# Land Use and Climate Change Impacts on the Reliability of Hydroelectric Energy Production

*E.A. Baltas and M.C. Karaliolidou*

## ABSTRACT

This article examines the impacts of land use and climate change on the operational reliability of a multipurpose reservoir in Northern Greece. Four land use change scenarios (deforestation by 5%, 10%, and 20%, and reduction of agricultural land by 10%) and a climate change scenario (HadCM2) were examined. A reservoir simulation model was applied for the period 2008-2050, and the sensitivity of the risk associated with the annual hydroelectric energy production was evaluated under conditions of altered runoff. Significant increases of the risks associated with the annual energy production were observed, under both climate and land use change scenarios.

**Keywords**: Northern Greece, reservoir, simulation model, hydropower

## INTRODUCTION

A rising demand for electricity, likely increases in fossil fuel prices, and the need for clean, emission-free generation sources all appear to be trends in favor of increasing generation from alternative sources, including hydropower (Harrison & Whittington, 2002). In the mid 1990s hydropower plants accounted for some 19% of total electricity production worldwide, and the installed capacity amounted to 22% of the total installed capacity for electricity generation. The situation within Europe, although locally differentiated, is also generally in the same relative order of magnitude (European Commission, 2000).

Since the 1970s, the annual energy production of some existing hydropower stations in Europe has decreased, in particular in Portugal, Spain, and other southern European countries (UCTE, 1999). This reduction has been attributed to changes in average discharge, but it is not yet fully known whether this is due to temporary fluctuations or is already the consequences of long-term changing conditions, such as climate and land use changes. However, given the importance of hydropower, and anticipating the scenarios of increasing water stress, the assessment of environmental change impacts on discharge and the linked hydroelectricity production is of high interest.

Land use and climate changes are among the most urgent issues of today's hydrological research, as they directly or indirectly influence many hydrological processes and consequently, water resources management. There are several indications that changes in land cover have influenced the hydrological regime of various river basins. In addition, the effects of climate change on the hydrological cycle and on runoff behavior of river catchments have been discussed extensively in recent years (Bronstert *et al*, 2002).

Hydropower generation is the energy source that is most likely to be affected by these changes, because it is sensitive to the amount, timing, and geographical pattern of streamflows. Where reduced streamflows occur, they are expected to negatively impact hydropower production, and greater streamflows, if they are timed correctly, might help hydroelectric production. In some regions, change of streamflow timing from spring to winter may increase hydropotential more in the winter than it reduces it in the spring and summer, but there is a question of whether the electric system can take advantage of the increases in winter flows and whether storage would be adequate. Hydroelectric projects generally are designed for a specific river flow regime, including a margin of safety. Climate and land use changes are expected to change flow regimes outside these safety margins in some instances (Scott *et al*, 2001). Although it is not yet possible to provide reliable forecasts of shifts in flow regimes, what is known suggests that these changes are likely to induce important consequences on hydroelectric projects designed and operated under current conditions.

To study impacts of land use and climate change on hydrological processes and the linked hydroelectricity production, information on the way they will occur in the future is necessary. The analysis of land use changes in a region is a rather complex task, since different aspects must be taken into account. The question as to which areas of the actual land use will be converted into what other type depends both on the physical properties of the specific region and on various socio-economic factors. A range of models has been developed to better understand, assess, and project changes in land use and land cover. However, in spite of progress in integrating biophysical and socioeconomic drivers of land use change, prediction of future land use change remains difficult. So, scenario analysis provides an alternative tool to assist in explorations of the future (Rounsevell *et al*, 2006). The challenge in modelling such changes is to take into account as many influencing factors as possible in the simulation calculations (Lahmer *et al*, 2000).

As regards climate change, quantitative estimates of changes in major long-term climatic variables such as temperature, precipitation, and evapotranspiration are needed in order to provide reliable forecasts of regional hydrological processes. On the other hand, we still do not know in detail how these changes will affect water availability. Influences of climate change on water balance may result from both spatial and temporal precipitation shift, changes of the actual evapotranspiration due to temperature increases, and an increase of extreme meteorological events. General circulation models (GCMs) are still not able to provide valuable detailed information on regional impacts on water supplies. Nevertheless, they are considered to provide the best basis for the construction of climate change scenarios and, in combination with regional hydrological models, they can be a method of exploring the effects of a range of possible climate change scenarios (CRU, 2000a).

This article is focused on the assessment of the impacts of both climate and land use changes on the operational reliability of the Ilarion reservoir, a multipurpose reservoir in Northern Greece. The operation of the reservoir was simulated using a water budget model, under different land use and climate change scenarios, and the sensitivity of the risk associated with the annual hydroelectric energy production of the reservoir was evaluated under conditions of altered runoff.

## STUDY AREA AND DATA USED

The Ilarion reservoir is a multipurpose reservoir that is currently under construction. It is the forth reservoir along the Aliakmon river, in Northern Greece, and the first starting from upstream. The reservoir will be used mainly for hydroelectric power generation, but it will also provide water in order to satisfy irrigation and water supply needs. Necessary information on the characteristics of the reservoir, and on the hydroelectric production of the power plant, were acquired from the archives of the Public Power Corporation of Greece. Some technical characteristics are shown in Table 1, while Figure 1 depicts the Ilarion basin and the reservoir site.

The river basin (between 39°30′S to 40°30′N and 20°30′W to 20°E) at the Ilarion dam site has a drainage area of 5005 km$^2$, and its topography varies from narrow gorges to wide flood plains. Some general characteristics of this basin are given in Table 2.

**Table 1. Design characteristics of the Ilarion reservoir**

| | |
|---|---|
| Maximum storage capacity ($\times 10^6 m^3$) | 520 |
| Minimum storage capacity ($\times 10^6 m^3$) | 108 |
| Storage capacity corresponding to maximum flood level ($\times 10^6 m^3$) | 626 |
| Maximum power pool (m) | 403 |
| Maximum flood level (m) | 407.6 |
| Pool area corresponding to maximum power pool (km$^2$) | 21.9 |
| Minimum (guaranteed) energy (GWh/year) | 220.2 |
| Maximum (guaranteed) energy (GWh/year) | 415.7 |
| Number of turbines | 2 |
| Power of each turbine (MW) | 60 |

**Table 2. General characteristics of the Ilarion basin**

| | |
|---|---|
| Area (km$^2$) | 5005 |
| Mean elevation (m) | 917 |
| Mean annual historical temperature (°C) (1970 – 2002) | 11.0 |
| Mean annual historical precipitation (mm) (1970 – 2002) | 825.1 |
| Mean annual historical runoff (m$^3$/sec) (1970 – 1988) | 49 |
| Mean annual specific runoff (m$^3$/sec/km$^2$) (1970 – 1988) | 0.0098 |
| River length (km) | 161 |

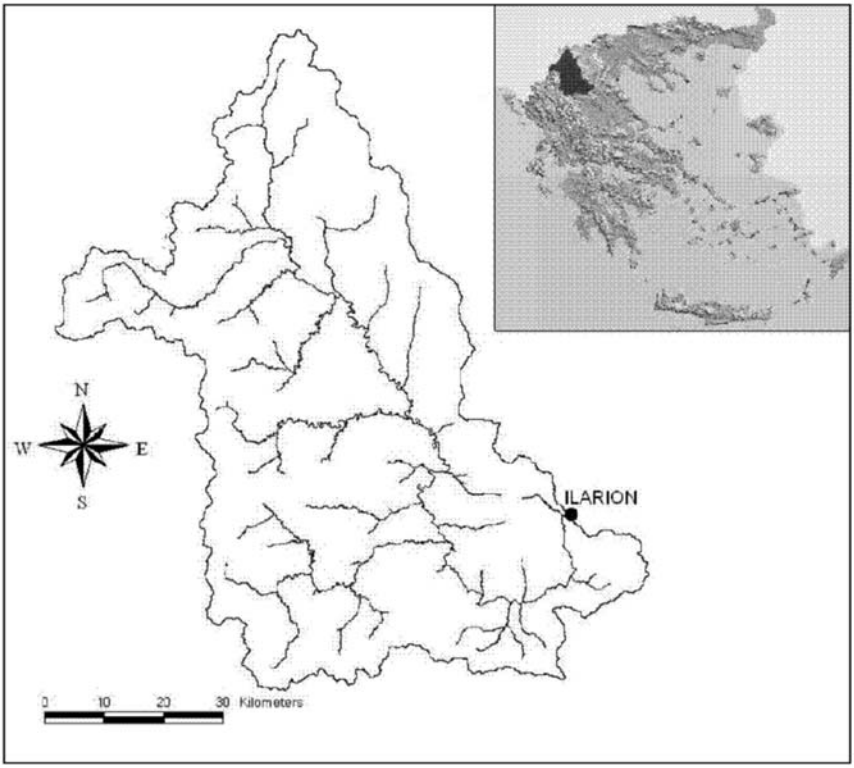

**Figure 1.** The Ilarion basin (Aliakmon river), in Greece

For the application of the reservoir simulation model, mean monthly runoff values at the Ilarion site (outlet of Ilarion basin) were necessary in order to be used as monthly reservoir inflows. Mean monthly runoff at this site was estimated in a previous study, under current conditions as well as under different climate and land use change scenarios. In this study, the hydrologic model Soil and Water Assessment Tool (SWAT) was calibrated and validated using historical data of the period 1971-2002, and then it was implemented using a climate change scenario (HadCM2) and four land use change scenarios (deforestation by 5%, 10%, and 20%, and reduction of agricultural land by 10%). In this way, mean monthly runoff was calculated at the Ilarion site for each scenario and for the period 2003-2050. For more details the reader is referred to Baltas & Karaliolidou (2007).

## RESERVOIR MODEL

The operation of the Ilarion reservoir is described by the water balance equation under various constraints concerning storage volume and outflow from the reservoir and energy production. The water balance equation applied on a monthly basis has the following form (Mimikou & Baltas, 1997, Baltas & Mimikou, 2005):

$$V_{t+1} = V_t + I_t + P_t - R_t - a_t W - q_t - N_t \qquad (1)$$

where:

$V_t$ = the storage volume at the beginning of month $t$ ($m^3$)
$V_{t+1}$ = the storage volume at the end of month $t$ ($m^3$)
$I_t$ = the monthly reservoir inflow ($m^3$)
$P_t$ = the monthly precipitation over the pool ($m^3$)
$R_t$ = the monthly evaporation from the pool ($m^3$)
$W$ = the annual quantity of water supply through the turbines ($m^3$)
$a_t$= the monthly distribution coefficient of W, $(\sum_{t=1}^{12} a_t = 1)$
$q_t$= the releases over the spillway during month t ($m^3$)
$N_t$= the uncontrollable losses (seepage) during month t ($m^3$)

In this approach, a modified version of equation (1) was used. It was assumed that seepage losses $N_t$ are of minor importance and that no releases over the spillway will be allowed, with the whole water quantity passing through the turbines ($q_t = 0$). Also, calculations have shown that precipitation $P_t$ and evaporation $R_t$ almost cancel each other, a hypothesis which, for simplicity reasons, was kept throughout all runs of the model under the different scenarios. Overall, these discounts do not affect the specific sensitivity analysis pursued. So the following equation was finally used:

$$V_{t+1} = V_t + I_t \qquad (2)$$

The constraint concerning storage volume $V_t$ is:

$$V_{min} \le V_t \le V_{max} \qquad (3)$$

where $V_{min}$ is the minimum storage capacity and $V_{max}$ is the storage capacity corresponding to the maximum flood level.

The mean monthly outflow discharge $Q_t$ during month t must satisfy the constraint:

$$Q_t \leq Q_{max} \tag{4}$$

where $Q_t = (a_tW+q_t)/\Delta t$, where $\Delta t$ is the time interval (month), $q_t$ is the spillway releases taken here equal to zero, and $Q_{max}$ is the maximum flow capacity through the turbines.

The energy $E_t$ produced during month t must not be less than the guaranteed value. Hence:

$$b_tE \leq E_t \tag{5}$$

where E is the annual primary energy supply (GWh) and $b_t$ is the monthly distribution coefficient of E, $(\Sigma_{t=1}^{12} b_c = 1)$.

As regards the monthly distribution coefficients $a_t$ and $b_t$, as the reservoir is under construction and there are not data, it was assumed that $a_t = b_t = 1/12$.

The mean monthly energy values $\overline{E}_t$ (GWh) for the Ilarion reservoir are related to the mean monthly outflow discharges $\overline{Q}_t$ ($10^6$ $m^3$) by the following equation:

$$\overline{E}_t = 0.252019\overline{Q}_t - 0.92925 \tag{6}$$

The relationship between $\overline{E}_t$ and $\overline{Q}_t$ was obtained using data collected from the archives of the Public Power Corporation of Greece. These data included estimations of energy produced and outflow discharges from the reservoir, using as inflows to the reservoir the observed runoff values at the Ilarion site for a 20-year period (1962-1982). The relationship, with a least square curve fitted to the data, is shown in Figure 2.

The water balance in equation (1), under the constraints in equations (3)-(5) and the relationship given in equation (6), were applied in order to simulate the operation of the Ilarion reservoir, under both current conditions and climate and land use change scenarios.

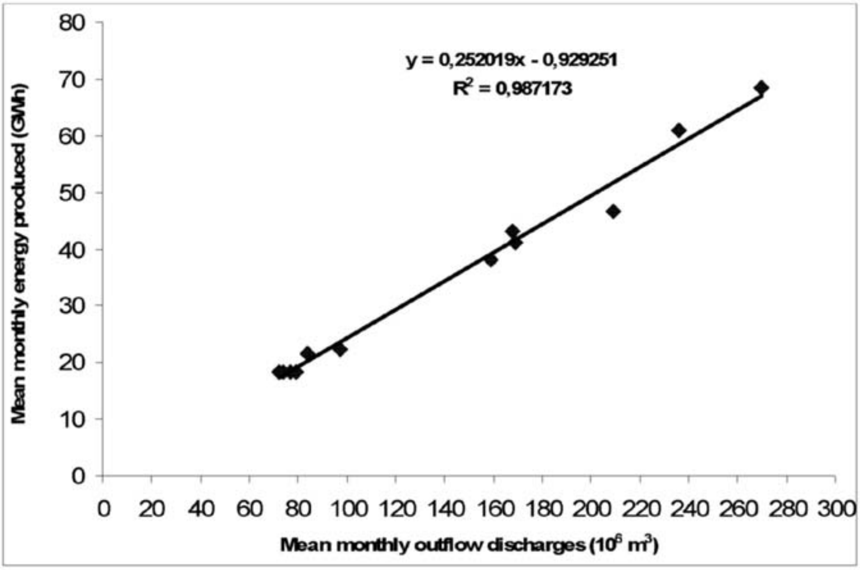

**Figure 2. Mean monthly energy *vs* mean monthly outflow discharge for the Ilarion reservoir**

## IMPACTS ASSESSMENT

### Risk Assessment of Annual Energy Supply Levels

The sensitivity of the operational reliability of the Ilarion reservoir is based on a risk analysis of the annual energy quantities produced from the reservoir. The procedure of risk analysis requires the preselection of a variety of values of the annual primary energy E within a specified range of values in accordance with the reservoir's characteristics. The annual primary energy E was taken to vary between 180 GWh and 420 GWh with a step of 20 GWh, a range which includes the minimum (220.2 GWh) and the maximum (415.7 GWh) energy supply levels guaranteed annually from the Ilarion reservoir. For every E value, the reservoir operation was simulated using equations (1)-(6) for the period from 2008 to 2050.

First, the model was applied for the current climate and land use conditions (base run). As regards the reservoir inflows $I_t$, the values were taken from a previous study (Baltas & Karaliolidou, 2007), where 20 time series of the total basin runoff were calculated using the hydrological model SWAT for the present conditions and for the period

2008-2050. The reservoir model using these 20 inflow series was run to assess the risk for each E value. Thus, for every E value a total of 20 runs of the reservoir model were performed. Further, a failure or risk value was assigned to each inflow series that was equal to the relative (percentage) frequency of monthly failures within the series. A failure was considered to occur when the monthly storage volume $V_t$ and/or the energy $E_t$ violated the constraints in equations (3) and (5), respectively. Then, the risk (or probability of failure) associated with the given E value was estimated as an average value over the 20 time series. By repeating the simulations for every E value in the aforementioned range, a complete set of risk values was constructed, corresponding to the preselected set of E values.

## Risk Assessment under Land Use Change Scenarios

Analysis of different land use change scenarios provides a tool to study impacts of such changes on the surrounding environment and on the hydrological cycle and water resources. In general, the land use change scenarios developed for a region strongly depend on the specific aims of the investigation, the model used, the spatial scale, and the natural and socio-economic characteristics of the study region itself (Lahmer *et al*, 2000).

In the present case, first the current state of the river basin was analyzed to acquire a basis for the quantitative assessment of various land use alternatives. Agricultural land and land for pasture dominate in Ilarion basin (32.4% and 40.4% of the basin respectively); also, forests cover a significant area (26%), while a small part (0.4%) of the basin is occupied by urban and commercial areas.

As regards future changes of land use types in the Ilarion basin, nothing certain can be said. Therefore, impacts of land use changes were studied using the following four scenarios: reduction of forests by 5%, 10%, and 20%, and reduction of agricultural land by 10%. The changes were balanced by the use of land for pasture in the same areas. These scenarios were used in a previous study (Baltas & Karaliolidou, 2007) as input data to the hydrological model SWAT, which was applied to estimate total basin runoff under land use changes for the period 1971-2002. In order to acquire values of reservoir inflows $I_t$ for the aforementioned scenarios and for the period 2008-2050, 20 synthetic series of total basin runoff were produced for each scenario and for this period, taking into account the statistical characteristics of the runoff time series that resulted from the SWAT runs. For each land use change scenario, reservoir operation was simulated and risk analysis performed following the procedure described above.

### Risk Assessment under Climate Change Scenario

To study climate change consequences on the study region, a climate change scenario was used. The Hadley Center, and previously the UK Met Office, have over the years been developing GCMs. One of these, termed the unified model, was modified in 1994 to produce a new coupled ocean-atmosphere GCM that was used to perform the first warm-start, historically forced, climate change experiments. The most important version of the unified model for climate change impacts studies has been termed HadCM2 (CRU, 2000b). Had CM2 has a spatial resolution of 2.5° × 3.75° (latitude by longitude), and the representation produces a grid box resolution of 96 × 73 grid cells. This produces a surface spatial resolution of about 417km × 278 km, reducing to 295 ×278 km at 45 degrees north and south. The atmospheric component of HadCM2 has 19 levels, and the ocean component 20. The equilibrium climate sensitivity of HadCM2, that is the global-mean temperature response to a doubling of effective $CO_2$ concentration, is approximately 3.0°C. The results of the HadCM2 climate model, including precipitation and temperature values, were interpolated statistically by the Climatic Research Unit of the University of East Anglia, UK, from the original climate model resolution to 0.5˚ × 0.5˚, using a simple interpolation procedure. Details of this method can be found in Hulme *et al*. (1994).

The climate change scenario was applied to the Ilarion basin in a previous study (Baltas & Karaliolidou, 2007), where the changes provided by HadCM2 were processed and used as input data to the hydrological model SWAT to estimate total basin runoff for the period 2008-2050 under climate change conditions. The time series of total basin runoff, which resulted from 20 runs of SWAT, were used as reservoir inflows $I_t$ with the reservoir simulation model. The reservoir model using these 20 inflow series was run and risk analysis performed in the same way described above.

# RESULTS

## Land Use Change

The results of the risk analysis performed (more specifically the percentage failures associated with different values of annual primary energy E) for the base run and for all land use change scenarios examined are presented in Table 3 and Figure 3. Regarding the current land uses (base run), the risk values range from 0% when the annual primary energy E is equal to 180 GWh, to 29.94% when E value is 420 GWh. The risk values for all land use change scenarios were significantly increased for all E values.

More specifically, observing Table 3 and Figure 3, it is obvious that the scenario of agricultural land reduction by 10% induced more significant increases of the risk than the other land use change scenarios, while the scenario of deforestation by 20% resulted in smaller increases of risk values. The scenarios of deforestation by 5% and by 10% exhibit almost the same behavior.

## Climate Change

The results of risk analysis performed using the climate change scenario are presented in Table 4 and Figure 4. The HadCM2 scenario

**Table 3. Risk associated with different values of annual primary energy E, for the land use change scenarios**

| E (GWh/year) | Risk | | | | |
|---|---|---|---|---|---|
| | base run | deforestation by 5% | deforestation by 10% | deforestation by 20% | agricultural land reduction by 10% |
| 180 | 0.00% | 0.49% | 0.52% | 0.55% | 0.51% |
| 200 | 0.00% | 1.32% | 1.32% | 1.34% | 1.39% |
| 220 | 0.00% | 2.89% | 2.87% | 2.50% | 3.02% |
| 240 | 0.02% | 5.20% | 5.14% | 4.49% | 5.40% |
| 260 | 0.17% | 8.19% | 8.12% | 7.13% | 8.63% |
| 280 | 0.61% | 12.36% | 12.17% | 10.51% | 13.05% |
| 300 | 1.83% | 17.08% | 16.91% | 14.50% | 17.88% |
| 320 | 4.29% | 22.12% | 21.93% | 19.18% | 23.10% |
| 340 | 8.41% | 27.21% | 26.86% | 23.83% | 28.32% |
| 360 | 14.09% | 32.28% | 31.99% | 28.64% | 33.63% |
| 380 | 19.68% | 37.17% | 36.79% | 33.45% | 38.44% |
| 400 | 25.20% | 41.70% | 41.45% | 38.00% | 42.99% |
| 420 | 29.94% | 45.90% | 45.61% | 42.50% | 47.18% |

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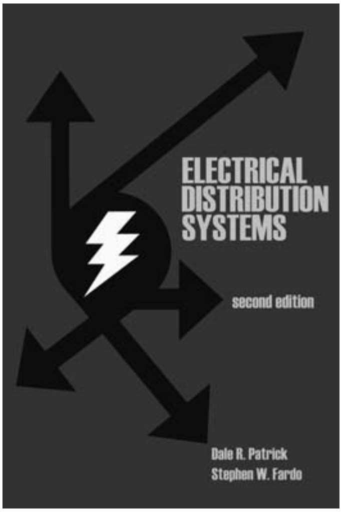

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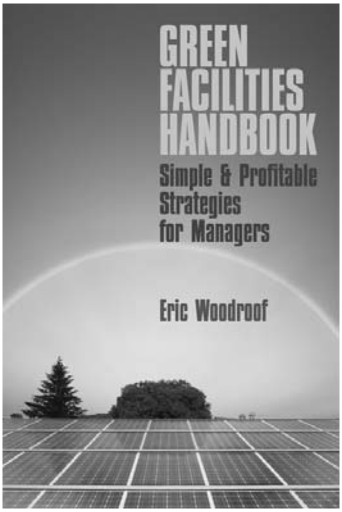

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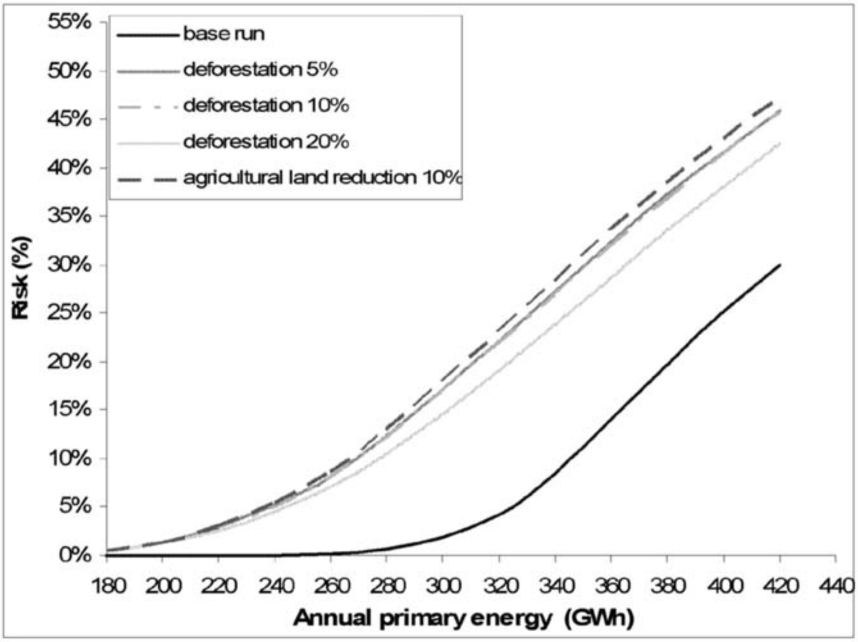

**Figure 3. Risk *vs* annual primary energy production for the land use change scenarios**

| E (GWh/year) | Risk | |
|---|---|---|
| | base run | HadCM2 |
| **180** | 0.00% | 0.00% |
| **200** | 0.00% | 0.33% |
| **220** | 0.00% | 1.49% |
| **240** | 0.02% | 3.94% |
| **260** | 0.17% | 8.65% |
| **280** | 0.61% | 14.25% |
| **300** | 1.83% | 21.13% |
| **320** | 4.29% | 28.08% |
| **340** | 8.41% | 34.51% |
| **360** | 14.09% | 40.31% |
| **380** | 19.68% | 45.28% |
| **400** | 25.20% | 50.31% |
| **420** | 29.94% | 54.39% |

**Table 4. Risk associated with different values of annual primary energy E, for the climate change scenario**

gave increased values of the risk, which range from 0% when the annual primary energy E is equal to 180 GWh, to 54.39% when E value is 420 GWh. In Figure 4, one can notice that risk values are considerably increased, especially for E values higher than 300 GWh.

## CONCLUSIONS AND DISCUSSION

The basic conclusions drawn from this study are concentrated in the following:

- The energy production of the Ilarion reservoir, designed under current conditions, would be affected by climate and land use changes. Increases of the risks associated with the annual energy production

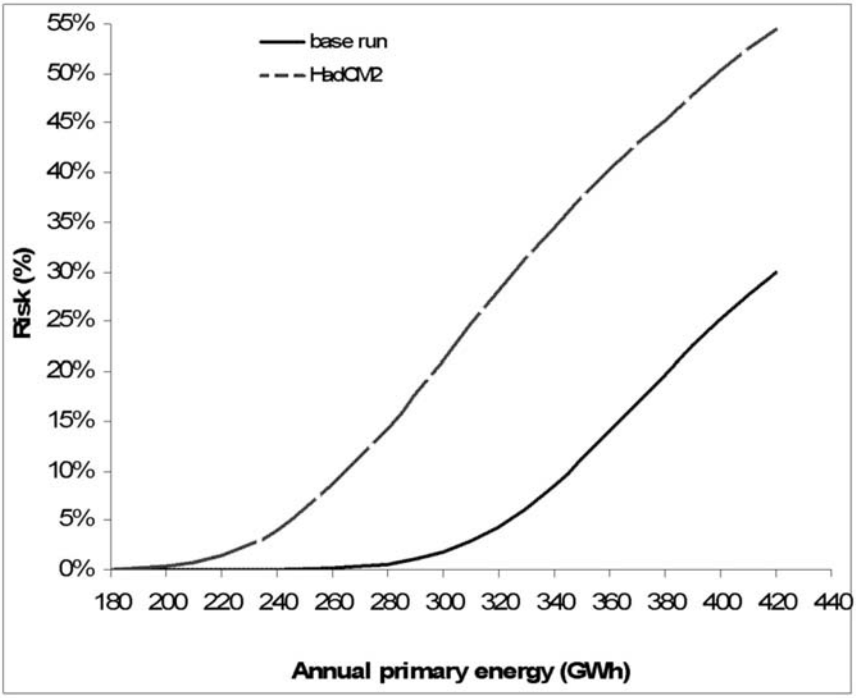

**Figure 4. Risk *vs* annual primary energy production for the climate change scenario**

were observed, under both climate and land use change scenarios examined.

- The HadCM2 scenario induced more significant effects on the risk associated with the annual energy production of the Ilarion reservoir, in comparison to the impact of the land use change scenarios.

Similar conclusions have been drawn from other relevant studies on the implication of climate change on the operation of another multipurpose reservoir in Northern Greece (Mimikou & Baltas 1997, Mimikou *et al*. 1999, Baltas & Mimikou 2005).

The findings presented in this study do not constitute predictions but are results based on sensitivity analysis performed in order to assess the expected range of changes under the specific scenarios examined. Further research into the potential impacts of climate and land use changes on hydroelectric energy production could be carried out in the future, based on more detailed data and scenarios. It is proposed that future studies be focused not only on the investigation of climate and land use change individually but also on understanding the interaction between land uses and climate systems and on estimating the combined effect of land use and climate change.

In conclusion, climate and land use changes have the potential to significantly affect hydrological regimes. These changes may produce conditions outside those for which dams are currently built and operated. The impacts of climate and land use changes on a reservoir may be affected by other pressures facing the reservoir; therefore, they must be seen in the context of other changes affecting reservoir reliability, such as changes in water demands, efficiency of use and operation, and altered management objectives. The key issue in managing reservoirs in the face of future changes is one of managing under uncertainty. This implies that the past can no longer be assumed to be the best guide for the future and that reservoir planners should not rely on historic conditions. As the future cannot be known with certainty, impact assessment should examine a range of future scenarios, rather than adopt a "best-guess" scenario (Arnell & Hulme, 2000). Thus, studies and research on impacts of future climate and land use changes, using different scenarios, can provide a valuable tool for reservoir planners and managers.

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