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Impact of climate change on water resources status: a case study for Crete Island, Greece.

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Abstract

An assessment of the impact of global climate change on the water resources status of the island of Crete, for a range of 24 different scenarios of projected hydro-climatological regime is presented. Three “state of the art” Global Climate Models (GCMs) and an ensemble of Regional Climate Models (RCMs) under emission scenarios *B1*, *A2* and *A1B* provide future precipitation (*P*) and temperature (*T*) estimates that are bias adjusted against observations. The ensemble of RCMs for the *A1B* scenario project a higher *P* reduction compared to GCMs projections under *A2* and *B1* scenarios. Among GCMs model results, the ECHAM model projects a higher *P* reduction compared to IPSL and CNCM. Water availability for the whole island at basin scale until 2100 is estimated using the SAC-SMA rainfall-runoff model And a set of demand and infrastructure scenarios are adopted to simulate potential water use. While predicted reduction of water availability under the *B1* emission scenario can be handled with water demand stabilized at present values and full implementation of planned infrastructure, other scenarios require additional measures and a robust signal of water insufficiency is projected. Despite inherent uncertainties, the quantitative impact of the projected changes on water availability indicates that climate change plays an important role to water use and management in controlling future water status in a Mediterranean island like Crete. The

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results of the study reinforce the necessity to improve and update local water management planning and adaptation strategies in order to attain future water security.

Keywords: Climate change impacts; Crete; water resources; hydrological changes;

1 Introduction

Climate change is expected to affect precipitation and evapotranspiration patterns (Tsanis et al., 2011), and consequently variables such as local water availability, river discharge, and the seasonal availability of water supply (Arnell et al., 2011). As demand for freshwater on a global scale rises due to a variety of factors including population growth, water pollution and economic progress, land use and climate change render its availability into the future uncertain (Davies and Simonovic, 2011). Social and environmental aspects such as agriculture, tourism and biodiversity conservation are connected to water resources quality and availability, and therefore adaptation measures for water will be strongly bound with policies in a wide spectrum of disciplines (Iglesias et al., 2011).

The latest review on the current state of the art on climate change research for the Mediterranean region by Ludwig et al., (2011) shows that recently observed trends and projections from climate model ensembles indicate a strong susceptibility to change in hydrological regimes, an increasing general shortage of water resources and consequent threats to water availability and management. These projections enhance the necessity for more robust water management, pricing and recycling policies, in order to secure adequate future water supply and prevent tensions among users (García et al., 2011).

Despite the increasing research efforts, there are still considerable uncertainties in the future climate drivers and in how global hydrological systems will respond to their behaviour

(Harding et al., 2011). A number of studies (e.g. Akhtar et al., 2008; Alcamo et al., 2007; Barnett and Pierce, 2009; Charlton and Arnell, 2011; Christensen and Lettenmaier, 2007; Fujihara et al., 2008; Georgakakos et al., 2011;) have described the impacts of the expected climate change on global and regional water resources with respect to the various inherent uncertainties. The increasing availability of climatic outputs from general and regional circulation models provide the potential of exploring model uncertainties in predicting future climate through the use of ensembles, at global (Manning et al., 2009) but more importantly at regional scales where forcing data is often less accessible but more accurate.

Indicative of the instability in the Mediterranean is the island of Crete, where analysis of climate models data depicts that precipitation on average is likely to be less frequent but more intense and droughts are likely to become more frequent and severe in some regions (Koutroulis et al., 2010, 2011; Tsanis et al., 2011). Shorter rainy periods and seasonality shifts could seriously affect water resources by significant reduction of water availability with wide ranging consequences for local societies and ecosystems. It is indicative that, during the last decade, the island of Crete has faced an increased number of droughts (Koutroulis et. al., 2011). Moreover, the rapid development of Crete in the last 30 years has exerted strong pressures on many natural resources. Urbanization and growth of agriculture and tourism industry have strong impact on the water resources of the Island by substantially increasing water demand. Water use in Crete increased following the expansion of irrigated land by over than 55% during the period 1985-2000 (Donta et al., 2005). . Regarding future water demands of the island, recent estimates forecast total uses for the year 2015 in the order of 550Mm^3/year, which represents 7% of the mean annual precipitation. This highlights that any arising water stress issue will be due to poor extraction or retention technology rather than actual availability. It is therefore considered essential to tackle the increasingly severe water problems that the island will face via strategic policies adopting to climate change by using integrated water management systems.

This paper assesses the implications of global climate change on the water resources status for the island of Crete for a range of 24 different scenarios from a combination of projected hydro-climatological regimes, demand and supply potentials. For this purpose, "state of the art" climate model results within WATCH FP6 (Harding et al., 2011) modelling framework under *A2* and *B1* emission scenarios and FP6 ENSEMBLES (Van der Linden and Mitchell, 2009) regional climate model results under *A1B* emission scenario are compared, to explore the water resources availability during the 21st century. A two-step bias correction procedure is adopted to adjust precipitation on the observed long-term frequency and intensity distribution based on the period 1970-2000 (Ines and Hansen, 2006; Law and Kelton, 1982; Wood et al., 2002). The correction involves truncating the RCM rainfall distribution and then mapping it onto a gamma distribution fitted to the observed intensity distribution. The SAC-SMA hydrological model (Burnash, 1995) is used to estimate the evolution of hydrological variables and water availability on the island of Crete. The outcome of the analysis is useful for the comprehension of the role and consequently the priority of certain water resources related infrastructure development.

2 Methodology

2.1 Framing the problem

The present water resources assessment includes various water management issues regarding actions up to present as well as future perspectives for policy, management and hydrological (climate) regime, resulting in the modelling framework presented in Figure 1. These future scenarios include the augmentation of agricultural practices, improvement and extension of the already established irrigation network as well as tourism, permanent population and demand trends. For the purposes of this study, it’s considered that demand can exceed supply, when for example scheduled irrigation is not fully satisfied. In this context, a poorly formed irrigation policy can lead to irrigation infrastructure always inferior to the demand for water resources. Furthermore, in this study water availability is defined as the sum of abstracted or potentially abstracted groundwater and available surface freshwater runoff that is or can be potentially exploited. For convenience, the reference periods were split to a historic hydrologic regime (1970-2000) and two future periods (2000-2050 and 2050-2100) and represent the spatial average of all the grid cells that cover Crete in the WATCH and ENSEMBLES domain. The observation period (1970-2000) was used for weighting of Ensembles RCMs, bias correction of Ensembles and WATCH model results and interpretation for the two future (2000-2050 and 2050-2100) periods.

2.2 Scenarios and storylines

The IPCC Third Assessment Report (TAR) has published a set of emissions scenarios, called the Special Report on Emissions Scenarios (SRES). Four scenario storylines, labeled A1, A2, B1 and B2, were the result of analyzing different possible future development pathways of the main demographic, economic and technological drivers of future greenhouse gas and sulphur emissions (Parry, 2000; Nakićenović et al., 2000) and a basis of a set of 40 scenarios. For the purposes of this study, three of these scenarios were chosen based on the hydrologic simulation of the WATCH and ENSEMBLES climate model input data through continuous rainfall-runoff modelling. In brief, the *B1* storyline and scenario family describes a confluent world that promotes sustainable development on a global scale, rapidly shifting towards a service and information economy based on clean and resource-efficient technologies. On the contrary, the *A2* storyline and scenario family, which is part of Scenario A or Business-as-

Usual (BAU), describes a weakly globalized world with continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower. Lying somewhere between the above, the *A1B*, a subgroup of the *A1* scenario family, describes a future world of very rapid economic growth, sustainable global population, and the rapid introduction of new and more efficient technologies leading to a balance across fossil intensive and non-fossil energy sources.

The developed demand and infrastructure scenarios are based on the water practices of the local water management authority (Papagrigoriou et al., 2001) and have two basic components: *D*, the level of demand of water for the various uses, and *S* the projected water supply potential derived from the combination of the technical infrastructure and the projected water availability (dams, barrages, groundwater abstractions, etc.). For each component, two alternative storylines were established focusing on the analysis periods (2000-2050 and 2050-2100) and the different climate models projections for the various emission scenarios.

Regarding the demand component, the *Existing situation of water demand (D1)* storyline includes the current level of demand (2000), based on data that was assembled from irrigation and water supply authorities in the Island. The estimation of irrigation demand is based on a detailed analysis of the irrigated areas per municipality and the potential of each basins for groundwater abstractions. The *Future water demand (D2)* storyline depicts a realistic future water demand as it is outlined by the local irrigation facilities development programs, the future irrigation extend plans, the estimate of future population trends and a projected increase of tourism activities.

In the supply component, the *Business as usual (S1)* storyline includes all the existing works of exploitation of water resources, as they have been recorded in the frame of the "Integrated water resources management of Crete study" (Papagrigoriou et al., 2001) including dams, barrages, groundwater abstractions, etc. Finally, the *Future technical infrastructure (S2)* storyline includes the future technical infrastructure based on the proposed technical work of exploitation of water resources that has been evaluated as mature enough for construction according to the local water authorities. The future infrastructure action also includes new groundwater abstraction wells in certain regions (very limited in number) where certain quantities can be withdrawn without endangerment of quality of groundwater resources.

2.3 Bias correction of climate model data

Statistical bias corrected hydrological variables significantly improve the ability of streamflow simulation when compared to raw outputs (Sharma et al., 2010). The method to adjust biases used in the present study, corrects the frequency and intensity of modeled precipitation relative to a target station (Ines and Hansen, 2006) in a two-step procedure for each one of the 12 months of the year. A calibrated threshold $\tilde{x}_0$ is used to discard rainfall values when modeled precipitation frequency F_{model} is greater than the observed frequency F_{obs}. The correction of intensity involves the mapping of modeled precipitation intensity distribution to the observed for values above the calibrated threshold using a predefined distribution for both datasets. The adjustment procedure of frequency truncates the empirical distribution of the raw model precipitation above a $\tilde{x}_i$ threshold dataset, so that mean frequency of precipitation above this threshold matches observed precipitation frequency. This threshold $\tilde{x}_i$ for each calendar month I is estimated according to Eq. (1),

$$\tilde{x}_i = F^{-1}_{model}\left(F_{obs}\left(\tilde{x}_0\right)\right) \qquad (1)$$

where $F(\cdot)$ and $F^{-1}(\cdot)$ are the cumulative distribution function (CDF) and its inverse for either modeled or observed values. In the final step corrected modeled precipitation x' of day i of month I is estimated by substituting the fitted CDFs into Eq. (2).

$$x_i' = \begin{cases} F_{I,obs}^{-1}\left(F_{I,\mathrm{model}}\left(x_i\right)\right), & x_i \geq \tilde{x}_i \\ 0 \quad , & x_i < \tilde{x}_i \end{cases} \qquad (2)$$

This same method was used to adjust modeled temperature biases but without the use of frequency distribution correction and no truncation to the modeled temperatures.

2.4 Hydrological modelling

The SAC-SMA Sacramento model is a lumped continuous rainfall-runoff model that can estimate stream flow from precipitation P and potential evapotranspiration ET_0 records (Podger, 2004; Tsanis and Apostolaki, 2009). The water balance simulation of a watershed is based on soil moisture accounting. The soil moisture storage increases by rainfall P and reduces by actual evapotranspiration ET_α, direct runoff from the impervious area, surface runoff Q_{sur} from the pervious area and baseflow that add up to total flow Q and infiltration I between the upper and lower zone that discharges at a slower rate (slow runoff). The size and relative wetness of the storage determines the depth of rainfall absorbed, actual evapotranspiration, and the amount of water moving vertically or laterally out of the store. These processes are described by 16 parameters (Vrugt et al., 2006) that need to be determined by the user or an optimization process using a suitable objective function. Because of the number and nature of those parameters, objective function responses can contain multiple optima. In order to apply the SAC-SMA hydrological model at basin scale, the input variables of P and ET_0 are first interpolated using the Inverse Distance Weighting (IDW) method (Wei and McGuinness, 1973) and then averaged over the area of each respective basin.

In order to eliminate subjective judgment of an expert user in model parameter selection, calibration was based on an application of Genetic Algorithms (GAs). GAs are adaptive random search algorithms that mimic the principal of selection and evolution of the fittest in a natural system. Given a defined search space, GAs have a globally oriented searching approach and are thus potentially useful in solving complex optimization problems (Wang, 1998) with one or more objective functions towards a Pareto solution, as discussed by van Werkhoven et al. (2009). While resulting hydrological model parameter estimates may lack direct physical sense, they often represent “effective” watershed properties that compensate for lamped model inadequacies (Vrugt et al., 2006). In this study, a set of three objective functions was used: (a) the Nash-Sutcliffe (Nash and Sutcliffe, 1970) model accuracy statistic calculated on flows (NSE_Q) given by:

$$NSE_Q = 1 - \frac{\sum_{t=1}^{T} \left(Q^t - Q_m^t\right)^2}{\sum_{t=1}^{T} \left(Q^t - \overline{Q}\right)^2} \tag{3}$$

where Q^t is the observed and Q_m^t the modeled discharge at time t and $\overline{Q}$ the average discharge of the dataset, (b) the Nash-Sutcliffe logarithmic transformed flows $NSE_{\ln Q}$ which shows better efficiency for low flows (Pushpalatha et al., 2012) and (c) the R^2 efficiency criterion, given by:

$$R^2 = \left(\frac{N \sum Q^t Q_m^t - \left(\sum Q^t\right)\left(\sum Q_m^t\right)}{\sqrt{N \sum \left(Q^t\right)^2 - \sum \left(Q^t\right)^2} \sqrt{N \sum \left(Q_m^t\right)^2 - \sum \left(Q_m^t\right)^2}} \right)^2 \tag{4}$$

representing the percentage of the initial uncertainty explained by the model. NSE_Q and $NSE_{\ln Q}$ range from $-\infty$ to 1 while R^2 ranges from 0 to 1. For all above criteria, the perfect fit between observed and calculated values, which is unlikely to occur, is the unity.

River basin scale simulation studies require long-term continuous streamflow records, which are unavailable in ungauged basins. As a rule, the calibrated parameter values of a specific catchment should not be used in other catchments, unless the reliability of this transfer can be assessed (Burnash, 1995). Several methods have been used in order to regionalize model parameters including applications of spatial proximity (Vandewiele and Elias, 1995; Merz and Blöschl, 2004; Parajka et al., 2005), flow duration curves (Yu and Yang, 2000), basin similarity (Parajka et al., 2005), neural networks (Heuvelmans et al., 2006), and regional calibration methods (Fernandez et al., 2000; Hundecha and Bardossy, 2004). In this study, the global parameter mean (e.g. Kim and Kaluarachchi, 2008, Jin et al., 2009) for all basins is used to make estimations on all 110 Cretan basins.

2.5 Limitations

The complexity of climate change impact studies is enhanced from the uncertainty in climate change modelling and the long planning horizons. Capturing the inter-annual weather variability and extremes rather than the statistical properties of climate still presents a challenge for models (e.g. Wilks, and Wilby, 1999; Srikanthan et al., 2001; Kyselý and Dubrovský, 2005) thus hindering the accuracy of a water availability estimation. A step further, the main shortcoming of statistical bias correction methods is the assumption of stationarity implying that the statistical properties of a time-series remain constant through time. As a result, the transfer functions estimated using the historical climate conditions is assumed to remain valid for correcting biases in future precipitation or temperature time-series (Rojas et al., 2011). The same limitation holds for hydrologic modeling of bias corrected future climate conditions using a model calibrated with historical time-series as, for example, future parameters and states may shift unpredictably due to temperature increase. Hydrological model parameter uncertainty resulting from both calibration and regionalization should also be carefully investigated and studied further. Moreover, demand and supply estimates of existing conditions for the present study are based on the latest large scale census in the frame of Papagrigoriou et al. (2001), by request from the Water Authority of Crete. As such, the estimates presented herein have inherent limitations, enhanced by the lack of information regarding technological advancement that may directly affect water treatment and therefore change the water balance. Finally, the modelling approach used herein ignores the dynamic interactions between elements of social-economic-environmental system and future is treated in a deterministic way.

3 Case study

The island of Crete occupies the southern part of the country of Greece (Figure 2). With an area of 8265km^2, Crete covers almost 6.3% of the area of Greece. The mean elevation is 482m ranging from sea level to 2450m and the average slope 228m/km with the topography fracturing into small catchments with ephemeral streams and karst geology. Crete has a typical Mediterranean island environment with about 53% of the annual precipitation occurring in the winter, 23% during autumn and 20% during spring while there is negligible rainfall during summer (Koutroulis and Tsanis, 2010; Naoum and Tsanis, 2004). The average precipitation for a normal year in the island of Crete is approximately 934mm or 7,697Mm^3 (Tsanis and Naoum, 2003). This in addition to non-uniform precipitation distribution in the island (a reduction of almost 300mm from the west to the east part of the island and a strong orographic effect) makes the water availability a very small but crucial portion of the total supply (Tsanis et al., 2011).

In order to calibrate the SAC-SMA hydrological model at basin scale input variables were collected from 53 rainfall and 15 temperature stations for the period 1970-1999 at monthly time step. While P could be used directly from measurements, values of ET_0 were estimated from temperature using the Blaney-Criddle equation (Blaney and Criddle, 1962) in order to have better comparison with future climatic data. Variables were spatially interpolated using the Inverse Distance Weighting (IDW) method (Wei and McGuinness, 1973) and then averaged over the area of each respective basin. The optimization process based on genetic algorithms was applied to 17 gauged basins (Figure 2) where surface runoff Q_{sur} measurements were available at a monthly time step. The calibration yielded satisfactory results for 15 out of the 17 basins (Table 1) with the R^2, NSE_Q and ranging from 0.52 to 0.90, 0.51 to 0.90 respectively. The $NSE_{\ln Q}$ of the calibration ranged from 0.20 to 0.81 showing that the model was somewhat less efficient in low flows for the calibrated basins. In two basins, Bramianos and Agios Vasillios, the calibrations results were not satisfactory and they were rejected from the rest of the methodology. A global mean of the SAC-SMA model parameters yielded a total R^2 of 0.81 in the comparison of observed and modeled surface flow and was therefore considered adequate to make estimations for the entire 110 basins on the Island.

Following the standardization with the respective basin areas, the annual water balance breaks down to 68-76% evapotranspiration, 14-17% infiltration and 10-15% runoff (Table 2). Total water uses in the region in 2000 amounted to 420Mm^3 (Papagrigoriou et al., 2001), approximately 5.5% of the precipitation of a normal year and 16% of the total water potential. An average of 65% of the total water use is supplied by groundwater exploitation while the remaining 35% is obtained from winter spring and stream discharges. Of this, 16% is used for domestic, tourist, and industrial uses, 3% for livestock and a vast 81% for irrigated agriculture on less than 30% of the total cultivated land, using mainly ground water in drip irrigation methods. Irrigation and tourism create a marked seasonal pattern in water demand with heavy summer loads, as the annual volume of water abstracted exceeds 50% of the average annual runoff and 35% of the groundwater potential.

In the frame of the EU FP6 project "WATCH" (WATer and global CHange"), ran from 2007-2011, a range of datasets were generated which are publicly available (http://www.eu-watch.org/data_availability) including 20th Century WATCH Forcing Data (WFD), the 21st Century WATCH Driving Data (WDD). Six datasets available for the period 2001-2100 based on 3 different GCMs, ECHAM5 (Jungclaus et al. 2006; Roeckner et al. 2003), CNRM (Deque et al. 1994; Deque and Piedelievre 1995), and IPSL (Hourdin et al. 2006) and two emission scenarios (A2 and B1), interpolated at a spatial resolution of 0.5^{o} (Figure 2), were used for analysis. For each GCM, three datasets were also available from the control period 1960-2000.

Furthermore, results of an ensemble of RCMs are used focusing on the Island of Crete (Tsanis et al., 2011). Simulations from 10 RCMs, here named ENSEMBLES, (Jacob et al., 2007, 2008; Roeckner et al., 2003; Van der Linden and Mitchell, 2009) are performed over the European continent at a horizontal resolution of about 25 km (Figure 2). The RCMs' lateral boundary conditions are provided by 7 GCMs for the period 1951-2100 (Table 3). Simulations are forced using observed GHG greenhouse gas and aerosol concentrations until 2000 and SRES *A1B* concentrations scenario until 2100. The RCMs were chosen based on their spatial and temporal extent as well as their ability to simulate the present climate. RCM specific weights are then calculated in order to construct the optimal ensemble output for precipitation and temperature at a monthly time step and at a watershed level. Weights are calculated according to the combination of two metrics for both precipitation and temperature time-series. The first metric is a composition of five functions related to probability density distribution match at specific percentiles of the cumulative distribution functions (Christensen et al., 2010). Each of the functions takes into account different aspects of the behavior of the model parameter (P, T), and thus, their combination gives a complete picture of the model skill. The second metric is related to the ability of the model to represent the annual cycle, that is believed as a good indication of the quality of atmospheric processes description affecting the overall model performance. This metric is based on the so called Taylor diagram (Taylor, 2001) which is used for presenting the data in terms of RMSE (Root Mean Square Error), standard deviation and correlation. Monthly weights per model were constructed from the combination of the above metrics for P and T. The overall weighting effect on historic skill for ENSEMBLES dataset is illustrated in Tsanis et al., (2011).

Climate models output (precipitation and temperature) is then bias corrected against daily time-series data obtained from 53 rainfall and 15 temperature stations for the period 1970-2000 and interpolated at basin scale. For precipitation bias correction, the threshold of observed precipitation amount $\tilde{x}$ of model daily precipitation is set to 0.1 mm. For the correction of precipitation intensity the gamma distribution is applied to fit the truncated daily modeled and observed precipitation data after Ines and Hansen (2006). Normal instead of gamma distribution is used to map temperature distribution (Grillakis et al., 2011). Detailed schematic representations of normal PDFs of the bias adjusted results of all WATCH models and Ensembles members for the two time slices under the three emission scenarios, for annual precipitation and temperature, as well as the seasonality shift of these hydro-climatic variables are presented in Figures 3 and 4, respectively. Eventually, monthly aggregated time-series of bias adjusted parameters used to drive the projections of the hydrological model.

For the *(D1)* storyline, the current total demand is estimated at 535.7Mm^3/year, from which 458.4Mm^3 are consumed in irrigation and 77.3Mm^3 in general water supply consisting of household supply and other minor uses (industrial, livestock-farming, etc.). The total existing water demand in storyline *D2* is estimated at 775.8Mm^3/year, from which 670.8Mm^3 come from irrigation due to increased cultivated areas and the remaining 105Mm^3 refer to general water supply. Compared to the *D1* storyline, the increase of irrigation demand is 44.8%, while the increase of demand of general water supply is 36%. For the above two conditions, the theoretical water demand also represents a “desirable” level of irrigation, taking irrigation system losses into account. In the *Business as usual (S1)* storyline, a total of 302.0Mm^3 are supplied for irrigation and 69.7Mm^3 for general water supply. An additional 42.8Mm^3, originating from groundwater abstractions, are supplied to the system, shaping the total supply to 414.6Mm^3 (under normal hydrological conditions). The total inflow in the system of water resources for this scenario amounts to 857.0Mm^3/year, including groundwater abstractions, spring discharges and basin outflows under current exploitation conditions or included in planed exploitation. For the *S2* storyline, a total of 398.3Mm^3 are supplied for irrigation (59.4% of the demand), 100.4Mm^3 for general water supply, and an additional 35.4Mm^3 from groundwater abstractions are supplied to the system, shaping the total supply to 534.2Mm^3 (under normal hydrological conditions). The total inflow in the system of water resources for this scenario amounts in 902.5Mm^3/year as a result of increase of certain groundwater withdrawals (308.0Mm^3/year) and better exploitation of certain surface flows. The quantity from the annual winter surplus from spring and stream discharges that are not exploited and runoff to the sea amounts to 434.0Mm^3. Finally, a direct connection of the decrease (%) of projected water availability (from Tables 4 and 6) to the supply formulated from the two technical infrastructure scenarios (S1 and S2) depicts the estimation of the impact of climate change to the projected supply potential. Table 5 includes results for the projected annual supply potential according to hydrological modelling for the island of Crete, under the 2 infrastructure (S1 and S2) and the 3 emission scenarios.

4 Results and discussion

4.1 *Historic hydrologic regime (1970-1999)*

Continuous hydrological modelling for the 1970-1999 period resulted to the hydrologic regime of the reference period. Standardizing the balances with the respective basin areas, runoff is 10%-15% of the approximately 934mm or 7,697Mm^3 of long term annual precipitation that falls on the island of Crete, almost equal with the fraction of water that infiltrates towards slow runoff (14-17%), whereas 68-76% of precipitation goes toward evapotranspiration (Table 2). The monthly estimated actual evapotranspiration, runoff and infiltration per basin for the entire island for the period 1970-1999 are shown in Figure 5. As expected, the estimated runoff and infiltration is high during the winter while actual evapotranspiration increases during spring. The hydrological balance of the Island of Crete under normal, wet and dry conditions are included in Table 2. Actual evapotranspiration on a dry year consumes a significant amount of precipitation but not as much as on a wet year when there is more water to be evaporated and plants are able to readily transpire. Also, on a dry year, the total volume of water that discharges is less (about half than on a wet year) but represents a larger fraction of the hydrological balance.

4.2 *Projected water resources availability*

4.2.1 Period 2000-2050, emission scenario B1

For the period 2000-2050 and according to WATCH modelling results (Table 4, Figure 3) for emission scenario B1, projected average annual precipitation is expected to be similar to that of the control period (1970-2000). The three GCMs (IPLS, ECHAM, CNCM) indicate that average annual precipitation could slightly increase (1%) to an average of 945mm (from

931mm to 961mm depending on the model). The current long term average annual temperature (16.3^{o}C) could increase by an average of 1.5^{o}C (from 1.1^{o}C to 2.0^{o}C). Hydrological modelling shows that during this period we can expect a decreasing trend of water availability of 2.6mm per year (Figure 6a) which nevertheless stabilizes the abrupt change during the control period (1970-2000) leading to an average increase of water availability between 4% and 11% (Figure 7). Compared the control period, during infrastructure scenarios S1 and S2, an additional 34Mm^3 (15Mm^3 to 47Mm^3) and 45Mm^3 (20Mm^3 to 54Mm^3), respectively, are expected to flow into the system (Table 5). Furthermore, the combination of D1 and S1 results to an additional 35Mm^3 available water resources, thus reducing the deficit from 23% to 16% (Table 7). In the case of D1 and S2 an excess of 43Mm^3 is estimated. In the case of D2 and S1, a severe lack of water resources by 327Mm^3 (-42%) could be observed, compared to the future demand. A similar status of water stress, with a deficit of 197Mm^3 could affect the region under the assumption of D2 and S2 scenarios.

4.2.2 Period 2000-2050, emission scenario A2

For the period 2000-2050 and according to WATCH modelling results (Table 4) for emission scenario A2, projected average annual precipitation is expected to be similar to that of the control period. The three GCMs indicate that average annual precipitation could slightly decrease (2%) to an average of 919mm (from 908mm), (Figure 3). Average annual temperature could increase by an average of 1.4^{o}C (from 1.0^{o}C to 1.7^{o}C). Hydrological modelling shows that projected average annual supply is expected to have a slight decrease by 1% (Table 4, Figure 7) or 2.1mm per year (Figure 6b) over the control period. For both S1 and S2 scenarios, 5Mm^3 less water (from 2Mm^3 to 9Mm^3) is expected to flow into the system (Table 5), compared to the control period (1970-2000). For the A2 scenario, the combination of D1 and S1 results to a water status similar to that of the control period (1970-2000), with a deficit of 24% (Table 7). In the case of D1 and S2 a slight deficit of 7Mm^3 could be observed. For the combination of D2 and S1, a severe lack of water resources by 366Mm^3 (-47%) could be observed. A similar status of severe water stress, with a deficit of 247Mm^3 could affect the region under the assumption of D2 and S2.

4.2.3 Period 2000-2050, emission scenario A1B

According to the Ensembles results from 10 RCMs (Table 4), and based to the control climatology, future projections show an average decrease of 14% in average annual rainfall (807mm) and an average temperature increase of 1.7^{o}C, leading to a water availability decrease by 28%. For the period 2000-2050 and according to Ensembles modelling results (Table 4) for emission scenario *A1B*, projected average annual supply is expected to decrease by 28% (Figure 7), nevertheless without any significant trend (Figure 6c). For the infrastructure scenarios S1 and S2, a decrease of 118Mm^3 and 152Mm^3, respectively, is expected to flow into the system, denoting a more severe situation (Table 5). According to scenario A1B based on the Ensembles modelling results, and in contrast with WATCH climate modelling results, for the period 2000-2050, the combination of D1 and S1 (BAU) indicates an extreme water deficit of 239Mm^3 (-45%), (Table 7). In the cases of D1 and S2 the deficit is less than that of the previous case, but still emerging. A deficit of 154Mm^3 (-29%) could be observed. For the combination of D2 and S1, a severe lack of water resources by 479Mm^3 (-62%) could be observed. A similar status of severe water stress, with a deficit of 394Mm^3 could affect the region under the assumption of D2 and S2.

4.2.4 Period 2050-2100, emission scenario B1

According to WATCH modelling results (Table 6) for emission scenario B1, projected average annual precipitation is expected to decrease slightly (4%, 989mm) in comparison to the control period (1970-2000). Average annual temperature could increase by an average of 3.1^{o}C (varying from 2.6^{o}C to 3.7^{o}C depending on the model). Hydrological modelling shows that during this period we could expect a stabilized 10% less available water resources, varying from 3% to 22%, depending on the model (Figure7) but without significant trends (Figure 6a).. For the period 2000-2050 and according to WATCH modelling results (Table 5) for emission scenario B1, projected average annual supply is expected to be 10% less. For the infrastructure scenarios S1 and S2, an average decrease of 41Mm^3 (a decrease from 13Mm^3 to 92Mm^3, depending on the model) and 52Mm^3 (from 16Mm^3 to 118Mm^3 less, depending on the model), respectively, is expected to flow into the system, in comparison to the control period (Table 7).

4.2.5 Period 2050-2100, emission scenario A2

WATCH modelling results (Table 6) under emission scenario A2, show more severe changes to hydro-climatic variables. Projected average annual precipitation is expected to drop to 735mm (varying from 673mm to 769mm depending on the model), 21% less in comparison to the period 1970-2000. Average annual temperature could increase by an average of 4.5^{o}C (from 3.9^{o}C to 5.4^{o}C depending on the model). Under these changes, average water availability could decrease by 40% (from 33% to 48% less, depending on the model) compared to past climate conditions (Table 6). For the period 2000-2050 and according to WATCH modelling results (Table 5) for emission scenario A2, projected average annual supply is expected to decrease by 40%. It is important to note that out of all scenarios, this appears to be the most alarming, showing an ever decreasing water availability trend (Figure 6b). For the infrastructure scenarios S1 and S2, an average decrease of 164Mm^3 (from 153Mm^3 to 200Mm^3, depending on the model) and 211Mm^3 (from 180Mm^3 to 257Mm^3, depending on the model), respectively, is expected to flow into the system, in comparison to the control period (1970-2000), (Table 7).

4.2.6 Period 2050-2100, emission scenario A1B

According to the Ensembles results (Table 6), in comparison to the control climatology, future projections show an mean decrease of average annual rainfall by 26%, reaching 688mm, and an average temperature increase of 4.6^{o}C, leading to a water availability decrease of 48%. For the period 2050-2100 and according to Ensembles modelling results (Table 5) for emission scenario *A1B,* projected average annual supply is expected to be decrease by 52%. While the trend of availability is not significant (Figure 6b) hydrological modelling predicts that by the end of the century, annual water availability will be as low as 80mm/year, which is a record value for the studied dataset. For the infrastructure scenarios S1 and S2, the flow into the system is expected to decrease by 215Mm^3 and 277Mm^3, respectively, denoting the most severe situation among the analyzed scenarios (Table 7).

5 Conclusions

Despite limitations and uncertainties, this study presents a wide range of draft estimates and results, providing water resources management community with a glimpse into a very plausible future where the quantitative impact of climate change on water availability can be substantial, especially in a Mediterranean island like Crete. RCM model results (Ensembles) project increased precipitation reduction and consequently show increased water insufficiency compared to GCM projections (WATCH). Among WATCH GCM results, ECHAM model projects higher water resources reduction compared to IPSL and CNCM results. Overall, a robust signal of water insufficiency is projected for all the combinations of emission, demand and infrastructure scenarios, with the estimated deficit ranging from 10% to 74%. Assuming that all climate scenarios are equally probable, average water availability is expected to drop from 93% during 2000-2050 to a devastating 70% of the observed average (Figure 7), which is already insufficient to cover current demand.

The outcomes of the above analysis are useful for understanding the role and consequently the priority of certain water resources related infrastructure development. Out of all discussed demand and supply scenarios, the only window for improving the current status is given under scenario *B1* for the period 2000-2050, with the assumption that the demand during this period does not increase (an outcome against development strategies) and water resources infrastructure improves. Even as such, assuming demand scenarios equally probable or an average rise of demand by 20%, it becomes evident that water resources management should consider infrastructure and adaptation strategies to mitigate risks of the forecasted deficit.

For the combination of *D2* and *S2* and for a normal hydrological year, it is observed that the increase of irrigated cultivated areas causes an increase in water demand and despite the increase of allocated quantity for irrigation by roughly 100Mm^3/year, the service of water demand is lower by 6.5%. This is an important conclusion which should enjoy further attention with regard to growth policies as current policy for new water resources infrastructures is very closely related to the growth of new irrigated areas. This leads to a great increase of irrigation demand level, as this has been determined in the present study, precluding the practicability of this scenario. The conclusion is that an alternative policy of development of new infrastructures should be adapted. This policy should not only give priority to the increase of irrigated areas but also promote a more sustainable irrigation practice for existing and new agricultural land.

The EU Water Framework Directive and the policies of droughts and adaptation to climate change (CEC 2008, 2009), provides a specific framework of objectives, principals, definitions and measures to adopt, for assessing the impact of climate change on water resources. This enables decision-makers to develop and constantly review water management plans. According to the local water authorities, the overwhelming majority of small scale works (barrages, small dams) are projects of purely local character regarding their incorporation in the integrated system of water resources, thus yielding negligible effects at municipal or greater level. Therefore, they should be evaluated only based on technical, economically and social criteria of the local region in which they are sited and which they will serve. Regarding large scale water resources constructions, which have a wider-than-regional character, some of them are presented as additional supply for covering existing demand (e.g. the dam of Valsamiotis under construction at Chania district in Western Crete), while others have a capacity exceeding present demand and are consequently be associated with agricultural expansion (e.g. the dams of Roumatianos and Derianos in Chania, the dam of Plakiotissa in Heraklion and Amariou dam in Rethymno).

Despite this growth of infrastructure aiming to store winter and spring stream flows, the inadequacy to control large outflow quantities that runoff or infiltrate to the sea remains a problem. Adaptation is unlikely to be facilitated through the introduction of new and separate policies, but rather by the revision of existing policies that currently undermine adaptation and the strengthening of policies that currently promote it (Iglesias et al., 2011). Such strategies of adaptation to consider include wastewater recycling and reuse that are estimated to lead to water savings of up to 5% of the total irrigation water of Crete (Tsagarakis et al., 2004; Agrafioti and Diamadopoulos, 2012). In view of the new results presented here, local long-term water resources management plans could be updated including the procedure on data analysis and output interpretation. The current financial stress and the continuously reduced national investment programmes call for low cost, short and long term water management strategies in order to tackle the climate induced changes in water resources.

Acknowledgments

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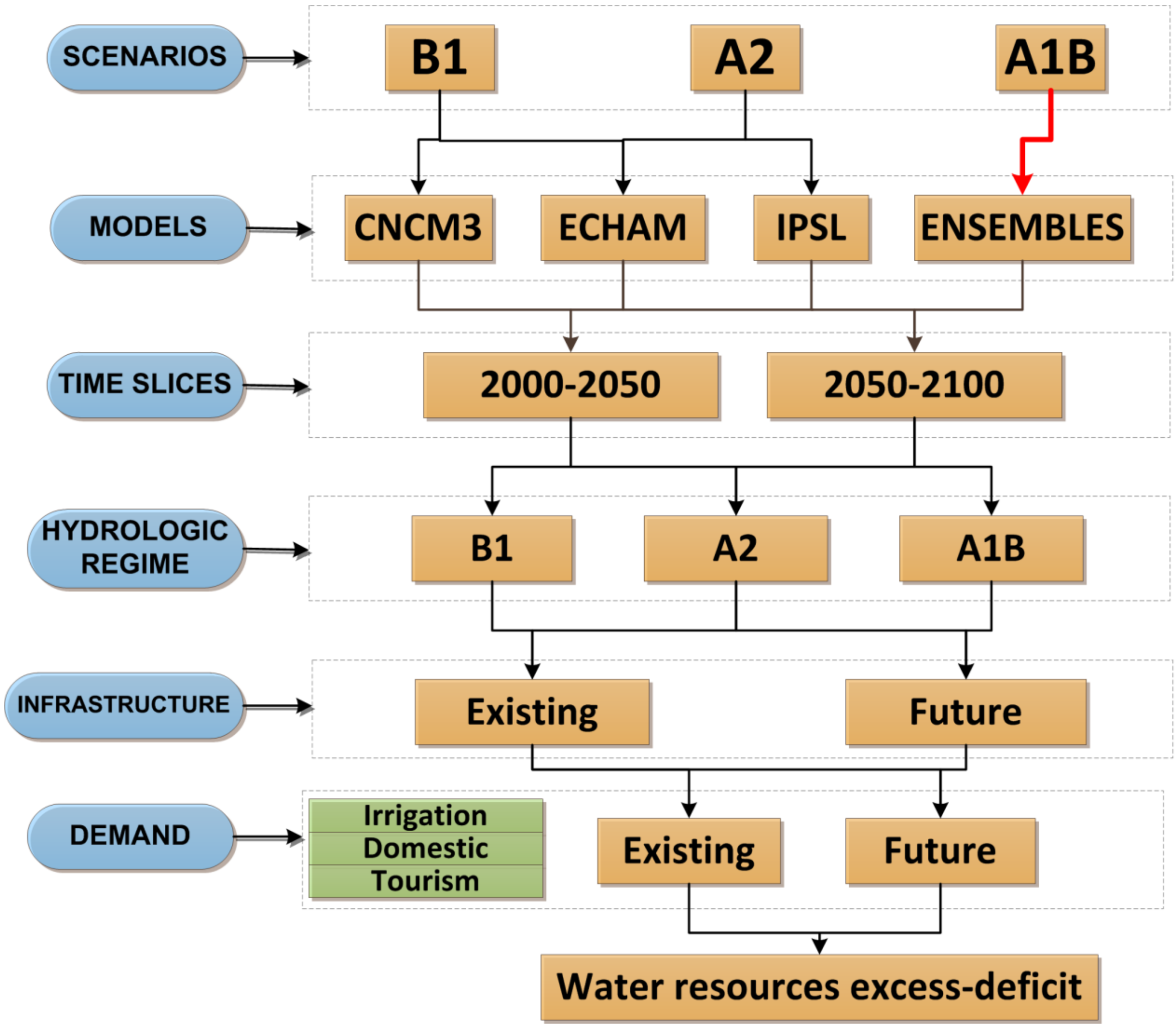


Figure 1. Water resources assessment framework.

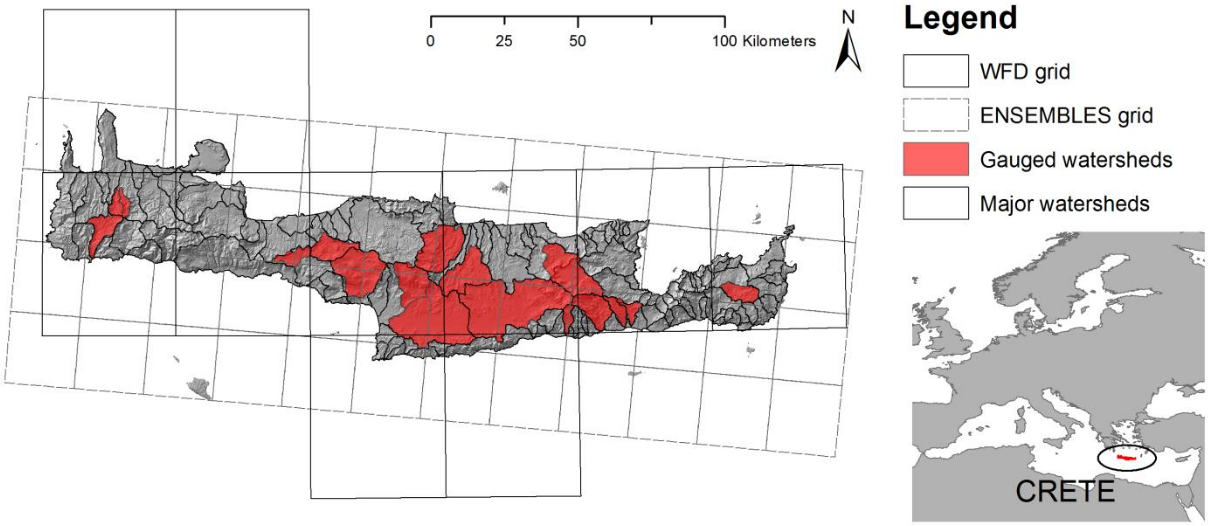


Figure 2. Location of Crete Island, delineated watersheds and the mesh of the ENSEMBLES RCMs and WATCH climate models data (WFD). Red areas represent gauged watersheds at the outlets.

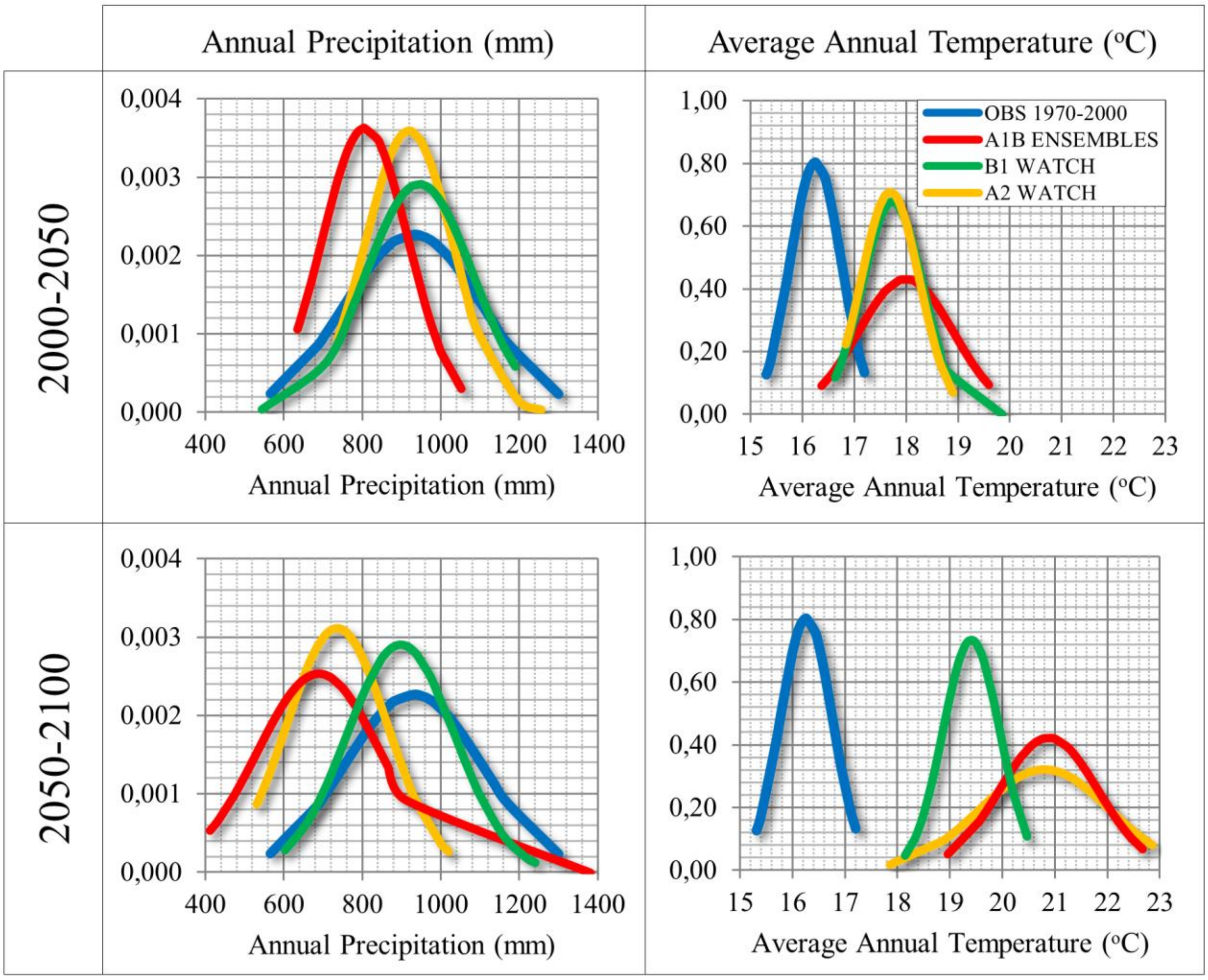
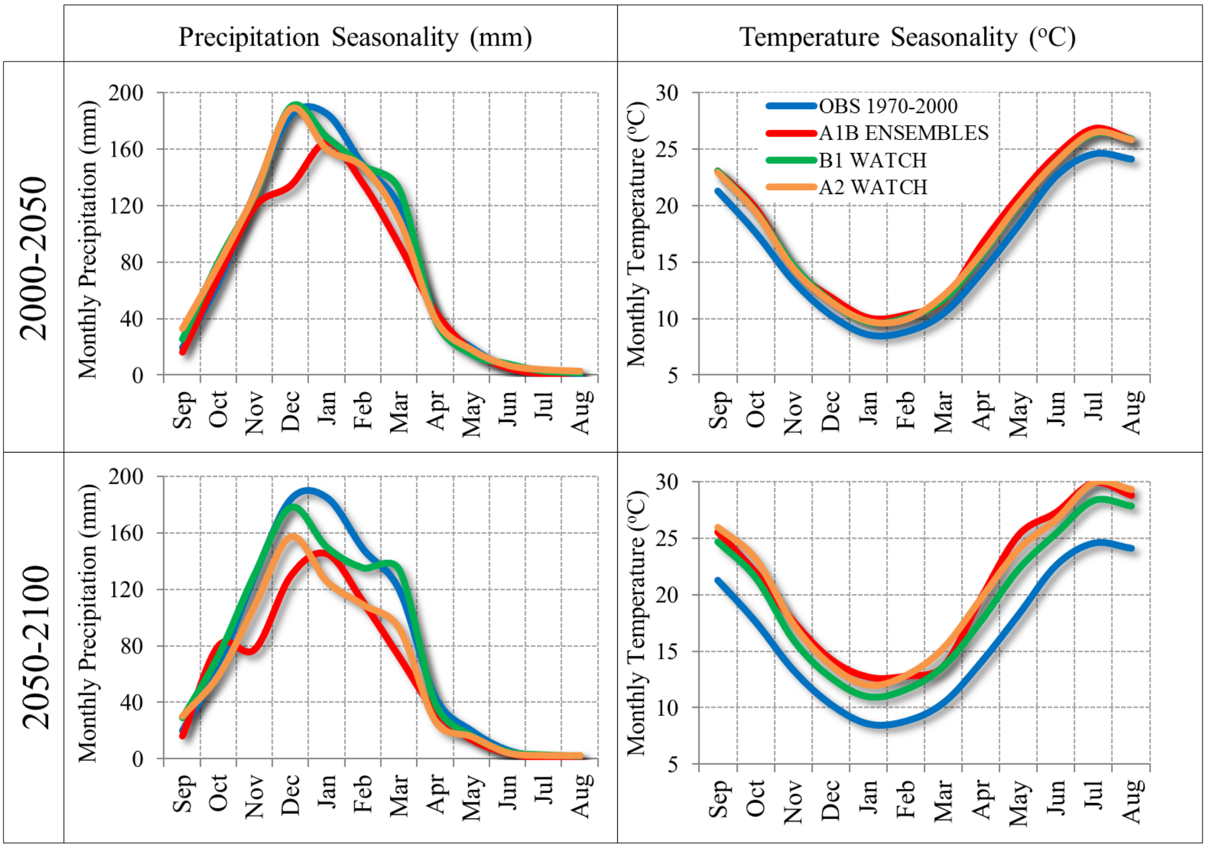


Figure 3. Normal PDFs representing the average bias adjusted WATCH models and weighted bias-adjusted results of all ENSEMBLES members per time slice for (a) annual precipitation (left panels) and (b) average annual temperature (right panels).



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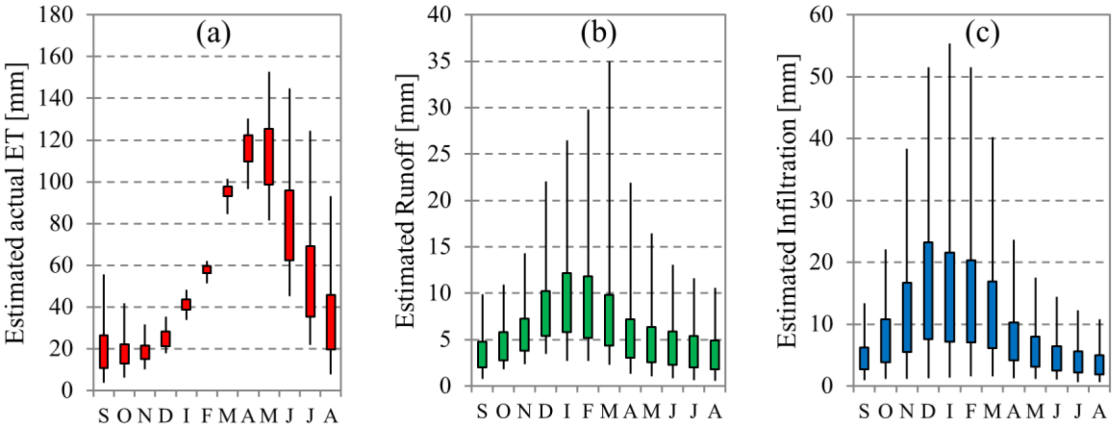

Figure 5. Monthly estimated (a) actual ET, (b) Runoff and (c) Infiltration for the period 1970-1999. Solid boxes signify values from 1st to 3rd quantile while whiskers extend for the zero to the 4th quantile.

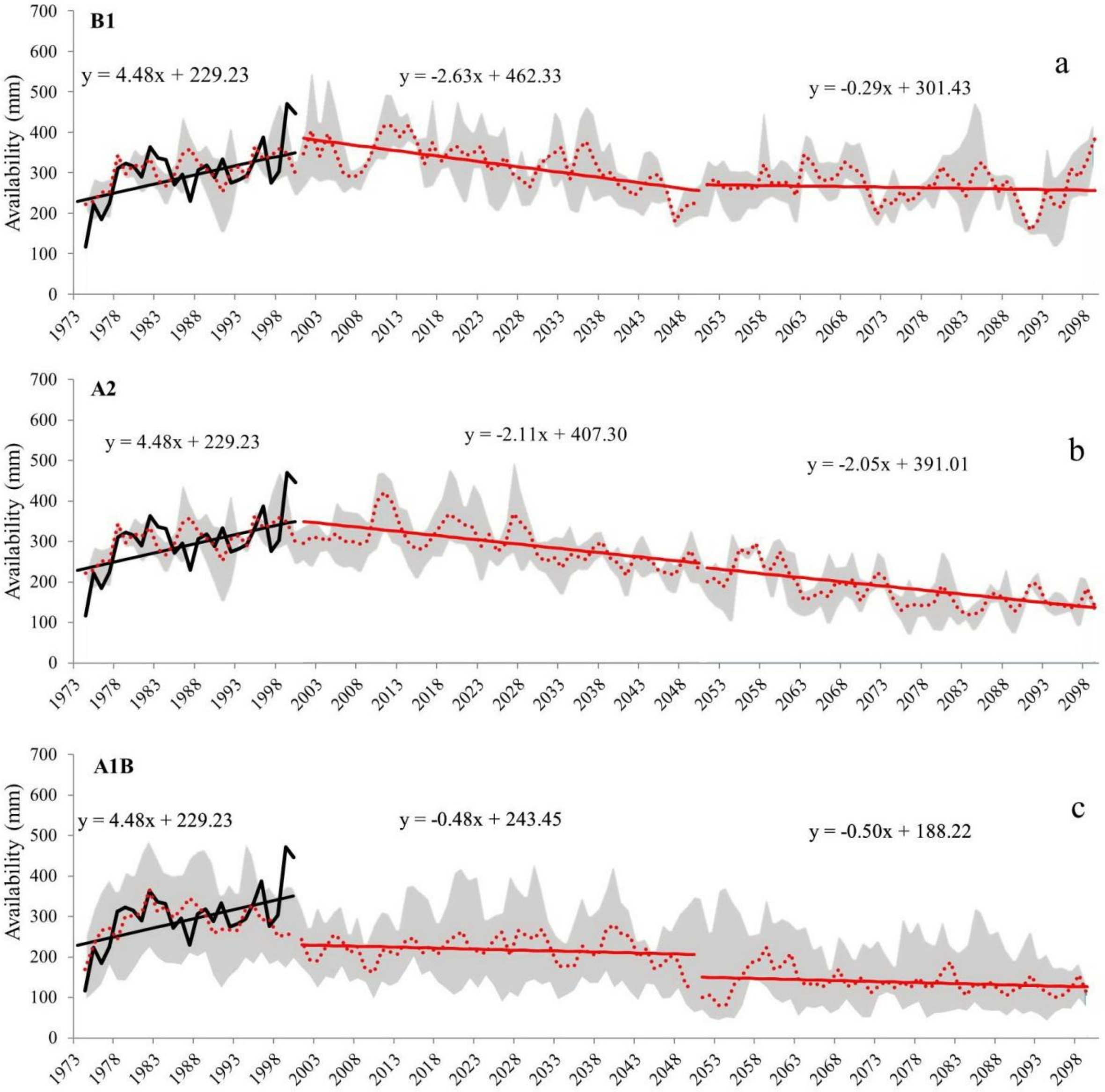

Figure 6. Black lines depict the historical simulated annual availability based on observations. Red dotted lines correspond to historical and projected multi-model mean annual availability. Trend lines represent the average annual availability slopes for the observed period (in black) and for the ensemble projections (in red) under (a) B1, (b) A2 and (c) A1B emission scenarios. Grey areas indicate the amplitude of historical and projected availability of multi-model RCM and GCM ensembles and hydrological modeling.

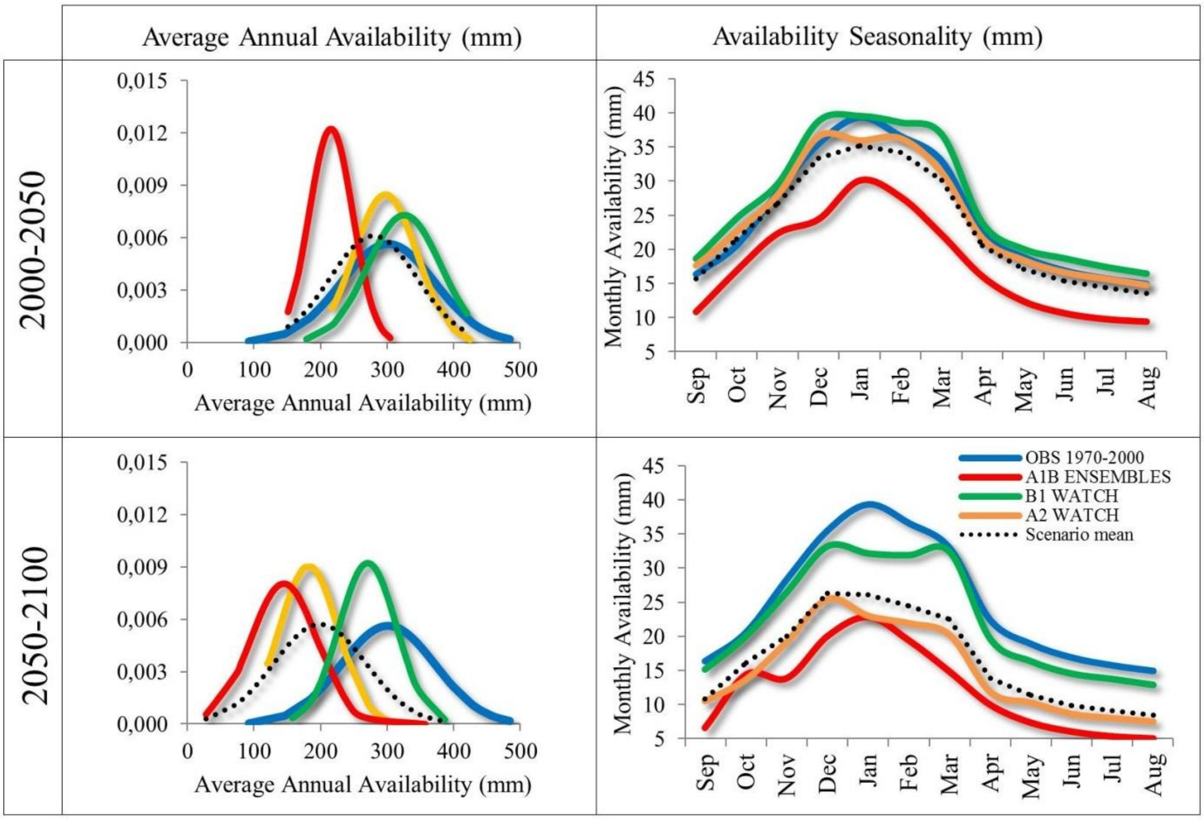

Figure 7. Normal PDFs representing the average bias adjusted WATCH models, weighted bias-adjusted results of all ENSEMBLES members and scenarios mean per time slice for average annual availability (left panels). Seasonality shift of monthly availability (right panels). Three models for WATCH and 10 for ENSEMBLES used to construct the corresponding PDFs.

Tables

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Table 1. Selected hydrologic characteristics and SAC-SMA calibration results for 15 gauged basins on the island of Crete.

	Area [km^2]	**Average Annual [mm]**	**Average Anuual [mm]**	**Average Runoff [mm]**			
Patelis	60.5	804.0	1,460.0	102.3	0.87	0.87	0.73
Kalamafkianos	35.2	733.1	1,516.8	176.9	0.78	0.80	0.75
Myrtos	97.8	759.6	1,501.1	63.9	0.63	0.63	0.59
Arvi	26.1	723.2	1,471.7	240.7	0.79	0.79	0.64
Aposelemis	201.0	922.2	1,383.1	31.0	0.69	0.69	0.53
Anapodaris	506.1	670.3	1,399.7	11.8	0.89	0.89	0.69
Giofyros	158.4	802.8	1,414.4	37.2	0.80	0.79	0.75
Gazanos	186.7	884.5	1,399.1	31.3	0.71	0.70	0.50
Koutsoulidis	121.0	924.8	1,427.8	48.3	0.86	0.86	0.80
Geropotamos	396.5	680.9	1,423.6	14.8	0.90	0.89	0.21
Platys	203.2	925.9	1,450.6	28.9	0.90	0.90	0.69
Prassanos	88.2	1,100.6	1,451.3	67.0	0.64	0.64	0.80
Kakodikianos	77.4	1,292.8	1,482.4	76.8	0.52	0.51	0.48
Sebroniotis	27.5	1,285.3	1,441.9	217.2	0.83	0.82	0.82
Roumatianos	22.1	1,318.0	1,432.9	271.9	0.66	0.65	0.70

Table 2. Observed and simulated annual inputs and outputs in the hydrological budget of the island of Crete during normal, humid and dry years using Sacramento for the period 1970-1999.

	Annual	**Annual**	**Runoff**	**Infiltration**
Observed Average [mm]	934	635-710	93-140	131-159
Observed Fraction of Precipitation [%]		68-76%	10-15%	14-17%
Observed Average [1000Mm^3]	7.70	0.77-1.56	5.23-5.85	1.08-1.30
Simulated Normal year (1978) [1000Mm^3]	7.95	5.84 (73%)	0.87 (11%)	1.25 (16%)
Simulated Wet year (1981) [1000Mm^3]	8.88	5.82 (66%)	1.39 (16%)	1.67 (19%)
Simulated Dry year (1985) [1000Mm^3]	5.63	3.96 (70%)	0.73 (13%)	0.94 (17%)

Table 3. List of Ensembles Regional Climate models (RCMs).

No	Institute	RCM	Driving GCM	References
1	ETH	CLM	HadCM	Jaeger et al. (2008)
2	ICTP	RegCM	ECHAM5-r3	Giorgi and Mearns (1999)
3	KNMI	RACMO2	ECHAM5-r3	van Meijgaard et al. (2008)
4	METOHC	HadRM3Q0	HadCM3Q0	Collins et al. (2010)
5	METOHC	HadRM3Q3	HadCM3Q3	Collins et al. (2010)
6	METOHC	HadRM3Q16	HadCM3Q16	Collins et al. (2010)
7	C4I	RCA3	HadCM3Q16	Kjellström et al. (2005)
8	MPI	REMO	ECHAM5-r3	Jacob (2001)
9	SMHI	RCA	BCM	Kjelltrom et al. (2005)
10	DMI	HIRHAM	ARPEGE	Christensen et al. (2006)

Table 4. Projected (2000-2050) climate models and hydrological model results for annual precipitation, temperature and availability for the island of Crete, under 3 emission scenarios.

PRECIPITATION (mm)						Comparison to control climate (1970-2000)			
		IPSL	ECHAM	CNCM	ENSEMBLES	IPSL	ECHAM	CNCM	ENSEMBLES
OBS (1970-2000)		934							
2000-2050	B1	961	943	931		103%	101%	100%	
	A2	911	939	908		98%	101%	97%	
	A1B				807				86%

TEMPERATURE (°C)						Comparison to control climate (1970-2000)			
		IPSL	ECHAM	CNCM	ENSEMBLES	IPSL	ECHAM	CNCM	ENSEMBLES
OBS (1970-2000)		16.3							
2000-2050	B1	18.3	17.4	17.6		2.0	1.1	1.3	
	A2	18.0	17.3	17.7		1.7	1.0	1.4	
	A1B				18.0				1.7

Availability (mm)						Comparison to control climate (1970-2000)			
		IPSL	ECHAM	CNCM	ENSEMBLES	IPSL	ECHAM	CNCM	ENSEMBLES
OBS (1970-2000)		299							
2000-2050	B1	329	333	310		110%	111%	104%	
	A2	294	298	296		98%	100%	99%	
	A1B				214				72%

Table 5. Projected annual supply potential according to hydrological modeling results for the island of Crete, under the 2 infrastructure (S1 and S2) and the 3 emission scenarios.

		Supply S1 (Mm^3)					Supply S2 (Mm^3)				
		IPSL	ECHAM	CNCM	ENSEMBLES	Average	IPSL	ECHAM	CNCM	ENSEMBLES	Average
2000-2050	B1	456	462	430		449	588	595	554		579
	A2	408	413	410		410	525	532	529		529
	A1B				297	297				382	382
2050-2100	B1	402	323	397		374	518	416	511		482
	A2	275	215	262		251	354	277	338		323
	A1B				200	200				257	257

Table 6. Projected (2050-2100) climate models and hydrological model results for annual precipitation, temperature and availability for the island of Crete, under 3 emission scenarios.

PRECIPITATION (mm)						Comparison to control climate (1970-2000)			
		IPSL	ECHAM	CNCM	ENSEMBLES	IPSL	ECHAM	CNCM	ENSEMBLES
OBS (1970-2000)		934							
2050-2100	B1	932	827	935		100%	89%	100%	
	A2	769	673	764		82%	72%	82%	
	A1B				688				74%

TEMPERATURE (°C)						Comparison to control climate (1970-2000)			
		IPSL	ECHAM	CNCM	ENSEMBLES	IPSL	ECHAM	CNCM	ENSEMBLES
OBS (1970-2000)		16.3							
2050-2100	B1	20.0	19.3	18.9		3.7	3.0	2.6	
	A2	21.5	20.2	20.7		5.2	3.9	4.4	
	A1B				20.9				4.6

Availability (mm)						Comparison to control climate (1970-2000)			
		IPSL	ECHAM	CNCM	ENSEMBLES	IPSL	ECHAM	CNCM	ENSEMBLES
OBS (1970-2000)		299							
2050-2100	B1	290	233	286		97%	78%	96%	
	A2	198	155	189		66%	52%	63%	
	A1B				144				48%

Table 7. Estimated excess-deficit of the water balance from the combination of all components.

SCENARIO	Period	Emission scenario	Hydrologic regime	Demand	Infrastructure	Est. Demand (Mm^3)	Est. Supply (Mm^3)	Est. Deficit (Mm^3)	Est. Excess or Deficit (%)	Difference from BAU (Mm^3)
1 BAU	1970-2000		Normal	D1	S1	536	414	-122	-23%	0
1	2000-2050	B1	WATCH	D1	S1	536	449	-87	-16%	35
2				D1	S2	536	579	43	8%	165
3				D2	S1	776	449	-327	-42%	-205
4				D2	S2	776	579	-197	-25%	-75
5		A2	WATCH	D1	S1	536	410	-126	-24%	-4
6				D1	S2	536	529	-7	-1%	115
7				D2	S1	776	410	-366	-47%	-244
8				D2	S2	776	529	-247	-32%	-125
9		A1B	ENSEMBLES	D1	S1	536	297	-239	-45%	-117
10				D1	S2	536	382	-154	-29%	-32
11				D2	S1	776	297	-479	-62%	-357
12				D2	S2	776	382	-394	-51%	-272
13	2050-2100	B1	WATCH	D1	S1	536	374	-162	-30%	-40
14				D1	S2	536	482	-54	-10%	68
15				D2	S1	776	374	-402	-52%	-280
16				D2	S2	776	482	-294	-38%	-172
17		A2	WATCH	D1	S1	536	251	-285	-53%	-163
18				D1	S2	536	323	-213	-40%	-91
19				D2	S1	776	251	-525	-68%	-403
20				D2	S2	776	323	-453	-58%	-331
21		A1B	ENSEMBLES	D1	S1	536	200	-336	-63%	-214
22				D1	S2	536	257	-279	-52%	-157
23				D2	S1	776	200	-576	-74%	-454
24				D2	S2	776	257	-519	-67%	-397