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Abstract This paper presents the assessment of climate change impacts on some critical water management issues such as reservoir storage and hydroelectric production. Two equilibrium scenarios (UK Meteorological Office High Resolution model, UKHI and Canadian Climate Centre model, CCC) referring to years 2020, 2050 and 2100 and one transient scenario (UK High Resolution Transient output, UKTR) referring to years 2032 and 2080 were applied to represent both "greenhouse" warming and induced changes in precipitation and potential evapotranspiration. By using these scenarios, the sensitivity of the risk associated with the annual hydroelectric energy production of a large multipurpose reservoir in northern Greece has been evaluated under conditions of altered runoff. It is shown that the operational characteristics of the reservoir designed and operated under current climatic conditions are, in general, affected by the climate change scenarios examined. Increases of the risks associated with the annual quantities of energy production have been observed, particularly under the UKHI and the UKTR scenarios. For the UKHI scenario, increases of reservoir storage volumes of up to about 12% and 38% are required in order to maintain at current risk levels the minimum and mean annual energy yields respectively, while for the UKTR scenario the corresponding increases are estimated to be about 25% and 50%.

Impacts du changement climatique sur la production d'énergie hydroélectrique

Résumé Cet article présente une évaluation des impacts du changement climatique sur quelques aspects critiques de la gestion des ressources en eau, comme le stockage d'eau dans les réservoirs et la production hydroélectrique. On a appliqué deux scénarios d'équilibre (UKHI, CCC) relatifs aux années 2020, 2050 et 2100 et un scénario transitoire (UKTR) relatif aux années 2032 et 2080 afin de représenter le réchauffement du à l'"effet de serre" et les modifications correspondantes des précipitations et de l'évapotranspiration. Ces scénarios nous ont permis d'évaluer la sensibilité du risque associé à la production annuelle d'énergie hydroélectrique d'un grand réservoir à buts multiples situé en Grèce du Nord lorsque le régime d'écoulement est altéré. Nous avons démontré que les caractéristiques opérationnelles du réservoir qui a été dimensionné et est géré en fonction des conditions climatiques actuelles, sont en général influencées par les scénarios de changements climatiques examinés. On a observé, en particulier pour les scénarios UKHI et UKTR, une augmentation du risque associé à la production annuelle d'énergie. En ce qui concerne le scénario UKHI, des augmentations de près de 12 et 38 % du volume de stockage seraient nécessaires afin de maintenir la production d'énergie, respectivement minimale et moyenne, et le risque tolérable associé aux niveaux actuels, alors que pour le scénario UKTR les augmentations correspondantes ont été estimées à 25 et 50 %.

INTRODUCTION

It is widely known that the atmospheric concentration of radiatively active "greenhouse" gases, principally carbon dioxide (CO_2), nitrous oxide (N_2O), methane

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(CH_4) and chlorofluorocarbons (CFCs), has increased steadily over the past century (Mimikou & Kouvopoulos, 1991). There is considerable consensus among the international scientific community that global warming due to this growing concentration of greenhouse gases in the atmosphere needs to be faced. It has been estimated that the average global temperature has increased 0.5–0.7°C since the turn of the century, whereas current estimates from models indicate that a doubling of CO_2 and other gases may increase the annual temperature by 3.0–1.5°C during the next 50–100 years (US National Academy of Sciences, 1979, 1983). The regional climate change effects on hydrology and water resources have gained widespread research interest since the early 1980s. Hydrological research suggests that climate changes will strongly influence various forms of water resources such as mean and extreme surface runoff, soil moisture and groundwater, changes in sea level, and water quality (Gleick, 1989). These climatic change impacts involve important implications for future water resources planning and management associated with serious environmental and socio-economic dislocations. Research conclusions strongly suggest that reservoirs designed and operated under current climatic conditions will be severely stressed by climatic changes (Němec & Schaake, 1982; Mimikou *et al.*, 1991b; Mimikou, 1995). The relationship between the amount of water that can reliably be taken from a reservoir and the storage capacity of the reservoir, the so-called storage–yield relationship, is significantly affected by altered runoff due to changes in temperature, precipitation and evapotranspiration (Klemeš, 1985). Němec & Schaake (1982), in their evaluation of reservoir reliability under conditions of altered runoff, concluded that increased storage may be needed to take into account the effects of climatic changes, if reliable yields are to be maintained.

The research work presented herein originates from a major EU funded research programme that addresses the impacts of "greenhouse" warming on water resources and water management on a catchment, at regional and at European scales (Mimikou, 1996). More specifically the paper presents the research work on the assessment of the impacts of climate change on the operational reliability of the Polyfyto reservoir in northern Greece. Two climate change scenarios based on equilibrium results and one based on transient results were produced for the whole of Europe by the UK Climate Research Unit (CRU) (Hulme *et al.*, 1994). The two equilibrium models are the UK Meteorological Office High Resolution model (UKHI) and the Canadian Climate Centre model (CCC), while the transient model is the UK High Resolution transient output (UKTR). The aforementioned scenarios were applied in the Aliakmon River basin, which drains into the Polyfyto reservoir. For each scenario the climatically altered inflows to the reservoir have been estimated through the use of a conceptual water balance model, whereas the resultant implications for the operation of the reservoir have been assessed by using a reservoir simulation model developed for this purpose.

STUDY REGION AND DATA USED

The study area, shown in Fig. 1, is the Aliakmon River basin which is located in northern Greece between 39°30′S to 40°30′N and 20°30′W to 22°E. The river basin

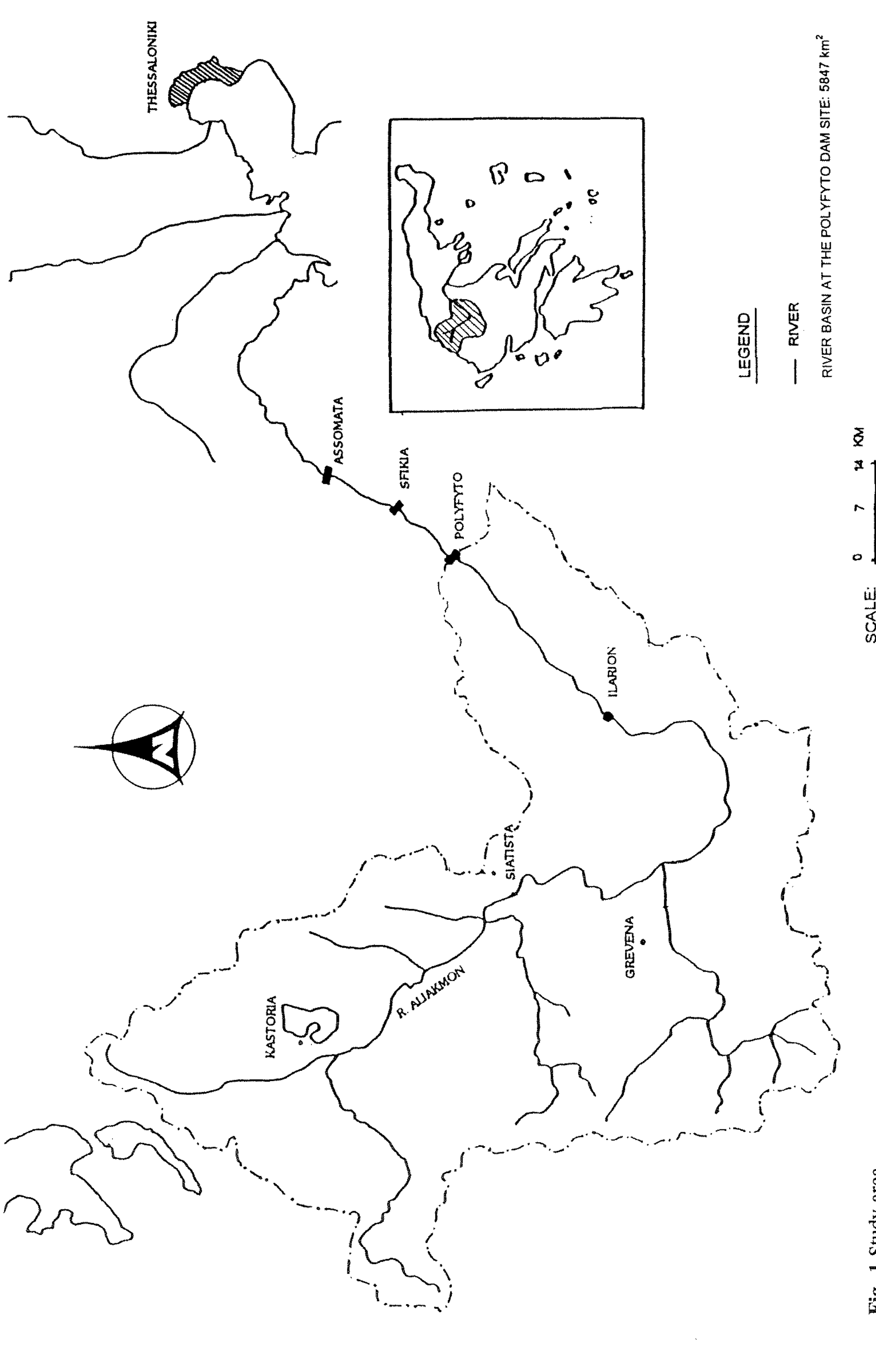

Fig. 1 Study area.

Table 1 General characteristics of the study area.

Area (km^2)	5847
Mean elevation (m)	876
Mean annual historical temperature (°C)	11.0
Mean annual historical runoff (m^3 s^{-1})	57.3
Mean annual specific runoff (m^3 s^{-1} km^{-2})	0.0115
River length (km)	193.0

at the Polyfyto dam site has a drainage area of 5847 km^2 and its topography varies from narrow gorges to wide flood plains. Some general characteristics of this basin are given in Table 1.

A number of stations located within and near the study area were used to acquire all the required monthly hydrometeorological data for a 30-year period (1961–1990), while the monthly runoff data at the Ilarion site, which is the nearest to the Polyfyto reservoir hydrometric station, were obtained from the archives of the Public Power Corporation (PPC) of Greece. The hydrometeorological data included precipitation, snow, evaporation, wind velocity, relative humidity, sunshine duration and temperature values. These data were analysed and processed in order to be used as inputs (directly or indirectly) to the water balance model utilised for the assessment of the climate change effects on the surface runoff of the study region (Mimikou *et al.*, 1991a). The inflows to the Polyfyto reservoir, located 32 km downstream of the Ilarion station, were estimated from the streamflows at the Ilarion site proportionally to the ratio of the corresponding drainage areas.

Three multipurpose reservoirs are currently in operation along the Aliakmon River route in order to satisfy irrigation, water supply and power generation needs. These are, starting from upstream, Polyfyto, Sfikia and Assomata, as shown in Fig. 1. Efforts to model the operation of the three reservoirs as a system were unsuccessful because the Sfikia and Assomata reservoirs are mainly regulating reservoirs (one day storage) in order to provide water downstream and also to contribute to power generation. Therefore only the Polyfyto reservoir has been examined in this paper, whose technical characteristics are shown in Table 2. Regarding the operation of the Polyfyto reservoir, all relevant data have been acquired from different divisions of the PPC and the Ministry of Agriculture of Greece. The data included inflows and outflows to and from the reservoir/plant for all historical years of operation (1975–1994). Necessary information on the characteristics of the reservoir and the hydroelectric production of the power plant, such as water level, storage capacity-water surface relationships, functions of turbines and transformers, hydraulic characteristics etc., were also provided.

CLIMATE CHANGE SCENARIOS

The climate change scenarios used in this study were constructed at 0.5° latitude/longitude resolution by the Climatic Research Unit (CRU) of the University of East Anglia, UK. The methodology adopted used the CRU 1961–1990 baseline

Table 2 Design characteristics of the Polyfyto reservoir.

Design head (m)	146.40
Maximum storage capacity ($\times 10^6$ m^3)	1160
Minimum storage capacity (m^3)	655
Minimum (guaranteed) energy (GWh year^{-1})	199.4
Mean (guaranteed) energy (GWh year^{-1})	515
Firm water supply ($\times 10^6$ m^3)	640
Maximum outflow capacity through the turbines (m^3 s^{-1})	345
Number of turbines	3
Power of each turbine (MW)	125

climatologies for Europe, the results from three GCM (General Circulation Models) climate change experiments (UKHI, CCC and UKTR) and a range of projections of global warming calculated by MAGICC (Model for the Assessment of Greenhouse gas Induced Climate Change), a simple upwelling-diffusion energy balance climate model (Hulme *et al.*, 1994).

Scenarios using results from the two equilibrium experiments UKHI and CCC can be constructed for any given magnitude of global warming or for any future year between 1990 and 2100. To construct a climate change scenario for a future date, it is necessary first to select an emissions scenario, then to choose a climate sensitivity and finally to decide whether one wishes to incorporate the effect of sulphate aerosols on global warming. None of the GCM experiments used here included the negative forcing of aerosols on climate. The two equilibrium experiments using high resolution atmospheric GCM (UKHI and CCC) and assuming the standard 1992 IPCC emissions scenario, a "central" climate sensitivity of 2.5°C and ignoring the effects of sulphate aerosols, produced climate change scenarios for the years, 2020, 2050 and 2100. These resulting climate change fields were applied to the baseline climatology representing the 30-year period 1961–1990 (Hulme *et al.*, 1994).

Scenarios using results from the UKTR transient experiment are expressed as a fixed magnitude of climate change, but associated with a range of dates by which these changes may be realized. The fields derived from the UKTR experiment need to be handled in a slightly different way from those of the equilibrium experiments. The two sets of change fields relate to model years 1931–1940 and 1966–1975 which have associated global-mean warmings in UKTR of 0.68°C and 1.76°C respectively. These changes have not been standardized and since the patterns of climate change differ between the two decades, it is not appropriate to scale these change fields using a global warming projection. Instead the two sets of UKTR change fields were applied directly to the baseline climatology and then the results from MAGICC were used to associate a range of years by which such climate scenarios might be realized. The transient experiment UKTR, using the high resolution coupled ocean-atmosphere GCM of the Hadley Centre, gave climate change scenarios with a climate sensitivity of 2.5°C and assuming no sulphate aerosol effect corresponding to the years 2032 and 2080 respectively (Hulme *et al.*, 1994).

Scenarios were produced for rainfall R (% change), temperature T (°C) and potential evapotranspiration PE (% change). Specifically, two scenarios were developed concerning the potential evapotranspiration: PE1 representing change in potential evapotranspiration from a change in temperature only; and PE2 representing change in potential evapotranspiration from changes in radiation, humidity and wind speed. The two scenarios (UKHI and CCC) based on equilibrium results and the one (UKTR) based on transient results were extracted from the gridded historical global data sets including variables such as precipitation, temperature, wind speed, sunshine hours, vapour pressure and rain day frequencies, which were acquired by and processed at the Climatic Research Unit. The GCM output of the variables precipitation, temperature and evapotranspiration was interpolated to $0.5° \times 0.5°$ from the original GCM resolution ($3.75° \times 2.5°$ UKHI, $3.75° \times 3.75°$ CCC and $3.75° \times 2.5°$ UKTR).

For the application of the climate change scenarios, the Aliakmon River basin was divided into grids with dimensions $0.5° \times 0.5°$. For all scenarios, the precipitation, temperature and evapotranspiration values were estimated by using the provided original gridded data and through the appropriate use of a code number and a weighting coefficient associated with each cell (grid) constituting the basin. The weighting coefficient used for each cell was estimated according to the percentage contribution of the cell to the entire area, while the code number was calculated based on the longitude and latitude of the south west corner of the cell through the use of the following relationship (Hulme *et al.*, 1994):

$$\text{Code} = [(\text{longitude} + 180.0) \times 100000.0] + [(\text{latitude} + 90.0) \times 10.0] \quad (1)$$

The weighting coefficients and the corresponding code numbers of the cells which constitute the study basin are given in Table 3.

Table 3 The weighting coefficients and the code numbers used for each cell of the study basin.

Code number	Weighting coefficients
20051300	0.05
20101295	0.10
20101300	0.42
20101305	0.18
20151295	0.08
20151300	0.17

REGIONAL WATER RESOURCES UNDER CLIMATE CHANGE SCENARIOS

The assessment of climate change impacts on regional water resources was based on the use of a robust monthly water-balance model (WBUDG). The model is able to provide data for performing sensitivity analyses of regional water resources under varying climatic conditions and to make optimal use of the information available in the specific study area. The format of the model input is compatible with the rough monthly estimates of these climatic variables that were not adequately measured in

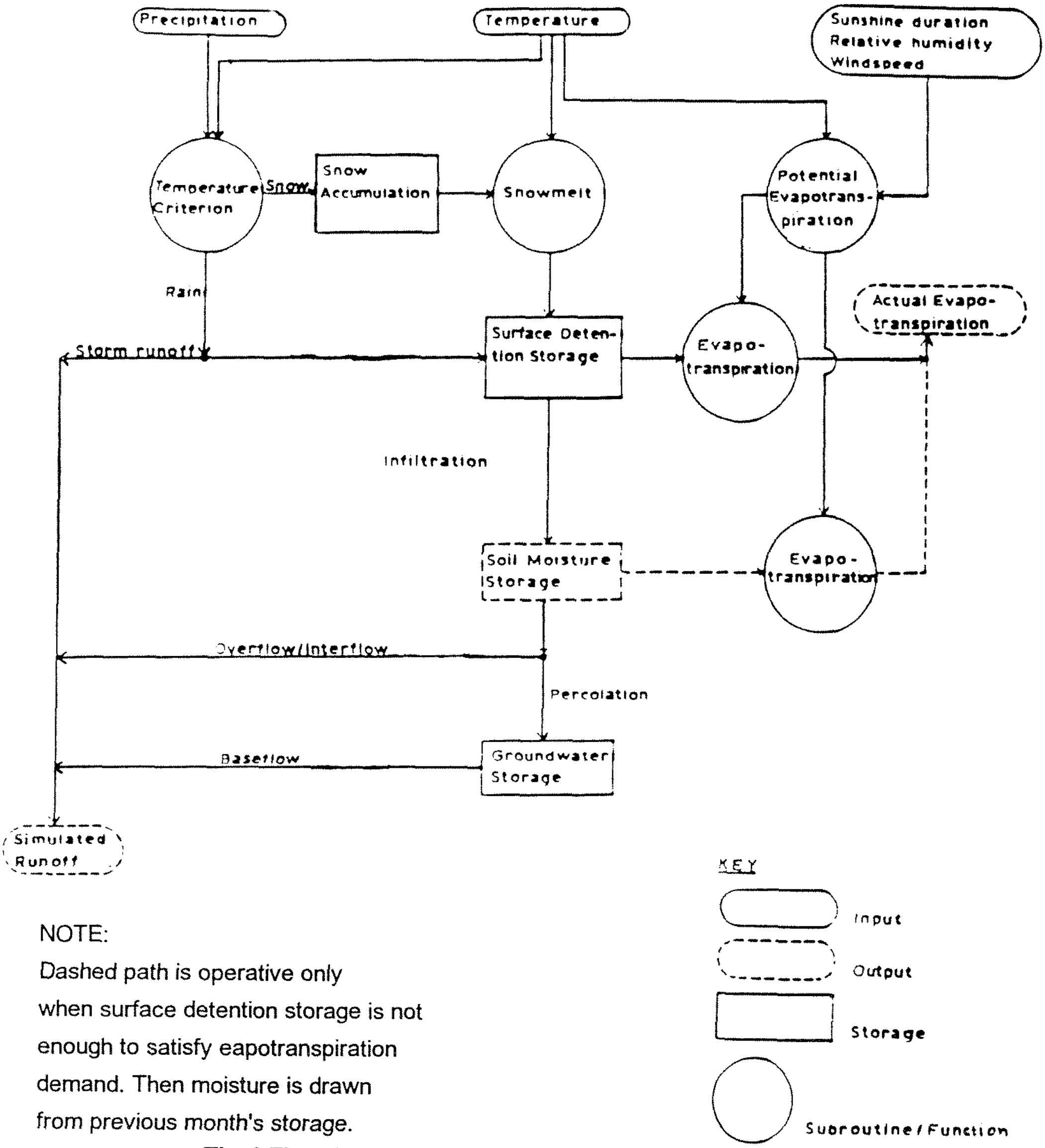

Fig. 2 Flow chart of the water balance model.

the study area, such as relative humidity, wind speed and sunshine duration. The flow chart of the water balance model structure is shown in Fig. 2, where one can notice the various subroutines which function interactively in order to simulate the stream runoff values. The main input parameters of the model are precipitation, temperature, relative humidity, sunshine duration and wind speed which, through the operation of a number of subroutines, as schematically shown in Fig. 2, estimate the rain, snow, snowmelt, snow storage, evapotranspiration, groundwater storage, soil moisture and finally the stream runoff. More details of the model can be found in previous publications

(Mimikou & Kouvopoulos, 1991; Mimikou *et al.*, 1991a).

The model was successfully calibrated using the 30-year historical hydrometeorological and hydrometric data for the study area. For applying all the climate change scenarios to the hydrometeorological data of the study region, synthetic series (from 1990 up to 2100) of precipitation, temperature and potential evapotranspiration based on the historical data, were produced. The stochastic autoregressive models AR(1) and AR(2) were applied and the Port manteau test was used as a criterion in order to check their efficiency. Finally by using in each case the better performing (between AR(1) and AR(2)) stochastic model, 50 synthetic series of each variable were generated. The synthetically generated series were modified in order to take into account properly the changes provided for each climate change scenario and hydrometeorological variable. Runs of the water balance model were performed for all 50 modified synthetic series of each climate change scenario, whereas the results are the values averaged over the 50 series. Regarding the potential evapotranspiration, it should be noticed that the results obtained by using the previously mentioned PE1 and PE2 scenarios and the simple Blaney-Criddle method did not significantly differ. For this reason the potential evapotranspiration was finally estimated through the use of the Blaney-Criddle method which was applied simultaneously with the precipitation and temperature scenarios. Runs of the water balance model using the hydrometeorological data already generated and considering zero climate change (no application of climate change scenarios) are referred to as base runs and were used for comparison purposes. The selection of the base runs as a basis of comparison was made for uniformity reasons and since each base run for the period 1961–1990 was found to be similar to the historical record. The results of the two equilibrium (1990–2100) and one transient (1990–2080) scenarios for the basin up to the Ilarion measuring station are given in Table 4, where one can see the differences between the base run values and the changed values of several hydrological indicators. From this Table, one can notice the reduction of the mean annual and winter runoff values, as well as the serious reduction of the summer runoff in all cases. Also the maximum and minimum monthly values continue to occur almost at the same months, while the mean annual potential and actual evapotranspiration values were eventually increased due to temperature increase resulting in a significant reduction of soil moisture. Details concerning the assessment of the climatically induced changes in the Aliakmon River flows under all aforementioned scenarios through the application of the WBUDG model can be also found in another relevant publication (Mimikou, 1996).

For each of the climate change scenarios including the base run one with zero change, 50 series of monthly runoff values covering the period from 1990 up to the terminal year of the corresponding scenario were obtained as outputs of the water balance model at the outlet of the Ilarion basin. These series were transferred proportionally to the Polyfyto dam site, as previously explained, and an equal number of reservoir inflow series was obtained.

RESERVOIR MODEL

The operation of the Polyfyto reservoir is described by a model which consists of the water budget given in equation (2) under various constraints concerning storage

Table 4 Estimated mean hydrological indicators for the equilibrium (1990–2100) and the transient (1990–2080) scenarios (Mimikou *et al.*, 1996).

Hydrological indicators	Ilarion 1990–2100: Equilibrium scenarios					Ilarion 1990–2080: Transient scenario		
	Base run	UKHI		CCC		Base run	UKTR	
	(mm)	(mm)	(%)	(mm)	(%)	(mm)	(mm)	(%)
Mean annual precipitation	845.7	832.3	-1.6	832.3	-1.6	847.6	726.3	-14.3
Mean annual PET	704.9	875.6	24.2	849.9	20.6	705.1	847.1	20.1
Mean annual ET	536.4	545.6	1.7	548.6	2.3	537.3	519.6	-3.3
Mean annual runoff	309.2	286.7	-7.3	283.7	-8.2	310.3	206.7	-33.4
Mean summer runoff	59.8	46.6	-22.1	46.3	-22.6	59.9	40.1	-33.1
Mean winter runoff	249.5	240.1	-3.8	237.4	-4.8	250.3	166.6	-33.4
Annual max runoff	599.1	626.5	4.6	613.9	2.5	578.9	393.7	-32.0
Annual min runoff	94.8	87.6	-7.6	88.3	-6.9	95.4	80.8	-15.3
Monthly max runoff	136.5	182.2	33.5	181.0	32.6	131.3	93.2	-29.0
Occurrence	Dec.	Dec.		Dec.		Dec.	Jan.	
Monthly min runoff	0.2	0.1	-50.0	0.1	-50.0	0.2	0.1	-50.0
Occurrence	Aug.	Jul.		Aug.		Aug.	Aug.	

volume, outflow from the reservoir and energy production given in equations (3), (4) and (5) respectively. The reservoir water budget equation applied on a monthly basis has the following form:

$$V_{t+1} = V_t + I_t + P_t - R_t - a_t W - q_t - N_t \tag{2}$$

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

In the current approach a modified version of equation (2) was used. According to soil investigation, seepage losses N_t are anticipated to remain of minor importance, while data 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 climate change scenarios. Moreover, no releases over the spillway have been allowed (q_t = 0) and the entire water quantity passes through the turbines of the HEP. Therefore, for simplicity, the corresponding terms were dropped ($V_{t+1} = V_t + I_t$). Overall, these discounts do not affect the specific sensitivity analysis pursued.

The constraint concerning storage volume V_t is:

$$V_{\min} \leq V_t \leq V_{\max} \tag{3}$$

where $V_{\min}$ = minimum storage capacity, and $V_{\max}$ = maximum storage capacity (corresponding to the maximum power pool level).

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

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

where $Q_t = a_t W/\Delta t$, with Δt = the time interval (month) and $Q_{\max}$ = maximum flow capacity through the turbines.

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

$$b_t E \leq E_t \tag{5}$$

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

The monthly distribution coefficients a_t and b_t were estimated based on historical data obtained since the beginning of the operation of the reservoir. The twelve monthly distribution values a_t and b_t are mean values over the period of operation (1975–1994) and are given in Table 5.

The general operation rules for the Polyfyto reservoir are the following:

- The Polyfyto reservoir is a reservoir which is mainly used for hydroelectric

Table 5 The mean values of the monthly distribution coefficients a_t and b_t.

Month	a_t	b_t
October	0.072	0.007
November	0.077	0.007
December	0.077	0.007
January	0.068	0.007
February	0.064	0.007
March	0.076	0.016
April	0.057	0.028
May	0.088	0.082
June	0.104	0.180
July	0.120	0.280
August	0.106	0.261
September	0.091	0.118

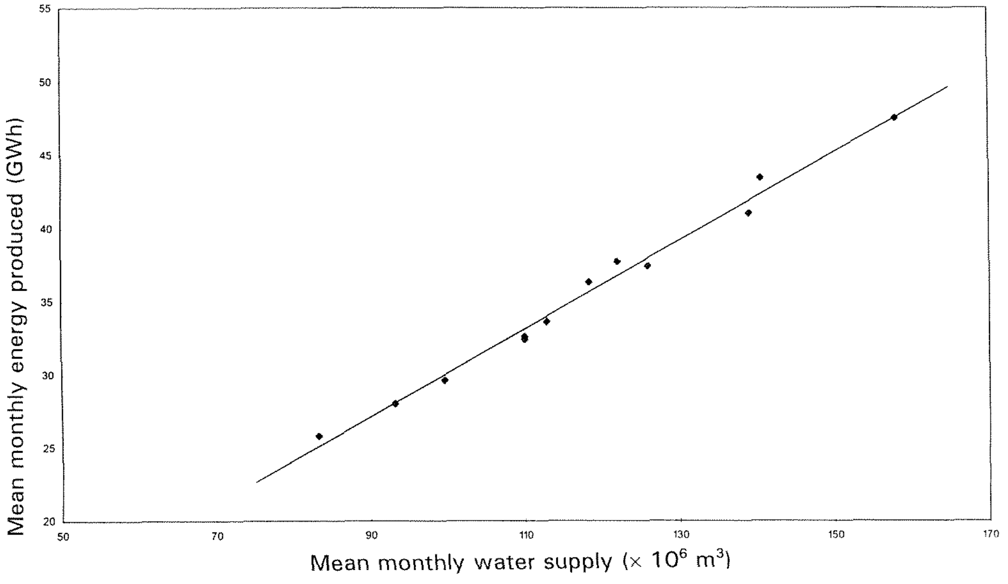

Fig. 3 Mean monthly energy *vs* mean monthly water supply for the Polyfyto reservoir.

power generation and up to now the rule curve has not been followed up. The rule curve, which has been derived by PPC gives the optimum monthly water level in the reservoir. However, if the storage volume at the end of a month corresponds to a water level higher than the maximum power pool level, additional water releases occur and additional (secondary) energy is produced, provided the capacity of the turbines is not exceeded.

- All the water used for water supply or irrigation purposes passes through the turbines thus producing hydroelectric power generation.

Based on these rules, the mean monthly energy values $\overline{E_t}$ (GWh) for the

Polyfyto reservoir are related to the mean monthly outflow discharges $\overline{Q_t}$ ($\times 10^6$ m^3) by the following expression:

$$\overline{E_t} = 0.300689\overline{Q_t} + 0.030489 \tag{6}$$

The $\overline{E_t}$ and $\overline{Q_t}$ values have been estimated by averaging the monthly water and energy quantities supplied from the Polyfyto reservoir over the operation period. The relationship, with a least square curve fitted to the data, is shown in Fig. 3.

The water budget given by equation (2) under the constraints of equations (3), (4) and (5) and the relationship given in equation (6) were applied in order to simulate the operation of the Polyfyto reservoir under both current and climatically changed conditions.

RISK ASSESSMENT OF ANNUAL ENERGY SUPPLY LEVELS

The sensitivity of the operational reliability of the Polyfyto reservoir under different climatic conditions is based on a risk analysis of the annual production energy quantities 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 to the reservoir's characteristics. The annual primary energy E was taken to vary between 150 GWh and 550 GWh, with a step of 15 GWh, a range which includes the minimum (199.4 GWh) and the mean (515 GWh) energy supply levels guaranteed annually from the Polyfyto reservoir for a climatically critical (dry) and an average year, respectively. For every E value and for all scenarios and time steps—namely the two equilibrium UKHI and CCC referring to years 2020, 2050, 2100, the transient UKTR to years 2032 and 2080 and finally the zero climate change scenarios (base runs) for all time steps representing a projection to the future of the current climatic conditions—a reservoir operation was simulated using equations (2)–(6). In each case, 50 synthetic series of reservoir inflows I_t were produced by using the water balance model and the procedure previously described. The reservoir model using as input these 50 inflow series ($50 \times [(2 \times 3) + (1 \times 2) + (1 \times 5)] =$ 650 runs in total), was run to assess the risk at 2020, 2050 and 2100 for UKHI and CCC and at 2032 and 2080 for the present climate (base run) for each E value. In the simulations, the monthly outflow discharges Q_t and energy values E_t were taken equal to their mean monthly historical values. Thus for every E value a total of 650 runs of the reservoir model were performed. Further, a failure or risk value was assigned to each synthetic inflow series, 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) or (5) corresponding to the selected value of E. The risk (or probability of failure) associated with the given E value was then estimated as an average value over the 50 synthetic series. By repeating the simulations, a complete set of risk values was constructed for each scenario separately, corresponding to the preselected set of E values.

RESULTS OF RISK ANALYSIS

The results of the risk analyses performed, and more specifically the percentage failures associated with the different values of annual primary energy E for the base run and all climate change scenarios examined, are presented in Figs 4 and 5. Particularly, Fig. 4 depicts the evolution of the risk values for the periods 1990–2020, 1990–2050 and 1990–2100, resulting from the application of the two equilibrium scenarios, whereas in Fig. 5 can be seen the risk diagrams for the transient experiment and for the periods 1990–2032 and 1990–2080. In Fig. 4 it will be observed that the two equilibrium scenarios exhibit different behaviour for the different time steps. More specifically, for the time steps 2020 and 2050, the risks for the CCC scenario do not deviate significantly from the base run curves, while the UKHI results indicate a significant increase of the risk especially for E values higher than 450 GWh. The results of the two models almost coincide for the time step 2100

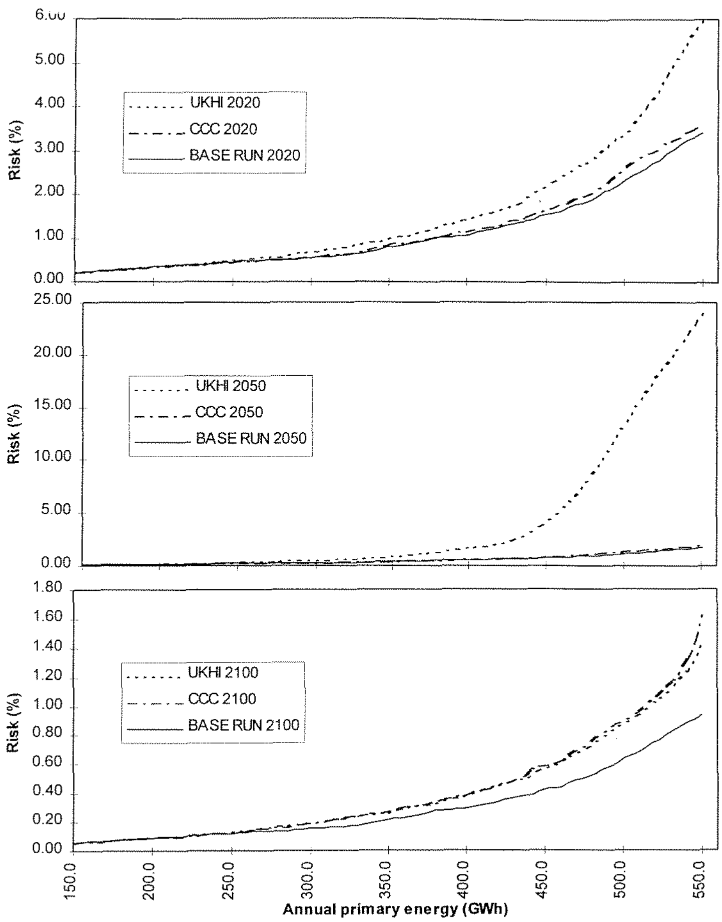

Fig. 4 Risk *vs* annual primary energy production for the Polyfyto reservoir by applying the equilibrium scenarios UKHI and CCC for the periods 1990–2020. 1990–2050 and 1990–2100.

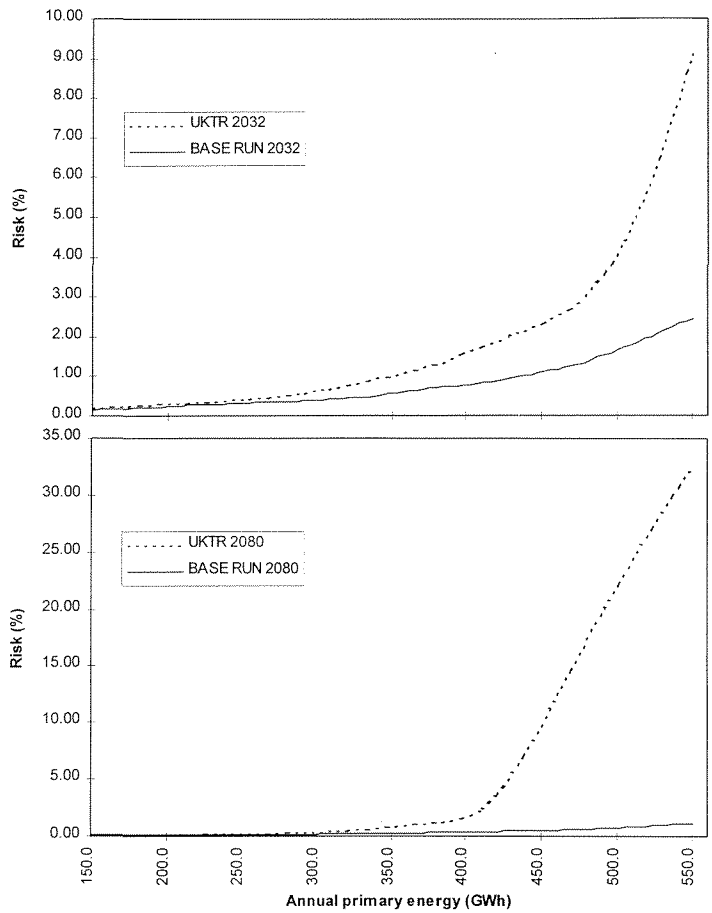

Fig. 5 Risk *vs* annual primary energy production for the Polyfyto reservoir by applying the transient scenario UKTR for the periods 1990–2032, 1990–2080.

and indicate a moderate increase of risk compared to the base run values. The differentiation in the results of the two equilibrium models can be mainly attributed to the different precipitation change scenarios involved in each experiment. Significant increases of the risk compared to the base run values are also seen in Fig. 5 with the transient experiment and for both time steps, especially for E values higher than 400 GWh. From this figure one can also notice that the deviation of the risk is higher using the period 1990–2080 than using the period 1990–2032. Moreover, the results from the UKTR scenario, especially for the former period, appear to be inconsistent with all other results, which could be probably interpreted as being due to shortcomings of the transient experiment. Diverging results in this kind of analysis where long projections to the future are based on different assumptions, are not unusual. Nevertheless, the findings presented herein do not constitute predictions but are results based on sensitivity analyses performed in order to assess the expected range of climatically induced changes under the specific scenarios examined. These conclusions can also be drawn from Tables 6 and 7 which depict the specific risks associated with the two characteristic energy values of the Polyfyto reservoir, namely the minimum (199.4 GWh) and the mean (515 GWh) annual (guaranteed) energy production, respectively. In general, one can state that the energy production of the Polyfyto reservoir, designed and operated under current climatic conditions, is affected by the climate change scenarios examined. Increases of the risks associated with the annual quantities of energy production have been observed, particularly under the UKHI and the UKTR scenarios. Similar conclusions have been drawn from another relevant research on the implications of a climate change represented by a set of plausible hypothetical scenarios for a system of reservoirs in central Greece (Mimikou *et al.*, 1991b; Mimikou, 1995).

Table 6 The risk values (%) for the minimum annual (guaranteed) energy for all scenarios.

Scenario	2020	2032	2050	2080	2100
Base run	0.3343	0.2386	0.1669	0.1113	0.0910
CCC	0.3343		0.1725		0.0925
UKHI	0.3398		0.1975		0.0925
UKTR		0.3062		0.1465	

Table 7 The risk values (%) for the mean annual (guaranteed) energy for all scenarios.

Scenario	2020	2032	2050	2080	2100
Base run	2.6128	1.8648	1.3046	0.8694	0.7112
CCC	2.9248		1.5605		0.9977
UKHI	3.9889		16.4312		0.9735
UKTR		5.1730		25.1566	

INFLUENCE OF NET STORAGE VOLUME ON RISK LEVELS

Net storage volume is a very important parameter for energy production and consequently for the design of a reservoir (Klemeš, 1979). Within the complex system of interrelated parameters that affect reservoir reliability in meeting water and energy demands, net storage volume plays an important role. The sensitivity analysis already presented has shown increased levels of risk associated with the energy supply of the Polyfyto reservoir, particularly with the UKHI and the UKTR scenarios. Since the Polyfyto reservoir guarantees energy and water for various purposes (irrigation of the western Macedonia plains, water supply for the city of Thessaloniki etc.), it is very important to keep risk at tolerable levels. Although tolerable levels cannot be quantified with precision, as this is a problem of optimisation beyond the scope of this research, one cannot, in general, accept significant departures from the original design values. High risk levels can be reduced in design by increasing the net storage volume (Mimikou *et al.*, 1991b). Therefore the question arises: how much should the net storage volume of the

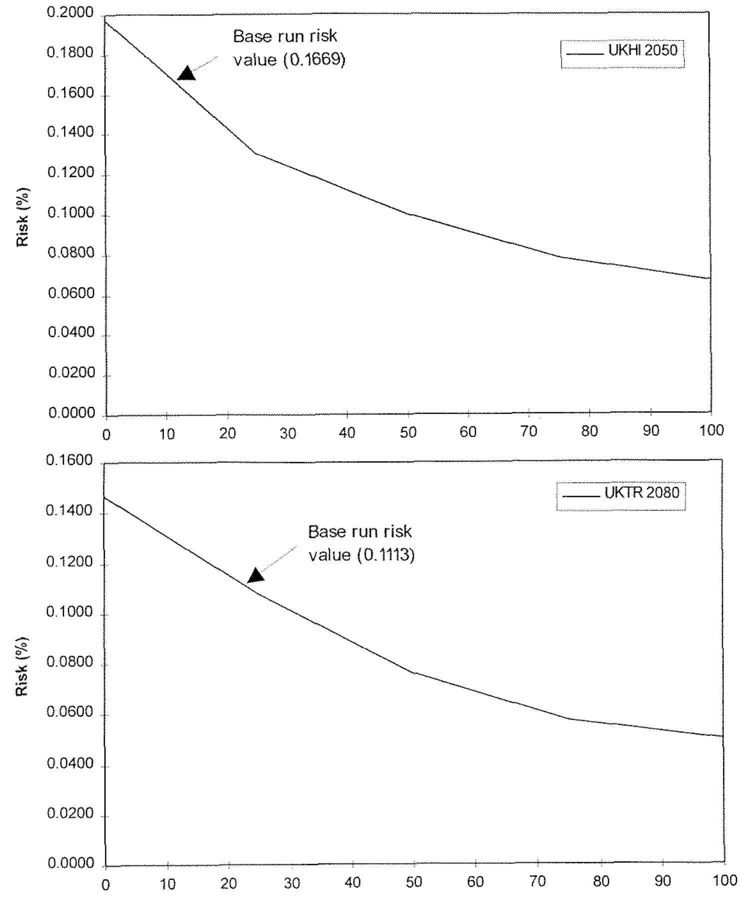

Fig. 6 Risk of the minimum annual (guaranteed) energy production (199.4 GWh) energy production (199.4 GWh) as a function of storage volume increase for the Polyfyto reservoir under the equilibrium scenario UKHI for the period 1990–2050 and the transient UKTR for the period 1990–2080.

Polyfyto reservoir be increased in order to maintain tolerable risk values for existing energy production under changed climatic conditions? To get an idea of the relevant answer, the entire work of the risk analysis has been repeated for the two specific energy supply levels, the minimum (199.4 GWh) and mean (515 GWh) annual (guaranteed) production of the Polyfyto reservoir, and for the two scenarios which indicated the most sensitive behaviour, namely the UKHI (1990–2050) and UKTR (1990–2080), by using increased (percentage) reservoir storage volumes. For both scenarios examined, the results are depicted in Figs 6 and 7 for the minimum and mean annual energy production, respectively. In these Figures, one can see a graphical representation of the decrease of risk (percentage) as a result of the percentage increase of storage volume. One can easily see from Figs 6 and 7 that, for the UKHI scenario, increases of reservoir storage volume of up to about 12% and

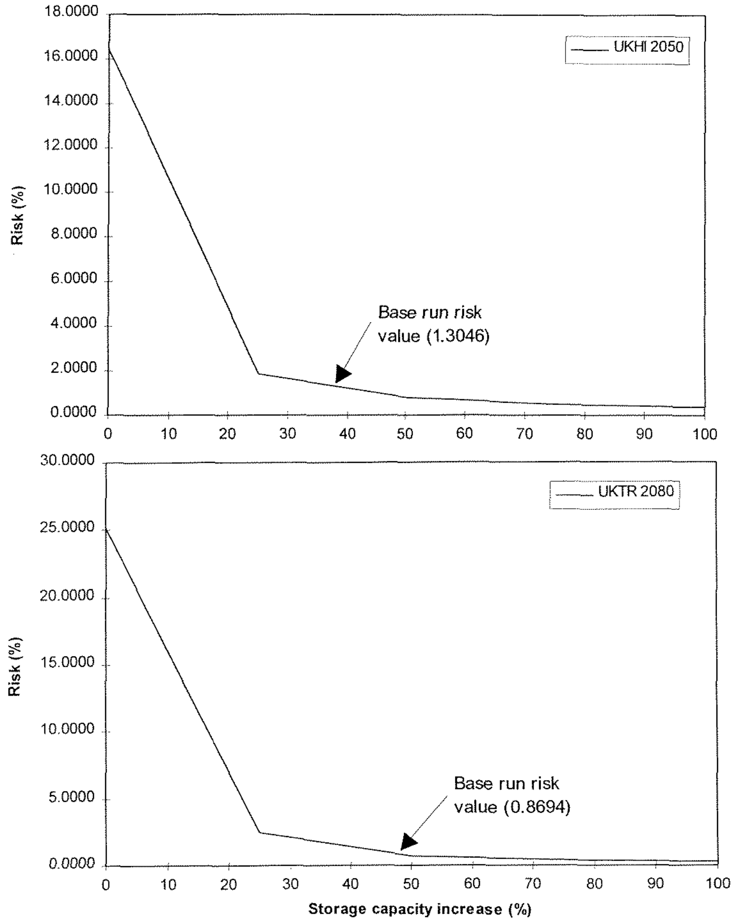

Fig. 7 Risk of the mean annual (guaranteed) energy production (515 GWh) as a function of storage volume increase for the Polyfyto reservoir under the equilibrium scenario UKHI for the period 1990–2050 and the transient UKTR for the period 1990–2080.

38% are required in order to maintain at current risk levels (base run values) the minimum and mean annual energy yields respectively, while for the UKTR scenario the corresponding increases are estimated to be about 25% and 50%.

CONCLUSIONS

The basic conclusions drawn from this research are the following:

- The Polyfyto reservoir, designed and operated under current climatic conditions, would be affected by the climate change scenarios examined. Increases of the risks associated with the annual quantities of energy production were observed, particularly under the UKHI and the UKTR scenarios.

- For the UKHI scenario, increases of reservoir storage volume of up to about 12% and 38% are required in order to maintain at current risk levels the minimum and mean annual energy yields respectively, while for the UKTR scenario corresponding increases are estimated to be about 25% and 50%.

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