Sensitivities of groundwater-streamflow interaction to global climate change

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Abstract The sensitivities of groundwater-streamflow interaction to global climate change over the medium-sized mountainous Mesochora catchment in central Greece have been analysed. The global climate change was simulated through a set of hypothetical and monthly GISS (Goddard Institute for Space Studies) scenarios of temperature increases coupled with precipitation changes. The catchment hydrological regime, which is dominated by spring snowmelt runoff, was simulated by the coupling of the snowmelt and soil moisture accounting models of the US National Weather Service River Forecast System (US NWSRFS). The groundwater was represented through a lower zone one-tension water storage and two free water storages parameterized by the soil moisture model, while the streamflow was the sum of direct runoff, surface runoff and interflow from the upper zone free water, plus the primary and secondary baseflows yielded by the model. The interaction between groundwater and streamflow was expressed by the ratio of the two variables on a seasonal and monthly basis. Both representations of global climate change resulted in a moderate influence on the groundwater-streamflow interaction during the winter months and in a very high one in the spring and summer months. In particular, the major seasonal shift in the snow accumulation pattern related to climate change, as well as the large runoff reduction and evapotranspiration increase occurring in spring and summer months, boosted considerably the groundwater to streamflow ratio. This latter would probably have negative impacts on various problems of water resources management (e.g. droughts, water supply, irrigation, water pollution).

Sensibilité des relations entre les cours d'eaux et les eaux souterraines à une modification climatique planétaire

Résumé On a analysé ici la sensibilité de l'interdépendance entre les eaux souterraines et les cours d'eau dans le Mesochora (bassin montagneux de la Grèce Centrale) à une modification climatique planétaire. Cette dernière a été simulée par une série de scénarios d'augmentation de la température associée à une modification des précipitations élaborés à l'échelle mensuelle par le GISS (Institut des Etudes Spatiales). Le régime hydrologique du bassin, marqué par des écoulements printaniers de fonte des neiges, a été simulé en combinant des modèles de la fonte de neige et d'humidité du sol établis par l'US NWSRFS (Service Américain National de Météorologie). Les eaux souterraines ont été représentées par un réservoir inférieur captif et deux

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réservoirs d'eau libre paramétrisés par le modèle d'humidité du sol, tandis que l'écoulement de surface était la somme du ruissellement et de l'écoulement hypodermique provenant de la zone d'eaux libres, auxquels s'ajoutent les écoulements de base primaire et secondaires fournis par le modèle. L'interaction entre les eaux souterraines et les cours d'eau a été exprimée par le rapport de ces deux variables à l'échelle mensuelle et saisonnière. L'influence des différents scénarios de modification climatique sur la relation "eaux souterraines/cours d'eau" est modérée pendant l'hiver mais très importante au printemps et en été. En particulier, l'importante modification de la structure saisonnière de l'accumulation de neige due au changement climatique, ainsi que la forte diminution du ruissellement, accompagnée d'une augmentation de l'évapotranspiration au printemps et en été, augmentent considérablement la part de l'écoulement d'origine souterraine. Ce fait pourrait avoir de fâcheuses conséquences au niveau de la gestion des eaux, qu'il s'agisse de problèmes de sécheresse, d'alimentation en eau, d'irrigation ou de pollution de l'eau.

INTRODUCTION

The interaction between groundwater and streamflow has gained increasing attention in hydrology, hydrogeology and land reclamation when solving problems dealing with the management of water resources (e.g. droughts, water supply, irrigation, water pollution) and with the prediction of changes in the water regime arising as a result of human activity. It provides the basis for the study of the ecological consequences of alterations in a natural water regime.

The interconnection between groundwater and streamflow in a natural environment is driven by a number of agrophysical and hydroclimatological processes interacting among themselves (Vasiliev, 1987). Since these processes are influenced by climate change associated with global warming, or the *greenhouse effect*, the above interconnection becomes more and more important.

To obtain a mathematical formulation of the issue considered, it is necessary to couple models describing adequately the surface water and groundwater flows, which would be in agreement with the character of the problems encountered including time-space scales of flows. Most authors have adopted hydraulic methods for the conjunctive modelling of surface water and groundwater (e.g. Pinder & Sauer, 1971; Freeze, 1972; Cunge *et al.*, 1980). The water exchange (leakage) between the surface and groundwater along a stream is usually represented through the coupling of these two different flows (Swain, 1994; Vasiliev, 1987). Still, a number of mathematical questions have risen (Vasiliev, 1987) regarding the correctness of the coupled surface water-groundwater models.

According to the hydrological aspect, the usual method of estimating the contribution of groundwater to river flows is through baseflow separation from a flow hydrograph (Miles & Rushton, 1983). This technique is especially valid when surface and groundwater flows are examined at one location, but less appropriate when the spatial variation of flows is to be represented.

In the case of hydrological simulations, a more realistic and detailed representation of the surface-groundwater system is expressed by deterministic conceptual models which produce spatially and temporally varying flows. The appropriateness of these models varies from the simple water balance methods (Thornthwaite & Mather, 1955, 1957) to the more sophisticated ones, such as the energy-soil-water balance of Vaccaro (1992), the Stanford Watershed IV model (Crawford & Linsley, 1966), the soil moisture accounting model of Burnash *et al.* (1973), etc.

In this study, the methodology of conceptual hydrological simulation was adopted to explore the sensitivity of groundwater-streamflow interaction to projected climate changes over a medium-sized mountainous catchment. The connection of this work to other related studies is very limited. Many investigations have dealt with the effects of global climate change on snow storage, runoff, soil moisture and evapotranspiration (e.g. Nemeč & Schaake; 1982, Gleick, 1987; Lettenmaier & Gan, 1990; Panagoulia, 1991, 1992a; Panagoulia & Dimou, 1994), as well as on groundwater recharge (Vaccaro, 1992). In contrast, there is only one investigation referring to the effect of climate changes on aquifer storage and river recharge using a hydraulic approach, i.e. a simple model of an idealized aquifer/river system (Wilkinson & Cooper 1993).

Another critical problem to be noted is the validation of the climate changes predicted by the General Circulation Models (GCMs) over areas at the catchment scale. It is well known that the GCMs operate at scales of hundreds to thousands of kilometres and up, while any tested dissaggregation scheme of GCM predictions over catchment scales (Bardossy & Plate, 1991; Hay *et al.*, 1992) is mostly stochastic, yielding limited physical meaning to modelled climatological data (Barros & Lettenmaier, 1993; Burges, 1993). Thus, in this study, the coupling of atmospheric circulation simulations and hydrological models was achieved through the adjustment of present day surface climatological inputs to account for climate change scenarios.

HYDROLOGICAL SYSTEM DESIGN

The Mesochora catchment of the Acheloos river (Fig. 1) was selected for a sensitivity analysis of the interaction between groundwater and streamflow to global climate change. The basic criterion for this selection was the geographical and hydrological significance of the catchment due to the partial diversion of the river for irrigation and hydropower purposes. The part of the river which drains the Mesochora catchment flows freely (no upstream diversions or flow regulations).

The Mesochora catchment, with an area of about 633 km^2 (Fig. 1), lies in the central mountain region of Greece and extends nearly 32 km from north (39°42′) to south (39°25′) with an average width of about 20 km. The climate in the Mesochora catchment is elevation-dependent, with hot summers and mild winters at low elevations and mild summers and cold winters at high elevations. Because of its high mean elevation (1390 m a.s.l.), its hydrology is controlled by snowfall and snowmelt.

The network of meteorological stations installed in and around the Mesochora catchment is relatively dense, but 3.5% of daily precipitation values and 15.5% of daily min-and-max temperature values were missing for the 15-year period used in this study (1972-1986). The catchment mean annual precipitation (weighted average over elevation bands) is about 1900 mm and its mean annual runoff is 1170 mm.

The soils of the catchment have been formed from the decay of hard

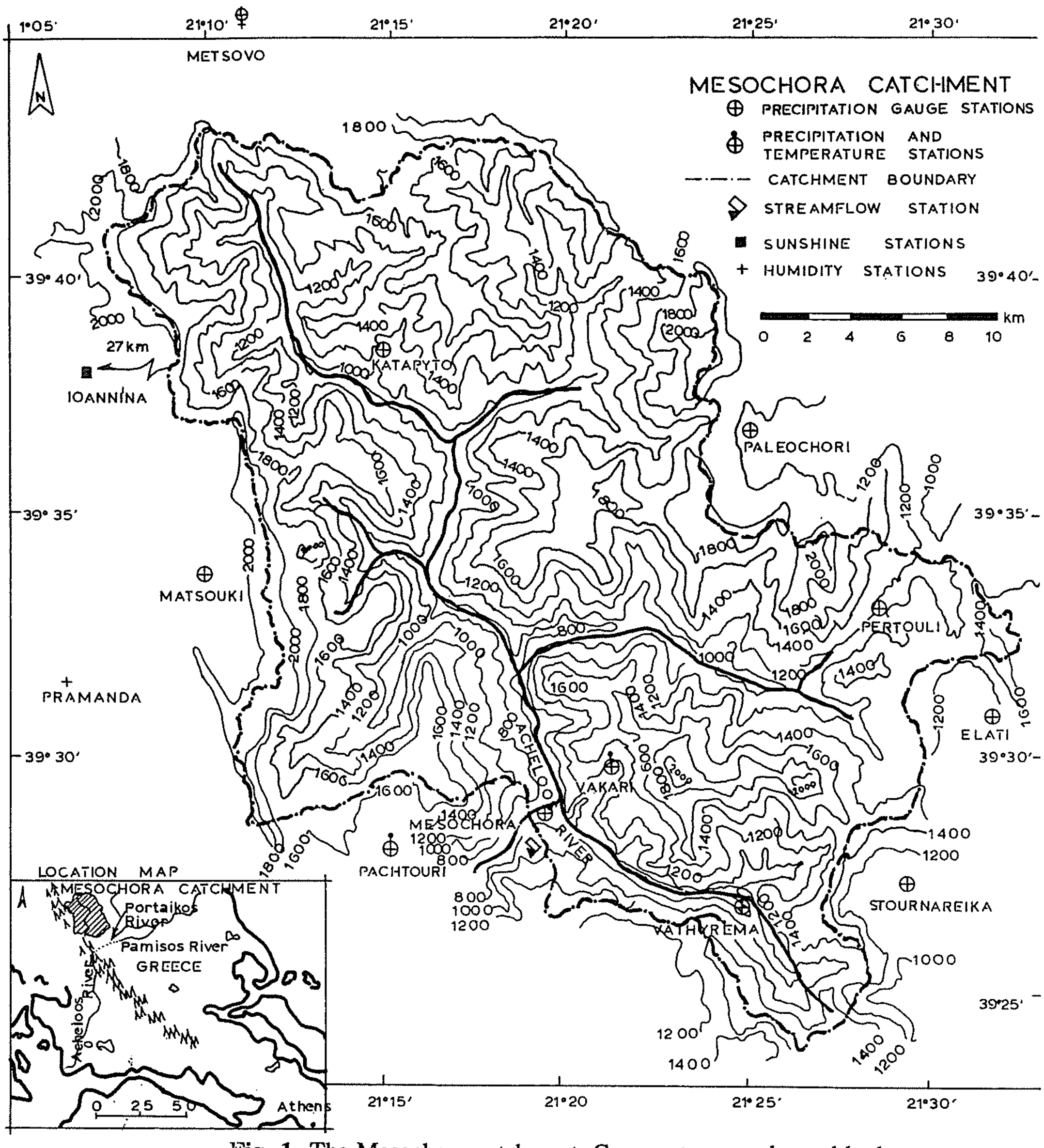

Fig. 1 The Mesochora catchment, Greece: topography and hydrometeorological stations.

limestones and flysch. They are varied, but generally permeable. A more detailed description of the catchment has been presented by Panagoulia (1991, 1992a, 1992b).

Two hydrological models were used: the snow accumulation and ablation model developed by Anderson (1973) and the soil moisture accounting model proposed by Burnash *et al.* (1973). Both models were developed at the US National Weather Service Hydrologic Research Laboratory. The snowmelt model describes the change in storage of water and heat in the snowpack, based on six-hourly precipitation and temperature data. In particular, it accounts for accumulation of the snowcover, heat exchange at the air-snow interface, areal extent of snowcover, heat storage within the snowcover, liquid-water retention and transmission, and heat exchange at the soil-snow interface. These model components are shown in Fig. 2.

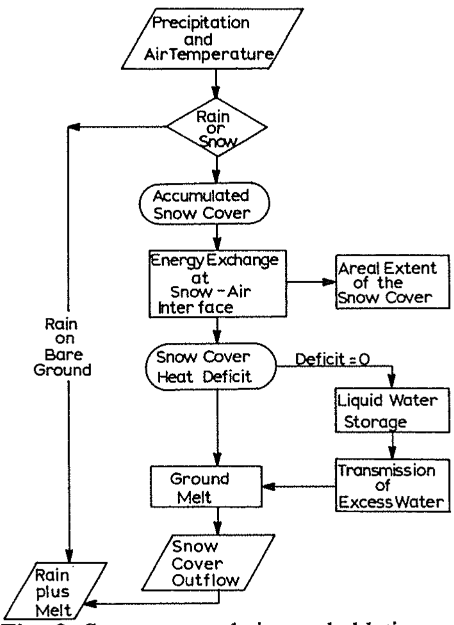

Fig. 2 Snow accumulation and ablation model components.

The soil moisture model is based on a system of percolation, as well as soil moisture storages, drainage and evapotranspiration characteristics. The model is conceptually made up of an upper zone, which represents topsoils and the basin interception layer, and a lower zone, which represents a groundwater reservoir (Fig. 3).

The upper zone is divided into tension water storage and free water storage for the permeable portion of the catchment. Tension water is considered as the water which is closely bound to soil particles. This water is available for evapotranspiration. Tension water storage should be filled before moisture

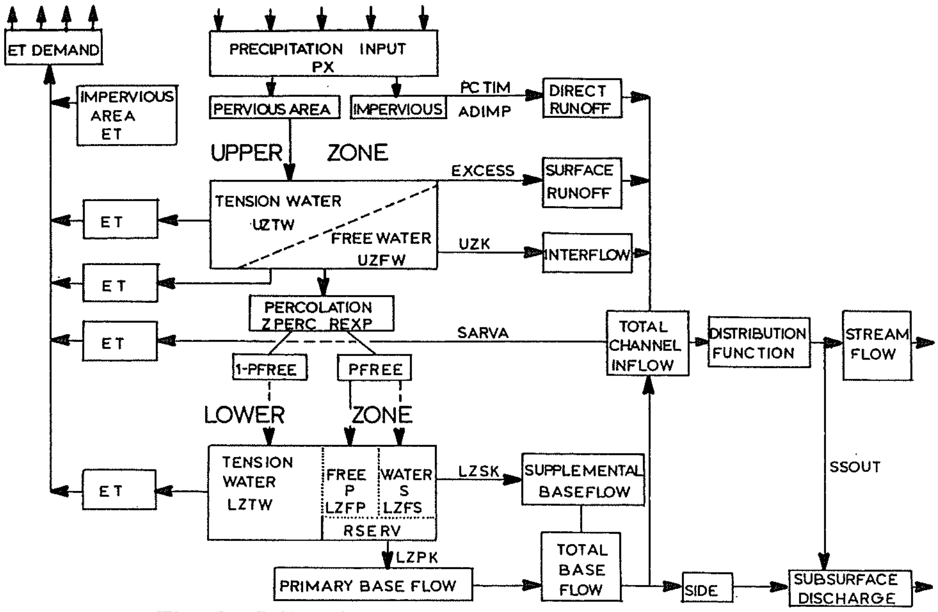

Fig. 3 Soil moisture accounting model components. (Source: Burnash *et al.*, 1973).

becomes available to enter the free water storage. Free water can descend to the lower zone by percolation or can move laterally to produce interflow.

Percolation is controlled by the contents of the upper zone free water and the deficiency of lower zone moisture volume. When the precipitation rate exceeds the percolation rate and the maximum interflow drainage capacity, then the upper zone free water capacity is filled completely and the excess rainfall will result in surface runoff.

The lower zone consists of one tension water storage and two free water storages. Again, the water is available for evapotranspiration. The two free water storages (called primary and supplemental) fill simultaneously from percolated water and drain independently at different rates, generating primary and supplemental baseflow. The reason for using three storage zones is to allow the nonlinear characteristics of baseflow to be represented. Direct runoff from impervious and water surfaces, surface runoff and interflow from the upper zone free water, and primary and supplemental baseflows from the lower zone all combine to generate the streamflow.

For the purposes of the study, the interaction between groundwater and streamflow was expressed by the ratio of the two variables (i.e. groundwater/streamflow = *GWR*). Although the contribution of groundwater to river flows is baseflow, it is to be noted that, beyond the baseflows, the lower zone tension water was included in the catchment groundwater due to its high mean annual value (lower zone tension water/total baseflow = 2.5).

The snowmelt model output "daily rain plus melt" and long term average monthly potential evapotranspiration were used as inputs to the soil moisture accounting model. The potential evapotranspiration was estimated using the Penman equation (Veihmeyer, 1964) and disaggregated into daily increments by the model.

For better performance of the snowmelt model, the catchment was divided into three elevation zones (about 30% of the total area for each of the upper and middle zones and 40% for the lower zone). Eleven precipitation stations and three temperature stations were operated. Because the daily precipitation records were incomplete, the zone areal precipitation was assessed through the Thiessen method for all the combinations of zone stations which were yielding data for that particular day. The estimated zone areal precipitation was corrected for the median zone elevation. The above mentioned combination technique was also used to estimate the zone areal daily max-and-min temperature (Panagoulia, 1992b, 1993, 1994, 1995). The study catchment mean areal precipitation (*MAP*) was taken as the average of the snowmelt output over the elevation zone areas. The *MAP* was then used as input to the soil moisture accounting model.

The calibration period was 15 years (1972-1986) for both models. The models were manually calibrated 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, 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 summarized results of the calibration, shown in Fig. 4, demonstrate the capacity of the soil moisture accounting model to reproduce the observed streamflow at the outfall of the Mesochora catchment. Details of the development, calibration, and statistical verification of the models are presented by Panagoulia (1992b).

The historical input data were adjusted to reflect the altered climates simulated by:

(a) fifteen hypothetical scenarios denoted as HYPO(ΔT, ΔP), where ΔT is temperature increase by 1, 2, 4°C and ΔP is precipitation change by 0, $\pm$10, $\pm$20% (Panagoulia 1991, 1993); and

(b) two GISS (Goddard Institute for Space Studies) predicted scenarios with both monthly precipitation and temperature changes denoted as GISS (t, p) and with monthly temperature changes alone denoted as GISS (t, 0) (Panagoulia, 1992a, 1993).

Assuming that the daily precipitation arrival process (i.e. the structure of wet and dry day sequences) remained the same as in the historical record, all the input precipitation time series were multiplied for the HYPO cases by a uniform factor and for the GISS cases by the monthly precipitation ratio (the ratio of GISS-predicted monthly precipitation for CO_2-doubling to the control run (1 $\times$ CO_2), ranging from 0.925 to 1.487) applied for the centre of the catchment (39°34'N latitude and 21°19'E longitude). The HYPO temperature increases were applied uniformly to all daily values of the historical input series, while the GISS-predicted monthly temperature differences (ranging from 3.37 to 4.98°C) between the CO_2-doubling and control run were added to the

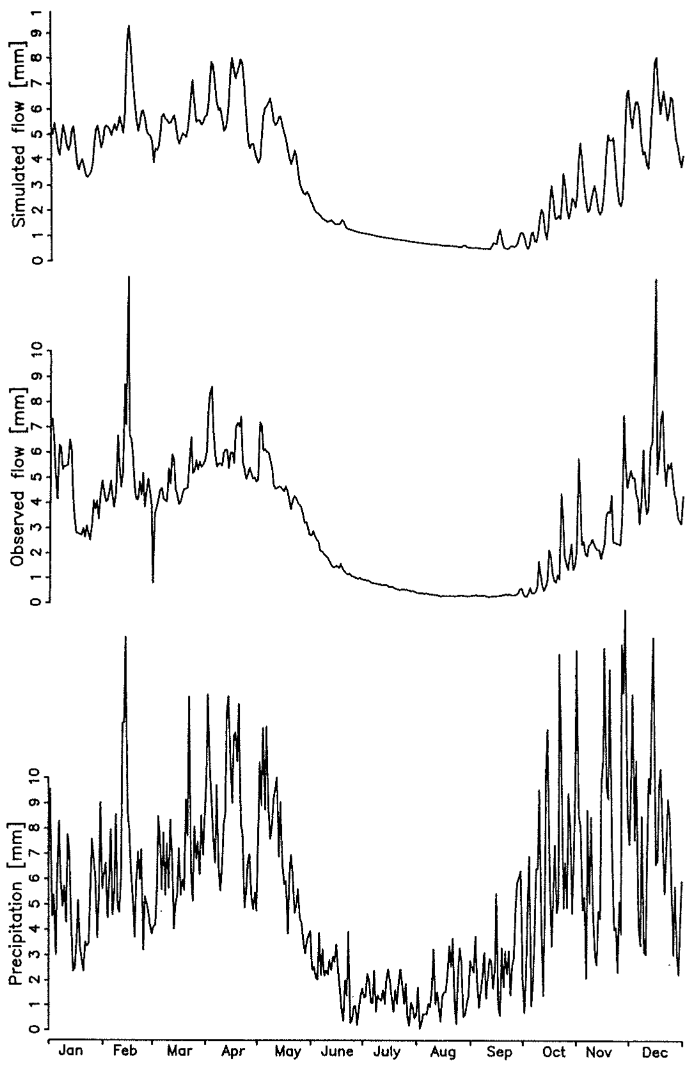

Fig. 4 Mesochora catchment: average daily precipitation (rain plus melt), observed flows and soil moisture accounting model predicted flows for the 15-year calibration period.

input historical data as well (Panagoulia, 1991, 1992a).

For the HYPO cases the potential evapotranspiration (*PET*) was computed using the Penman equation with the indicated temperature increases, which were applied uniformly to the historical monthly temperature data. For the GISS cases, the *PET* was also computed with the same equation for the monthly temperature data for the CO_2-doubling and the control run. The monthly differences in *PET* were computed and these differences were added to the historical *PET* data. The other variables (wind speed, humidity, solar radiation, etc.) remained unaltered in the Penman equation for both the HYPO and GISS cases.

GROUNDWATER-STREAMFLOW INTERACTIONS

Since the snow accumulation and ablation model as well as the soil moisture accounting model operate on daily or shorter time steps, and 18 alternative climates (15 HYPO, 2 GISS and base case) involved running both models for 15 years, a significant volume of daily interaction data between groundwater and streamflow was obtained. To simplify the analysis of the results, reported as averages over the 15 year period, four variables were selected: monthly average catchment groundwater, monthly average streamflow, and seasonal and monthly changes of the groundwater to streamflow ratio (*GWR*). The long term monthly distribution of the *GWR* for all climates (HYPO and GISS) has been described in another study (Panagoulia & Dimou, 1995). The scenarios of the above four variables are plotted in Figs 5 to 8. An interpretation of these figures follows.

Groundwater

The long term catchment-average groundwater storage by month for all the alternative (HYPO, GISS and base case) climates is presented in Fig. 5. There were significant changes in the catchment groundwater for all 17 climate scenarios. The warmer and wetter climates resulted in more rainfall than 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 the mean content of groundwater storage. This trend was stronger during summers and early autumns rather than during the other seasons because these seasons experienced larger changes in moisture supply.

The content of the groundwater storage peaked in March in 16 of the 17 climate change scenarios, while those of the base case and HYPO(1, −20) scenario reached their maximum in April. For 13 of the 15 HYPO scenarios, the two GISS cases and the base case, the groundwater content was minimal in October. The other two scenarios HYPO(2, 20) and HYPO(4, 20) caused the groundwater content to come to a minimum in September.

Streamflow

Figure 6 shows significant changes in the seasonal distribution of the Mesochora catchment streamflow for all climate scenarios. The effect of reduced snow storages and change in the timing of snowmelt (Panagoulia, 1991, 1993) is seen clearly in all streamflow responses. The annual hydrograph peak shifted to a time earlier in the year because of a decrease in the amount of snowfall compared to rainfall. The summer streamflow went down considerably in the GISS scenarios and in 14 of the 15 HYPO cases. The summer streamflow resulting from the scenario HYPO(1, 20) went up a little due to the small temperature increase and the large precipitation increase. The winter

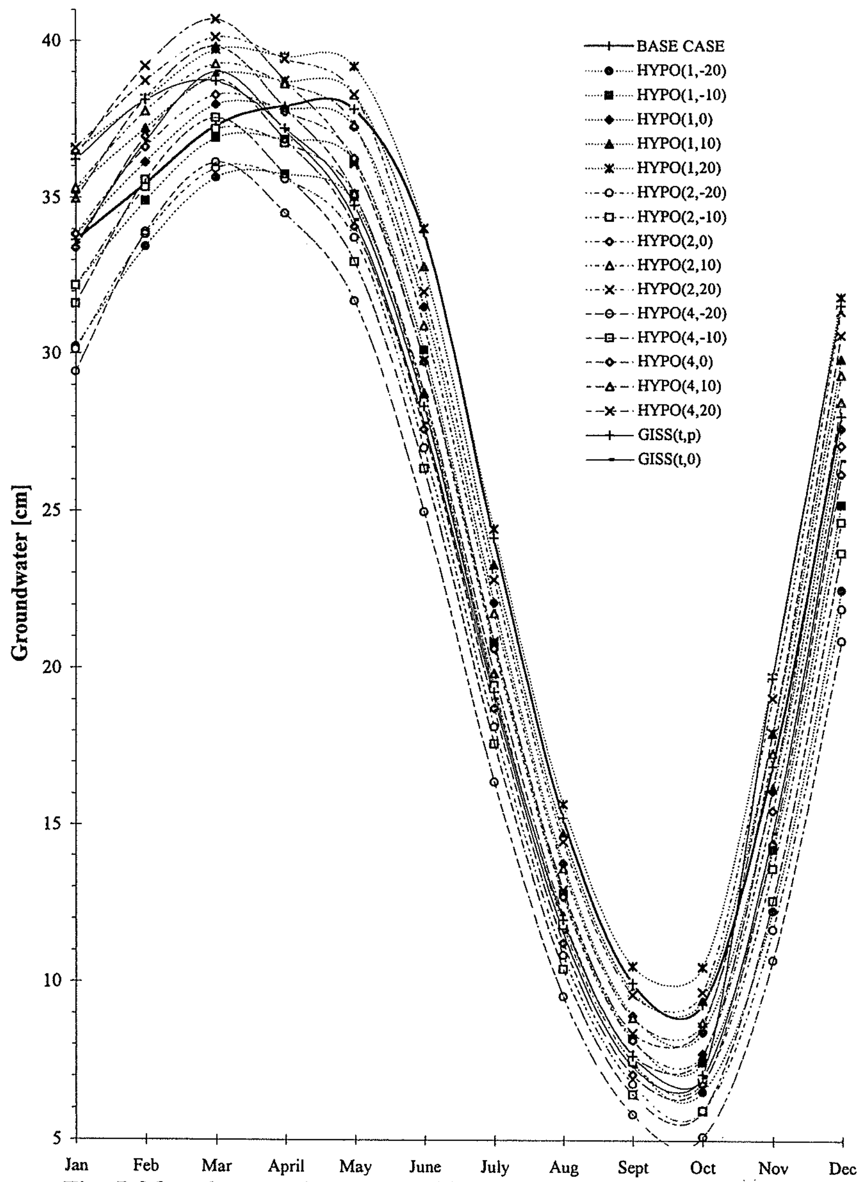

Fig. 5 Mesochora catchment: monthly mean groundwater for HYPO, GISS and base case climate scenarios.

streamflow increased in the two GISS scenarios and 10 of the 15 HYPO cases. It decreased in the case of the climate scenarios HYPO(1, 10), HYPO(2, 10) and HYPO(Δt, 20). For the April to August period the scenarios of HYPO(1, -20) and HYPO(2, -10) were similar to GISS(t, p).

Seasonal interactions

Figure 7(a) shows the percentage change of the long term catchment ground-

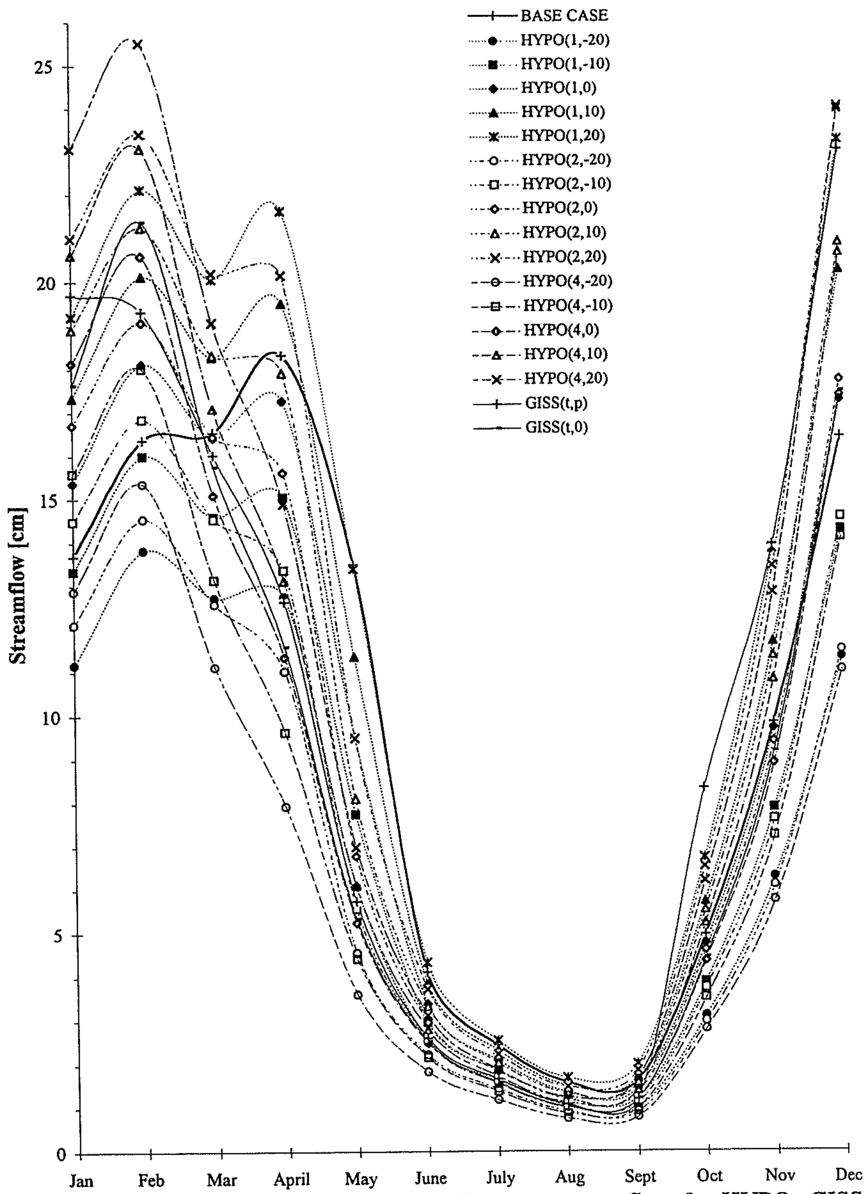

Fig. 6 Mesochora catchment: monthly mean streamflow for HYPO, GISS and base case climate scenarios.

water to streamflow ratio (*GWR*) by season as a function of HYPO precipitation and temperature changes. There is a contrasting behaviour of *GWR* between winter (December-February) and summer (June-August) seasons, as well as between autumn (September-November) and spring (March-May) seasons. Thus, while a temperature increase for every precipitation change reduces the winter (or autumn) *GWR*, it increases the summer (or spring) *GWR*. The reason underlying this behaviour is that the temperature changes controlling the accumulation and melting of snow-storages influence the seasonal runoff.

Accounting for the HYPO precipitation changes, the *GWR* was reduced as precipitation increased by a manner depending on the snow-storages and temperature conditions. This latter is reflected in the overlapping regions of the *GWR* seasonal changes.

The percentage change of the catchment *GWR* by season for the GISS climate scenarios is presented in Fig. 7(b) in the form of histograms. Most of the seasonal histograms reflect changes similar to those of the HYPO(4, 0)

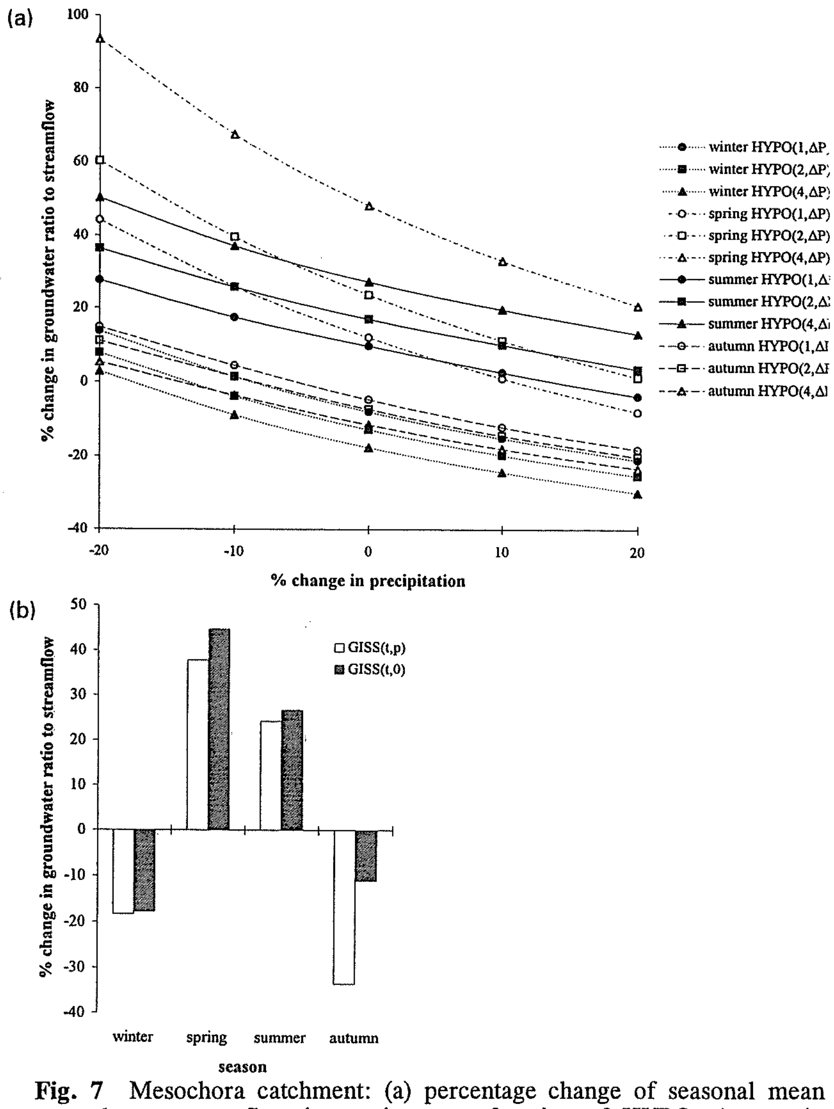

Fig. 7 Mesochora catchment: (a) percentage change of seasonal mean groundwater-streamflow interaction as a function of HYPO changes in precipitation and temperature; and (b) histograms of percentage change of seasonal mean groundwater-streamflow interaction for GISS climate scenarios.

climate case, thereby boosting again the prevailing role of temperature on the seasonal behaviour of GWR through the seasonal snow accumulation melting and runoff influences.

The larger increases of *GWR* for the HYPO and GISS cases were noticed in spring; the largest one (by 93%) was produced by the HYPO (4, −20) scenario. The latter effect is attributed to the considerable reduction in spring runoff (by 53%) which is also associated with the large reduction in spring snow water equivalent (by 96%) and the largely increased spring evapotranspiration (by 294%).

Monthly interactions

The long term monthly changes of the *GWR* over the catchment for all climates (HYPO and GISS) are presented in Fig. 8. The HYPO and the GISS climate scenarios yielded very similar interannual profiles of *GWR* changes.

A progressive reduction of the *GWR* in respect of the precipitation increases (HYPO and GISS) for every HYPO and GISS temperature increase was remarked. However, this reduction is erratic for most months among all the climate cases (intersect lines). This is perhaps the result of the contrasting behaviour of snow-storages and runoff by season, as analysed in the previous section. The *GWR* peaked in July and minimized in December for all climate scenarios (HYPO, GISS and base case). Months in which the *GWR* fell short of the base case are September-February for most of the climate cases.

The monthly *GWR* was increased in relation to that of the base case at the maximum rate in May for most of the climate scenarios. The latter is the effect of the maximum runoff reduction also occurring in May. The driest scenario HYPO(4, −20) generated the maximum *GWR* increase (by 214%), which is associated with the maximum runoff reduction (by 73%) in the aforesaid month. For the May-August period the scenarios HYPO(1, −20) and HYPO(2, −10) are similar to the GISS(t, p).

CONCLUSIONS

Perhaps the most significant result of the study was that the interaction between the catchment groundwater and streamflow was dominated by temperature-related changes in snowmelt and runoff, which were more important than the precipitation changes simulated by the HYPO and GISS scenarios. In this study the groundwater modelling used does not account for explicit representation of groundwater flows, while the use of the ratio of streamflow to groundwater is an oversimplified mechanism for describing the interaction between these two different flows. However, the primary value of this study is not in terms of the specific simulation results but rather the insight it provides into the possible manifestations of climate change in interconnection between catchment runoff

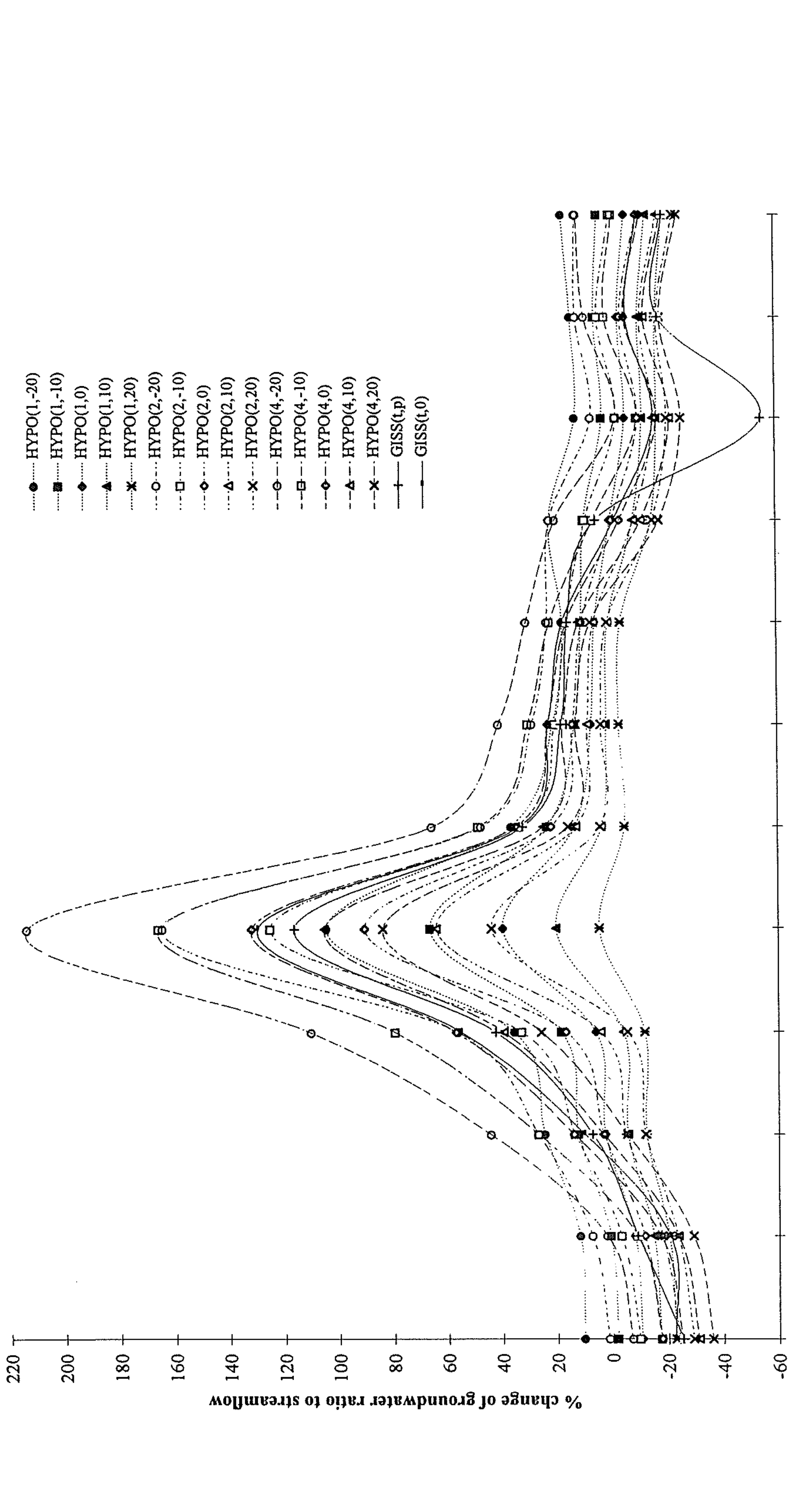

Fig. 8 Mesochora catchment: percentage change of monthly mean groundwater-streamflow interaction for HYPO and GISS climate scenarios.

and groundwater, as well as in the linkages among surface-groundwater processes and climate. This should be the subject of future research. The appropriate level of spatial aggregation for catchment simulation is a major unresolved problem which is associated with the improvements of GCMs concerning the spatial and temporal scales they use. Having considered the preliminary nature of the study and the limitations imposed by the assumptions, the following conclusions can be reached:

1. The monthly change patterns of the interaction between the catchment groundwater and streamflow for the HYPO and GISS climate scenarios were very similar. Both cases showed that the groundwater-streamflow interaction is moderately affected by global climate change during the wet period (October-February), while, in the spring and summer period, this interrelationship is highly influenced. In particular, the major seasonal shift in the snow accumulation pattern related to climate change, as well as the large runoff reduction and evapotranspiration increase occurring during the spring and summer months, boost the groundwater to streamflow ratio considerably.
2. The impacts of global warming on the interaction between groundwater and streamflow are more critical than those of each variable examined separately. For example, in May, the driest climate posted a 73% runoff reduction and a 16% groundwater reduction, as well as a 214% interaction increase, which is about three times greater than the runoff reduction. This fact denotes that all the issues of water resources management (e.g. droughts, water supply, irrigation) which depend on the groundwater-streamflow interrelationship, would in all likelihood be highly ill-affected by global warming.
3. Differences were noted in the interaction results among the HYPO and GISS cases due to the wide range of the climate variables changes (e.g. the GISS precipitation increase in October was up 50%).

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