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Linking space–time scale in hydrological modelling with respect to global climate change
Part 2. Hydrological response for alternative climates

Dionysia Panagoulia[a,*], George Dimou[b]

[a]*National Technical University of Athens, Department of Civil Engineering, Division of Water Resources—Hydraulic and Maritime Engineering, 5 Iroon Polytechniou, 15780 Zographou, Athens, Greece*
[b]*7 Voutyra, 16673 Voula, Athens, Greece*

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[b]*7 Voutyra, 16673 Voula, Athens, Greece*

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Abstract

The variability in monthly and seasonal runoff and soil moisture has been analysed with respect to global climate change. The seasonal runoff and soil moisture for the Mesochora catchment in Central Greece were simulated using two hydrological models that were different in structure and time resolution. Variability was investigated via a monthly water balance (MWB) model which has a first-order memory and includes a rough estimation of snowmelt component, and via the coupling of the snow accumulation–ablation (SAA) conceptual model and the soil moisture accounting (SMA) conceptual model of the US National Weather Service (US NWS). The last two models operated at a 6 h and daily time step, respectively. The SMA model predicted greater interannual variability of runoff changes than did the MWB model, for all alternative climates. However, greater runoff increases in winter (by month and season) and greater decreases in summer (by month and season) were predicted by the MWB model. During the spring and autumn months the results were much more complicated. The variability of runoff changes with respect to temperature increase showed that the MWB model is less sensitive to large temperature increase than the SAA–SMA models for all precipitation climates. Whereas the SMA model soil moisture varied substantially for the alternative climates and a particular month (and season), the MWB model soil moisture remained unaffected by any climate during winter. The soil moisture reduction predicted from the MWB model was greater than that predicted from the SMA model in late spring and summer. There was a slight reduction in the SMA model soil moisture with respect to temperature increase in winter, for all precipitation climates. During winter and August the MWB model soil moisture remained unaffected by any temperature increase, whereas during the other months the soil moisture reduction varied proportionally with respect to temperature increase for both models (SMA and MWB) and all precipitation climates.

* Corresponding author.

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1. Introduction

The subject of this paper is the hydrological simulation under alternative climate scenarios for the medium-sized mountainous Mesochora catchment using the models described in Part 1 (Panagoulia and Dimou, 1997), i.e. the monthly water balance (MWB) model (Thornthwaite and Mather, 1955, 1957) and the US National Weather Service snow accumulation–ablation model (SAA) (Anderson, 1973) and soil moisture accounting model (SMA) (Burnash et al., 1973). These models have been used to investigate the hydrological effects of climate change over the Mesochora catchment. The MWB model was used by Mimikou and Kouvopoulos (1991) and Mimikou et al. (1991), and the SAA–SMA models were used by Panagoulia (1991, 1992, 1993) and Panagoulia and Dimou (1994a,b). Calibration, verification and comparison aspects of the models have been reported in Part 1, and showed that the SAA–SMA models are better than the MWB model in predicting the Mesochora catchment measured flows. The hydrological results of both models were analysed and discussed, and emphasis was given to the common model outputs (streamflow and soil moisture expressed on monthly and seasonal time scale).

The objective of this paper is to compare the changes in long-term average monthly and seasonal streamflow and the soil moisture predicted by the MWB and SAA–SMA models for alternative climate change scenarios. The simulated streamflow and soil moisture series for historical conditions (see companion paper) were used as reference runs (base cases). It is useful to compare changes predicted by two different hydrological models, because this gives a better understanding of the variability in simulation effects from one model to another, and indicates which effects of climate change are real and which are just the product of using a particular model (D.R. Maidment, personal communication, 1994). The SAA–SMA models have been examined for hypothetical climate change scenarios (Panagoulia, 1991, 1993; Panagoulia and Dimou, 1994b) and scenarios resulting from the application of the GISS (Goddard Institute for Space Studies) model to the Mesochora catchment (Panagoulia, 1992, 1993; Panagoulia and Dimou, 1994a,b). For comparison reasons, this study is limited to the set of hypothetical percentage changes in precipitation and temperature that were used by Mimikou and Kouvopoulos (1991) and Mimikou et al. (1991) in the MWB model.

The climate change scenarios and the adjustment of the model inputs for both approaches are described in the following section. The key points of simulated hydrologies for both models (MWB and SAA–SMA) for the assumed set of hypothetical changes in precipitation and temperature are presented in Section 3. Furthermore, the changes in streamflow (total runoff) and soil moisture produced by the models and hypothetical changes (in precipitation and temperature) are compared in detail. The conclusions of this study are presented in Section 4.

2. Climate change scenarios and model input

Most of the early studies on the effects of climate changes on hydrology and water resources relied on hypothetical scenarios of precipitation and temperature change (e.g. Němec and Schaake, 1982; Revelle and Waggoner, 1983; Flaschka, 1984; Gleick, 1986). This dependence on hypothetical changes was dictated by the limited capabilities of existing global climate models to predict accurately the details of regional climate changes.

The development of general circulation models (GCMs), which are the most comprehensive climate models, has provided a more realistic representation of future climate change. As the GCMs incorporate a description of the physics of atmospheric circulation, surface energy and water fluxes, they use a spatially coarse grid of cells with a linear scale on the order of hundreds to thousands of kilometres (Hansen et al., 1983, 1988; Mitchell and Qingcum, 1991). GCMs use computational time steps of 1 month or shorter, but it is doubtful if their predictions on time scales shorter than 1 month reflect the natural variability of field data, because such predictions represent grid-cell averages.

The climate simulations by the GCMs could be used directly to run hydrological models, but this issue is complicated by the incompatibility of space (and, to a lesser extent, time) scales in different hydrological processes, which account for variations from small to medium catchment scales (i.e. hundreds of metres to ten kilometres) (Lettenmaier and Gan, 1990). GCMs operate at scales of hundreds to thousands of kilometres or more. In addition, the GCM conceptualizations of atmospheric energy and moisture fluxes need further improvement in parameterization of cloud physics, energy transfer within the oceans, and land surface processes.

For these reasons, another form of climate change scenarios has been developed from GCM simulations such as those of the GISS (Goddard Institute for Space Studies) (Hansen et al., 1983), GFDL (Geophysical Fluid Dynamics Laboratory) (Manabe, 1969) and OSU (Oregon State University Department of Meteorology) (Schlesinger, 1984), for control and carbon dioxide doubling runs. Such scenarios, computed on a monthly basis for the centroid of catchments, have been used in many recent studies concerning the impacts of global warming on hydrology (e.g. Gleick, 1986; Lettenmaier and Gan, 1990; Panagoulia, 1992).

The most recent investigations related to climate change effects are focused on the large field experiments and projects, such as the EPOCH (European Programme on Climate and Natural Hazards), ECHIVAL (European International Project on Climate and Hydrological Interactions between Vegetation, Atmosphere, and Land Surfaces—part of the EPOCH Programme), EFEDA (ECHIVAL Field Experiment in Desertification-threatened Area) and HAPEX (Hydrologic–Atmospheric Pilot Experiment) (BAHC Core Project Office, 1993). The target of such projects is to improve the ecosystem–hydrology models, develop a database for establishing both the direction and magnitude of climate change, and validate the feedback mechanism of upscaling and downscaling procedures in GCMs (BAHC Core Project Office, 1993). However, the climate change scenarios remain in use, as they provide the ability to vary inputs to evaluate the model sensitivity. From the two above-mentioned forms of scenarios (hypothetical and GCM), only the hypothetical ones are considered in the present study, because, as mentioned above, GCM climate scenarios have not been examined in the MWB approach.

In both approaches (MWB and SAA–SMA models), the same set of hypothetical scenarios was used, including per cent changes in long-term average precipitation and increase in the global average surface air temperature. The values of precipitation change

Table 1
Hypothetical climate change scenarios of temperature increase and precipitation change ΔP (%)

ΔT (°C)	ΔP (%)				
1	−20	−10	0	10	20
2	−20	−10	0	10	20
4	−20	−10	0	10	20

drawn from the recent climatological literature (US National Academy of Sciences, 1983; Manabe and Wetherald, 1985; MacCracken and Luther, 1986) were: reduction by 10% and 20%, zero changes, and increase by 10% and 20%. It should be noted that the 10% precipitation increase is approximated by the 8.3% increase in mean monthly precipitation which was predicted by the GISS scenarios for the Mesochora catchment (Panagoulia, 1992).

The temperature increase ranged between 1.5 and 4.5°C, which could be reached in the year 2070 owing to the expected doubling of CO_2 concentration (Dickinson, 1982; US National Academy of Sciences, 1983; MacCracken and Luther, 1986). The selected values were 1°C, 2°C and 4°C. Again, it may be noted that the temperature increase of 4°C is practically the same as the mean monthly temperature increase of 3.94°C which has been predicted by the GISS scenarios for the Mesochora catchment (Panagoulia, 1992).

The combination of plus 1°C, 2°C and 4°C, and minus and plus 20%, 10% and 0% precipitation results in 15 hypothetical climate change scenarios (Table 1), which were coupled with the MWB and SAA–SMA models through the historical data which were used for their calibration. The adjustment of historical input series to account for the combined scenarios is described below.

2.1. MWB model climate input

The input data to the MWB model, which were adjusted for climate change scenarios, were the monthly precipitation and temperature time series of 15 hydrological years (from 1971–1972 to 1986–1987) of the Mesochora catchment. Assuming that the precipitation arrival process (that is, the probabilistic structure of wet and dry month sequences) remained the same as in the historical record, the indicated precipitation percentage change was applied uniformly to all monthly values of the historical precipitation input series by a multiplying factor corresponding to the selected percentage of change. Four modified monthly precipitation input series resulted, corresponding to the four climate change scenarios, and one input series with zero precipitation change.

The temperature increase scenarios were also applied uniformly to all the monthly values of the historical temperature input series, by adding a corresponding factor to each of the three temperature increases. Three altered monthly temperature input series resulted.

2.2. SAA–SMA models climate input

The daily precipitation series and the minimum and maximum daily temperature series for 15 years (1972–1986), for each of the three elevation zones into which the Mesochora catchment was divided (see companion paper), were the SAA model input data which were adjusted for climate change scenarios. In addition, the monthly long-term average potential evapotranspiration (PET) time series of the catchment estimated through the Penman equation (Veihmeyer, 1964), adjusted for the alternative scenarios, was used as input to the SMA model.

Assuming that the daily precipitation arrival process remained the same as in the historical record, the precipitation changes were applied uniformly to all daily values of the historical series for each elevation zone precipitation by multiplying them by a factor that represented the particular reduction (factor less than unity) or increase (factor greater than unity). Thus, for each zone, four modified daily precipitation series resulted for the four climate change scenarios and one for the zero precipitation change.

The temperature increase scenarios were applied uniformly to both minimum and maximum daily values of the historical series for each elevation zone temperature by adding a factor that represented the particular increase. Thus, for each zone, three modified daily temperature time series of minima and three of maxima were obtained, corresponding to the three temperature increase scenarios.

In Penman's equation, the only variable related to climate change was the monthly temperature, whereas all others (wind speed, humidity, solar radiation, etc.) were kept constant. The monthly temperature increase scenarios were the same as those applied to the daily time series (1°C, 2°C and 4°C) because the mean monthly temperature is estimated by averaging either the mean minimum and maximum daily temperature or three mean daily temperature values (8 h observations), by doubling the third temperature value (night temperature). Therefore, if the minimum and maximum daily temperature increase by the same amount, this implies that during all hours of the day the same temperature increase will prevail, a fact that attributes this increase to the mean monthly temperature regardless of the way it was actually computed. The above scenarios were applied uniformly to monthly values of the historical time series for the Mesochora catchment temperature, by adding a factor (1°C, 2°C, 4°C). Three modified monthly temperature time series were obtained. These modified temperature time series were used as input to the Penman equation, which consequently provided three monthly time series of PET corresponding to the three principal temperature increases. The long-term average of each monthly PET series was used as input to the SMA model.

3. Hydrological response

The long-term hydrological response of the Mesochora catchment was simulated for climate regimes associated with a base case (see the companion paper) and 15 hypothetical climate change scenarios (considered in the present paper) through two different approaches (MWB and SAA–SMA models).

In the MWB model (Mimikou and Kouvopoulos, 1991, Mimikou et al., 1991), the variables simulated for the alternative climate scenarios were the monthly catchment total runoff and soil moisture, both averaged over the 15 year (1971–1972 to 1986–1987) simulation period. Although the monthly snow storage (SNT) and actual evapotranspiration

(*ET*) are also variables of the model, and although Mimikou and coworkers often referred to them to explain their effect on runoff and/or soil moisture under global warming, these variables were not analysed for the modified climates.

For the 15 climate change scenarios the MWB model streamflow and soil moisture variables provided 15 monthly streamflow scenarios and 15 monthly soil moisture scenarios. The mean seasonal (winter–summer) and annual streamflow and soil moisture variables were set up for each scenario. Thus, the catchment hydrological response scenarios reached a total of 120 plus eight scenarios of the base case (MWB outputs for present climate conditions). These hydrological scenarios presented as percentages of changes of the base runs have been analysed by Mimikou and Kouvopoulos (1991) and Mimikou et al. (1991).

For the SAA–SMA models, more variables, operated on daily or shorter time steps and integrated on monthly increments as averages over the 15 year simulation period (1972–1986), were involved in the corresponding analysis (Panagoulia, 1991, 1992, 1993, Panagoulia and Dimou, 1994b). The variables used to describe the alternative hydrologies in the SAA–SMA models were: (1) monthly average snow water equivalent over catchment; (2) monthly average catchment total runoff; (3) monthly average catchment actual evapotranspiration; (4) monthly average catchment soil moisture storage in the simulated zones; (5) monthly average catchment cumulative soil moisture.

For the 15 climate change scenarios the simulated variables yielded 15 monthly snow water equivalent scenarios, 15 monthly total runoff scenarios, 15 monthly actual evapotranspiration scenarios, 15 monthly soil moisture storages for each of the five SMA moisture zones, and 15 monthly cumulative soil moisture scenarios, giving in total 135 catchment hydrological response scenarios plus nine of the base case (SAA–SMA model outputs for present conditions). The mean seasonal (winter–summer) and annual values of the above hydrologies were computed and analysed when it was considered necessary. An extensive analysis of the above hydrological scenarios described in terms of distributions of real (absolute) values has been presented by Panagoulia (1991, 1992, 1993) and Panagoulia and Dimou (1994b).

Before the comparison of the common alternative hydrologies (streamflow–soil moisture scenarios) predicted by the two models (MWB and SAA–SMA) begins the key points of all the above indicated hydrological scenarios are described. This is considered particularly useful for the hydrologies that are not included in the comparative analysis, as they may characterize or affect the compared ones and their possible differences. For example, the snow storage scenarios simulated by the SAA model are not compared, but they strongly influence the annual hydrograph peaks in the compared runoff scenarios. Likewise, the SMA model cumulative soil moisture scenarios, which were compared and which resulted from the summation of the soil moisture scenarios corresponding to the five soil moisture storages, were different. As indicated below, the large differences between MWB and SMA model soil moisture alternative simulations, may be attributed, at least in part, to the complicated behaviour that is hidden behind the cumulative SMA soil moisture scenarios (Panagoulia and Dimou, 1994b). The main features of the above alternative hydrological scenarios are reported according to their simulation by the particular model.

3.1. MWB model response

3.1.1. Total runoff

The annual runoff (Table 2 and Fig. 4 of Mimikou et al. (1991)) increased remarkably with the precipitation increase and decreased substantially with the precipitation decrease. The temperature increase yielded reduction in the annual runoff almost proportional to the temperature increase.

The two seasonal runoff quantities (winter and summer) (Table 2 and Figs. 5 and 6 of Mimikou et al. (1991)) reflected a contrasting behaviour. Thus, whereas the winter runoff increased with temperature increase, the summer runoff decreased. Summer runoff seems more sensitive to temperature increase. This behaviour was attributed to the earlier melting of snowcover and the increased evapotranspiration, which are strongly controlled by the temperature status.

The monthly runoff (Table 3 and Fig. 7 of Mimikou et al. (1991)) increased with respect to temperature increase during the winter months and the spring snowmelt runoff shifted towards winter. Consequently, a considerable decrease in runoff was observed during spring and summer months. For the case presented in Fig. 7 of Mimikou and Kouvopoulos (1991), the runoff peak shifted 2 months earlier (from April to February) for the combined scenarios of 2°C and 4°C temperature increase and unchanged precipitation, with respect to that of the base run. In the scenario of 1°C temperature increase and unchanged precipitation the peak shifted 4 months earlier (from April to December). The temperature increase of 4°C and precipitation decrease by 20% resulted in the maximum runoff decrease of 65% in July.

3.1.2. Soil moisture

The annual and summer soil moisture (Table 4 of Mimikou et al. (1991)) decreased significantly even for precipitation increase of 20%. The maximum decrease of summer soil moisture reached 70% for the driest combined scenario of 4°C temperature increase and 20% precipitation reduction. In contrast, the winter soil moisture remained almost unaffected by any climate scenario.

Regarding the monthly distribution of soil moisture changes (Table 4 of Mimikou et al. (1991)), a significant decrease appeared in May owing to the reduced spring snowmelt runoff and its shifting towards winter, and owing to the increased evapotranspiration. In the summer months, the largest soil moisture reduction occurred in August, and reached 100% for the combined scenarios of 4°C temperature increase and almost all precipitation changes.

3.2. SAA–SMA model response

3.2.1. Snow water equivalent

There was a remarkable decrease in the average snow water equivalent (Fig. 2 of Panagoulia (1991)) for all alternative climate scenarios. The combined scenarios of temperature increase by 4°C and all precipitation changes yielded the maximum decrease, reflecting the fact that for a temperature rise of several degrees Celsius, the temperature is the basic factor of snow storage control compared with precipitation. The other combined scenarios caused progressive decrease in the average snow water equivalent from the wetter to the drier climate.

Regarding the monthly distribution of the snow water equivalent for the combined scenarios of temperature increase of 1°C and 2°C and all precipitation changes, the average snow water equivalent peak occurred in March, whereas for the drier combined scenarios (ΔT = 4°C and all ΔP values) the snow water equivalent maximum occurred 1 month earlier (February).

3.2.2. *Total runoff*

Significant changes in the monthly distribution of runoff (Fig. 3 of Panagoulia (1991)) were observed for all climate scenarios. The effect of reduced snow storages and change in the timing of snowmelt (Fig. 2 of Panagoulia (1991)) was apparent in all runoff responses. The annual hydrograph peak shifted earlier in the year because of the decrease in the amount of snowfall with respect to rainfall. In 12 of the 15 climate change scenarios, the runoff peak shifted 2 months earlier compared with that of the base case (the peak shifted from April to February). In the other three scenarios (ΔT = 1°C, ΔP = + 10% or 20%; ΔT = 2°C, ΔP = + 20%) the peak shifted 4 months earlier (from April to December). The greatest monthly runoff decrease was observed in May for most climate cases.

The summer (June, July, August) runoff decreased considerably in almost all climate cases. For the driest scenario of 4°C temperature increase and 20% precipitation decrease, the summer runoff dropped about 50%. The winter runoff increased in ten of the 15 combined climate cases. The maximum winter runoff increase reached 60% for the temperature increase of 4°C and precipitation increase of 20%. The climate scenarios which reduced the winter runoff were the 20% precipitation increase for all temperature increases and the 20% precipitation increase for 1°C and 2°C temperature increase.

3.2.3. *Evapotranspiration*

The actual evapotranspiration (ET) (Panagoulia, 1991) simulated by the SMA model depends on the soil moisture status, and on the potential evapotranspiration (*PET*). Although the *PET* increased during months and for all climates owing to temperature increase, the direction of change of the ET varied from season to season. During the wet November–April period, the ET remained unaffected by precipitation changes, but increased compared with the base case ET. During the dry May–October period the ET increased with precipitation increase and decreased with precipitation decrease. The peak value of the monthly ET occurred in June for the base case and for nine of the 15 climate scenarios, whereas for the other six scenarios (characterized by precipitation decrease) the peak values occurred in May. The climate scenarios with minor precipitation decrease showed a flatter crest in the monthly distribution of ET.

3.2.4. *Upper zone tension water*

The moisture content in the upper tension zone (Fig. 5 of Panagoulia (1991)) was not significantly affected by climate change scenarios in the winter period, whereas during all other months the moisture content was significantly affected. The tension moisture content of the zone decreased for all months and its maximum decrease occurred in May for all climate cases. The fact that a considerable tension moisture reduction occurred in spring and early summer months is due to snowmelt reduction.

3.2.5. Lower zone tension water

The moisture content in the lower tension zone (Fig. 6 of Panagoulia (1991)) was minimum in October for the driest combined scenarios of 4°C temperature increase and 20% precipitation decrease. Generally, the larger lower zone tension moisture decrease shifted forward 2 or 3 months with respect to those of the upper zone tension moisture storages.

3.2.6. Upper zone free water

The free water contents in all three zones of the model (Figs. 7–9 of Panagoulia (1991)) are strongly and randomly influenced by all climate scenarios, as well as from month to month under the same scenario. It should be noted that the free moisture content in the upper zone (Fig. 7 of Panagoulia (1991)) showed greater fluctuations than those in the lower zones. Specifically, the peak occurred in January for the drier climate scenarios and in December for the others, whereas during the dry summer period, the upper zone free water decreased for all climate cases.

3.2.7. Lower zone primary free water

The free moisture content in the lower zone (Fig. 8 of Panagoulia (1991)) supplies the baseflow with larger amounts than those supplied to the lower supplemental zone. Its peak occurred in March for 13 of the 15 climate scenarios, whereas the peak for the base case occurred in May. For the other two scenarios of 1°C temperature increase and precipitation decrease by 10% and 20%, the primary free moisture content was maximum in April. For all climate cases the primary free moisture was minimum in October.

3.2.8. Lower zone supplemental free water

For 12 of the 15 climate scenarios the supplemental moisture content (Fig. 9 of Panagoulia (1991)) was maximum in March, whereas for the scenarios of 4°C temperature increase and 10% and 20% precipitation decrease, as well as for the scenario of 2°C temperature increase and 10% precipitation decrease, the peak shifted to February. The moisture content was minimum in August for all climate cases.

3.2.9. Cumulative soil moisture

Despite the fact that the five soil moisture storages provided random monthly distributions for all climate cases, the cumulative soil moisture scenarios (Fig. 1 of Panagoulia and Dimou (1994b)) were characterized by a smoothing effect probably owing to the method of computing, i.e. the summation of reversely interacting distributions. However, there was a definite phase shift to cumulative soil moisture (over all storages) particularly during the October–April period. This has been attributed to the warmer and generally wetter climates, owing to the greater rainfall compared with snowfall; more moisture is available during winter and early spring at the expense of late spring and summer. The greatest cumulative soil moisture decrease occurred in September for the driest scenario of 4°C temperature increase and 20% precipitation decrease.

3.3. Comparison of results

The comparison is between the results of the MWB and SAA–SMA models concerning the average total runoff and soil moisture response, expressed as percentages of change of base run by season and month, to hypothetical climate scenarios. Fig. 1 and Fig. 2 show the changes in mean seasonal (winter–summer) runoff and soil moisture, respectively, for both models, as a function of precipitation and temperature changes.

Fig. 3 and Fig. 4 show the changes in mean monthly runoff for both models with respect to temperature increase and all precipitation changes, as well as with respect to precipitation change and all temperature increases. Fig. 5 and Fig. 6 reflect the changes in mean monthly soil moisture for both models with respect to the climate scenarios adopted for runoff.

3.3.1. Seasonal runoff

The changes in mean (long-term) winter runoff over the catchment for all alternative climates and both models are presented in Fig. 1(a), as a function of precipitation changes, and in Fig. 1(b), as a function of temperature increases. There was an increase in winter runoff with respect to precipitation and temperature increase for all alternative scenarios and both MWB and SAA–SMA models. The temperature increase from 2°C to 4°C produced a smaller rate of increase of winter runoff than that from 1°C to 2°C, for all precipitation cases in the MWB model, showing that the MWB model is less sensitive to large temperature increases than the SAA–SMA models, in which the runoff increased much more proportionately to temperature increase. The weakness of the MWB model in accurately simulating the runoff is due to the rough representation of snow accumulation and melting processes which control the seasonal runoff.

Regarding the results of both models, the low precipitation climates provided comparable (almost the same) values of winter runoff changes (mostly reductions) for both models, whereas the high-precipitation climates provided slightly different values of winter runoff increases, with the greater values provided from the MWB model.

Fig. 1(c) and Fig. 1(d) show the changes in summer runoff for both models as a function of precipitation change (Fig. 1(c)) and temperature increase (Fig. 1(d)). Both models predicted increased summer runoff with respect to precipitation increase and temperature decrease. The MWB model was less sensitive to large temperature increase. The rate of decrease of summer runoff was smaller when temperature increased from 2°C to 4°C than when it increased from 1°C to 2°C for all alternative climates. As noted above, the most probable reason for the MWB model weakness is the lack of a dynamic representation of snow storages, of which the reduced values (Section 3.2.1) caused earlier snowmelt in the year and shifted the late spring and summer runoff to winter, and thus resulted in large runoff reductions in summer.

Concerning the comparison of summer runoff between the two models, the MWB model predicted larger reductions (about 10%) than those predicted from the SAA–SMA models. This may be attributed to the MWB model snowmelt runoff mechanism, which resulted in greater winter runoff values, as well as to the use of different methods in computing *PET* and soil moisture, under the increased evapotranspiration and soil moisture deficits in summer (see the companion paper, Panagoulia and Dimou (1997)).

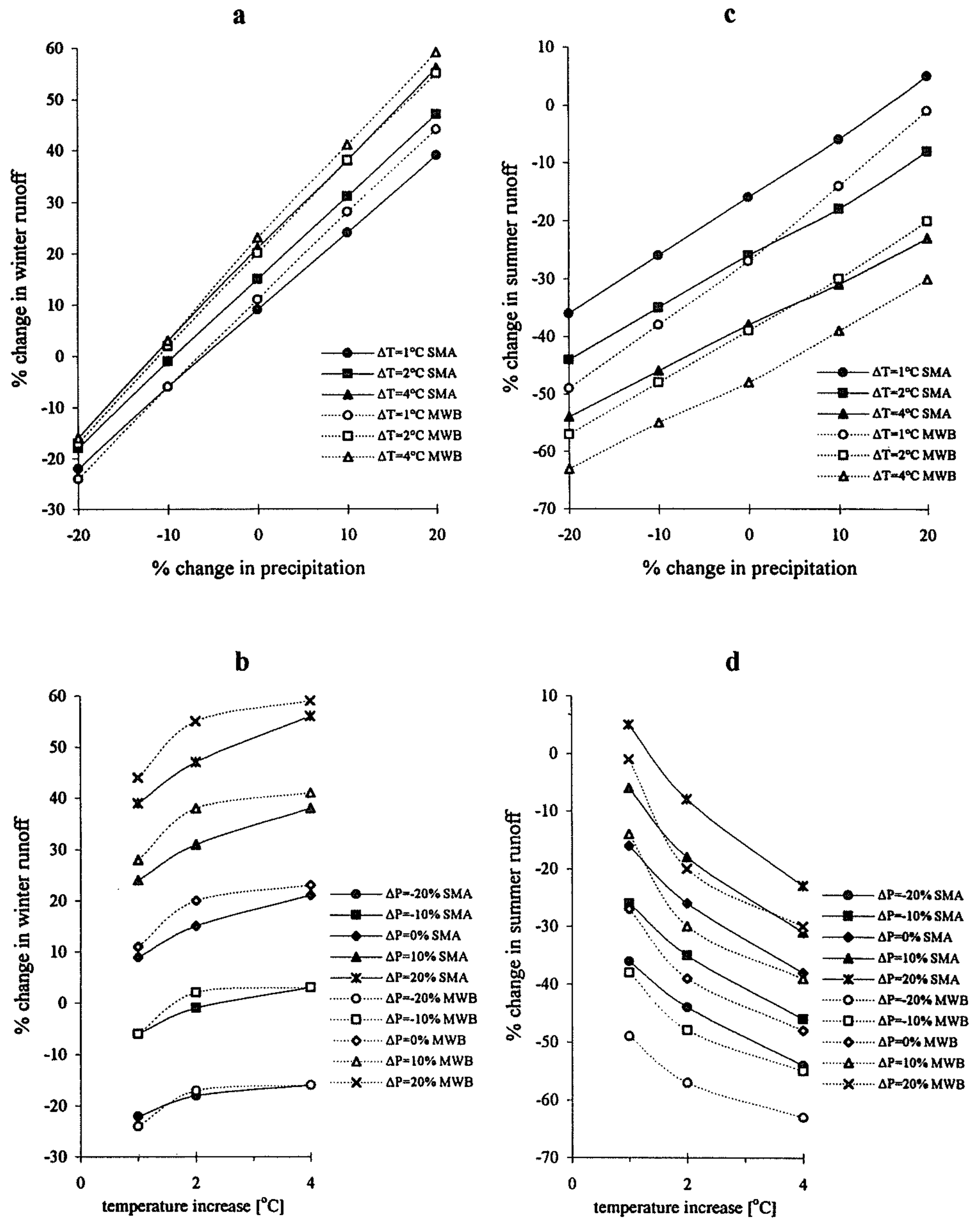


Fig. 1. Mesochora catchment mean seasonal runoff changes predicted by the MWB model (dashed line) and the SMA model (continuous line) as a function of precipitation and temperature: (a) winter runoff changes vs. precipitation changes; (b) winter runoff changes vs. temperature changes; (c) summer runoff changes vs. precipitation changes; (d) summer runoff changes vs. temperature.

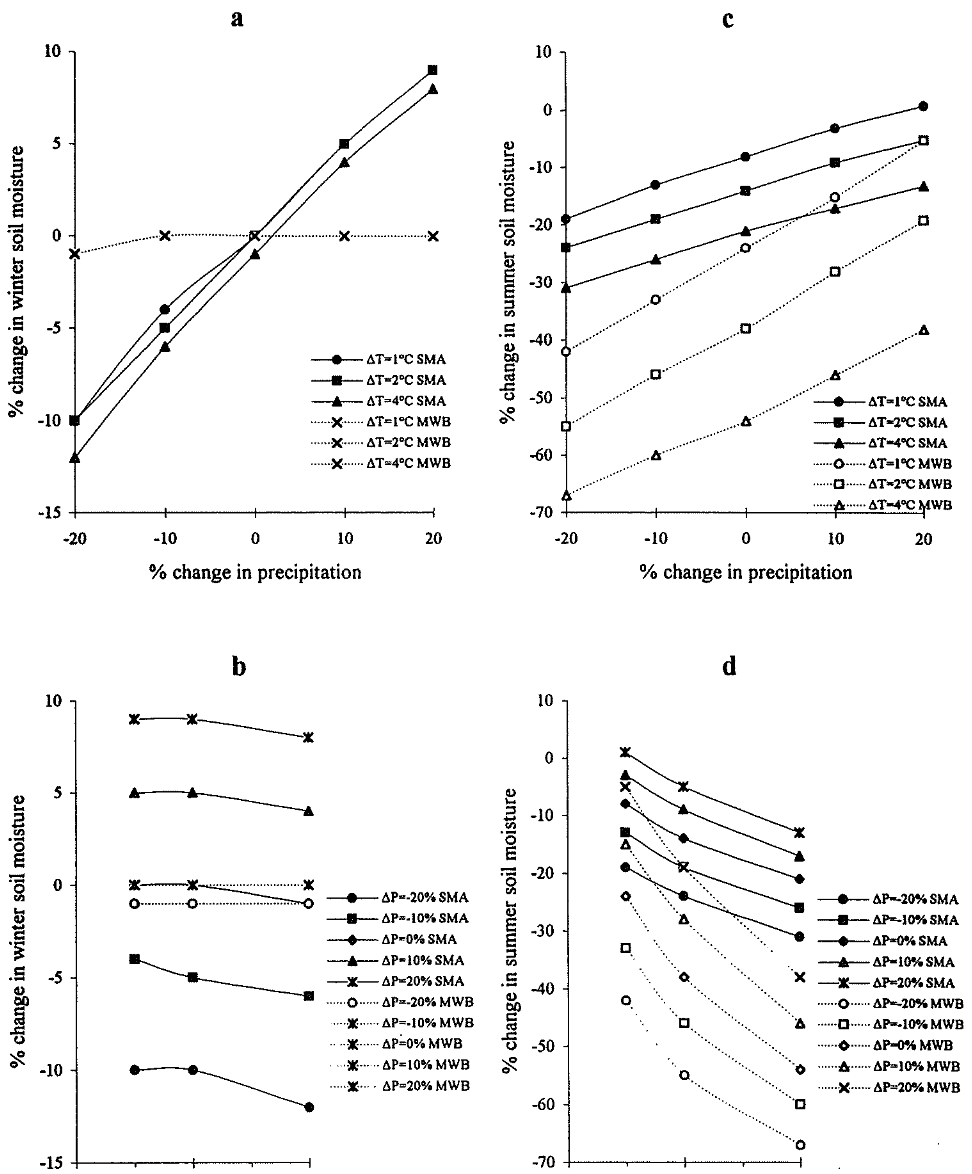


Fig. 2. Mesochora catchment mean seasonal soil moisture changes predicted by the MWB model (dashed line) and the SMA model (continuous line) as a function of precipitation and temperature: (a) winter runoff changes vs. precipitation changes; (b) winter runoff changes vs. temperature changes; (c) summer runoff changes vs. precipitation changes; (d) summer runoff changes vs. temperature.

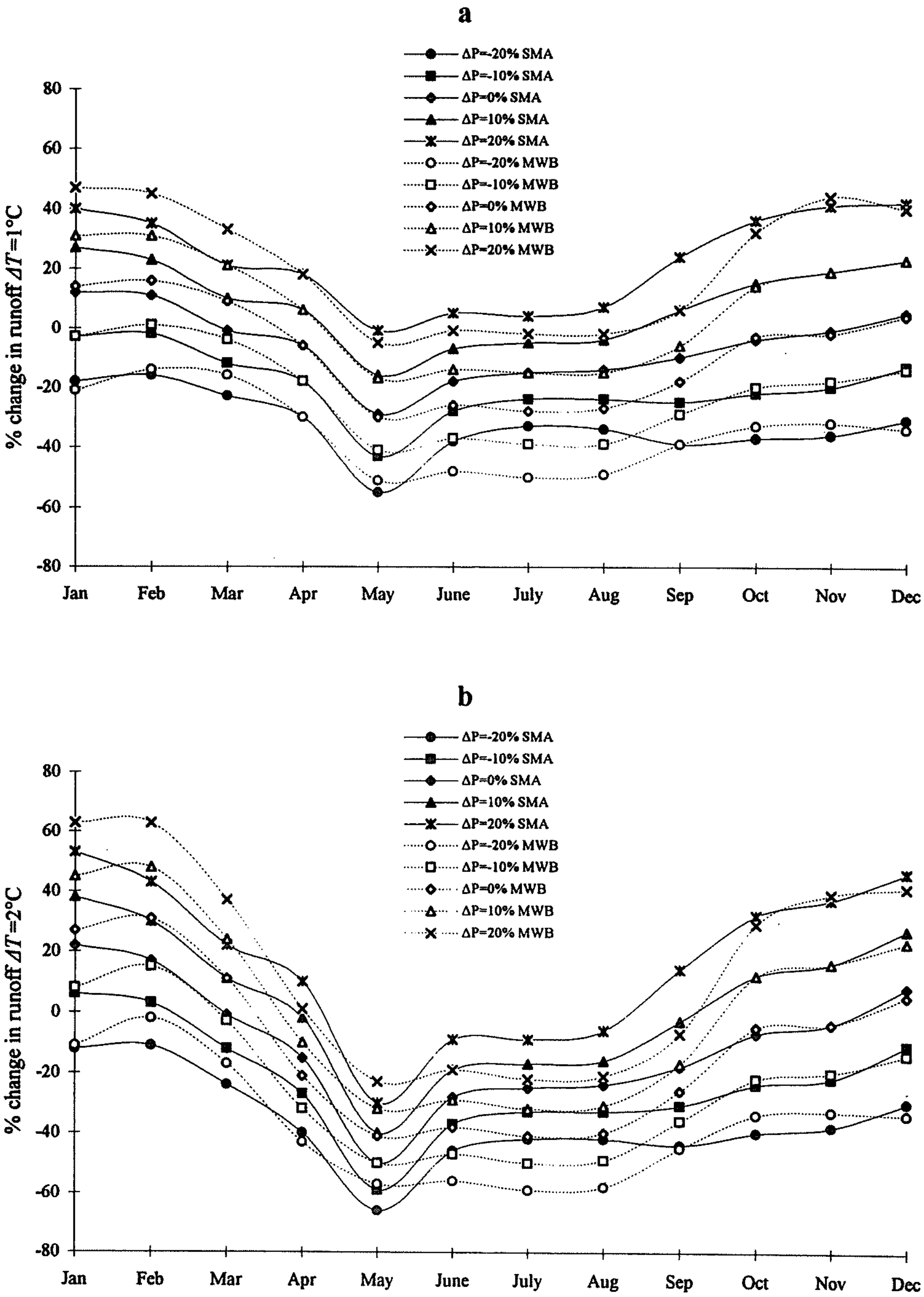


Fig. 3. Mesochora catchment mean monthly runoff changes predicted by the MWB model (dashed line) and the SMA model (continuous line) for the associated scenarios of all precipitation changes and (a) 1°C temperature increase ($\Delta T = 1$°C), (b) 2°C temperature increase ($\Delta T = 2$°C), and (c) 4°C temperature increase ($\Delta T = 4$°C).

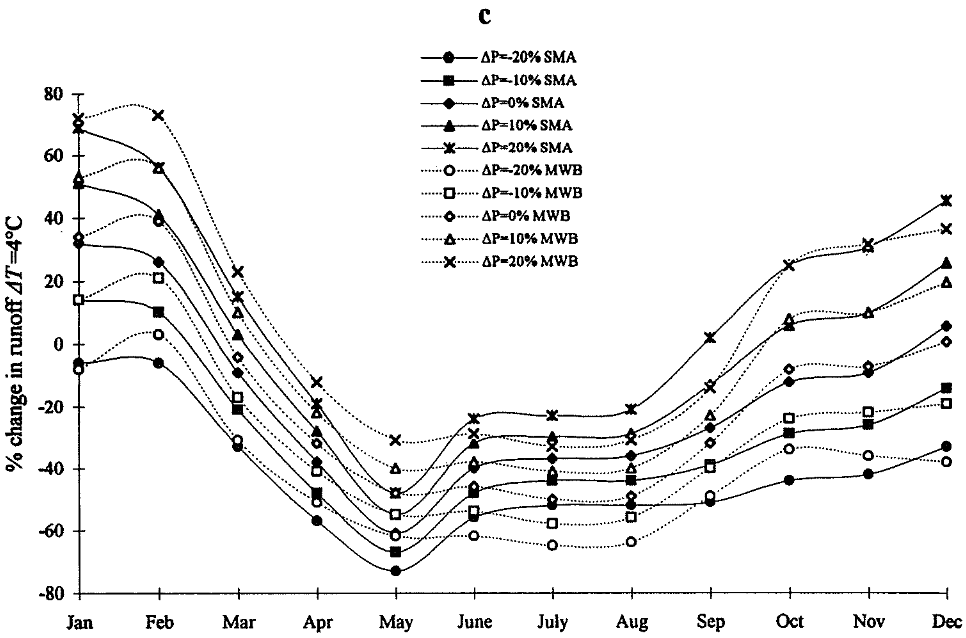


Fig. 3. Continued.

3.3.2. Seasonal soil moisture

Fig. 2(a) and Fig. 2(b) indicate a decrease in winter soil moisture with respect to precipitation decrease, and, to a lesser degree, with respect to temperature increase under all climate cases for the SMA model. The winter soil moisture predicted from the MWB model remained unaffected by almost all combined precipitation and temperature climates. Fig. 2(b) shows the greater sensitivity of SMA soil moisture predictions with respect to modified climates, during the winter period when the soil is near to saturation and *PET* is low.

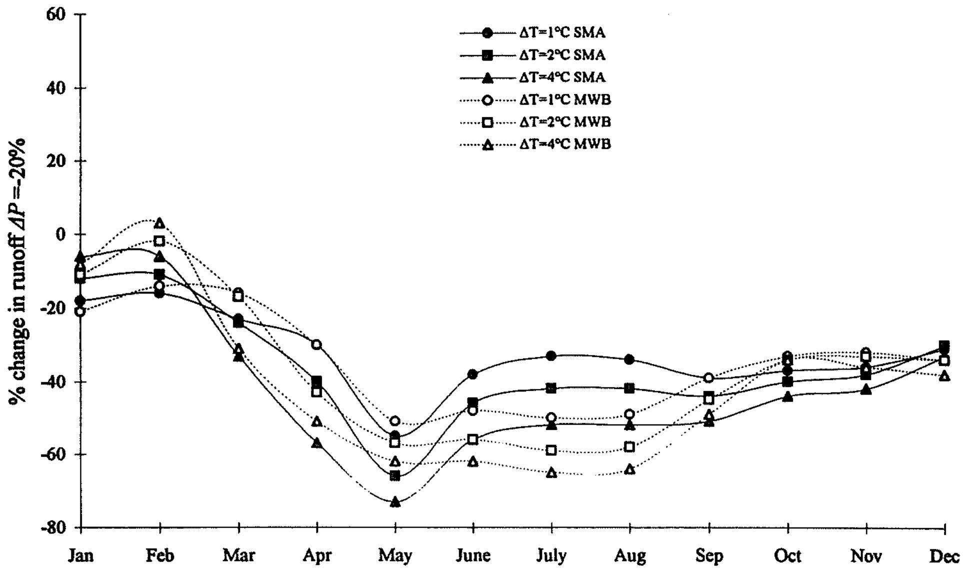
Fig. 2(c) and Fig. 2(d) show a progressive decrease in summer soil moisture with precipitation decrease and temperature increase for all climate cases, which is more apparent in the MWB simulations than the SMA ones. The significantly greater decrease of the summer soil moisture predicted by the MWB model is attributed to the greater summer runoff decrease resulting in limited availability of surface water needed for soil moisture saturation.

3.3.3. Monthly runoff

Fig. 3 shows the monthly distribution of long-term (mean) runoff changes for both models and all climate scenarios with temperature increase. Generally, there was a greater monthly variability of SMA runoff changes than of MWB ones for all scenarios.

For the scenarios of 1°C temperature increase and all precipitation changes (20%, 10%, 0%) the runoff changes (Fig. 3(a)) were comparable for both models during the wet period (January–May). However, in this period, a trend for larger reduction and lesser increase in SMA compared with MWB model predicted runoff was observed. This was more apparent

a



b

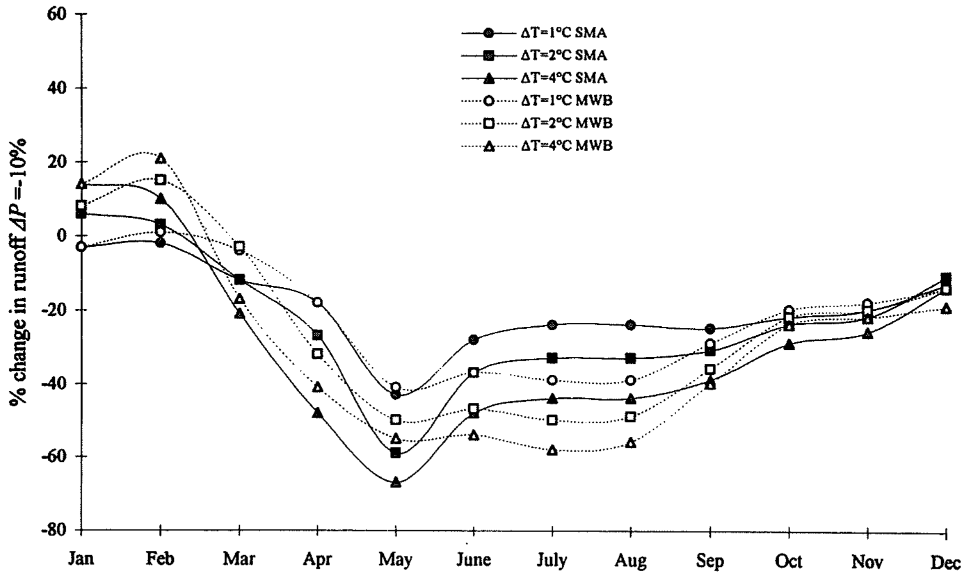
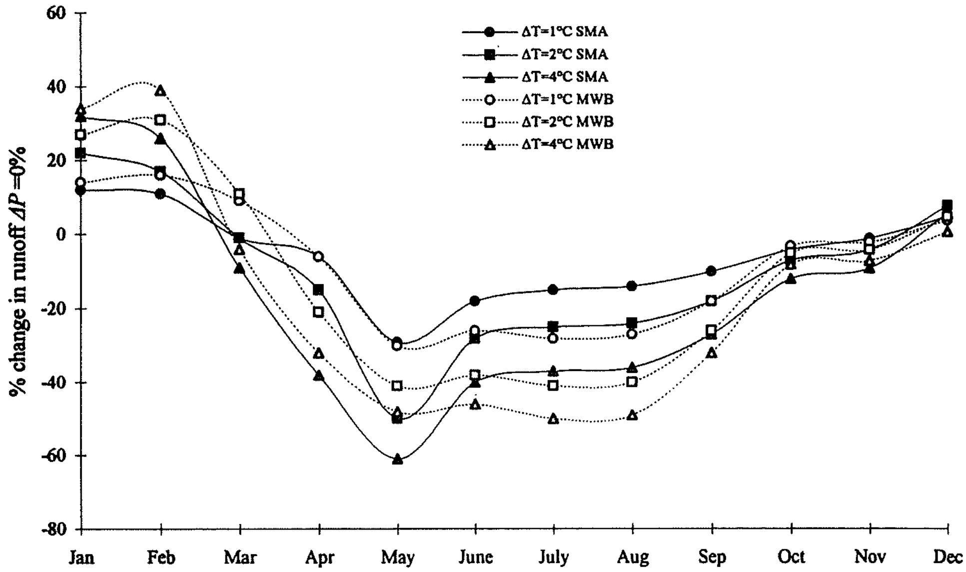


Fig. 4. Mesochora catchment mean monthly runoff changes predicted by the MWB model (dashed line) and the SMA model (continuous line) for the associated scenarios of all temperature increases and (a) 20% precipitation reduction ($\Delta P = -20\%$), (b) 10% precipitation reduction ($\Delta P = -10\%$), (c) zero precipitation change ($\Delta P = 0\%$), (d) 10% precipitation increase ($\Delta P = 10\%$), and (e) 20% precipitation increase ($\Delta P = 20\%$).

c



d

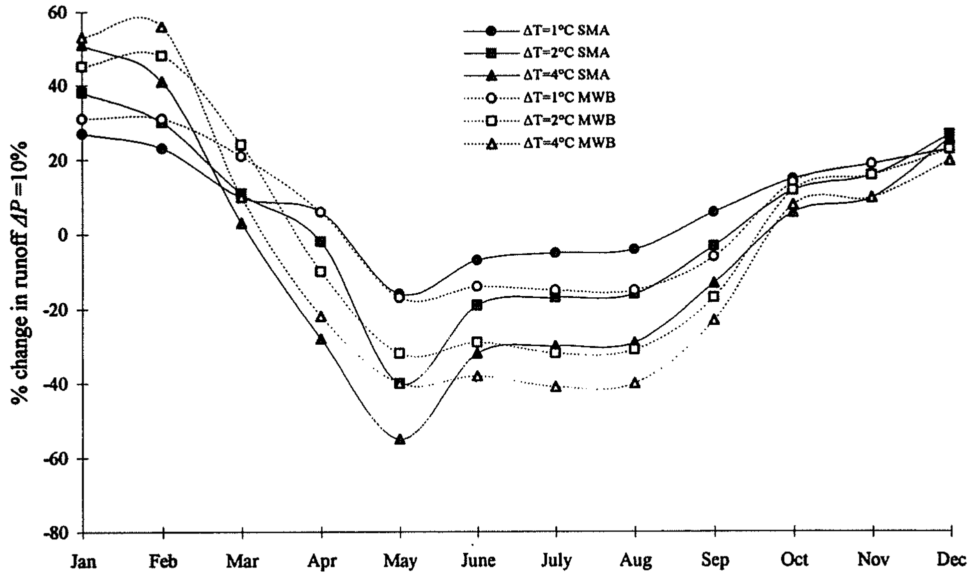


Fig. 4. Continued.

e

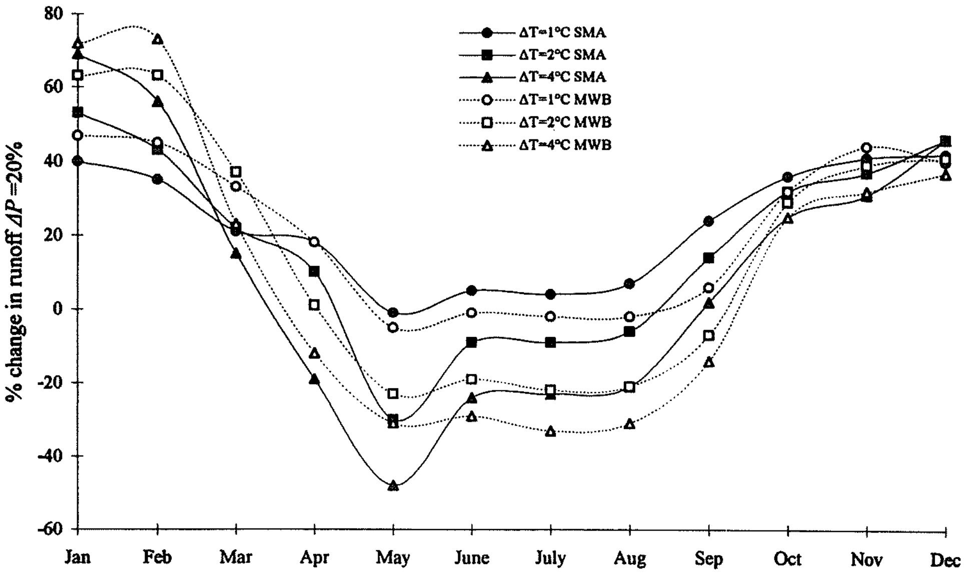


Fig. 4. Continued.

in March. During the dry period (June–September) for the same climate cases, clearly lesser reductions and larger increases in runoff were predicted by the SMA model compared with those of the MWB model. During the autumn period the runoff changes predicted from both models under the above-mentioned climates were approximately the same.

For the scenarios of 2°C temperature increase and all precipitation changes, for most months of the wet period, the SMA model predicted larger reductions and lesser increases of runoff than the MWB model (Fig. 3(b)). In contrast, the runoff changes in April predicted by the SMA model were characterized by lesser reductions and larger increases. During the dry period, the runoff decrease was greater, with the same profile as for the scenarios of 1°C temperature increase, i.e. lesser reductions and larger increases were predicted by the SMA model than by the MWB model. The autumn runoff changes were similar in both SMA and MWB predictions for the examined scenarios (2°C temperature increase). Nevertheless, in December, a trend for lesser reductions and larger increases was observed for the runoff predicted by the SMA model.

The runoff changes during the 3 months of the wet period predicted by the SMA and MWB models were similar for the scenarios of 4°C temperature increase and all precipitation changes (Fig. 3(c)). In February and May the runoff changes reflected larger reductions and lesser increases for the SMA model compared with the MWB model. In the dry period the runoff decrease was even greater, with the same profile as for the scenarios of 1°C and 2°C temperature increase, i.e. lesser reductions were predicted by the SMA model than by the MWB model. During the autumn period the runoff changes were similar for both SMA and MWB models. Nevertheless, in October and November, a trend for larger reductions and lesser increases was observed for the runoff predicted by the SMA model. However, in December, a trend for lesser reductions and larger increases was noticed for the runoff predicted by the SMA model.

From the above analysis (Fig. 3), it is apparent that the greater runoff increase occurs during the winter months and the greater decrease during the summer months for the predictions of the MWB model. This is probably due to the different mechanisms of snow accumulation and melting processes involved in the models. The effect of reduced snow storage is apparent in both cases, but with different magnitude and timing: the shifting in the year of the annual hydrograph peak occurred earlier, under more and different climate scenarios, for the MWB (Section 3.1.1) in relation to the SMA model. Thus, the MWB runoff increase in winter months was greater than the SMA one, resulting in greater MWB runoff decrease in summer months. The different algorithms for the calculation of the *PET* and soil moisture (see the companion paper, Panagoulia and Dimou (1997)), taking into account the increased evapotranspiration and soil moisture deficits in summer months, may be the reason for the greater runoff reductions during summer predicted by the MWB model compared with the SMA model.

The monthly distribution of mean (long-term) runoff changes for both models and all climate scenarios with precipitation change (from –20% to 20%) is presented in Fig. 4. Runoff increased with respect to temperature increase during January and February for both models and all precipitation changes owing to the decrease in the amount of snowfall (reduced snow storages). During the other months of the year, and especially in May, runoff decreased with respect to temperature increase for both models and all precipitation changes. However, the rate of the MWB predicted runoff change (increase or decrease) for temperature increase from 2°C to 4°C was less than that predicted for temperature increase from 1°C to 2°C, showing, as in the seasonal case, that the MWB model is rather less sensitive to higher temperatures, a fact not so compatible with reality. This MWB weakness, as previously discussed, may occur because snow accumulation and melting are not accurately simulated by the MWB model.

3.3.4. Monthly soil moisture

Fig. 5 shows the simulated changes in the monthly distribution of soil moisture with respect to temperature increase for all climate scenarios and both models. There was a slightly greater variability of soil moisture predicted by the SMA model than by the MWB model during the wet period (January–April). During this period, the MWB soil moisture remained almost unaffected for all climate scenarios, whereas the SMA soil moisture varied substantially for all climate scenarios and for every month. In particular, the MWB soil moisture simulations were compatible with the SMA upper and lower tension moisture contents (almost zero changes), a fact attributed to the soil saturation and mainly to low actual evapotranspiration during the wet period. In contrast, the free moisture content in the three zones (one upper and two lower) of the SMA model were considerably affected by climate changes, especially those of lower storages (Sections 3.2.7, 3.2.8). These two lower storages are not parameterized by the MWB model and thus, it is not possible to simulate winter (wet period) changes in soil moisture with the MWB model.

During the dry period (May–September), the MWB soil moisture showed large reductions, which in August reached 100% for the driest scenarios of 4°C temperature increase

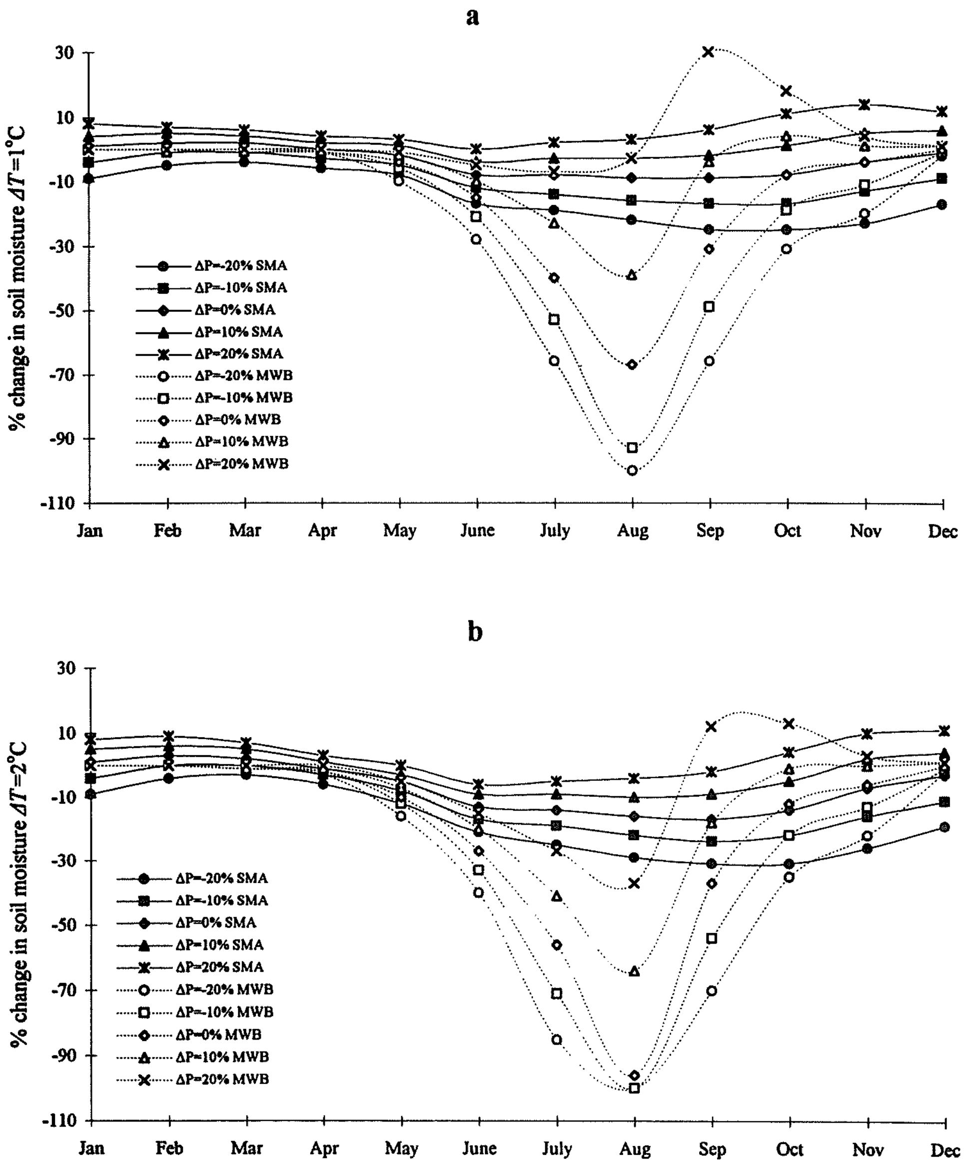


Fig. 5. Mesochora catchment mean monthly soil moisture changes predicted by the MWB model (dashed line) and the SMA model (continuous line) for the associated scenarios of all precipitation changes and (a) 1°C temperature increase (ΔT = 1°C), (b) 2°C temperature increase (ΔT = 2°C), and (c) 4°C temperature increase (ΔT = 4°C).

and precipitation changes of 0%, ±10% and ±20%. The larger reductions in spring snowmelt runoff and the earlier shifting towards winter, which were predicted from the MWB model, caused major reductions in surface water available for evapotranspiration and soil moisture, resulting in larger soil moisture deficits (compared with the SMA ones).

c

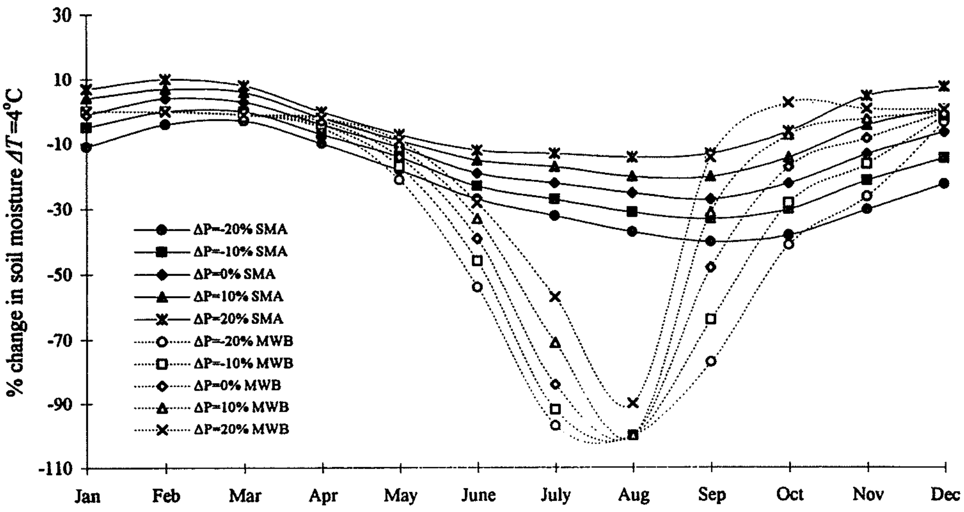


Fig. 5. Continued.

Furthermore, the different parameterization of soil layers, i.e. the upper layer in the MWB model and the five storages in the SMA model, three of which are at a greater depth (SMA model lower zone), is the main reason for the large differences between the results of the models, especially for the dry period, given that each moisture storage responds to climate change very inconsistently (Section 3.2.6). The upper and the lower supplemental free water predicted by the SMA model were almost the same as the free water predicted by the MWB (one-layer) model. The SMA lower zone primary free water values contributed to the greatest differences between MWB and cumulative SMA soil moisture. Moreover, the different methods in calculating *PET* under the dry conditions of summer months resulted in different soil moisture values for the MWB and SMA models.

During the autumn period (October–December), both models predicted comparable soil moisture changes. Smaller changes were predicted by the MWB model in December. In October and November the soil moisture changes were similar for both models. Smaller changes were predicted by the SMA model in October, whereas greater changes were predicted by the SMA model in November. In contrast, during December the predicted soil moisture changes were substantially different between the two models, showing greater changes for the SMA model.

The monthly distribution of long-term (mean) soil moisture changes for both models and all climate scenarios with precipitation change (from 20% to 20%) is presented in Fig. 6. There was a slight reduction in soil moisture with respect to temperature increase for the SMA model and almost all precipitation changes during the wet period (December–April). During this period, the MWB soil moisture remained almost unaffected by temperature increase. In contrast, during the other months the reduction rate of soil moisture was significantly greater proportional to temperature increase for both models and all precipitation changes. In August, the MWB soil moisture remained unaffected by all

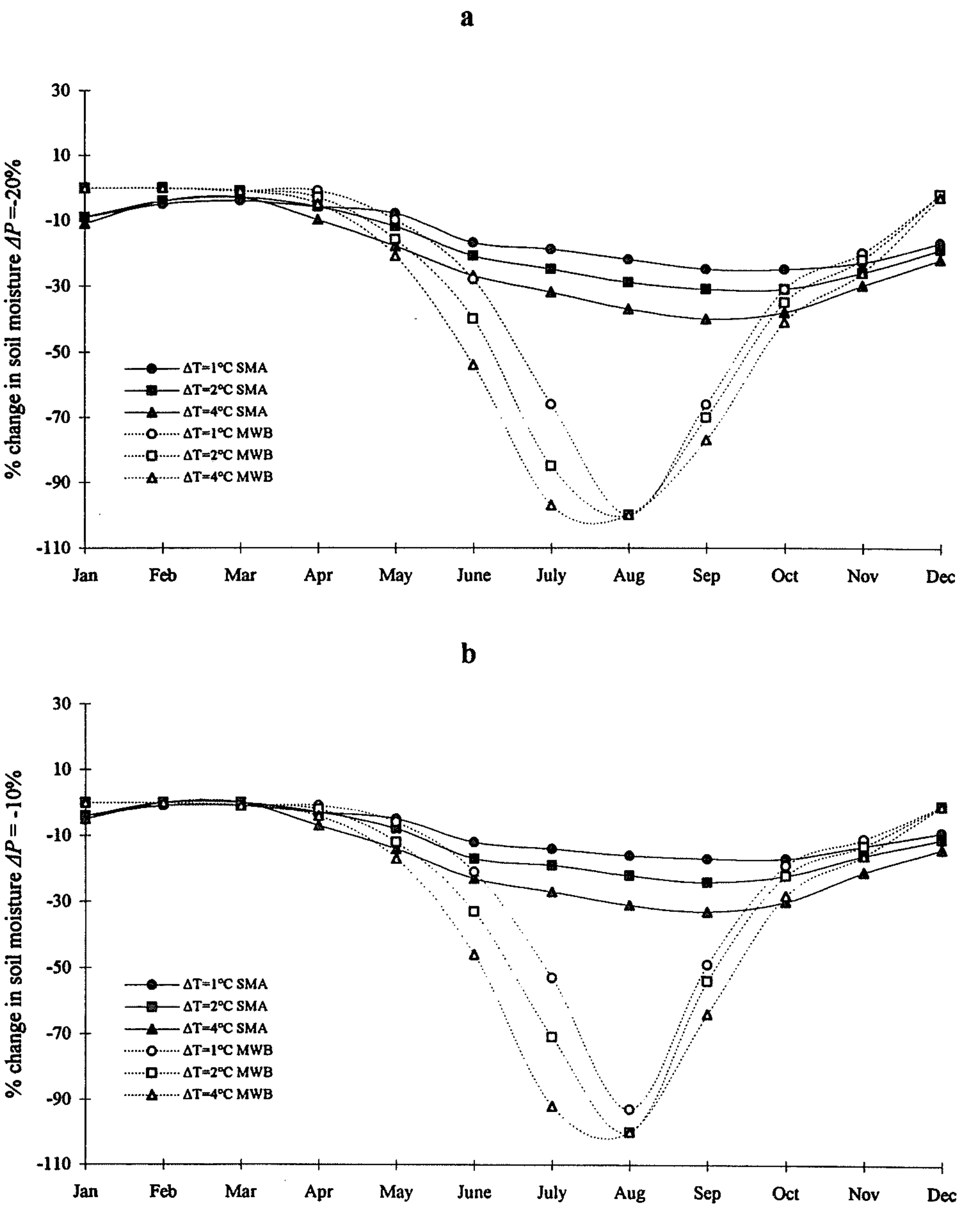


Fig. 6. Mesochora catchment mean monthly soil moisture changes predicted by the MWB model (dashed line) and the SMA model (continuous line) for the associated scenarios of all temperature increases and (a) 20% precipitation reduction ($\Delta P = -20\%$), (b) 10% precipitation reduction ($\Delta P = -10\%$), (c) zero precipitation change ($\Delta P = 0\%$), (d) 10% precipitation increase ($\Delta P = 10\%$), and (e) 20% precipitation increase ($\Delta P = 20\%$).

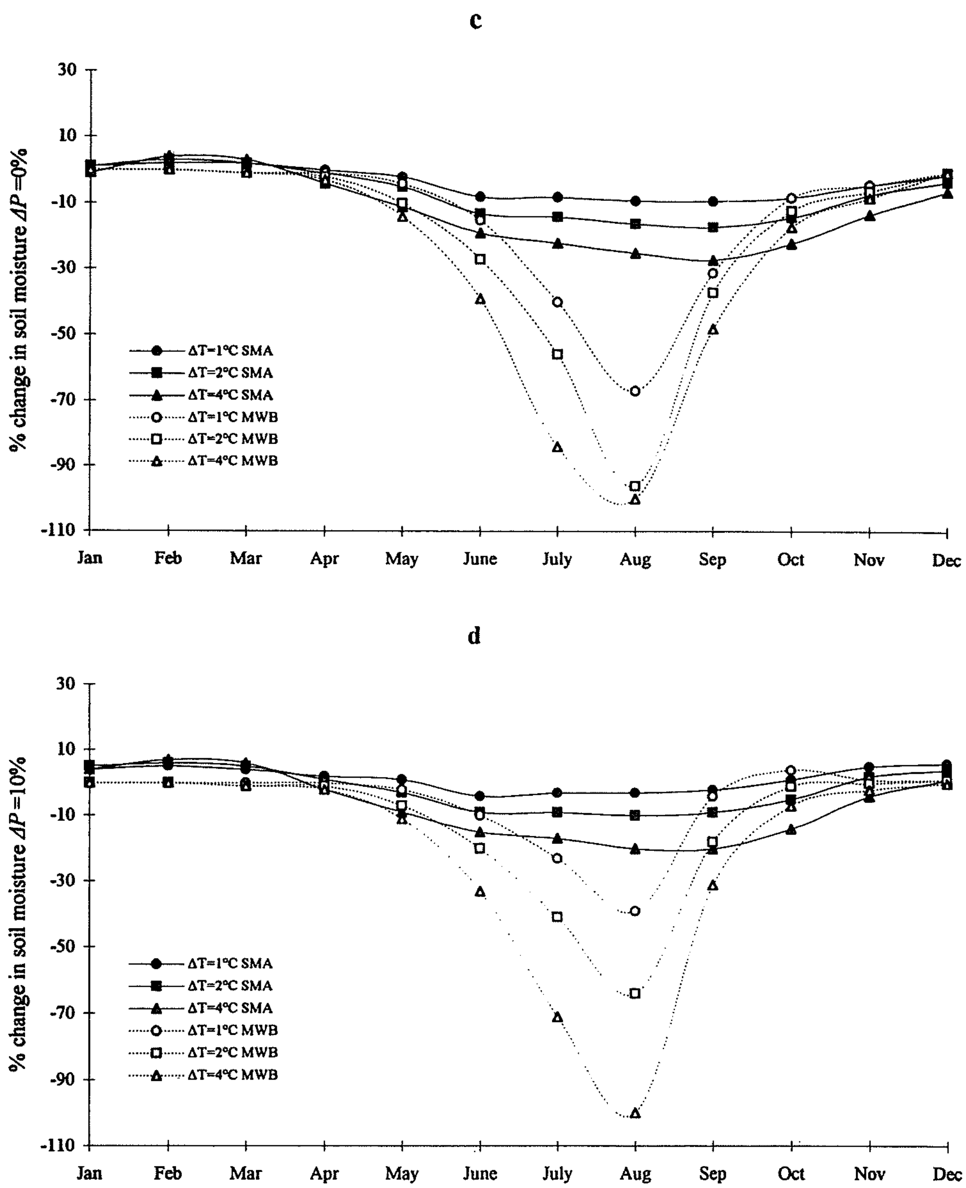


Fig. 6. Continued.

temperature increases for the reduced precipitation climate of 20% and by the greater temperature increase (2°C, 4°C) for the reduced precipitation climate of 10%, whereas it varied with respect to temperature and precipitation increase (0%, 10%, 20%). The profile of soil moisture in August as predicted by the MWB model indicates that soil moisture is mainly controlled by precipitation changes rather than temperature increase, in the dry

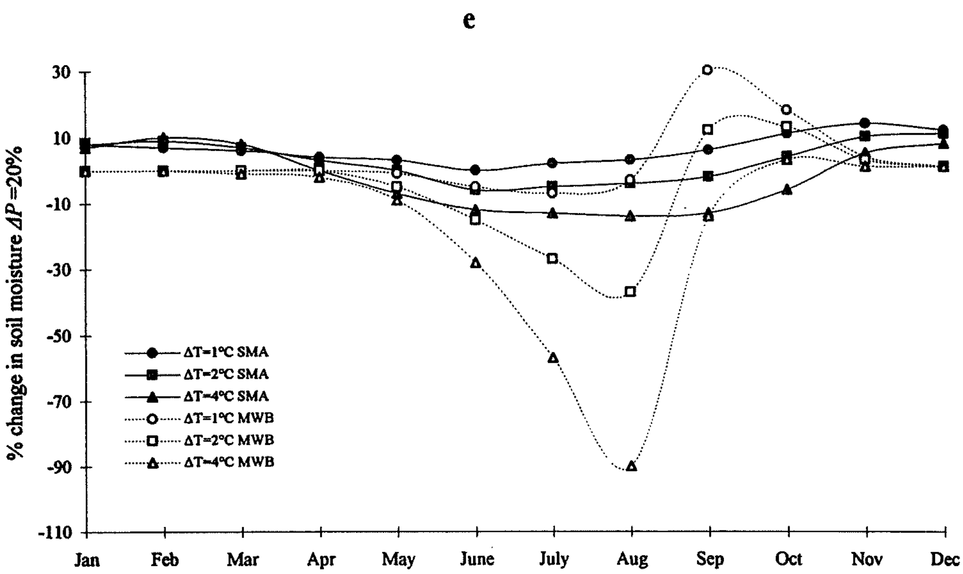


Fig. 6. Continued.

season. In other words, the MWB model is less sensitive to temperature increase than the SMA model during the wettest and driest months of the year.

4. Conclusions

The variability in simulated monthly and seasonal total runoff and soil moisture over the same catchment through the monthly water balance (MWB) model and the coupled snow accumulation–ablation and soil moisture accounting (SAA–SMA) models for a number of climate change scenarios was investigated. A medium-scale, mountainous catchment (area less than a thousand square kilometres), namely the Mesochora catchment in Central Greece, was examined. The MWB model, with a first-order memory, was clearly addressed to the upper soil layer and involved a roughly represented snowmelt component. The SAA model, which operated at 6 h increments, is a conceptual model describing explicitly the accumulation and ablation of the snowpack. The SMA model, which operated at daily time steps, is also a conceptual model explicitly accounting for hydrological subprocesses (e.g. surface runoff, interflow, baseflow) leading to streamflow generation (total runoff).

The inputs to both models, i.e. precipitation, temperature and potential evapotranspiration, were integrated over area and elevation by different methods. In the SAA–SMA simulations, a more reliable method was used for the input data integration. The division of the catchment area into elevation zones for better representation of snow accumulation and ablation was performed for only the SAA model. Despite the fact that uncertainties in parameter estimates or in numerical procedures were introduced for both models, and an objective method for model calibration was absent from both models, the SAA–SMA models appeared to be more reliable in simulating fluxes dynamics of the catchment. The calibrated inputs of both models (MWB and SAA–SMA) were adjusted to account for climate change scenarios. Based on the results of this study the following conclusions can be reached:

1. both MWB and SAA–SMA models predicted, over the winter season, comparable runoff decrease for reduced precipitation climates and slightly different runoff increases for increased precipitation climates. The larger runoff increases in winter were predicted by the MWB model. During this season, the MWB model proved to be less sensitive to large temperature increase compared with the SAA–SMA models, which raised runoff proportionately to temperature increase.
2. The MWB model predicted, over the summer season, larger runoff decrease, of the order of 10%, for all alternative climates compared with the SAA–SMA models. The MWB model was less sensitive to large temperature increase. The decrease rate of summer runoff was smaller for greater temperature increase than that for smaller ones, for all precipitation climates.
3. The MWB soil moisture, over the winter season, remained unaffected by almost all precipitation and temperature climates. In contrast, the SMA soil moisture showed a significantly greater sensitivity to all climate scenarios during the winter period, when the soil is near saturation and potential evapotranspiration is low.
4. The MWB model predicted, over the summer season, significant soil moisture decrease which was greater than that predicted by SMA model for all climates.
5. The SMA model predicted a greater interannual variability in runoff changes compared with the MWB model for all climates. However, greater runoff increase during the winter months and greater decrease during the summer months were predicted by the MWB model. During the spring and autumn months the results were much more complicated: greater reductions and smaller increases or smaller reductions and greater increases in runoff changes occurred in a random manner for both MWB and SMA simulations. In addition, the monthly runoff changes with respect to temperature increase showed that the MWB is less sensitive to greater temperature increase than the SAA–SMA models for all climates.
6. Whereas the SMA soil moisture varied substantially for the climate scenarios and each particular month, the MWB soil moisture remained unaffected for all climate scenarios during the winter months and decreased much more in late spring and summer months, reaching 100% decrease in August for the driest climates. There was a slight reduction in soil moisture with respect to temperature increase for the SMA model and all climates in the winter months. During these months and during August, the MWB soil moisture remained unaffected by temperature increase, whereas during all other months the rate of soil moisture decrease was proportional to temperature increase for both models (MWB and SMA) and all precipitation climates.

The reduction of snow storages in the MWB model, owing to the lack of dynamic representation of the snowmelt component, resulted in greater runoff increase during the winter months and greater runoff decrease during the summer months for the MWB model predictions. On the other hand, in the upper soil layer considered by the MWB model, the soil moisture is also responsible for the greater decrease in runoff and soil moisture prediction during the summer months compared with the SMA model predictions. In contrast, in the SMA simulations the soil moisture flux is parameterized in five storage zones of which the lower free primary one contributes to streamflow. Finally, the different algorithms by which the potential evapotranspiration is computed in the MWB and SMA models is the main reason for the different soil moisture deficits predicted by the models.

References

Anderson, E.A., 1973. National Weather Service river forecast system. Snow accumulation and ablation model. NOAA Tech. Memo. NWS HYDRO 17. National Oceanic and Atmospheric Administration, Silver Spring, MD, 198 pp.

BAHC Core Project Office, 1993. Biospheric aspects of the hydrological cycle. Rep. 27, Institut für Meteorologie, Freie Universität Berlin, 103 pp.

Burnash, R.J.C., Ferral, R.L. and Macquire, R.A., 1973. A generalized streamflow simulation system in conceptual modelling for digital computers. US National Weather Service, Sacramento, CA.

Dickinson, R.E., 1982. Modelling climate change due to carbon dioxide increases. In: W.C. Clark (Editor), Carbon Dioxide Review. Oxford University Press, New York.

Flaschka, I.M., 1984. Climatic change and water supply in the Great Basin. Master's Thesis, Dept. of Hydrology and Water Resources, University of Arizona.

Gleick, P.H., 1986. Regional water availability and global climatic changes: the hydrologic consequences of increases in atmospheric CO_2 and other trace gases. Ph.D. Thesis, University of California, Berkeley.

Hansen, J., Russell, G., Rind, D., Stone, P., Laus, A., Lebedeff, S., Ruedy, R. and Travis, L., 1983. Efficient three-dimensional global models for climate studies: Models I and II. Mon. Weather Rev., 111(4): 609–662.

Hansen, J., Fung, I., Laus, A., Rind, D., Lebedeff, S., Rueddy, R., Russell, G. and Stone, P., 1988. Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. J. Geophys. Res., 93(D8): 9341–9364.

Lettenmaier, D.P. and Gan, T.Y., 1990. Hydrologic sensitivities of the Sacramento–San Joaquin River Basin, California, to global warming. Water Resour. Res., 26(1): 69–86.

MacCracken, M. and Luther, F. (Editors), 1986. Projecting the climatic effects of increasing carbon dioxide. US Office of Energy Research, Office of Basic Energy Sciences, Carbon Dioxide Research Division, Washington, DC.

Manabe, S., 1969. Climate and ocean circulation. I. The atmospheric circulation and hydrology of the Earth's surface. Mon. Weather Rev., 97: 739–774.

Manabe, S. and Wetherald, R., 1985. CO_2 and hydrology. In: Advances in Geophysics 28(a). Academic Press, New York.

Mimikou, M.A. and Kouvopoulos, Y.S., 1991. Regional climate change impacts: I. Impacts on water resources. Hydrol. Sci. J., 36(3): 247–258.

Mimikou, M., Kouvopoulos, Y., Cavadias, G. and Vayianos, N., 1991. Regional hydrological effects of climate changes. J. Hydrol., 123: 119–146.

Mitchell, J.F.B. and Qingcum, Z., 1991. Climate change prediction. In: J. Jager and H.L. Ferguson (Editors), Climate Change: Science, Impacts and Policy, Proc. 2nd World Climate Conf., Geneva, October–November 1990, pp. 59–70.

Němec, J. and Schaake, J., 1982. Sensitivity of water resources systems to climate variation. Hydrol. Sci., 27(3): 327–343.

Panagoulia, D., 1991. Hydrological response of a medium-sized mountainous catchment to climate changes. Hydrol. Sci. J., 36(6): 525–547.

Panagoulia, D., 1992. Impacts of GISS-modelled climate changes on catchment hydrology. Hydrol. Sci. J., 37(2): 141–163.

Panagoulia, D., 1993. Catchment hydrological responses to climate changes calculated from incomplete climatological data. IAHS Publ., 123: 461–468.

Panagoulia, D. and Dimou, G., 1994a. Temporal scale effects on modelled catchment hydrological processes in respect of global climate change. In: A.C. Demetracopoulos, C.D. Hadjitheodorou and G.P. Korfiatis (Editors), Restoration and Protection of the Environment II. Proc. Int. Conf., Patras, Greece, 24–26 August 1994. University of Patras Press, pp. 65–71.

Panagoulia, D. and Dimou, G., 1994b. Catchment tension moisture responses to climate changes assessed from incomplete climatological data. In: W.R. Blain and K.L. Katsifarakis (Editors), Hydraulic Engineering Software V: Water Resources and Distribution, Vol. 1, Proc. 5th Int. Conf. Hydraulic Engineering Software HYDROSOFT 94, Porto Carras, Greece, 21–23 September 1994. Computational Mechanics Publications, Southampton, UK, pp. 115–122.

Panagoulia, D. and Dimou, G., 1997. Linking space–time scale in hydrological modelling with respect to global climate change: Part 1. Models, model properties, and experimental design. J. Hydrol., 194: 15–37.

Revelle, R.R. and Waggoner, R.E., 1983. Effects of a carbon dioxide-induced climatic change on water supplies in the Western United States. In: Changing Climate. National Academy of Sciences. National Academy Press, Washington, DC.

Schlesinger, M.E., 1984. Climate model simulation of CO_2-induced climate change. In: B. Saltzman (Editor), Advances in Geophysics, 26. Academic Press, San Diego, CA, pp. 141–235.

Thornthwaite, G.W. and Mather, J.R., 1955. The water balance. Drexel Inst. Technol. Publication in Climatology, Laboratory of Climatology, VII, No. 1, 104 pp.

Thornthwaite, G.W. and Mather, J.R., 1957. Instructions and tables for computing the potential evapotranspiration and the water balance. Drexel Inst. Technol. Publications in Climatology, Laboratory of Climatology, X, No. 3, 311 pp.

US National Academy of Sciences, 1983. Changing Climate. National Academy of Sciences. National Academy Press, Washington, DC.

Veihmeyer, F.J., 1964. Evapotranspiration. In: V.T. Chow (Editor), Handbook of Applied Hydrology. McGraw-Hill, New York.