methods

## Hydrological model

We used here a hydrological model for snow fed and mountainous catchments (Groppelli *et al.* 2011b, Bocchiola *et al.* 2011). This is a semi-distributed altitude belts based model able to mimic snow cover and ice dynamics, evapotranspiration losses, recharge of the groundwater reservoir and eventually formation of in channel discharge. Serio river has negligible ice cover, so ice melt was neglected.

**Figure 3. Main features of the selected altitude belts**



*S* is belt surface, *A* is belt altitude, $S_{Max}$ is belt maximum water content of soil, $f_v$ is belt vegetated fraction. $S_{Max}$ and $f_v$ reported in the right *y* axis, with inverse scale.

## Climate projections and downscaling

6 The Special Report on Emission Scenarios - SRES by the Intergovernmental Panel on Climate Change (Nakicenovic *et al.* 2000) described four possible future storylines (A1, A2, B1, B2), describing the effect of different potential causes of greenhouse gas (GHG) emissions. We used here temperature and precipitation data generated via the IPCC SRES A1B (weakly optimistic, peak of population at mid-century, rapid introduction of more efficient technologies), A2 (pessimistic, often referred to as "business as usual"), B1 (weakly optimistic, increasing population slower than in A2, introduction of efficient technologies slower than under A1B scenario). We considered the time window 2045-2054, centred around 2050. We used two *GCM* models, ECHAM5 (Max Planck Institute for Meteorology in Hamburg, Germany), and CCSM3 (National Center for Atmospheric Research in Boulder, Colorado). We carried out a number of studies to evaluate suitability of these (and others) *GCM* models to represent climate of Northern Italy, finding that CCSM3 and ECHMA5 depict reasonably well the climate of the Alpine area, and especially the seasonality of rainfall (Garavaglia and Marzorati 2010, Groppelli *et al.* 2010, 2011a, Soncini and Bocchiola, 2011). Within *GCM* models the earth-atmosphere system is discretized using a structure of three-dimensional cells with different size in the horizontal and vertical direction. The size (resolution) of these volumes of integration (*boxes*) changes from model to model but processes occurring at a smaller resolution (*subgrid processes*) cannot be represented explicitly and most typically *GCMs* provide bad representation of precipitation. Therefore, downscaling is necessary. We downscaled precipitation scenarios using the method of stochastic space random cascade, SSRC (explained in Groppelli et al. 2010, 2011a), tuned using ten years of daily precipitation data (2000-2009) upon the Serio catchment. In table 2 the main features of the two chosen models are given. In figure 1 the grids of the two models on the study area are shown.

**Table 2. Description of GCM models**

| Model | Research Centre | Nation | Grid size [°] | n° cells [.] | n° layers [.] |
|---|---|---|---|---|---|
| ECHAM5 | Max Planck Institute for Meteorology | Germany | 1.5° x 2.1° | 192 x 96 | 31 |
| CCSM3 | National Center for Atmospheric Research | U.S.A. | 1.4° x 1.4° | 256 x 128 | 26 |

## Hydrological projections

7 To obtain hydrological scenarios for the area, we fed the climate scenarios (2045-2054) to the tuned model. As a control run (henceforth referred to as CO) we used the simulated (*i.e.* by the hydrological model) series of discharge during 2000-2009, when we could gather climate data. This was done to obtain one decade of reference discharge data, because observed discharge were available only during 2005-2011, and we wanted to filter out the effect of river regulation to highlight the impact of climate variability. We considered here five sections of the river, including Grabiasca (figure 2, table 3), to test the effect of climate change at various altitudes. We chose the highest section by topographic consideration and because outlet from the Barbellino dam is entirely delivered upstream of this section. The lowest altitude was instead chosen because thereafter several water withdrawal points (without restitution) are present. All the chosen sections are so that water withdrawal (flowing water) upstream is already delivered upstream (*i.e.* water mass conservation applies).

**Table 3. Five stream sections considered**

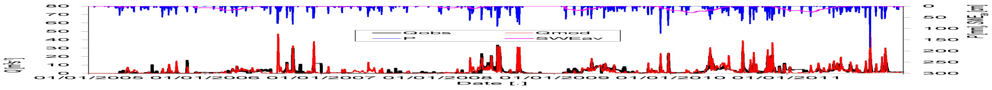
| Stream sections | *A*<br>[m a.s.l] | *S*<br>[km$^2$] | $A_{av}$<br>[m a.s.l] | $L_m$<br>[km] |
|---|---|---|---|---|
| S1 | 900 | 38 | 2180 | 4.6 |
| S2 | 800 | 67 | 1963 | 8,8 |
| Grabiasca S3 | 738 | 92 | 1903 | 12,2 |
| S4 | 600 | 176 | 1751 | 19,2 |
| S5 | 500 | 264 | 1614 | 26,8 |

# Results

## Model calibration

8 In figure 4 we report observed and modelled discharges at the Grabiasca (S3) river station during 2005-2011. Since Serio is subjected to regulation (with restitution) and we do not know operation strategies, a validation study of daily discharges from the model should be taken with care. The hydrological model is aimed to forecast the "natural", or undisturbed discharges within the river, *i.e.* in response to present climate conditions, that are a benchmark for comparison against future expected hydrological conditions. Therefore, we carried out here calibration of the model to reasonably depict flow volumes, keeping in mind that a perfect match is not possible. In table 4 we report the parameters effectively used for calibration and those that were estimated a priori. Degree day, $D_D$ = 3.6 mm°C$^{-1}$d$^{-1}$ was calibrated from snow gage observations at the snow depth three stations. The analysis of lithology and land use allowed to construct a map of $CN_{II}$ value, and therefore of $S_{Max}$. The wilting point $\theta_w$ = 0.20 is chosen based upon available references and the field capacity was set to $\theta_l$ = 0.5, using an average value for mixed grounds. The number of reservoirs both for overland and groundwater flow used was 3 (Rosso 1984). Due to the greater uncertainty to define the lag times of catchments, we estimated $k_s$ and $k_g$ values according to two criteria, namely i) the adaptation of the simulated discharges against the "observed" ones, in term of average flow and using the Nash Sutcliffe $R^2$ coefficient, and ii) the ability of the model to describe flood discharges. We carried out several simulations, trying to maximise $R^2$ against $k_s$ and $k_g$ (table 4). Within the range of acceptable values, we chose $k_s$ to obtain the best adaptation of the average yearly flood peak, or index flood $Q_{ind}$ (Groppelli *et al.* 2011b). The maximum value of $R^2$ = 0.42 was obtained taking $k_s$ = 1 day, $k_g$ = 5 days. Finally the resulting saturated permeability value $K$ = 0.4 mmd$^{-1}$ is consistent with the available literature. The simulated index flood would be $Q_{ind,m}$ = 29.70 m$^3$s$^{-1}$, against an observed value of $Q_{ind,o}$ = 22.75 ± 6.83/m$^3$s$^{-1}$ ($\alpha$ = 5%), acceptably close. In figure 4 model calibration is reported. Flow regulation is evident during periods of constant, relatively high discharge, with neither rainfall nor snow melt, clearly due to flow releases. The observed series of flow discharges at Grabiasca has a number of missing data (ca. 32%). Neglecting those days when discharge was not available the yearly average observed discharge is $Q_{av,o}$ = 3.37 m$^3$s$^{-1}$, while the simulated value is $Q_{av,m}$ = 3.37 m$^3$s$^{-1}$. The average flow simulated during 2005-2011 including the days with missing observations was $Q_{av,m}$ = 2.70 m$^3$s$^{-1}$. In figure 4 precipitation *P* and stored water in snow pack $SWE_{av}$ averaged upon altitude belts are also reported, displaying clearly the dependence of hydrological regime upon snowpack melt, feeding river discharges during Spring and Summer.

**Figure 4. Grabiasca station, S3. Model calibration**



$Q_{oss}$ is observed daily stream discharges, $Q_{mod}$ is modeled daily stream discharge, *P* is daily total precipitation, $SWE_{av}$ is daily snow water equivalent averaged upon the catchment area. *P* and $SWE_{av}$ reported in the right *y* axis, with inverse scale.

**Table 4. Serio at Grabiasca, 2005-2011. Hydrological model parameters**

| | **Description** | **Value** | **Method** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| $k_g$, $k_s$ [d] | Reservoir time constant, ground/overland | *5/1* | Max $R^2$ - $Q_{ind}$ |
| $n_g$,$n_s$ [.] | Reservoirs, ground/ overland | 3/3 | Literature |
| $K$ [mmd$^{-1}$] | Saturated conductivity | *0.4* | Flow volumes |
| $k$ [.] | Groundwater flow exponent | 3.5 | Literature |
| $f_v$ [.] | Vegetation fraction, average value | 0.70 | Soil cover |
| $\#_w$, $\#_l$ [.] | Water content, wilting / field capacity | 0.2/0.5 | Literature |
| $S_{Max}$ [mm] | Maximum soil storage, average | 243 | Soil cover/Land use |
| $D_D$ [mm°C$^{-1}$d$^{-1}$] | Degree day factor for snow melt | 3.6 | Snow depth data |
| **Statistics** | **Description** | **Value** | **Method** |
| $R^2$ [.] | Nash-Sutcliffe coefficient | 0.42 | Maximization ($k_s$, $k_g$) |
| $Q_{av}$ [m$^3$s$^{-1}$] | Mean flows observed/ simulated/simulated full period | 3.37/3.35/2.70 | Calibration $K$ |
| $Q_{ind}$ [m$^3$s$^{-1}$] | Average yearly floods, observed (± 5%) /simulated | 22.75 ± 6.83/29.70 | Calibration $k_s$ |

In *Italic* values calibrated against observed discharges.

## Hydrological scenarios

9 In table 5 we report average yearly flows for the five sections and the two GCMs (all storylines). Also in table 5 we report yearly evapotranspiration averaged upon the whole catchment $ET_{av}$, and mean daily snow ware equivalent on the ground (snow pack), $SWE_{av}$ at catchment scale. Evapotranspiration decreases in all scenarios, and especially for CCSM3 model. Snow water equivalent decreases notably under every scenario, unless for CCSB1, where it is only slightly smaller than the CO value.

10 For all the scenarios except ECHB1 and all river sections average flow is increased. In table 6, we report for Grabiasca station some objective flow descriptors. We estimated first the values of flow discharges exceeded for a given number of days, *d*, *i.e.* $Q_d$. We considered $Q_{37}$, or flow exceeded for 10% of the time, $Q_{91}$, 25% of the time, also known as ordinary flood, $Q_{182}$, *i.e.* median flow, and $Q_{274}$, also known as ordinary low flow. Also, we evaluated the yearly minima and maxima average flows for a given duration *d*, *i.e.* $Q_{Maxd}$ and $Q_{Mind}$. In table 6 we report the average yearly values of $Q_{Maxd}$ and $Q_{Mind}$, for $d$ = 37, 91, 182, and 274 days. We also estimated index flood $Q_{ind}$. In figures 5 and 6 we report mean monthly flows within the stream sections 1 and 5, but we found equivalent results for all the five chosen sections (not shown for shortness). CCSM3 model (all three storylines) provides evidence of increased discharges during Fall and Winter and of earlier stream flows during Spring, *i.e.* for snowmelt. ECHAM5 model (all three storylines) provides increased discharges during Fall and Winter, with decrease in Spring and more in Summer.

11 The CCSM3 model results clearly show a transition from an Alpine unimodal behaviour, driven by snow melt during April to June and more evident at the highest altitudes (maximum at S1), to a bimodal behaviour with two maxima (April and November) at all altitudes (S1 and S5, and similarly for S3-S4, not shown). ECHAM5 model displays behaviour similar to CCSM3, albeit less pronounced. Increased Winter flows are found everywhere and Spring floods may be anticipated by one month (from May to April). Monthly temperature in Grabiasca (not shown for shortness) are increasing under CCSM3 scenarios and differently for each storylines, but decreasing during August to October. ECHAM5 provides increasing temperature yearly but on average less than CCSM3. Precipitation trends are similar and both models always project drier (than CO) periods during May to September and wetter elsewhere (not shown). In figure 7 we report average monthly snow water equivalent *SWE* in

belt 12, representative of the snow dynamics at 2000 m a.s.l. All scenarios depict less snow than CO, unless CCSB1, giving slightly deeper snow cover during Winter (JFM, given by high precipitation, and lower temperature), which however is quickly depleted during April, producing earlier snow melt and in stream flows.

**Table 5. Serio river, projections using CCSM3 and ECHAM5**

| Variable | Description | Values | | | |
|---|---|---|---|---|---|
| **CCSM3** | | **CO** | **CCSA1B** | **CCSA2** | **CCSB1** |
| $P_{CUM}$ [mm] | Total yearly precipitation | *1344* | *1255* | *1103* | *1192* |
| $T_{av}$ [°C] | Temperature Grabiasca | *9.4* | *11.3* | *11.6* | *10.0* |
| $ET_{av}$ [mm] | Mean yearly evapotranspiration | 430 | 364 | 360 | 350 |
| $SWE_{av}$ [mm] | Mean daily snow water equivalent | 45.8 | 29.5 | 23 | 44.6 |
| $Q_{av}$ $[m^3s^{-1}]$ S1 | Mean in stream discharge | 1.01 | 1.24 | 1.05 | 1.18 |
| $Q_{av}$ $[m^3s^{-1}]$ S2 | Mean in stream discharge | 1.61 | 1.98 | 1.66 | 1.87 |
| $Q_{av}$ $[m^3s^{-1}]$ S3 | Mean in stream discharge | 2.16 | 2.65 | 2.22 | 2.50 |
| $Q_{av}$ $[m^3s^{-1}]$ S4 | Mean in stream discharge | 3.85 | 4.75 | 3.95 | 4.45 |
| $Q_{av}$ $[m^3s^{-1}]$ S5 | Mean in stream discharge | 5.46 | 6.76 | 5.57 | 6.29 |
| **ECHAM5** | | **CO** | **ECHA1B** | **ECHA2** | **ECHB1** |
| $P_{CUM}$ [mm] | Total yearly precipitation | *1344* | *1200* | *1188* | *1068* |
| $T_{av}$ [°C] | Temperature Grabiasca | *9.4* | *10.8* | *11.2* | *10.5* |
| $ET_{av}$ [mm] | Mean yearly evapotranspiration | 430 | 415 | 397 | 395 |
| $SWE_{av}$ [mm] | Mean yearly snow water equivalent | 45.8 | 25.9 | 37.9 | 25.6 |
| $Q_{av}$ $[m^3s^{-1}]$ S1 | Mean in stream discharge | 1.01 | 1.13 | 1.12 | 0.98 |
| $Q_{av}$ $[m^3s^{-1}]$ S2 | Mean in stream discharge | 1.61 | 1.79 | 1.78 | 1.54 |
| $Q_{av}$ $[m^3s^{-1}]$ S3 | Mean in stream discharge | 2.16 | 2.39 | 2.38 | 2.05 |
| $Q_{av}$ $[m^3s^{-1}]$ S4 | Mean in stream discharge | 3.85 | 4.23 | 4.23 | 3.61 |
| $Q_{av}$ $[m^3s^{-1}]$ S5 | Mean in stream discharge | 5.46 | 5.97 | 5.98 | 5.06 |

Average yearly precipitation and temperature at Grabiasca (738 m a.s.l) and average flow discharge at the five control station. Control run 2000-2009, and scenarios, 2045-2054. In *Italic* values taken from *GCMs* and observations, normal font outputs from the hydrological model.

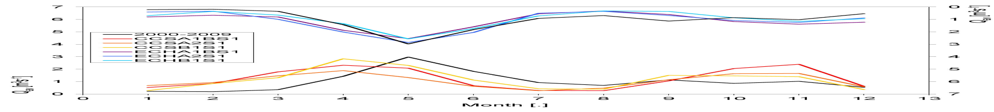
**Table 6. Serio at Grabiasca, flow variables**

| Variable | Description | Values | | | |
|---|---|---|---|---|---|
| **CCSM3** | | **CO** | **CCSA1B** | **CCSA2** | **CCSB1** |
| $Q_{37}$ $[m^3s^{-1}]$ | Exc. 10% | 5.81 | 7.21 | 5.59 | 6.57 |
| $Q_{91}$ $[m^3s^{-1}]$ | Exc.25% (ordinary flood) | 2.36 | 2.93 | 2.55 | 2.95 |
| $Q_{182}$ $[m^3s^{-1}]$ | Exc.50% (median) | 0.59 | 0.83 | 0.81 | 0.82 |

| | | | | | |
|---|---|---|---|---|---|
| $Q_{274}$ [m$^3$s$^{-1}$] | Exc. 66% (ordinary low) | 0.31 | 0.36 | 0.35 | 0,39 |
| $Q_{ind}$ [m$^3$s$^{-1}$] | Index flood | 23.95 | 32.59 | 27.06 | 27.80 |
| $Q_{Min37}$ [m$^3$s$^{-1}$] | Min av. flow 37 days | 0.22 | 0.19 | 0.20 | 0.32 |
| $Q_{Max37}$ [m$^3$s$^{-1}$] | Max av. flow 37 days | 6.66 | 8.98 | 6.46 | 7.52 |
| $Q_{Min91}$ [m$^3$s$^{-1}$] | Min av. flow 91 days | 0.55 | 0.40 | 0.46 | 0.65 |
| $Q_{Max91}$ [m$^3$s$^{-1}$] | Max av. flow 91 days | 4.57 | 5.63 | 4.13 | 5.09 |
| $Q_{Min182}$ [m$^3$s$^{-1}$] | Min av. flow 182 days | 1.55 | 1.20 | 1.26 | 1.55 |
| $Q_{Max182}$ [m$^3$s$^{-1}$] | Max av. flow 182 days | 3.22 | 3.43 | 2.64 | 3.35 |
| $Q_{Min274}$ [m$^3$s$^{-1}$] | Min av. flow 274 days | 2.18 | 2.19 | 1.75 | 2.38 |
| $Q_{Max274}$ [m$^3$s$^{-1}$] | Max av. flow 274 days | 2.68 | 2.95 | 2.44 | 2.96 |
| **ECHAM5** | | **CO** | **ECHA1B** | **ECHA2** | **ECHB1** |
| $Q_{37}$ [m$^3$s$^{-1}$] | Exc. 10% | 5.81 | 6.32 | 6.80 | 5.61 |
| $Q_{91}$ [m$^3$s$^{-1}$] | Exc.25% (ordinary flood) | 2.36 | 3.15 | 2.96 | 2.06 |
| $Q_{182}$ [m$^3$s$^{-1}$] | Exc.50% (median) | 0.59 | 0.86 | 0.69 | 0.58 |
| $Q_{274}$ [m$^3$s$^{-1}$] | Exc. 66% (ordinary low) | 0.31 | 0.35 | 0.35 | 0.35 |
| $Q_{ind}$ [m$^3$s$^{-1}$] | Index flood | 23.95 | 22.20 | 23.82 | 25.75 |
| $Q_{Min37}$ [m$^3$s$^{-1}$] | Min av. flow 37 days | 0.22 | 0.30 | 0.28 | 0.24 |
| $Q_{Max37}$ [m$^3$s$^{-1}$] | Max av. flow 37 days | 6.66 | 6.43 | 7.25 | 6.57 |
| $Q_{Min91}$ [m$^3$s$^{-1}$] | Min av. flow 91 days | 0.55 | 0.56 | 0.64 | 0.38 |
| $Q_{Max91}$ [m$^3$s$^{-1}$] | Max av. flow 91 days | 4.57 | 4.75 | 4.98 | 4.29 |
| $Q_{Min182}$ [m$^3$s$^{-1}$] | Min av. flow 182 days | 1.55 | 1.29 | 1.41 | 1.12 |
| $Q_{Max182}$ [m$^3$s$^{-1}$] | Max av. flow 182 days | 3.22 | 3.23 | 3.16 | 2.78 |
| $Q_{Min274}$ [m$^3$s$^{-1}$] | Min av. flow 274 days | 2.18 | 1.98 | 2.19 | 1.79 |
| $Q_{Max274}$ [m$^3$s$^{-1}$] | Max av. flow 274 days | 2.68 | 2.64 | 2.76 | 2.36 |

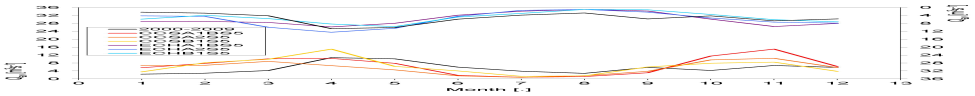
Control run 2000-2009 and scenarios, 2045-2054.

**Figure 5. Hydrological projections, 2045-2054**



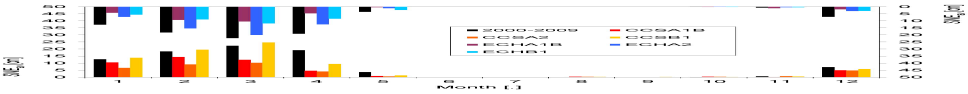
Monthly in stream discharges $Q_{av}$ at S1. Notice different scale on $y$ axis between sections. Results for ECHAM5 reported in the right $y$ axis, with inverse scale.

**Figure 6. Hydrological projections, 2045-2054**



Monthly in stream discharges $Q_{av}$ at S5. Notice different scale on *y* axis between sections. Results for ECHAM5 reported in the right *y* axis, with inverse scale.

**Figure 7. Hydrological projections, 2045-2054**

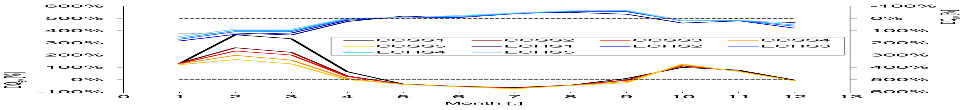


*SWE$_{av}$* is mean monthly snow water equivalent on the ground in altitude belt 12 (ca. 2000 m a.s.l). Results for ECHAM5 reported in the right *y* axis, with inverse scale.

## Discussion

12 Our simulations display potential future (2045-2054) variation of water resource distribution within the Alpine Serio River. Temperatures are consistently expected to increase. Average yearly variation of temperatures ranges from +0.6 °C for CCSB1 (and +1.1 °C for ECHB1), and +2.2°C for CCSA2, or *business as usual* (and + 1.8 °C for ECHA2), distributed unevenly as reported. Yearly precipitation $P_{CUM}$ ranges from 1068 mm (- 21% *vs* CO) for ECHA2 (and 1103 mm, -18% for CCSA2) to 1255 mm (-7%) for CCSA1B (and 1200 m, -11% for ECHA1B), always decreasing yearly, but unevenly distributed monthly, with wetter Fall and Winter and drier Spring and Summer. All scenarios show shorter and thinner snow pack (table 5, figure 7). The late Spring flows, normally linked to snowpack ablation, would therefore decrease (figures 5 and 6). Average discharge yearly would remain approximately constant or even increase (table 5), but the seasonal distribution of water would be dramatically changing. At all altitudes in stream flows would increase in Fall (OND), and in Winter (JFM) due to trading of snowfall for rainfall, because increased precipitation during Fall and Winter will fail in accumulating snow (figure 7). In turn, lack of stored *SWE* together with lower Spring and Summer precipitation, will produce lower discharges during typically dry periods (figures 5 and 6). Notice that for the highest catchments, thaw season may actually shift from May to April on average (figures 5 and 6, sections S1, and S2-S4, not shown, CCSA1B, CCSB1, sections S4, not shown, and S5 ECHA2), or even to March under the A2 scenario (sections S3-S4, not shown, and S5 CCSA2, figure 6). Higher in the catchment snow dynamics is more and more important for hydrological regime, so that catchments at the highest altitudes are more impacted. Evapotranspiration is decreasing at yearly scale under every scenario (table 5). Although potential evapotranspiration *ETP* increases linearly according to temperature increase (here modelled via Hargreaves equation, only depending upon temperature, *e.g.* Groppelli *et al.*, 2011b), considerably decreasing precipitation year round (table 5) limits soil moisture, and thence actual evapotranspiration *ET*. This is especially true during Summer, when warmer and drier climate is seen under all scenarios, thus increasing *ETP*, and decreasing *ET*. Decreased snow cover at thaw will also result into decreased soil moisture, again feeding back into decreased evapotranspiration. Notice that water deficit and decreasing evapotranspiration may hamper agricultural yield, and generally vegetation and orchards growth (*e.g.* Bocchiola *et al.*, 2013), and therefore prospective effect of modified climate as shown here may have a fallout upon food production within this area. In figure 8 we show the relative variation (*vs* CO) of mean monthly discharges in the five selected stream sections, averaged upon the three storylines. During Spring and Summer all catchments would display decrease of in stream flows, down to -75% or so. However, during Winter the highest catchments would display an increase of up to +350% or so, according to CCSM3 (three storylines), and up to +150% or so, according to ECHAM5 (three storylines).

**Figure 8. Hydrological projections, 2045-2054**



*DQ$_{Av}$* is the relative variation (*vs* control period CO) of monthly in stream discharges for each control catchment. Monthly averaged values for the scenarios CCSM3 (A1B-A2-B1) and ECHAM5 (A1B-A2-B1). Results for ECHAM5 reported in the right *y* axis, with inverse scale.

13 Use of decadal reference periods (2000-2009 *vs* 2045-2054) here may not provide a long enough series to assess robust statistics. A remarkable source of uncertainty may dwell in future trends of precipitation, which are subject of a considerable debate (see *e.g.* Brunetti *et al.* 2006 and Groppelli *et al.* 2011b for a discussion on future precipitation in the Alps). A further source of uncertainty dwells within the downscaling method, based on the hypothesis that the difference between *GCMs* precipitation and that observed on the ground will remain similar in the future. The hydrological model we used considers only by temperature and precipitation, while an important role may be played by other variables, *e.g.* solar radiation, wind, etc. Here, we could explore a range of altitude limited between 500-900 m a.s.l for stream flow sections (and ca. 1600 to ca. 2200 in average catchment altitude), due to presence of water withdrawal. However future modelling of hydrological flows downstream could be carried pending availability of withdrawal data. Under the hydrological scenarios depicted here, actions will be necessary to mitigate the ecological and even economical effects caused from the lack of snow cover. The mountain area in the upper Serio catchment is presently exploited for Winter skiing activity, with several sites featuring trails and ski lifts for downhill skiing (*e.g.* in Monte Pora, Passo della Presolana, Colere, Lizzola, Spiazzi di Gromo), and skiing activity is widely diffused within Italian Alps and pre-Alps, so that decreased snow cover thickness as projected may affect local economy based upon tourism (*e.g.* Diolaiuti *et al.*, 2006). Rivers from the Alps of Lombardy region, including Serio, are heavily exploited for agriculture within the Po valley, among the most productive agricultural areas within Europe (*viz* for rice, wheat, maize, etc..), irrigated during Summer with surface water from the Alps. As shown above, increased temperature in Summer will results into increased potential evapotranspiration, but lack of precipitation will results into water stress, and more need for irrigation. This will in turn potentially decrease crop yield of cereals unless water supply is increased using irrigation strategies (Bocchiola *et al.*, 2013). Decreased flows during Summer may impact suitability of riverine habitat for fish colonization, depending upon water availability and stream morphology (Groppelli *et al.*, 2011c), and enhanced floods during Fall and Winter may disturb development of benthic communities, eventually resulting into spoiled river quality, and fishing activity. Decreased Summer flows and increased air temperatures may lead to increased water temperatures, with outbreaks of aquatic diseases (Peeler and Feist, 2011). While some catchments in the central Alps and pre-Alps feature noticeable ice cover, possibly providing buffer for water resources during Summer until down wasting (see *e.g.* Bocchiola *et al.*, 2010 for a case study in Italy, and *e.g.* Bocchiola *et al.*, 2011 for an application in a Himalayan catchment), Serio river does not display any glacierized area, potentially providing a buffer for water resources, and future lack of snow may hardly be dampened thence.

## Conclusions

14 Our results, even with some uncertainty as sketched, highlights the potential impact of climate change upon water resources within the Italian Alpine region. For half century we may expect heavier Winter floods and harder droughts in Summer, and moderate to heavy thinning of snow cover at the highest altitudes, affecting especially hydrology of high altitude catchments. Water resources management in the Alps is an increasingly debated topic under the observed transient climate change conditions, bearing upon energy production and food security of populations downstream, and policy makers need to take action rapidly. The present work may provide a benchmark for studies aimed to future water resources assessment and management and may help depiction of possible adaptation strategies, posing the methodological bases for future developments in this area.

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## *Pour citer cet article*

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## *Droits d'auteur*

## *Résumé*

Climate change will affect hydrological cycle and water resources in the Alps. Here we sketched potential future (2045-2054) hydrological cycle under prospective climate change scenarios within an Alpine river of Italy: Serio (ca. 300 km$^2$). Therein, hydrology is highly dependent upon snow cover cycle, very likely to be affected by climate changes. We set up and validated a hydrological model able to mimic water resources regime of the river. We then use downscaled future temperature and precipitation from two general circulation models *GCMs* to feed the hydrological model and obtain projected hydrological regimes, at flow sections at different altitudes within the catchment. The scenarios and storylines from the adopted *GCMs* differ from one another with respect to projected precipitation and temperature amount, but agree upon decrease of the former and increase of the latter. All hydrological scenarios agree upon prospective shrinkage of seasonal snow cover due to increased temperature, and upon prospective increase of Fall and Winter stream flows as due to increased liquid precipitation. Lower discharges are projected during Spring and Summer, in view of decreased rainfall and snow cover at thaw, and the CCSM3 model provides shifting of thaw season to one month earlier. Higher catchments are more impacted because Winter flows increase more proportionally.

***Entrées d'index***

***Keywords :*** climate change, Alpine watersheds, GCM models, hydrological projections

***Notes de l'auteur***

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