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Hydrological response of a medium-sized mountainous catchment to climate changes

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Abstract The long term hydrological response of a medium-sized mountainous catchment to climate changes has been examined. The climate changes were represented by a set of hypothetical scenarios of temperature increases coupled with precipitation and potential evapotranspiration changes. Snow accumulation and ablation, plus runoff from the study catchment (the Mesochora catchment in central Greece) were simulated under present (historical) and altered climate conditions using the US National Weather Service snowmelt and soil moisture accounting models. The results of this research obtained through alternative scenarios suggest strongly that all the hypothetical climate change scenarios would cause major decreases in winter snow accumulation and hence increases in winter runoff, as well as decreases in spring and summer runoff. The simulated changes in annual runoff were minor compared with the changes in the monthly distribution of runoff. Attendant changes in the monthly distribution of soil moisture and actual evapotranspiration would also occur. Such hydrological results would have significant implications on future water resources design and management.

Réponse hydrologique d'un bassin montagneux de dimension moyenne aux changements climatiques

Résumé La réponse hydrologique d'un bassin montagneux de dimension moyenne aux changements climatiques est présentée dans cet article. Les changements climatiques ont été représentés par une série de scénarios hypothétiques de changements de température, ceux ci ont été combinés avec des changements de hauteurs de précipitations et d'evapotranspiration potentielle. L'accumulation de neige et l'ablation, ainsi que l'écoulement que peut présenter le bassin sous étude, en l'occurrence le bassin de la Mesochora en Grèce Centrale, ont été simulés à partir des conditions climatiques actuelles et hypothétiques, ceci par application des modèles établis par le Service National Metéorologique des Etats Unis pour la fonte de neige et les variations de l'humidité du sol. Les résultats de cette recherche, obtenus avec des scénarios alternatifs, suggèrent fortement que tous les

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scénarios hypothétiques de changements climatiques ne sauraient que causer une baisse majeure de l'accumulation de neige en hiver, d'où augmentation de l'écoulement hivernal, ainsi que la baisse de l'écoulement au cours du printemps et de l'été. Les changements de l'écoulement annuel obtenus par simulation seraient moins graves que ceux de la distribution mensuelle dudit écoulement. Il faudrait s'attendre aussi à des changements concomitants en ce qui concerne la distribution temporelle de l'humidité mensuelle du sol et de l'evapotranspiration réelle. Ces résultats hydrologiques auraient des implications considerérables sur la planification et la gestion des ressources en eaux dans le futur.

INTRODUCTION

The design and operational reliability of a water resource system depends on the water demand as well as on the long term statistics of the reservoir inflows, including their averages, coefficients of variation, skewness, cross- and auto-correlations and persistence.

Most water resource systems are designed and operated for stationary natural or synthetic streamflow series, i.e. for inflows with no time-varying features. The classical method of reservoir storage design, which is based on historical streamflow records, cannot possibly specify how "safe" the draft will be in the future (Klemeš, 1978), while the stochastic methods, because of the change in the random part of a stochastic model (Monte Carlo technique), can generate a large number of synthetic streamflow series giving the possibility for a reservoir to be designed and operated with an *a priori* known and acceptable risk of failure.

Regardless of the methods actually adapted for systems design, be they stochastic or not, the possibility of permanent changes in historical streamflow series (or in the equivalent statistics of synthetic streamflows, (Schwarz, 1977)), such as might result from long term changes in climate, complicates considerably the problem of water resources system design and operation.

Although climate changes over the thousands of years which have passed are well documented, hydrologists differ as to whether changes within typical project planning periods (100 years or less) can be distinguished from the random variations that are to be expected in stationary time series (the Hurst phenomenon; Klemeš, 1974; Wallis, 1977; Lettenmaier & Burges, 1978).

The development of climate models, especially those of general atmospheric circulation (GCMs), as well as the consensus on the direction of future global climate change place the problem under a somewhat different light. There is now a quasi-deterministic basis for assuming that climate changes will occur in future as a result of increases in temperature.

All the climate models, including the better parameterized ones (GCMs), give different values of climate variable changes and so do not provide a single reliable estimate that could be advanced as a deterministic forecast for hydrological planning.

On the other hand, the current spatial and temporal resolution of the

GCM outputs is rather coarse and utterly inadequate for hydrological interpretation. The GCM results must be specified on a proper time scale (daily or less) for modelling river catchment storm response. Of course, the GCM results which are provided as grid-cell averages can be expressed in short time scales (daily or hourly), but it is doubtful if the results at these time scales properly reflect the short term dynamics of the atmospheric circulation process.

Accordingly, considering that no appropriate coupling has been developed yet between the GCM outputs (e.g. precipitation, temperature, and potential evaporation) and hydrological models, various climate change scenarios have been adopted in order to interpret the hydrological impacts of possible climate changes. The climate change scenarios include both hypothetical ones given as a range of changes in long term average values of meteorological variables and GCM (e.g. GISS, GFDL, OSU) scenarios which resulted from 1 × CO_2 and 2 × CO_2 runs. The climate change scenarios have been applied to the inputs of hydrological models which in their turn generate hydrological scenarios.

This paper deals with only the hypothetical scenarios of climate change and all results presented must be assessed in alternative meteorological and hydrological scenarios or a sensitivity analysis context.

The objectives of this work are: (a) to assess the hydrological response of a mountainous river catchment to global climate changes by developing a method which could be applied to medium-sized catchments (several hundreds of square kilometres) and account for the changes in snowmelt hydrology that would result from hypothetical scenarios of air temperature increases combined with possible changes in precipitation and evapotranspiration; and (b) to use the results of (a) to provide hydrological inputs for the assessment of water resource systems response to global climate changes.

The relationship of this work to other related studies is as follows: (a) Němec & Schaake (1982) simulated the streamflow in two river basins in the USA using the Sacramento model in order to study the sensitivity of water resource systems to climate variations. They introduced the global climate change (climate variations) by hypothetical scenarios of changes in precipitation (±10%, ±25%) and temperature (±1°C, +3°C), the latter converted into changes in potential evaporation (±4%, +12% Budyko-relation). They did not study snow covered basins nor deal with catchment hydrological procedures other than runoff; and (b) Lettenmaier & Gan (1990) investigated the hydrological effects in four sub-basins in the Sacramento-San Joaquin river basin (California) for increases in temperature and potential evapotranspiration as well as changes in precipitation that resulted from general circulation model scenarios. The researchers used the same hydrological modelling methodology as that of the present work.

CONCEPTUAL WATERSHED SIMULATION FOR PRESENT AND ALTERED CLIMATES

A medium-sized mountainous catchment, viz. the Mesochora catchment of the Acheloos river in central Greece (Fig. 1), was selected for analysing the catchment hydrological response to climate changes. The catchment was simulated conceptually by the US NWSRFS snow accumulation and ablation model, as well as the soil moisture accounting model under historical and altered climate conditions.

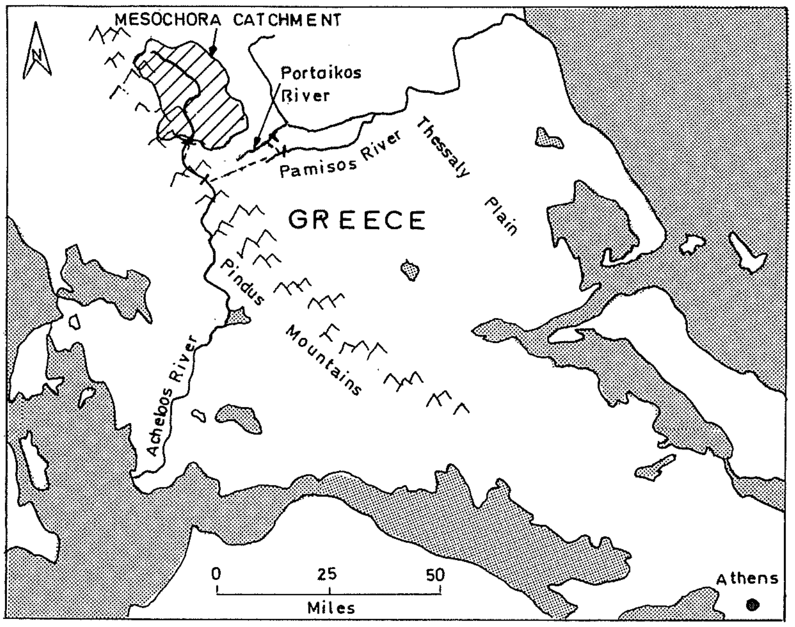

Fig. 1 The Mesochora catchment hydrological study area, central Greece.

The Mesochora is the upper drainage catchment of the Acheloos river and has a great significance for Greece because the river will be partially diverted at the outfall of the catchment through the Pindus mountains to irrigate the arid Thessaly Plain. The river's waters will be used also to boost hydropower generation in the surrounding area. It is the largest construction project in Greece, comprising five dams (one is Mesochora's), 40 kilometres of large tunnels and about 8000 kilometres of buried irrigation pipes. The operation and performance reliability of the costly hydraulic works depend largely on the hydrological regime of the catchment through its streamflow. A downward alteration to the catchment hydrology could result from possible climate changes and would have major effects of the reliability of water resources management and generally on the social and physical environment of the region.

The basic hydrometeorological characteristics of the Mesochora catchment are described in Table 1, all the data except runoff were obtained as weighted averages over three elevation zones from the catchment division chosen for better representation of snowmelt.

The snow accumulation and ablation model that was used to simulate the catchment snowmelt hydrology was developed by Anderson at the US

***Table 1** Hydrometeorological characteristics of the Mesochora catchment*

Catchment area	*Mean annual runoff*		*Mean annual precipitation*	*Mean January daily temperature (°C)*			*Mean July daily temperature (°C)*		
				Daily Average	*Minimum*	*Maximum*	*Daily Average*	*Minimum*	*Maximum*
km^2	*mm*	*$m^3 s^{-1}$*	*mm*						
632.8	*1170*	*23.5*	*1898*	*0.1*	*-3.5*	*3.7*	*17.5*	*11.4*	*23.6*

National Weather Service Hydrologic Research Laboratory (Anderson, 1973) and has been tested in a number of mountainous watersheds in the United States and elsewhere. This is a conceptual deterministic model consisting of a set of equations which describe the change in storage of water and heat in the snowpack. The model inputs are ambient air temperature and precipitation at a six-hourly time step. In this study, daily precipitation was interpolated to six-hourly increments and six-hourly temperature was estimated from daily temperature maxima and minima using equations given by Anderson (1973).

The soil moisture accounting model (rainfall–runoff) was developed by Burnash *et al.* (1973) and forms the basis of the US National Weather Service's basic catchment hydrological response model for operational forecasting. At first it was used for the Sacramento basin simulation and since then it has been widely used (e.g. WMO, 1975; Němec & Kite, 1981; Gupta & Sorooshian, 1983; Lettenmaier & Gan, 1990). It is a deterministic, lumped parameter, conceptual model. The model is based on a system of percolation, as well as on soil moisture storages, drainage and evapotranspiration characteristics.

The soil moisture storages include the upper zone which is divided into one tension and two free water storages and the lower zone which is also divided into one tension and two free water storages. Tension water storages are available for evapotranspiration. Free water can descend to the lower zone by percolation or can move laterally to produce interflow. When the precipitation rate exceeds the percolation drainage capacity, the upper storage free water capacity is filled completely and the excess rainfall results in surface runoff. The two free water storages fill simultaneously from percolated water, and drain independently and at different rates, giving a variable groundwater recession. Direct runoff from impervious area, surface runoff, interflow and baseflow combined generate the channel flow.

The model was operated on a daily time step and the daily pseudo-precipitation (snowmelt model output) and the long term average monthly potential evapotranspiration estimated from the Penman equation (Veihmeyer, 1964) were used as model inputs.

For better performance of the snowmelt model, the catchment was divided into three elevation zones (of about 30% of total area for each of the upper and middle zones and 40% for the lower zone). Eleven precipitation stations and three temperature stations were used. The precipitation stations are consistent and representative of the catchment, but the data were incomplete in some precipitation records. Rather than interpolate them, the technique used to estimate the areal precipitation was a combination of the Thiessen method and the station daily availability, including elevation correction (Panagoulia, 1990a, 1990b). The aforesaid technique was implemented for the median elevation of each zone of the catchment by considering the three nearest stations in the upper and middle zones and the six nearest stations in the lower zone. The maximum and minimum daily temperature records also included incomplete data. The above mentioned combinatorial technique was also used to estimate the areal maximum and minimum daily temperature, respectively. The elevation correction factor (for the median zone elevation) of the areal temperature was compatible with the temperature station daily availability (Panagoulia, 1990a).

The calibration period was 15 years for both models. The models were manually calibrated (Peck, 1976) and their final parameter estimates were obtained through a trial and error approach, which was carried out concurrently for both models. The typical monthly simulation errors (monthly differences between simulated and observed streamflows), expressed as a percentage of observed flows, were of the order of 10–15% (except for the August and September runoff which reached 23%).

The plot of the long term annual mean catchment pseudo-precipitation (rain plus melt) over 15 years showed three distinct periods with different climate conditions. A modified differential split sample test was implemented in order to verify the ability of the soil moisture accounting model (and hence the snowmelt model) to respond, though without significant bias, to the three different climate periods. The moisture model was run for each period separately, and such statistical variables as the long term annual mean runoff, the standard deviation thereof and the correlation coefficient of monthly runoff were computed. The null hypothesis H_0 of the differences in the variables between two climate periods and any climate period and the calibration period was also tested. The results for all the variables fell within 95% of the critical region. Details of the development, calibration, and statistical verification of the models are presented in Panagoulia (1990a).

The coupling of climate change and the hydrological models of catchment simulation was made through historical data that were used for calibration of the models. In particular, the climate change was applied to the historical time series of: (a) daily precipitation; (b) daily minimum and maximum temperature; and (c) monthly temperature in order to be converted into changes of potential evapotranspiration. The description of the climate change and its implementation on each of the (a), (b) and (c) time series is as follows.

(a) Precipitation

The changes in daily precipitation were represented by a set of hypothetical scenarios that belongs to the range of precipitation percentage changes given in recent climatological literature (US National Academy of Sciences, 1983; Manabe & Wetherald, 1985; MacCracken & Luther, 1986). Such scenarios have been previously used by Němec & Schaake (1982), Revelle & Waggoner (1983) and Gleick (1986) for streamflow modelling under climate change conditions. In this study, the selected scenarios were: reduction in daily precipitation by 10% and 20%, zero change and increase in daily precipitation by 10% and 20%.

The assumed percentage changes were applied uniformly to all daily values of the historical series of each elevation zone precipitation by a multiplying factor which represented the particular reduction (factor < 1) or increase (factor >1). Thus, for each zone, there resulted four altered daily precipitation series (time series scenarios) corresponding to the four climate change scenarios, and one series with zero precipitation change.

(b) Temperature

Climate predictions show that the global average surface air temperature would be increased by approximately 1.5 to 4.5°C due to a possible doubling of the CO_2 concentration by the year 2070 (US National Academy of Sciences, 1983; Dickinson, 1982; MacCracken & Luther, 1986). In this study the temperature increases that constitute the temperature change scenarios were taken from the above range of temperature increase, and are 1°C, 2°C and 4°C.

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

(c) Potential evapotranspiration

Potential evapotranspiration was computed on a monthly basis, using the Penman equation, as a function of the meteorological variables: temperature, relative humidity, wind speed, relative sunshine and mean solar radiation. Of those input variables, only temperature can be associated with the climate change through a poorly known mechanism that does not permit assessment of their change. Therefore, in Penman's equation the only variable which was linked to climate change was the monthly temperature, while the rest were assumed not to be affected by it.

The monthly temperature increase scenarios were the same as those applied to the daily time series because the mean monthly temperature is computed by averaging either the mean minimum and maximum daily temperature or three mean daily temperature values (8 h observations) with doubling of the third (night time). Therefore, if the minimum and maximum daily temperatures go up 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 monthly temperature increase scenarios were 1°C, 2°C and 4°C. Those scenarios were applied uniformly to monthly values of the historical time series of catchment temperature through an additive factor (1, 2, 4°C) and three altered monthly temperature time series (time series scenarios) were obtained. These altered temperature time series were used as inputs to the Penman equation which in its turn yielded three monthly time series of potential evapotranspiration (time series potential evapotranspiration scenarios) corresponding to the three principal temperature increases. The long term average of each monthly potential evapotranspiration series was used as input to the soil moisture accounting model.

CATCHMENT HYDROLOGICAL RESPONSE ANALYSIS

As described previously, the long term hydrological response of the Mesochora catchment was simulated for climate regimes associated with a base case (nominally, present climate conditions, solid line in graphs), as well as 15 hypothetical climate change scenarios involving combinations of plus 1, 2 and 4°C and minus and plus 20, 10 and 0% precipitation (Table 2).

Table 2 *Hypothetical climate change scenarios*

Temperature increase $\Delta T(^\circ C)$	*Precipitation change* ΔP (%)				
1	*-20*	*-10*	*0*	*10*	*20*
2	*-20*	*-10*	*0*	*10*	*20*
4	*-20*	*-10*	*0*	*10*	*20*

Because the snow accumulation and ablation model as well as the soil moisture accounting model operate on daily or shorter time steps and all scenarios involved running both models for 15 years, large amounts of computer output were generated. To simplify the analysis of the results, reported as averages over the 15 year simulation period, the following simulated variables to describe the alternative hydrologies were selected:

(a) monthly average snow water equivalent over the catchment;
(b) monthly average catchment runoff;
(c) monthly average catchment evapotranspiration; and
(d) monthly average catchment soil moisture storage in the simulated zones.

For the 15 climate change scenarios the simulated variable (a) yielded 15 monthly snow water equivalent scenarios; (b) yielded 15 monthly runoff scenarios; (c) 15 monthly evapotranspiration scenarios; and (d) 15 monthly soil moisture storages for each of the five model moisture zones, giving in total 120 catchment hydrological response scenarios plus the eight of the base case (model outputs for present climate conditions, solid line in graphs). Those hydrological scenarios are plotted in Figs 2 to 9 and an analysis of their results follows.

Snow water equivalent

The mean (long term) monthly weighted snow water equivalent over the catchment for all the alternative climates is presented in Fig. 2. There was a marked reduction in average snow water equivalent for all the alternative scenarios. The combined scenarios of temperature increase by 4°C (ΔT = 4°C, ΔP = ±20%, ±10%, 0) produced the maximum reduction in snow water equivalent, reflecting the fact that, for temperature increase by several degrees Celsius, the temperature is the basic factor of snow storage control in relation to precipitation. The other combined scenarios of temperature increase by 1°C and 2°C (for all ΔP values) caused progressive reduction in average snow water equivalent from the wetter to the drier climate. The temperature increase by 1°C and precipitation reduction by 20% produced an average snow water equivalent pattern similar to that of a temperature increase by 2°C and a precipitation increase by 10%. The same can be said about the snow water equivalent pattern generated from the scenarios ΔT = 2°C, ΔP = +20% and ΔT = 1°C, ΔP = −10%).

As regards the snow water equivalent monthly distribution for the combined scenarios of temperature increase by 1 and 2°C and all precipitation changes, the average snow water equivalent peaked in March, the same month for the base case snow water equivalent maximization. For the drier combined scenarios (ΔT = 4°C and all ΔP values) the snow water equivalent maximized one month earlier (February), vanished also one month earlier (May) and came back in November, just as happens in the climate scenarios and base case.

Runoff

Figure 3 shows significant changes in the seasonal distribution of catchment runoff for all 15 hypothetical scenarios.

Summer (June, July, August) runoff in 14 of the 15 cases dropped considerably in relation to the base case summer runoff. The summer runoff that resulted from temperature increase by 1°C and precipitation increase by 20% went up a little, reflecting the fact that the temperature increase was too small to cause early snowmelt and shift the summer runoff to the winter months, while the precipitation increase is simultanously the largest. The summer runoff drop is more obvious for the driest simulated climates. For a temperature increase by 4°C and a precipitation decrease by 20%, the summer runoff dropped by about 50%.

Winter (December, January, February) runoff increased in 10 of the 15 cases combined with any temperature increase and positive or no precipitation change. The maximum winter runoff increase reached 60% above the base case runoff and was caused by a temperature increase of 4°C and precipitation increase of 20%. These two high-value variables pushed up the winter runoff through earlier snowmelt and rainfall increase. The winter runoff fell for the remaining five climate scenarios combined with the changes: ΔP = 20% for all temperature increases and ΔP = 10% for ΔT = 1 and 2°C. The maximum

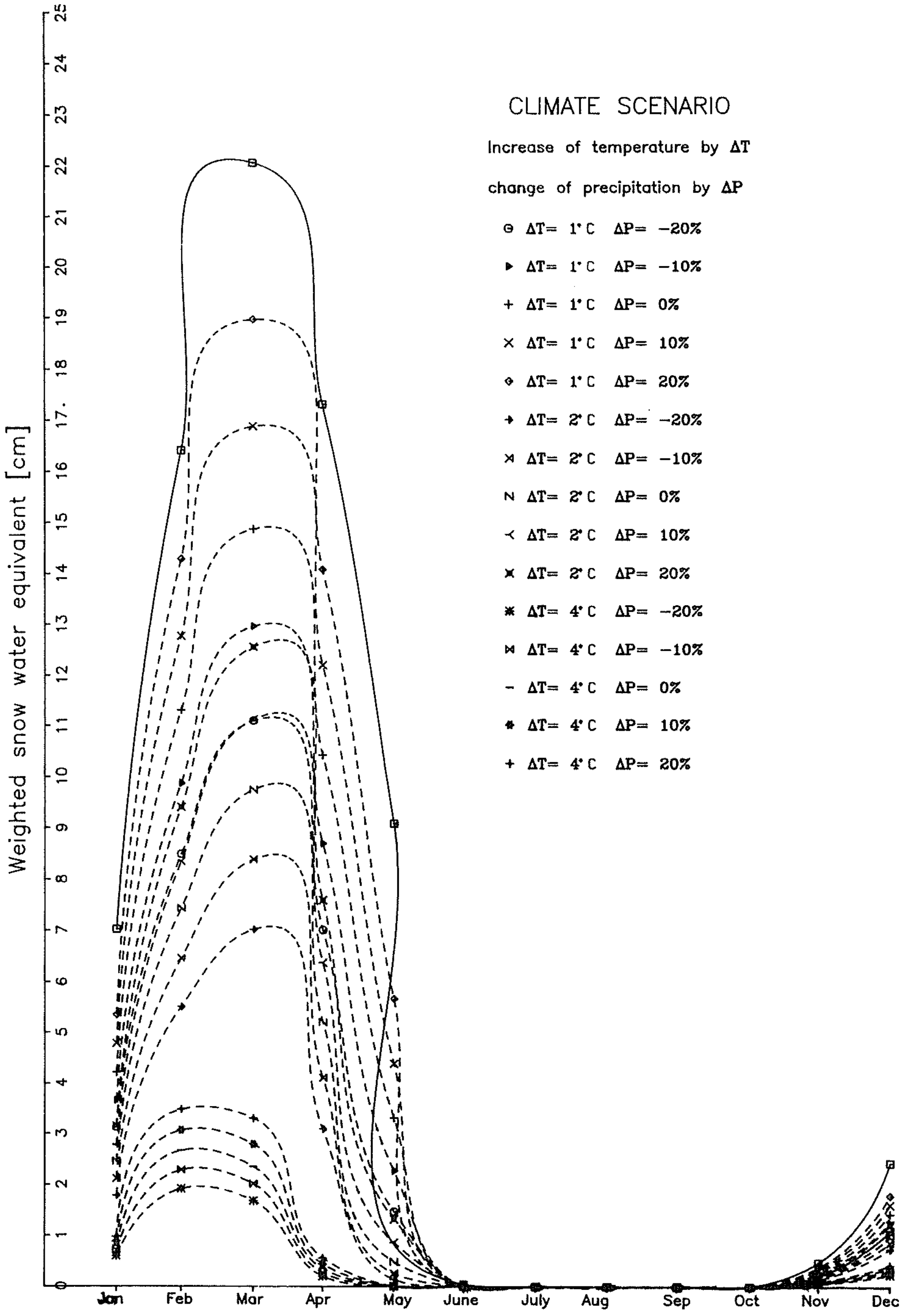

Fig. 2 Mesochora catchment monthly mean weighted snow water equivalent for the 15 climate change scenarios.

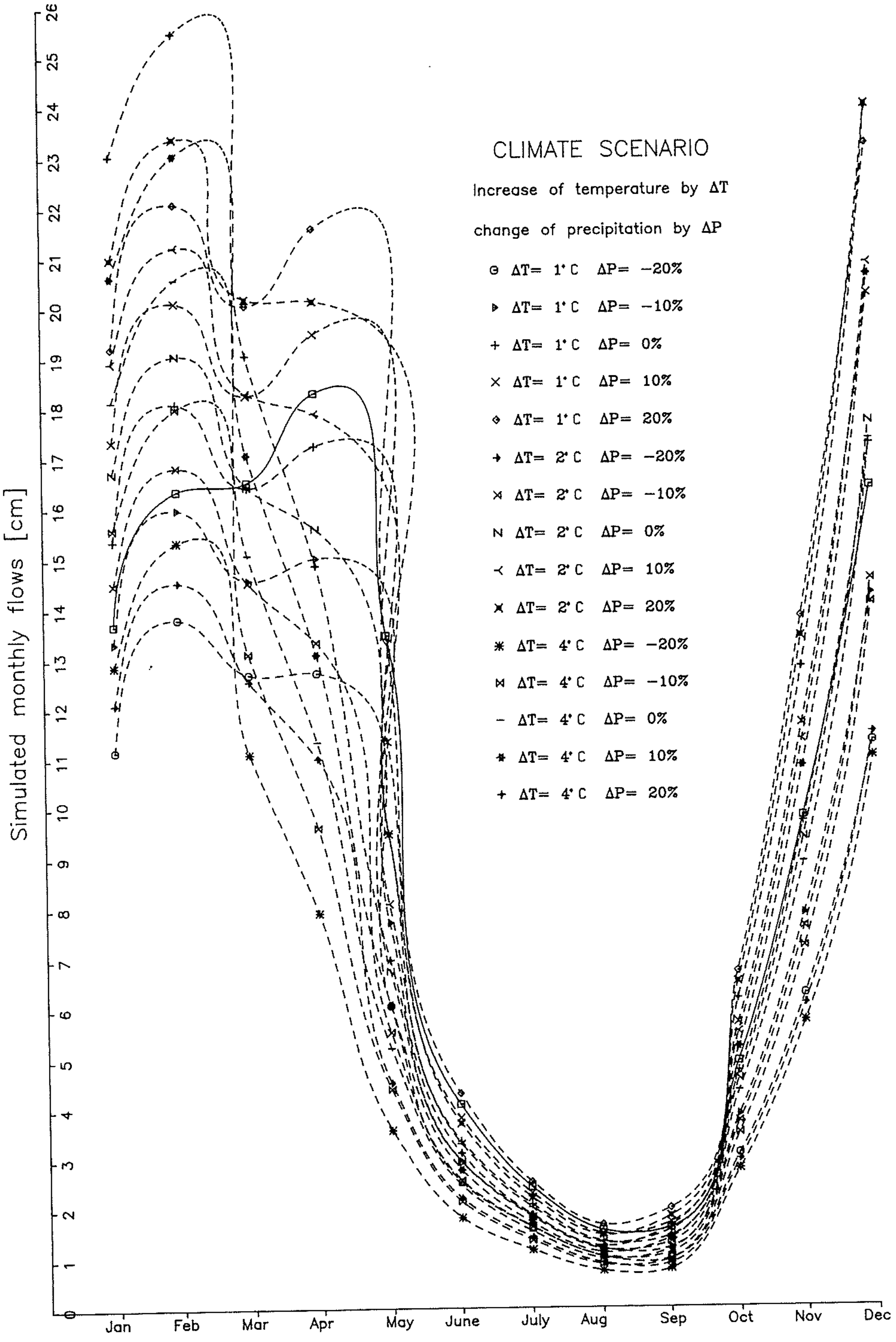

Fig. 3 Mesochora catchment monthly mean streamflow for the 15 climate change scenarios.

winter runoff reduction resulted from temperature increase by 1°C and precipitation decrease by 20% reflecting the fact that the snowmelt mechanism could not operate due to the low value of the temperature increase, while the precipitation dropped at the maximum percentage.

A full and detailed runoff analysis with respect to climate changes is obtained only when it is considered on a monthly rather than a seasonal time scale. The importance of looking at temporal changes of hydrological variables on a time scale smaller than annual is seen in Table 3 and Fig. 3 when, for example, the temperature increase by 4°C combined with no precipitation change produced annual runoff down only by 10%, while the same climate scenario increased the January runoff by 30% and reduced the June runoff by 40%. This fact implies that large changes in the timing of monthly runoff are thus hidden when only mean annual runoff changes are considered.

Table 3 *Simulated mean annual catchment runoff and its percentage change in relation to the base case for 15 climate change scenarios*

ΔT °C	ΔP %	*Simulated runoff* *Base case : 119.21cm*	*Runoff change* %
1	-20	83.31	-30.1
1	-10	99.85	-16.2
1	0	116.56	- 2.2
1	10	113.56	12.0
1	20	150.68	26.4
2	-20	80.70	-32.3
2	-10	96.99	-18.6
2	0	113.58	-4.7
2	10	130.40	9.4
2	20	147.41	23.7
4	-20	74.86	-37.2
4	-10	90.90	-23.8
4	0	107.14	-10.1
4	10	123.65	3.7
4	20	140.33	11.7

The effect of reduced snow storages (Fig. 2) is immediately apparent on all runoff scenarios (Fig. 3). The annual hydrograph peak shifted to earlier in the year because of a decrease in the amount of snowfall in relation to rainfall. In 12 of the 15 climate change scenarios, the runoff peak shifted two months earlier in the year in relation to that of the base case, i.e. the peak shifted from April to February. In the other three scenarios (ΔT 1°C, ΔP = 10 and 20%; ΔT = 2°C and ΔP = 20%) the peak shifted much more, four months earlier, to December. Months in which simulated runoff fell short of the base case are presented in Table 4. Figure 3 shows that the monthly runoff was reduced at the maximum rate in May for most of the climate cases. The shift in the annual distribution of runoff is critical for water resources management.

Evapotranspiration

The actual evapotranspiration, as simulated with the soil moisture model, depends on soil moisture, as well as on potential evapotranspiration. Therefore, although potential evapotranspiration increased for all months and climates due to temperature rise, the direction of change in actual evapotranspiration varied from season to season. During the wet November–April period the actual evapotranspiration remained completely unaffected by precipitation changes (Fig. 4), but increased in relation to base case actual evapotranspiration. During the dry May–October period the actual evapotranspiration went up for precipitation increase and dropped for precipitation reduction.

In nine of the 15 climate change scenarios and the base case, the actual evapotranspiration peaked in June, while for the other six scenarios, characterized by precipitation reduction, the peak shifted one month earlier (to May). Among those last scenarios those of minor precipitation reduction showed a flatter crest.

The soil moisture accounting model assumes that actual evapotranspiration depends on the moisture contents of the conceptual tension zones. The rate of actual evapotranspiration declines as the soil dries. Therefore, the change in the flow from spring to winter shifts likewise the actual evapotranspiration. Because the actual evapotranspiration also depends upon temperature, wet winter soils do not yield as much actual evapotranspiration as equally wet spring soils. The increased spring actual evapotranspiration suggests that agricultural irrigation demand might be increased over and above present-day requirements. Despite the change in seasonal distribution of evapotranspiration, the change in annual total evapotranspiration was relatively small (the maximum reached 19%).

Soil Moisture Storages

The soil moisture storage response for all hypothetical climate change scenarios is analysed for each storage separately, in relation to upper and lower zone, and totally for all storages put together.

The moisture content of the upper tension zone (Fig. 5) was somewhat affected by climate change during the wet October–March period and not at all during the wettest months (January and February) because it has as a first priority to absorb moisture. During the spring and early summer, the decrease in snowmelt caused severe moisture shortages, which translated into tension water storage reduction. The greatest reductions in tension soil moisture were formed in June commensurate with the mounting dryness of the climate change scenarios. For the driest climate (ΔT = 4°C and ΔP = −20%) the tension water storage suffered its greatest fall.

The lower tension zone (Fig. 6) is supplied after the upper tension zone through the percolation procedure. While the minimum moisture content of the upper zone occurred in August for the base case, the moisture of the lower zone reached its minimum in October, thereby providing the possibility

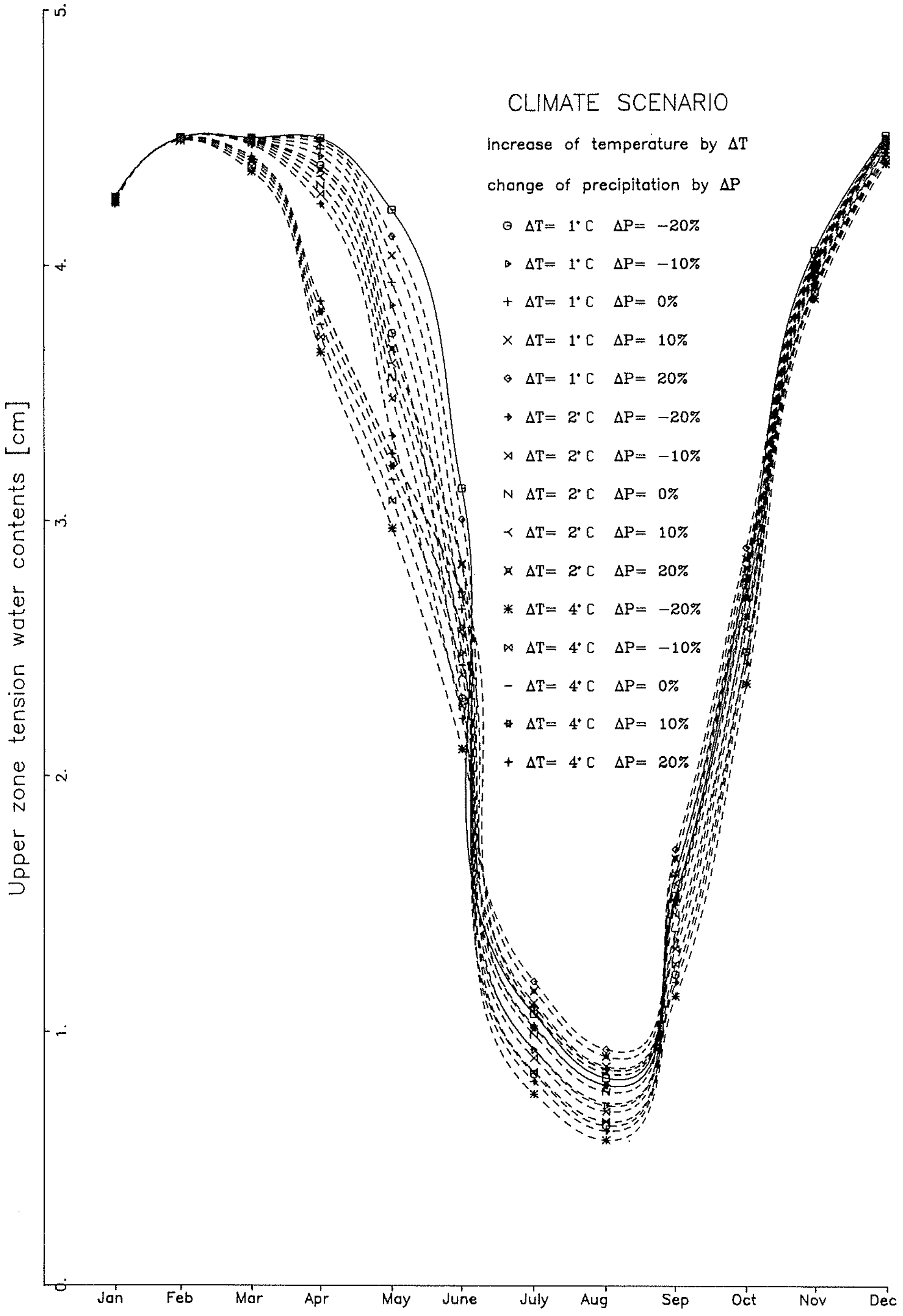

Fig. 5 *Mesochora catchment monthly mean upper zone tension water for the 15 climate change scenarios.*

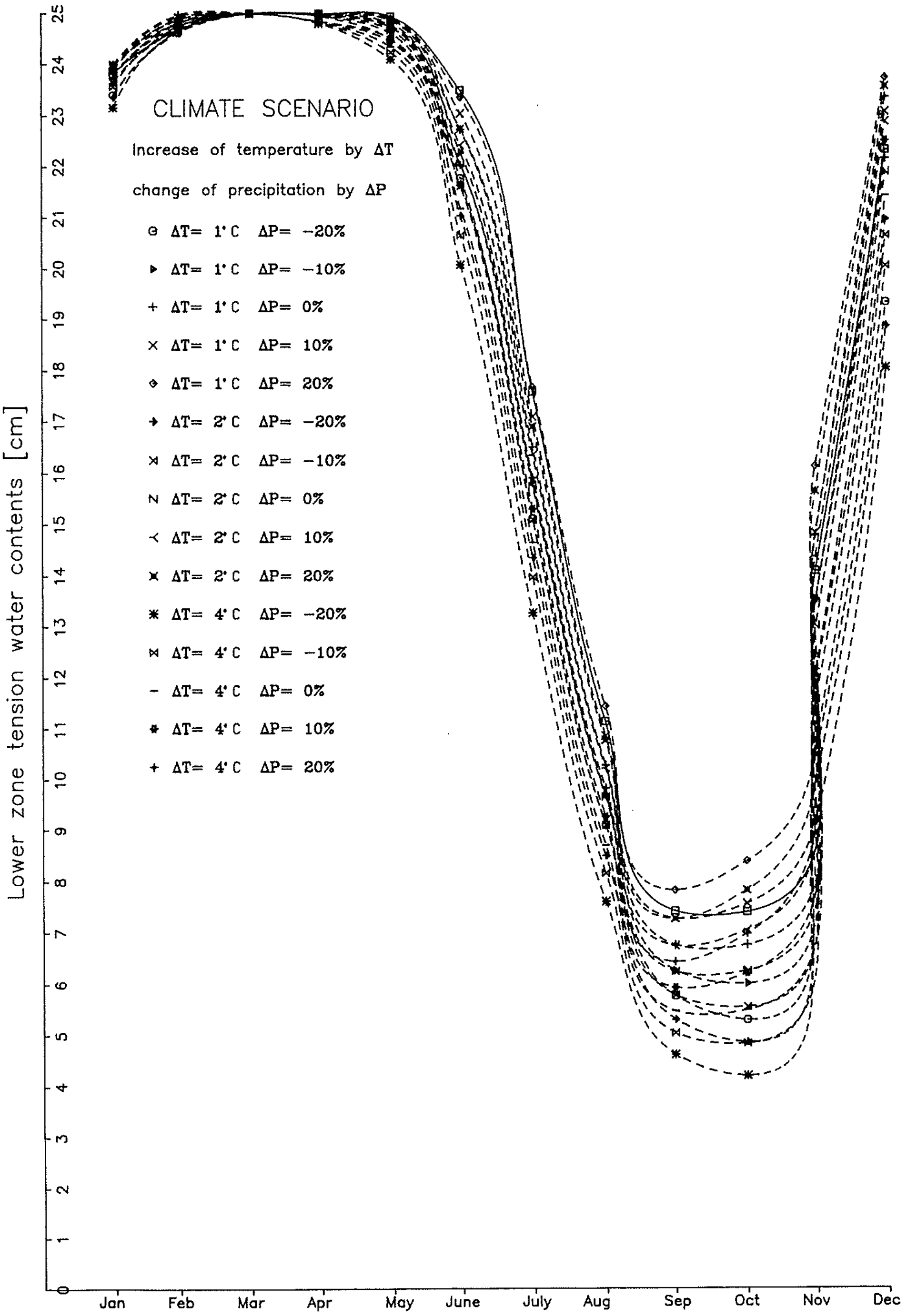

Fig. 6 Mesochora catchment monthly mean lower zone tension water for the 15 climate change scenarios.

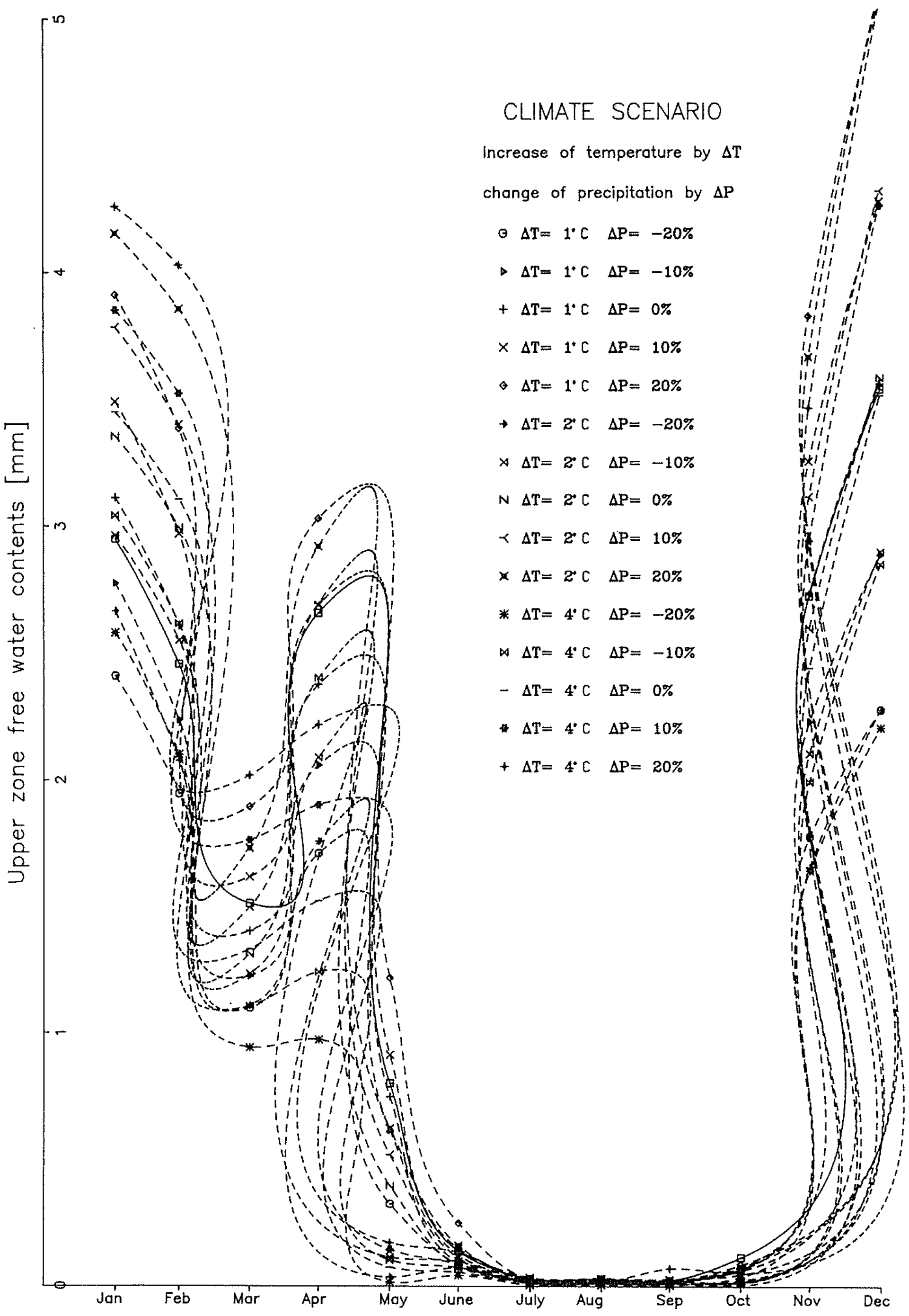

Fig. 7 Mesochora catchment monthly mean upper zone free water for the 15 climate change scenarios.

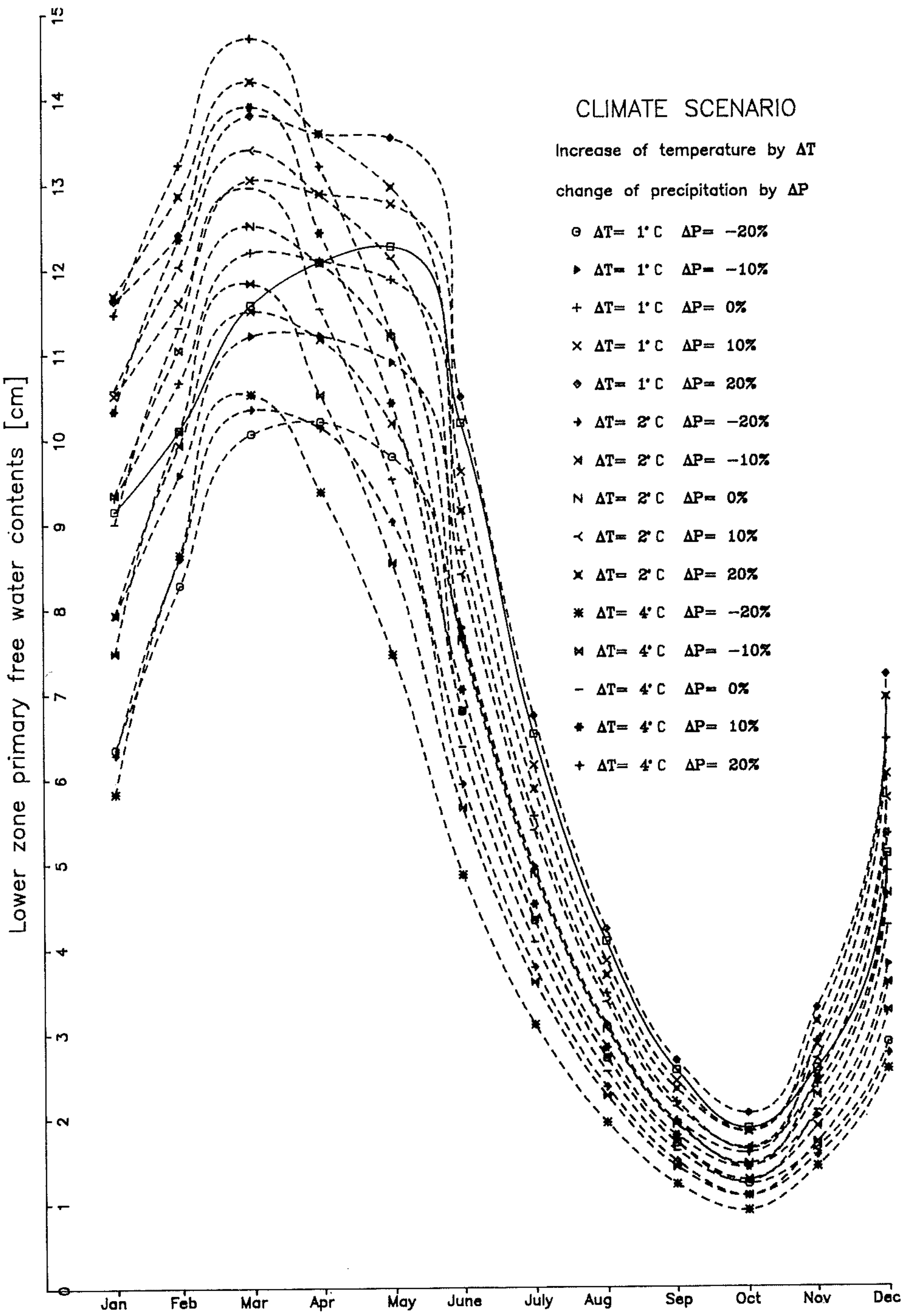

Fig. 8 Mesochora catchment monthly mean lower zone primary free water for the 15 climate change scenarios.

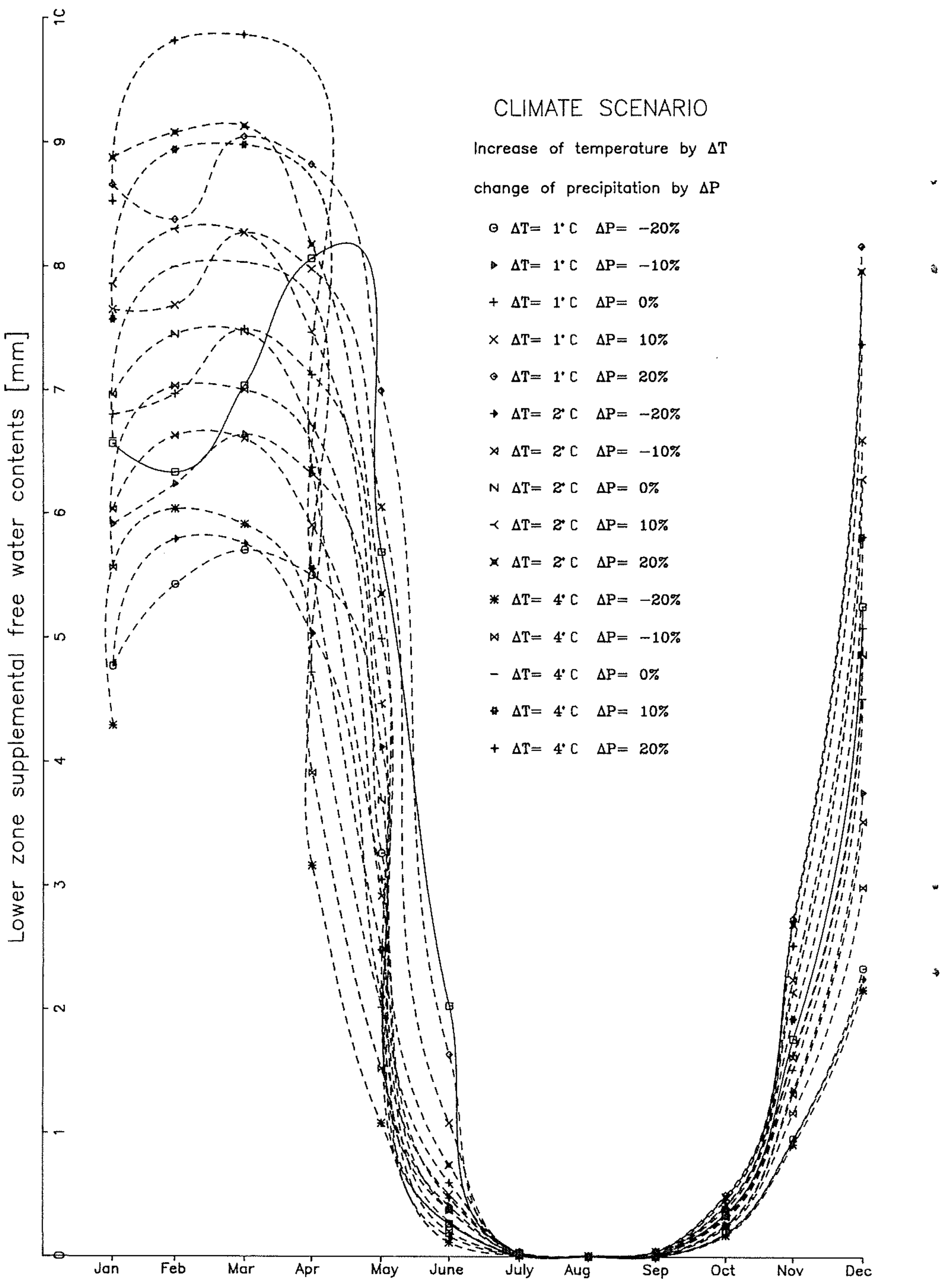

Fig. 9 Mesochora catchment monthly mean lower zone supplement free water for the 15 climate change scenarios.

The river baseflow also supplied the lower supplement free water zone with smaller amounts of moisture. For 12 of the 15 climate change scenarios, the supplemental moisture content peaked in March, while for the other three (ΔT = 2°C, ΔP = −10%; ΔT = 4°C, ΔP = −20 and ΔP −10%), the peak shifted to February, i.e. two months earlier in relation to the base case peak (in April). All climate change scenarios reduced to a minimum the supplemental moisture content in August.

As regards the general response of all the five moisture storage zones to climate change scenarios, it is noted that the warmer and wettest climates caused increased rainfall relative to snowfall, thus making more moisture available during winter and early spring, at the expense of late spring and summer. Therefore, there was a definite phase shift in practically all storages (Figs 5 to 9). This trend was stronger among the free water zones than in the tension zones and during summers rather than winters.

CONCLUSIONS

Before coming to the final conclusions of this research, it is necessary to make clear at this juncture that (a) the simulation results constitute alternative scenarios and are not deterministic predictions; and (b) because the assumptions and simplification incorporated in the models are reflected in the results, it is advisable to elaborate on these assumptions.

(i) **The application uniformity of climate change** Because the precipitation was adjusted for climate change with a fixed factor, this implied that the coefficient of variation (standard deviation divided by the mean) was the same for the altered climate scenarios as for the base case. For precipitation factors greater than one (when ΔP = +10%, ΔP = +20%) this means that the precipitation and its variability will increase, a fact that could affect the streamflow variability and hence the operation of a given reservoir or the design of new facilities.

(ii) **The capability of hydrological models to provide a sufficient description of the catchment dynamics to altered climates** Although the US NWS models contain the appropriate level of detailed dynamics for medium-sized catchments and can also capture the basic elements of the long term hydrological response of the catchment, their adaptability to altered climates is rather difficult to determine. The parameters of the soil moisture accounting model are climate-dependent and hence their yields for altered inputs are strongly model-dependent. Another major problem of this model is that it cannot possibly be relied on for long term changes in vegetation.

Having considered the limitations imposed by the various assumptions, the following general conclusions can be reached, viz:

(a) the three temperature increases, associated with all precipitation changes, could cause substantial decreases in average snow accumulations in the Mesochora catchment;

(b) reduction in the amount of precipitation that falls as snow could increase the winter runoff volumes and decrease the summer and spring runoff ones, thus causing floods to increase in winter and water shortages to occur in summer. Ten of the 15 climate change scenarios boosted the winter runoff, while the other five, associated with the largest reductions in precipitation, decreased it. The summer runoff was down for nearly all 15 climate change scenarios;

(c) increased precipitation falling as rain in the winter could increase the winter soil moisture storages, thereby making much more moisture available for actual evapotranspiration in the early spring. Increased temperatures could increase spring actual evapotranspiration; and

(d) the reduction in moisture supplied in the form of snowmelt in spring combined with increased spring actual evapotranspiration could reduce the soil moisture of late spring, summer and fall, which could in turn reduce runoff during these periods.

Recognizing the uncertain validity of the hypothetical climate change scenarios, more descriptive climate change scenarios that have resulted from GISS predictions for monthly temperature and precipitation changes have now been studied and are to be presented.

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