Man's Influence on Freshwater Ecosystems and Water Use

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Groundwater-streamflow interactions under changing climate conditions

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Abstract The long-term groundwater-streamflow interactions of the medium-sized mountainous Mesochora catchment under changing climatology have been analysed. The climate changes were simulated through a set of hypothetical and monthly GISS (Goddard Institute for Space Studies) scenarios of temperature increases coupled with precipitation changes. Two catchment hydrological models were used: the snowmelt and soil moisture accounting models of the US National Weather Service River Forecast System (US NWSRFS). The groundwater was represented through the 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, as well as the primary and secondary base flows yielded by the model. The interaction between groundwater and streamflow was expressed by the ratio of the two variables on a monthly basis. Both sets of climate change scenarios resulted in moderate influence on groundwater-streamflow interaction during the winter months and in a very high one in the spring and summer months. This will probably have negative impacts on various problems of water resources management.

INTRODUCTION

The interaction between groundwater and streamflow has gained increasing attention in hydrology, hydrogeology and land reclamation in 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. This issue also 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 them (Vasiliev, 1987). As 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 adequately describing 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 arisen (Vasiliev, 1987) as regards the correctness of the coupled surface water-groundwater models.

According to clearly hydrological aspects, the usual method of estimating the contribution of groundwater to river flows is through baseflow separation from a flow hydrograph (Miles & Rushton, 1983). A more detailed representation of the surface-groundwater system is expressed by deterministic conceptual models including simple water balance methods (Mather & Thorthwaite, 1955; 1957) as well as the more sophisticated ones, such as the energy-soil-water balance of Vaccaro (1992), the Stanford Watershed IV model (Grawford & Linsley, 1966) and the soil moisture accounting model of Burnash *et al.* (1973).

In this study we adopted the methodology of conceptual hydrological simulation to explore the sensitivity of groundwater–streamflow interaction over a medium-sized mountainous catchment to projected climate changes. The relationship of this work to other related studies is nil. While many investigations have dealt with the effects of global climate change on runoff, soil moisture and evapotranspiration (e.g. Nemec & Schaake; 1982, Gleick, 1987; Lettenmaier & Gan, 1990; Panagoulia, 1991, 1992a; Panagoulia & Dimou, 1994), as well as on groundwater recharge (Vaccaro, 1992), there is not even one investigation referring to the sensitivity analysis of groundwater- streamflow interaction to global warming.

Another critical problem that is worth mentioning is the validation of climate changes predicted by General Circulation Models (GCMs) over catchment scale areas. 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 stochastic (i.e. yields 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

We selected the Mesochora catchment of the Acheloos river in Central Greece for an analysis of the sensitivity of the interaction between groundwater and streamflow to global climate changes. 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 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), its hydrology is controlled by snowfall and snowmelt.

The catchment area is about 633 km^2, its annual precipitation is about 1900 mm and its runoff is 1170 mm. The soils of the catchment have been formed from decay of hard 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 of Anderson (1973) and the soil moisture accounting model of Burnash *et al.* (1973). The snowmelt model describes the change in storage of water and heat in the snowpack, based on six-hourly precipitation and temperature data. The soil moisture model is based on a system of percolation, as well as of 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.

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 up before moisture 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 secondary) fill simultaneously from percolated water and drain independently at different rates, generating primary and secondary 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 secondary baseflows from the lower zone 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, we included the lower zone tension water in the catchment groundwater, beyond the baseflows, due to its high mean annual value (lower zone tension water/total baseflow = 2.5).

As inputs to the soil moisture accounting model, we used the snowmelt model output "daily rain plus melt" and long-term average monthly potential evapotranspiration, which in this study was estimated from the Penman equation (Veihmeyer, 1964). To improve the performance of the snowmelt model, the catchment was divided into three elevation zones (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 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 maximum and minimum temperature (Panagoulia, 1992a; 1993; 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 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%). Details of the development, calibration, and statistical verification of the models are presented in Panagoulia (1990, 1992a).

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%; and
(b) two GISS (Goddard Institute for Space Studies)-predicted scenarios (with both monthly precipitation and temperature changes GISS(t,p), and with monthly temperature changes alone GISS(t,0),

in the manner used by Panagoulia (1991; 1992a; 1993).

GROUNDWATER-STREAMFLOW INTERACTIONS

The interaction between the catchment groundwater and streamflow was simulated for 15 years and 18 alternative climates (one is base case). The long-term monthly distributions of the groundwater to streamflow ratio (*GWR*) over the study catchment for all climates (HYPO and GISS) are presented in Fig. 1. The HYPO and the GISS climate scenarios yielded very similar GWR inter-annual profiles. A progressive reduction of the *GWR* in respect of the precipitation increases (HYPO and GISS) for every HYPO and GISS temperature increase was remarked. The *GWR* peaked in July and minimized in December for all climate scenarios (HYPO, GISS and base case (solid line)). Months in which *GWR* fell short of the base case are September to February for the most 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. This latter is the effect of the maximum runoff reduction which occurred also in May. The driest scenario HYPO(4, −20) generated the maximum *GWR* increase (about 200%) which is associated with the maximum runoff reduction (about 70%) in the aforesaid month. For the May to August period the scenarios HYPO(1, −20) and HYPO(2, −10) are similar to GISS(t,p).

CONCLUSIONS

The main conclusions from the present study can be summarized as follows:
(a) The monthly distribution patterns of the interaction between the catchment groundwater and streamflow for HYPO and GISS climate scenarios are very similar. Both cases showed that the groundwater-streamflow interaction is moderately affected by global climate change during the wet period (October to February), while, in the spring and summer one, this interrelationship is highly influenced.

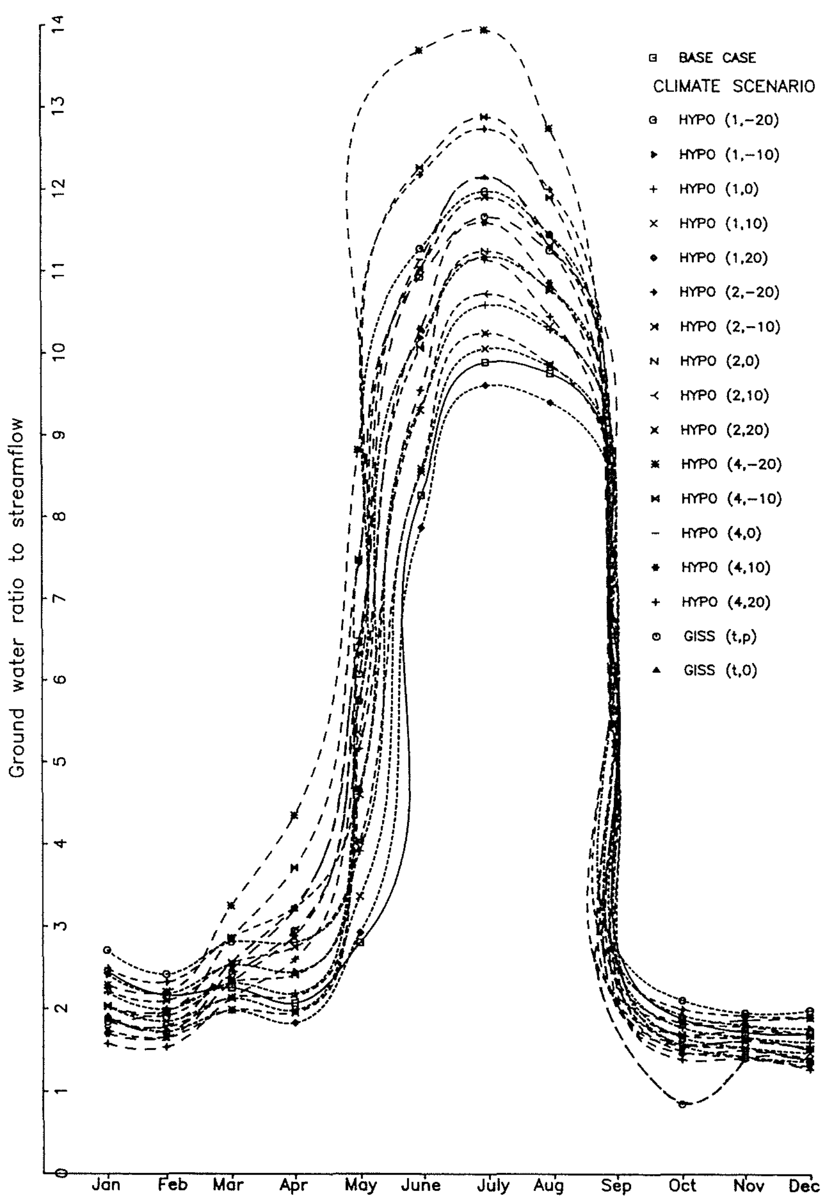

Fig. 1 Mesochora catchment monthly groundwater-streamflow interaction for the HYPO, GISS and base case climate scenarios.

(b) The impacts of global warming on the interaction between groundwater and streamflow are more critical than those of each variable separately examined. For example, in May, the driest climate posted a 70% runoff reduction and a 16% groundwater reduction, as well as 200% 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 badly affected by global warming.

(c) 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%).

REFERENCES

Anderson, E. A. (1973) US National Weather Service river forecast system. Snow accumulation and ablation model. *NOAA Technical Memorandum NWS HYDRO 17.*

Bardossy, A. & Plate, E. (1991) Modelling daily rainfall using a semi-Markov representation of circulation pattern occurrence. *J. Hydrol.* 122(1-4), 33-47.

Barros, A. & Lettenmaier, D. (1993) Multiscale aggregation and disaggregation of precipitation for regional hydroclimatological studies. In: *Macroscale Modelling of the Hydrosphere* (ed. by W. B. Wilkinson) (Proc. Yokohama Symp., July 1993), 183-193. IAHS Publ. no. 214.

Burges, S. J. (1993) Unny Symposium: Why are you here? International Conference in Honour of Professor T. E. Unny. *Stochastic and Statistical Methods in Hydrology and Environmental Engineering*, University of Waterloo, Waterloo, Ontario, Canada, 21-13 June 1993.

Burnash, R. J. C., Ferral, R. L. & Mcquire, R. A. (1973) A generalized streamflow simulation system conceptual model for digital computers. *US National Weather Service, Sacramento, California, USA.*

Crawford, N. H. & Linsley, R. K. (1966) Digital simulation in hydrology: Stanford Watershed Model IV. *Stanford Univ., Dept. Civ. Eng. Tech. Report 39.*

Cunge, J. A., Holly, F. M., Jr & Verwey, A. (1980) *Practical Aspects of Computational River Hydraulics.* Pitman Advanced Publishing Program, London.

Freeze, R. A. (1972) Role of subsurface flow in generating surface runoff. 1. Baseflow contributions to channel flow. *Wat. Resour. Res.* 8(3), 609-623.

Gleick, P. H. (1987) Global climatic changes and regional hydrology: impacts and responses. In: *The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources* (ed. by S. I. Solomon, M. Beran & W. Hogg) (Proc. Vancouver Symp., August 1987), 389-402. IAHS Publ. no. 168.

Hay, L., McCabe, G., Wolock, D. & Ayers, M. (1992) Use of weather types to disaggregate general circulation model predictions. *J. Geophys. Res.* 97(D3), 2781-2790.

Lettenmaier, D. P. & Gan, T. Y. (1990) Hydrologic sensitivities of the Sacramento-San Joaquin River Basin, California, to global warming. *Wat. Resour. Res.* 26(1), 69-86.

Miles, J. C. & Rushton, K. R. (1983) A coupled surface water and groundwater catchment model. *J. Hydrol.* **62**, 159-177.

Nemec, J. & Schaake, J. (1982) Sensitivity of water resources systems to climate variation. *Hydrol. Sci. J.* 27(3), 327-343.

Panagoulia, D. (1995) Assessment of daily catchment precipitation in mountainous regions for climate change interpretation. *Hydrol. Sci. J.* (in press).

Panagoulia, D. & Dimou, G. (1994) Temporal scale effects on modelled catchment hydrological processes in respect of global climate change. Oral presentation in: *1994 Western Pacific Geophysics Meeting* (Proc. Hong Kong Symposium, July 1994), Abstracts, p. 30. American Geophysical Union.

Panagoulia, D. (1993) Catchment hydrological responses to climate changes calculated from incomplete climatological data. In: *Exchange Processes at the Land Surface for a Range of Space and Time Scales* (Proc. Yokohama Symp., July 1993), 461-468. IAHS Publ. no. 212.

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

Panagoulia, D. (1992b) Hydrological modelling of a medium-sized mountainous catchment from incomplete meteorological data. *J. Hydrol.* 137(1-4), 279-310.

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

Panagoulia, D. (1990) Sensitivity analysis of catchment hydrological response to climate changes. PhD Thesis, National Technical University of Athens, Greece.

Pinder, G. F. & Sauer, S. P. (1971) Numerical simulation of flood wave modification due to bank storage effects. *Wat. Resour. Res.* 7(1), 63-70.

Swain, E. D. (1994) Implementation and use of direct-flow connections in a coupled groundwater and surface water model. *Groundwater* 32(1), 139-144.

Thornthwaite, G. W. & Mather, J. R. (1955) The water balance. *Drexel Inst. Technol. Publications in Climatology, Laboratory of Climatology, VII, no. 1.*

Thornthwaite, G. M. & 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.*

Vaccaro, J. J. (1992) Sensitivity of groundwater recharge estimates to climate variability and change, Columbia Plateau, Washington. *J. Geophys. Res.* 97(D3), 2821-2833.

Vasiliev, O. F. (1987) System modelling of the interaction between surface and groundwaters in problems of hydrology. *Hydrol. Sci. J.* 32(3), 297-311.

Veihmeyer, F. J. (1964) Evapotranspiration. Chapter 11 in: *Handbook of Applied Hydrology* (by V. T. Chow). McGraw Hill, New York.