Reprinted from

JOURNAL OF HYDROLOGY

Journal of Hydrology 191 (1997) 208–222

Sensitivity of flood events to global climate change

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Received 12 September 1995; revised 27 November 1995; accepted 19 February 1996

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Publication information

Journal of Hydrology (ISSN 0022-1694). For 1997 volumes 187–199 are scheduled for publication. Subscription prices are available upon request from the publishers. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL (Surface Air Lifted) mail is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan*, Malaysia, Mexico, New Zealand, Pakistan, China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues must be made within 6 months of our publication (mailing) date.
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Printed in The Netherlands

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Sensitivity of flood events to global climate change

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Received 12 September 1995; revised 27 November 1995; accepted 19 February 1996

Abstract

The sensitivity of Acheloos river flood events at the outfall of the mountainous Mesochora catchment in Central Greece was analysed under various scenarios of global climate change. The climate change pattern was simulated through a set of hypothetical and monthly GISS (Goddard Institute for Space Studies) scenarios of temperature increase coupled with precipitation changes. The daily outflow of the catchment, which is dominated by spring snowmelt runoff, was simulated by the coupling of snowmelt and soil moisture accounting models of the US National Weather Service River Forecast System. Two threshold levels were used to define a flood day—the double and triple long-term mean daily streamflow—and the flood parameters (occurrences, duration, magnitude, etc.) for these cases were determined. Despite the complicated response of flood events to temperature increase and threshold, both hypothetical and monthly GISS representations of climate change resulted in more and longer flood events for climates with increased precipitation. All climates yielded larger flood volumes and greater mean values of flood peaks with respect to precipitation increase. The lower threshold resulted in more and longer flood occurrences, as well as smaller flood volumes and peaks than those of the upper one. The combination of higher and frequent flood events could lead to greater risks of inundation and possible damage to structures. Furthermore, the winter swelling of the streamflow could increase erosion of the river bed and banks and hence modify the river profile.

1. Introduction

Man has always faced weather and climate vagaries and related problems of flooding. However, recent occurrences of extreme floods in parts of the world that had never experienced such events, or in countries adjacent to others suffering from prolonged

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PII S0022-1694(96)03056-9

droughts, have increased the need for thorough investigation of floods. Promising approaches to flood control planning and management, such as expert systems (Simonovic, 1991), combination of procedural and heuristic models and decision support systems (Sprague and Carlson, 1982), have been developed. However, the control of floods is 'ill structured' and subject to a high degree of uncertainty (Schultz, 1993; Kundzewicz et al., 1993). Thus, most attempts to deal with floods have focused on the better understanding of the cause and effect components of the physical process. Understanding floods, their occurrences, mechanisms, characteristics and regularities is of great importance for the design and management of water resources systems.

Although the weather system producing excessive rainfall and flash flooding is yet to be found (Kundzewicz et al., 1993), the greenhouse effect and direct anthropogenic operations (deforestation, agriculture, urbanization), as well as remote climate forcings (El Ni ño–Southern Oscillation phenomena), have been responsible for flood occurrences (Dickinson and Henderson-Sellers, 1988; Nicholls, 1989; Lean and Warrilow, 1989; Richey et al., 1989; Siegenthaler, 1990; Shuklaa et al., 1990; BAHC Core Project Office, 1993). However, none of the general circulation models (GCMs), or any downscaling scheme thereof, or even the most promising SVAT (Soil–Vegetation–Atmosphere Transfer) models (BAHC Core Project Office, 1993), can yet simulate and predict accurately such catastrophic events at any spatial or time scale.

Detailed time series of climate forcing fields and runoff derived principally from observational data and weather generators are required for analysing flood events, as well as low-flows and droughts. These data sets will initially be used to drive the ecosystem–hydrology models and thus to validate the coupled ecosystem–hydrology–atmosphere models at numerous spatial and time scales. Priority is given to the matching of ecological and hydrological models, because the nature of land use and its impacts are far more complex (spatial and temporal heterogeneity overlaid with potentially diverse patterns of revegetation). It is expected that models and database development will be of help in defining the direction and magnitude of year-to-year variation in water, carbon and nutrient dynamics, and in examining the effects of remote climate phenomena. For such an analysis, decadal and longer time series should be compiled. This major work obviously belongs to the future and is linked to 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), IGBP (International Geosphere–Biosphere Programme), GCTE (Global Change and Terrestrial Ecosystems—IGBP Core Project), etc. (BAHC Core Project Office, 1993), which were very recently set up.

Until a valid link between climate, hydrology and ecosystem models with respect to flood events can be defined, hydrological analysis of such episodes under scenarios of global climate change should be performed. In this respect, the available surface climatological input data to hydrological models must be adjusted to account for climate scenarios based on GCM predictions. Such predictions include those obtained from the GFDL (Geophysical Fluid Dynamics Laboratory) (Manabe, 1969), GISS (Goddard Institute for Space Studies) (Hansen et al., 1983) or OSU (Oregon State University Department of Meteorology (Schlesinger, 1984) for carbon dioxide doubling, or those obtained from the climatological literature as a range of plausible values of changes in meteorological variables (temperature, precipitation, etc.) (Dickinson, 1982; US National Academy of Sciences, 1983; Manabe and Wetherald, 1985; MacCracken and Luther, 1986).

The main objective of this paper is to analyse the sensitivity of flood event parameters (occurrences, duration, magnitude, etc.) to a set of hypothetical and monthly GISS modelled climate changes. A profound understanding of flood parameters under changing climate conditions is also necessary for deriving valid methods for flood frequency analysis under altered climates. The latter is related to management of risks and operational hydrology to control extreme flood events.

2. Experimental design

The Acheloos river at the outfall of the mountainous Mesochora catchment in Central Greece (Fig. 1) was selected for a sensitivity analysis of flood events to global climate change. The Mesochora catchment is of great significance for Greece because the Acheloos river will be partially diverted at the outfall of the catchment through the Pindus mountains to irrigate the arid Thessaly plain. The river's water will be also used to boost

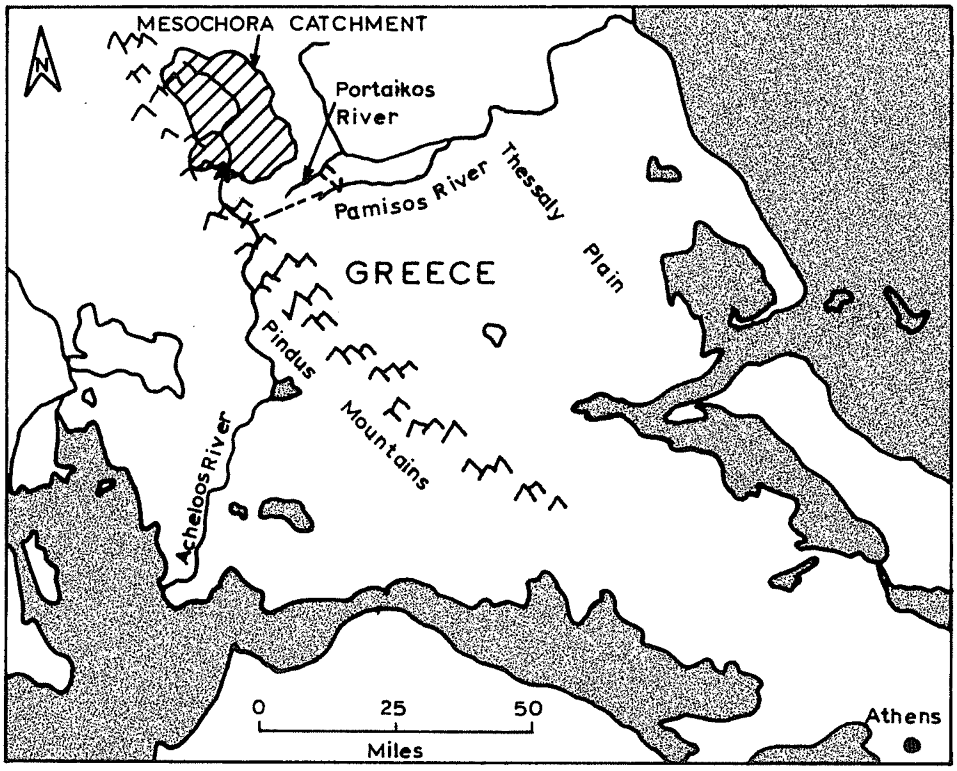

Fig. 1. The Mesochora catchment flood events study area, Central Greece.

hydropower generation in the surrounding area. It is the largest project in Greece, comprising five dams (one is the Mesochora dam), 40 km of large tunnels and about 8000 km of buried irrigation pipes. The operation and performance reliability of the costly hydraulic works depends largely on the overall hydrological regime of the catchment, including flood occurrences. Obviously, an increase of the flood parameters (peak, volume, duration, etc.), as a result of global climate change, could damage the hydraulic structures and consequently cause flooding of the surrounding agricultural region. In addition, the Mesochora catchment was selected for study purposes because there is no upstream diversion or flow regulation of the river, which is important as the effects of climate change on hydrological regimes are affected by anthropogenic interferences in the river flow.

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 minimum and maximum temperature values were missing for the 15 year period used in this study (1972–1986). The climate in the catchment is elevation dependent, i.e. hot summers and mild winters at low elevations, and mild summers and cold winters at high elevations. The mean elevation is 1390 m, and the hydrological regime of the catchment is controlled by snowfall and snowmelt at high elevations.

The catchment area is about 633 km^2, with a mean annual precipitation (weighted average over elevation bands) of about 1900 mm, and runoff of 1170 mm. Spatial variability of precipitation within the catchment is dominated by orographic effects, hence both precipitation and temperature are strongly related to elevation. A more detailed description of the catchment has been presented by Panagoulia (1991, 1992a,b).

The approach of conceptual hydrological simulation was adopted in this study to reproduce the outflow of a medium-sized catchment. Two hydrological models were used. As runoff in the Mesochora catchment is dominated by high-elevation snowmelt in the spring months, the snow accumulation and ablation process had to be modelled. The snowmelt model used was developed by Anderson (1973) and has been tested in a number of mountainous catchments in the Western USA, Mediterranean countries and elsewhere. It describes the change in storage of water and heat in the snowpack, based on data for precipitation and temperature measured at 6 h intervals. 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.

The soil moisture accounting model was developed by Burnash et al. (1973) and forms the basis of the US National Weather Service's 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 and Kite, 1981; Gupta and Sorooshian, 1983; Lettenmaier and Gan, 1990). It is a deterministic, lumped parameter, conceptual model, which explicitly accounts for the flux of soil moisture between five storage zones. Transfer of water between the soil moisture zones controls runoff response. The soil moisture zones are the upper one, including a free and a tension water zone, and the lower one, including a tension, a free primary and supplemental zone. Precipitation that does not contribute to direct runoff is split between upper free and tension water. Tension water is removed only through evapotranspiration. Free water can be transferred to the lower tension zone and free water zones. Likewise, the lower tension zone is depleted only through evapotranspiration. The lower free water zones are combined to produce a nonlinear baseflow recession. Direct runoff from impervious areas and water surfaces, surface runoff, interflow from the upper zone free water, and primary and supplemental baseflows from the lower zone generate streamflow. The runoff model input is the snowmelt model output 'daily-rain-plus-melt' and the long-term average monthly potential evapotranspiration, which in this study was computed according to the Penman equation (Veihmeyer, 1964) and disaggregated by the soil moisture model into daily increments.

The snowmelt model was implemented using an elevation band method. 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). A total of 11 precipitation stations and three temperature stations were used. As the daily precipitation records were incomplete, the zone areal precipitation was computed through the Thiessen method for all combinations of zone stations which provided data for a particular day. The estimated zone areal precipitation was corrected to median zone elevation (Panagoulia, 1992a, 1993, 1994, 1995). The other orographic and climatological parameters (e.g. orientation, slope, exposure, wind movement, storm direction, etc.) were not considered in the zonal distribution of the daily precipitation. However, several of the aforementioned meteorological parameters were taken into account in the snowmelt model, which has as input the zone areal distributed daily precipitation. These parameters were estimated in the calibration procedure of the snowmelt models (e.g. snow corrective factor (SCF), which considers vapour transfer and drifting effects, and the average wind function (UADJ), which considers the wind movement) (Panagoulia, 1995). The above-mentioned combination technique was also used to estimate the zone areal daily maximum and minimum temperature (Panagoulia, 1992a, 1993, 1994). The catchment mean areal precipitation (MAP) was estimated as the average of the snowmelt output over the elevation zones (weighting was proportional to elevation zone areas). The MAP was then used as input to the soil moisture accounting model.

The models were manually calibrated (Peck, 1976) and their parameters (over a 15 year period) 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% (in August and September they reached 23%). The results of the error analysis of daily flows, as well as the 3 day volume-error analysis, indicated a good representation of the observed daily streamflow (Panagoulia, 1992a).

The historical input data were adjusted to reflect the climate change which was simulated by: (1) 15 hypothetical scenarios denoted as HYPO(ΔT, ΔP), where ΔT is a temperature increase of 1, 2 and 4°C and ΔP is a precipitation change of 0, ± 10 and $\pm 20\%$ (Panagoulia, 1991, 1993); (2) two GISS-predicted scenarios, one with both monthly precipitation and temperature changes, denoted as GISS(t,p), and the other with monthly temperature changes, denoted as GISS(t,0) (Panagoulia, 1992b, 1993). Thus 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 to the centre of the catchment (39°34′N, 21°19′E). The HYPO temperature increases were applied uniformly to all daily values of the historical input series, whereas 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 input historical data as well.

For the HYPO cases the potential evapotranspiration (PET) was estimated 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 in the Penman equation (wind speed, humidity, solar radiation, etc.) remained unaltered for both HYPO and GISS cases.

3. Flood events: analysis of results

Two threshold levels were used to define a flood day: the double and triple long-term mean daily streamflow (Gellens, 1991; Panagoulia and Dimou, 1995a,b,c). For both levels and according to the positive 'runs theory' (Yevjevich, 1967; Dracup et al., 1980a,b), the flood parameters were determined by computing: (1) the number of flood days per year; (2) the number of flood episodes in the period under consideration; (3) the duration; (4) the flood volume; (5) the flood peak. For the selected thresholds (the double and triple long-term mean daily streamflow, 0.66 cm and 0.98 cm, respectively), the responses of these five parameters were simulated for 15 years and 18 alternative climates (15 HYPO, 2 GISS and base case–historical conditions). The mean values over a period of 15 years of parameters (1), (3), (4) and (5), and the value of parameter (2), in the form of real value histograms and per cent changes, are plotted in Figs 2–6 for both thresholds. An interpretation of these figures is given below.

3.1. Flood days per year

The mean number of flood days per year for both thresholds and all alternative climates is presented in Fig. 2(a), Fig. 2(b) and Fig. 2(c). There was a significantly smaller number of flood days than that of the base case for reduced precipitation HYPO climates for both thresholds. The flood days were more than those of the base case for increased precipitation HYPO climates and the GISS(t,p) case for both thresholds, as well as for the GISS(t,0) case for the upper threshold. The unchanged precipitation HYPO cases for both thresholds and the GISS(t,0) case for the lower threshold did not influence substantially the occurrences of flood days. Whereas the precipitation increase raised the number of flood days for both thresholds, the temperature increase left almost unaffected this number for reduced precipitation climates. In addition, the temperature increase decreased the number of flood days for increased precipitation climates for the lower threshold and increased it slightly for increased precipitation climates for the upper threshold. Furthermore, the lower threshold showed a larger number of flood days than the upper one, whereas the latter showed the greatest changes in the number of flood days.

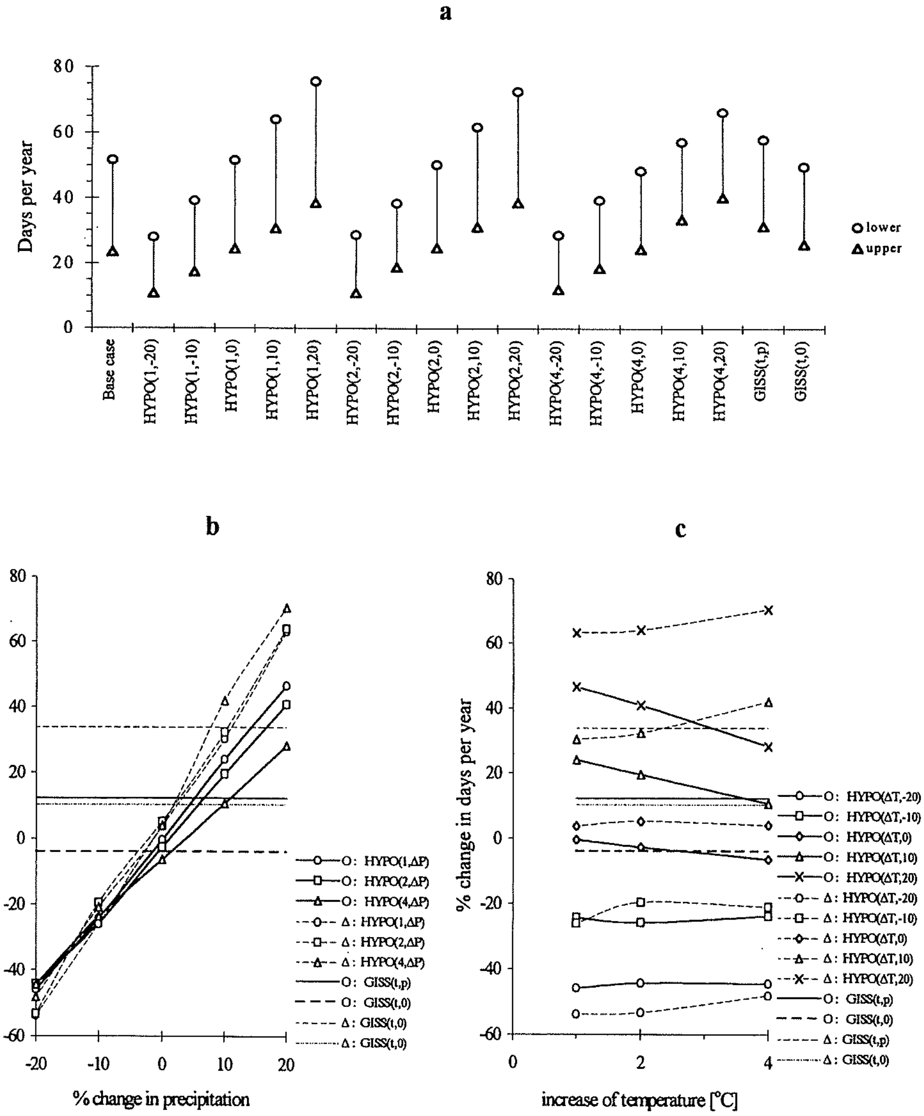

Fig. 2. Mean number of flood days per year of the Achellos river at the Mesochora catchment outfall for the HYPO, GISS and base case climate scenarios, for both the lower (O) and the upper (Δ) thresholds. (a) Histograms of real values; (b) changes vs. precipitation changes; (c) changes vs. temperature increases.

3.2. Episodes

Fig. 3(a), Fig. 3(b) and Fig. 3(c) indicate fewer flood episodes than those of the base case for reduced and unchanged precipitation HYPO cases for both thresholds and the GISS(t,0) case for the lower threshold. The flood episodes were slightly raised for increased precipitation HYPO climates and GISS(t,p) climate for the upper threshold,

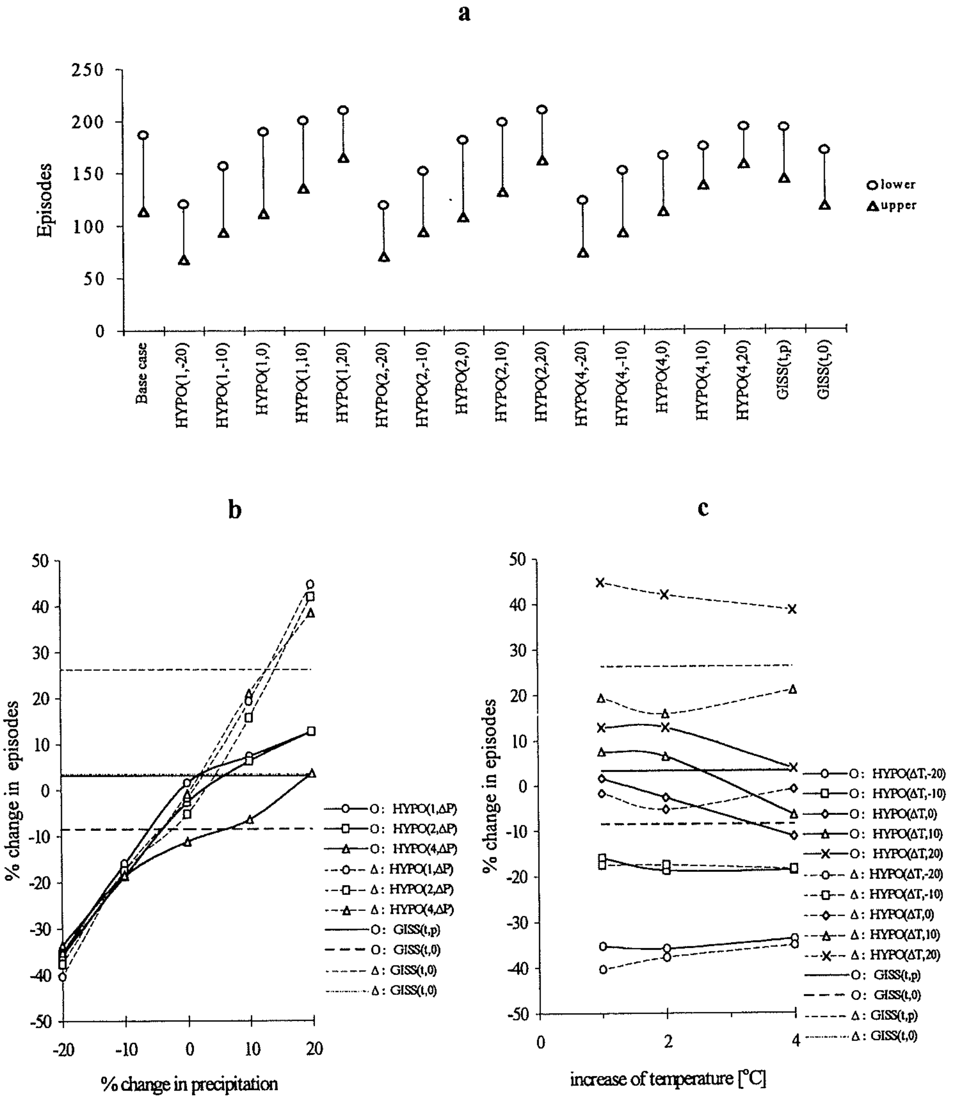

Fig. 3. Number of flood episodes of the Achellos river at the Mesochora catchment outfall for the HYPO, GISS and base case climate scenarios, for both the lower (O) and the upper (Δ) thresholds. (a) Histograms of real values; (b) changes vs. precipitation changes; (c) changes vs. temperature increases.

whereas they were significantly raised for increased precipitation HYPO climates and GISS(t,p) climate for the upper threshold. The temperature increase left almost unaffected the flood occurrences of reduced precipitation HYPO climates for both thresholds, and reduced substantially the flood occurrences for the increased precipitation HYPO climates for the lower threshold, as well as those of the maximized precipitation HYPO case for the upper threshold. The lower threshold indicated more flood episodes than the upper one, but the latter showed the greatest changes in the number of occurrences.

3.3. Duration

Fig. 4(a), Fig. 4(b) and Fig. 4(c) indicate longer flood episodes than the base case for increased precipitation HYPO climates and the two GISS cases for both thresholds. The reduced precipitation HYPO climates yielded shorter flood episodes than the base case for both thresholds. For the HYPO climates the precipitation increase yielded longer duration of the flood episodes, and the duration was even longer for the lower threshold. The

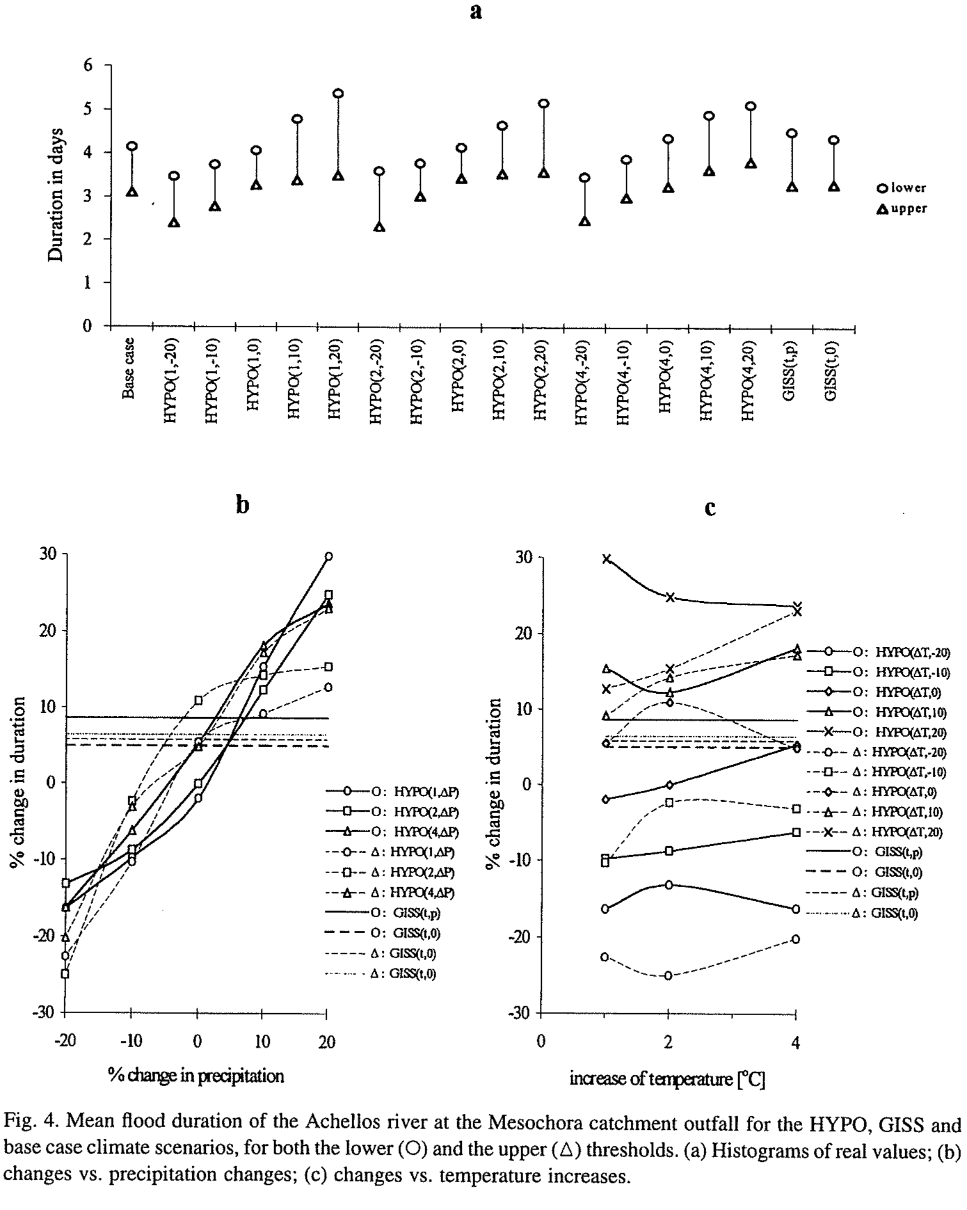

Fig. 4. Mean flood duration of the Achellos river at the Mesochora catchment outfall for the HYPO, GISS and base case climate scenarios, for both the lower (O) and the upper (Δ) thresholds. (a) Histograms of real values; (b) changes vs. precipitation changes; (c) changes vs. temperature increases.

temperature increase affected the flood duration erratically for most HYPO climates and both thresholds. Only the flood duration of the maximized precipitation HYPO case for the lower threshold indicated a shorter flood duration with respect to temperature increase. The increased precipitation HYPO cases for the upper threshold yielded a progressive increase of the flood duration with respect to temperature increase. It is apparent that the longer flood episodes correspond to the lower threshold. The longest flood episode was generated by the HYPO(1,20) case.

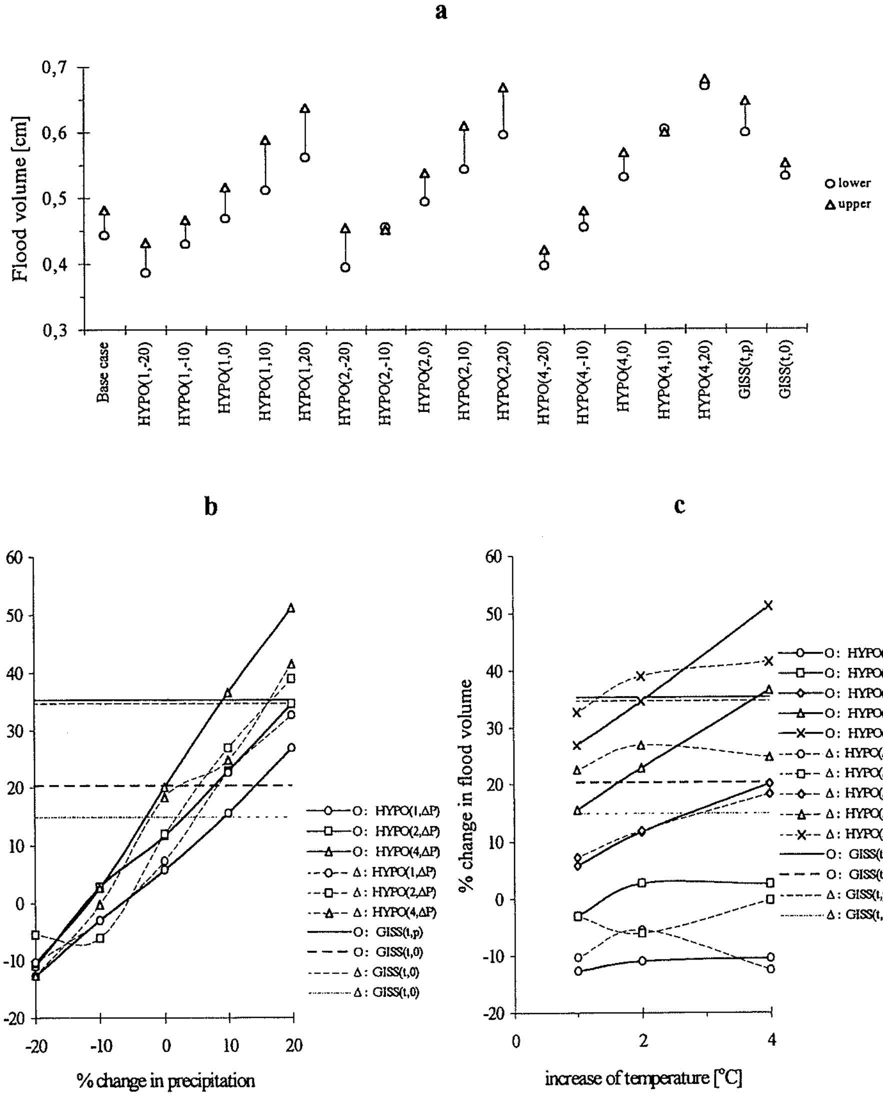

Fig. 5. Mean flood volume of the Achellos river at the Mesochora catchment outfall for the HYPO, GISS and base case climate scenarios, for both the lower (O) and the upper (Δ) thresholds. (a) Histograms of real values; (b) changes vs. precipitation changes; (c) changes vs. temperature increases.

3.4. Flood volume

Both HYPO and GISS climate cases produced increased flood volumes with respect to precipitation increase for both thresholds (Fig. 5(a), Fig. 5(b) and Fig. 5(c)). Only the reduced precipitation HYPO cases produced slightly smaller flood volumes than those of the base case for both thresholds. The temperature increase boosted the flood volumes of all HYPO precipitation changes for the lower threshold and those of the HYPO(ΔT,0) and

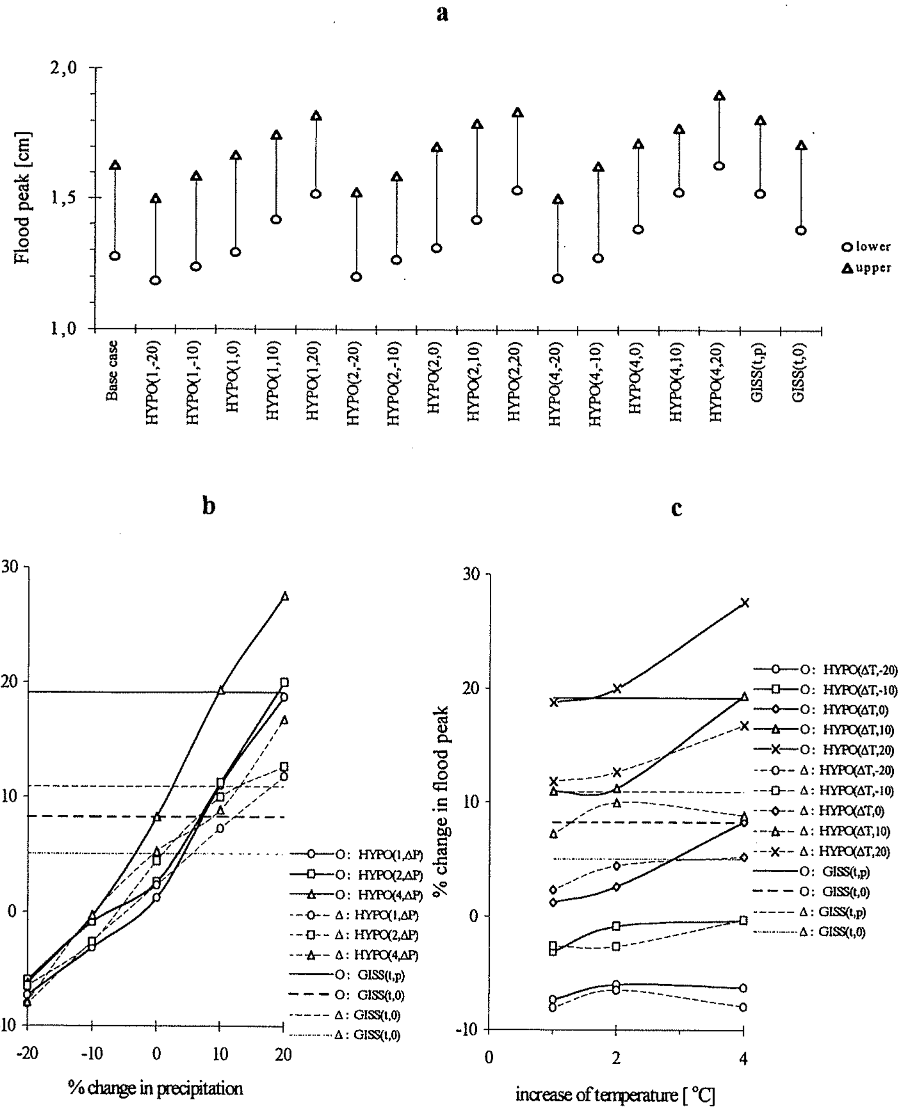

Fig. 6. Mean flood peak of the Achellos river at the Mesochora catchment outfall for the HYPO, GISS and base case climate scenarios, for both the lower (O) and the upper (Δ) thresholds. (a) Histograms of real values; (b) changes vs. precipitation changes; (c) changes vs. temperature increases.

HYPO(ΔT,20) cases for the upper threshold. The larger flood volumes occurred for the upper threshold, and of these the largest was yielded by the warmest and wettest HYPO(4,20) scenario.

3.5. Flood peak

The mean flood peak is larger than that of the base case for the increased and unchanged precipitation HYPO climates and the two GISS climates for both thresholds (Fig. 6(a), Fig. 6(b) and Fig. 6(c)). The reduced precipitation HYPO climates slightly deviated from the above behaviour. The precipitation increase boosted the flood peaks of increased precipitation HYPO climates for the lower threshold. The temperature increase progressively raised the flood peaks of all HYPO precipitation cases for the lower threshold, whereas it boosted in a less progressive manner the flood peaks of the HYPO(ΔT, − 10), HYPO(ΔT,0) and HYPO(ΔT,20) climates for the upper threshold. The flood peaks of the other two HYPO climates were inconsistently reduced with temperature increase. The upper threshold reflected the larger flood peaks, and of these the largest was yielded by the warmest and wettest HYPO(4,20) scenario.

4. Conclusions

From the present study it is concluded that the flood events, examined in terms of occurrences in annual and selected period, duration and magnitude, are primarily dominated by precipitation changes and secondarily by temperature increase, which are both simulated through hypothetical and GISS climates. Despite the secondary role of temperature increase, it caused the flood events to respond inconsistently between the two thresholds, particularly for the reduced precipitation climates and for the upper threshold, which decribes the most extreme floods. This complex behaviour could be due to the lack of a robust representation of flood flows by the models (Gan and Burges, 1990a,b; Panagoulia, 1992a), the uniform application of climate change, and mostly to the precipitation arrival process (i.e. the structure of wet and dry day sequences), which was held constant for all climate scenarios. However, we see the primary value of this study not in terms of the specific simulation results but rather for the insight it provides into possible manifestations of climate change in flood events and the relation between flood occurrences and climate. The reliable prediction of flood sequences under changing conditions is a major unanswered question that should be examined in future studies. Large projects (EPOCH, ECHIVA, IGBP, etc.) which study the coupling of climate, hydrology and ecosystem are closely related to such issues. A further area of great importance should be the statistical analyses of the defined flood event parameters, such as randomness, correlation and cross-correlation tests, as well as testing of distribution functions, under changing conditions. Having considered the preliminary nature of the study and the limitations imposed by the assumptions made, the following general conclusions can be drawn:

1. The HYPO and the GISS climate change scenarios displayed similar patterns of the flood event parameter behaviour.

2. The increased precipitation climates resulted in more flood days, which decreased progressively as the temperature increased for the lower threshold, and increased progressively as the temperature increased for the upper threshold (extreme floods). The number of flood episodes increased in the climates with increased precipitation, whereas the increased temperature decreased the flood occurrences of the lower threshold and affected randomly those of the upper threshold. The lower threshold showed more flood occurrences than the upper one, but the latter yielded the largest changes in these occurrences.
3. The increased precipitation scenarios yielded longer flood events despite the erratic behaviour of the occurrence duration with temperature increases for most climates. Only the maximized precipitation climate yielded a clear duration reduction with temperature increase for the lower threshold and a duration increase for the upper threshold.
4. All the climate cases generated larger flood volumes and peaks with precipitation increase, which were boosted with temperature increase for the increased precipitation climates and lower threshold. For the upper threshold, the increased temperature climates boosted the flood volumes and peaks only for the wettest scenario. The flood volumes and peaks of the upper threshold are significantly larger than those of the lower one.
5. Significant differences in numerical results among climate cases occurred, owing to the wide range of the climate variable changes. However, the combination of higher and frequent floods could lead to greater risks of inundation and possible damage of structures. Furthermore, the winter swelling of the streamflow could increase erosion of the river bed and banks and hence modify the river profile. In such critical cases a more robust design of water works could be needed.

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