Regional effects of climate change on hydrology and water resources in Aliakmon River basin

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Abstract The impacts of climate change on the water cycle of the Aliakmon River basin in Western Macedonia and the operation of the Polyfito reservoir are examined in the current study. Two climate change scenarios, the UKHI and HadCM2, are applied to estimate the climatically induced changes in the water cycle and the altered inflows to the reservoir. A reduction of the mean monthly runoff and an increase of the potential evapotranspiration in the study area are observed under climatically changed conditions. The results show an increase of the risk associated with the annual hydroelectric energy production of the Polyfito reservoir. In order to maintain the risk at the design level, storage volume increases are required. These results are in accordance with the results of previous studies referring to the assessment of climate change impacts on the water resources and on the design and operation of reservoirs in central Greece.

Key words climate change; hydrology; reservoirs; water resources

NOTATION

- \( b_t \) Is a monthly distribution coefficient of the primary annual energy production
- \( E \) Is the primary annual energy production (GWh)
- \( E_t \) Is the monthly energy production (GWh)
- \( I_t \) The monthly inflow in the reservoir (m\(^3\))
- \( N_t \) Losses (seepage) during month \( t \) (m\(^3\)).
- \( P_t \) The monthly precipitation on the reservoir (m\(^3\))
- \( Q_t \) Monthly discharge from the reservoir (m\(^3\))
- \( q_t \) Secondary releases during month \( t \) (m\(^3\)).
- \( R_t \) The monthly evaporation from the surface of the reservoir (m\(^3\))
- \( V_t \) The water volume stored at the beginning of month \( t \) (m\(^3\))
- \( V_{t+1} \) The water volume stored at the end of month \( t \) (m\(^3\))
- \( W \) The primary annual water quantity used by the turbines (m\(^3\))
- \( \alpha_t \) The monthly distribution coefficient of \( W \)

INTRODUCTION

The current study aims on the assessment of the climate change impacts on the hydrological cycle and the design and operation of multipurpose reservoirs (Mimikou,
The study area is the Ilarion basin of the Aliakmon River in Western Macedonia, whereas the Polyfito reservoir located on the Aliakmon River is used as a case study.

The impacts of climate change have been estimated with the use of two climate change experiments, one equilibrium, the UKHI and one transient the HadCM2. The hydrological cycle of the basin has been simulated using the WBUDG model (Mimikou et al., 1991a) for the base run (accounting for no climate change) and the results of the two climate change experiments. The terminal year for the simulations is the year 2050.

The impacts of climate change on the operation of the Polyfito reservoir have been studied using a simple reservoir budget model and performing sensitivity analysis of the risk associated with the annual levels of hydroelectric power production. The performed simulations used base run inflows and both UKHI and HadCM2 climatically changed inflows.

Finally, the results are compared with those of previous conducted studies, regarding four reservoirs in the mountainous region of central Greece. In this case, hypothetical climate change scenarios were used.

THE STUDY AREA

The study area is the Ilarion basin of the Aliakmon River in western Macedonia, situated between latitudes 39° 30’ N and 40° 30’ N and longitudes 20° 30’ E and 22° 00’ E. A representation of the basin can be seen in Figure 1. Some general characteristics of the basin are presented in Table 1. Geomorphologically, the basin consists of wide vegetated plains without deep slopes.

![Fig. 1 The study area, the Ilarion basin.](image-url)
Table 1 General characteristics of the Ilarion basin.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area, Mean elevation</td>
<td>5005 km², 901 m</td>
</tr>
<tr>
<td>Mean annual observed temperature</td>
<td>11.0°C</td>
</tr>
<tr>
<td>Mean annual observed rainfall</td>
<td>825.1 mm</td>
</tr>
<tr>
<td>Mean annual observed runoff</td>
<td>49.0 m³ s⁻¹</td>
</tr>
<tr>
<td>Sub-basin river length</td>
<td>161.0 km</td>
</tr>
</tbody>
</table>

CLIMATE CHANGE SCENARIOS

The UKHI climate change experiment

The UKHI scenario is an equilibrium climate change experiment performed using an atmospheric GCM coupled to a simple representation of the ocean (Hulme et al., 1994). Equilibrium climate change experiments simulate the climate system twice. First a control level of CO₂ concentration (or equivalent, representing the combined forcing of all the greenhouse gases) is specified for the atmosphere and the model is integrated until a stable climate is reached. The simulated climate was integrated for 10 years once equilibrium had been reached. The equivalent CO₂ concentration was then doubled and once again the model integrated until the simulated climate had reached equilibrium. The difference of the two climates can then be used as an estimate of the sensitivity of the climate system to a doubling of CO₂.

The HadCM2 climate change experiment

HadCM2 is the Hadley’s Centre’s second generation coupled ocean–atmosphere GCM (Hulme et al., 1994). It has been used to perform a series of transient climate change experiments that have been perturbed using both historic greenhouse gas and combined greenhouse gas and sulphate aerosol forcing. These generation experiments represent a large step forward in the way the climate system was modelled. These experiments overcome some of the major difficulties that were associated with the previous generations of equilibrium and transient climate change experiments.

Downscaling

Raw output from GCMs is rarely used in assessments of the environmental and economic impacts of climate change because of the relatively coarse spatial scale. Therefore the GCM information was downscaled using a statistical (empirical) approach which consisted of the identification of quantitative relationships between the observed large-scale and regional climate, which were then applied to the large-scale GCM output (Hewitson & Crane, 1996). For the Ilarion basin, the climate change information grid was downscaled from its initial resolution of 2.5° × 3.75° to a resolution of 50 × 50 km, resulting in nine grid cells for the study area (Fotopoulos, 2000).
THE HYDROLOGICAL WATER BALANCE MODEL—WBUDG

The water balance model has been fully described in a number of previous publications (Mimikou et al., 1991a, 1999; Mimikou & Kouvopoulos, 1991). The input parameters of the model are precipitation, mean monthly temperature, relative humidity, wind speed, and relative sunshine. The time step of the model is monthly.

For each month, the model estimates runoff, potential evapotranspiration (in the current simulations with the Blaney-Criddle method) and a number of other hydrological indicators, i.e. soil moisture, etc. The flow chart of the model and the input-output parameters and variables are shown in Figure 2.

IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

The results of the simulations under climatically changed conditions can be seen in the following figures. Figure 3 represents the mean monthly runoff for the base run (no climate change) and for HadCM2 and UKHI changed conditions. Figure 4 represents the induced changes in mean monthly potential evapotranspiration. From these figures one can see that a significant reduction of the mean monthly runoff and an increase of the evapotranspiration are observed for both scenarios. The two experiments examined provide consistent results, whereas the UKHI runs give smaller changes.

Fig. 2 Flow chart of the WBUDG model.
THE RESERVOIR MODEL

The Polyfito reservoir is situated on the Aliakmon River, east of the Ilarion basin. It is a multipurpose reservoir. Water stored is used for hydropower production, irrigation and water supply of the thermoelectric plant of Ptolemaida. In the near future it is intended to use water from the reservoir for the supply of drinking water for the city of Thessaloniki.

It is straightforward that a multipurpose reservoir like the Polyfito should operate with tolerable risk levels concerning water and energy availability.

The operation of the reservoir is described from the water balance equation, taking into account constraints regarding the storage volume, the reservoir outflow, and the energy production. The water balance equation used with a monthly time step is the following:

\[ V_{t+1} = V_t + I_t - P_t - R_t - \alpha_t W - q_t - N_t \]  

(1)
This equation operates under several constraints as follows:

\[ V_{\text{min}} \leq V_t \leq V_{\text{max}} \]  
\[ Q_{\text{min}} \leq Q_t = \alpha_t W + q_t \leq Q_{\text{max}} \]  
\[ b_t E \leq E_t \]

For the simulations, equation (1) was slightly modified. From field studies it has been found that the losses \( N_t \) are minor and thus can be neglected, whereas recorded data from neighbouring stations indicated that reservoir’s precipitation \( P_t \) and evaporation \( R_t \) cancel each other. Finally, there is no leakage from the spillway culvert and all the water stored in the reservoir flows through the turbines. In general, those simplifications do not affect the sensitivity analysis conducted.

**IMPACTS OF CLIMATE CHANGE ON THE DESIGN AND OPERATION OF THE POLYFITO RESERVOIR**

The main conclusion of the current study regarding the current operation of the Polyfito reservoir is that it is highly affected by the climate change scenarios considered. The risk associated with the annual energy production is increased, especially when applying the HadCM2 climate change experiment, as shown in Table 2 and in Fig. 5.

**Table 2** Results of risk analysis for the Polyfito reservoir.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base Run</th>
<th>UKHI</th>
<th>HadCM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of risk in annual primary energy E</td>
<td>0.25–1.76</td>
<td>0.26–2.03</td>
<td>0.3–2.05</td>
</tr>
<tr>
<td>Risk of minimum annual primary energy E</td>
<td>0.30</td>
<td>0.31</td>
<td>0.34</td>
</tr>
<tr>
<td>Risk of mean annual primary energy E</td>
<td>1.40</td>
<td>1.58</td>
<td>1.60</td>
</tr>
</tbody>
</table>

**Fig. 5** Changes in the annual primary energy production associated with risk for the base run (thick line), UKHI scenario (dashed line) and HadCM2 scenario (thin line).
Table 3 Increase of reservoir’s volume storage required to maintain the risk in same levels.

<table>
<thead>
<tr>
<th>Variable</th>
<th>UKHI</th>
<th>HadCM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum annual primary energy E (199.4 GWh)</td>
<td>12%</td>
<td>13%</td>
</tr>
<tr>
<td>Mean annual primary energy E (515 GWh)</td>
<td>31%</td>
<td>33%</td>
</tr>
</tbody>
</table>

The annual energy production is directly dependent on the water storage of the reservoir (Klemes, 1982; Fotopoulos, 2000). The current volume of storage does not guarantee the primary annual energy production under changed climatic conditions, as implied by the climate change scenarios considered. Therefore, it is necessary to increase the storage volume of the reservoir in order to maintain the risk at tolerable levels. The results of the sensitivity analysis performed are shown in Table 3. From this table one can see that increases of 12% and 31% for the minimum and mean annual energy production, respectively, for the UKHI and 13% and 33%, respectively, for the HadCM2 scenario are needed in order to maintain the risks at the design levels.

These conclusions are in accordance with the conclusions drawn up from previous conducted research (Mimikou et al. 1991b, 1999; Mimikou & Baltas 1997) related to the impact of climate change on reservoir reliability in central Greece. In these studies, severe increases of the risks associated with the annual water supply and the energy production of the four reservoirs examined were observed, by using hypothetical scenarios with temperature increases ranging from 1 to 4°C. In addition, radical increases of the reservoir storage volumes were required in all cases to maintain water yield at tolerable risk levels.

**CONCLUSIONS**

The conclusions drawn from this research are the following:

(a) A significant reduction in mean monthly runoff occurs throughout the year under the climatically changed conditions examined. The increase in mean monthly temperature also results in an increase of the potential evapotranspiration.

(b) A comparison of the results for the two climate change scenarios examined shows consistency for the two experiments. In all hydrological indicators, the HadCM2 runs give higher changes (with respect to the base run), whereas the UKHI runs give smaller changes.

(c) Regarding the reservoir operation, the two climate change experiments result in increased risk levels of hydroelectric power production, for both the minimum and the mean annual energy quantity. The risk associated with the HadCM2 runs is higher than the risk estimated with the UKHI runs. Concerning the increase of volume storage in order to meet the design energy demand, this would be 12% and 31% for the minimum and mean annual energy production, respectively, for the UKHI implied changes. For the HadCM2 changes, a further increase of the storage volume is needed (13% and 33%, respectively) due to the higher changes estimated from this scenario.

(d) The above results are in accordance with the results of previous conducted studies regarding reservoirs in central Greece. A dramatic increase of risk levels of the
examined reservoirs associated with the annual firm water and energy production is exhibited under plausible hypothetical scenarios. Radical increases of the reservoir storage volume are required in all cases to maintain water yield in tolerable risk levels.

REFERENCES


