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TEMPORAL SCALE EFFECTS ON MODELLED CATCHMENT HYDROLOGICAL PROCESSES IN RESPECT OF GLOBAL CLIMATE CHANGE

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ABSTRACT

The effects of temporal scale on catchment modelled runoff and soil moisture were analyzed in respect of global climate change. Two approaches with different time resolutions were adopted for the same catchment size (the Mesochora catchment in Central Greece). The first approach was a monthly water balance model and the second one was the coupling of the snowmelt and the soil moisture accounting models of the US National Weather Service operated at six-hourly (or daily) time steps. The models with finer time resolution produced milder hydrological responses (no large reductions in summer, no large increases in winter) compared to the responces of temporally larger-scaled models.

ΠΕΡΙΛΗΨΗ

Εξετάζουμε την επίδραση της χρονικής κλίμακας στην προσομοίωση της απορροής και εδαφικής υγρασίας λεκάνης σε σχέση με την παγκόσμια κλιματική αλλαγή. Υιοθετήθηκαν δύο, ήδη εφαρμοσμένες, τεχνικές (μεθοδολογίες) με διαφορετικό βήμα χρονικής ανάλυσης για το ίδιο μέγεθος λεκάνης (τη λεκάνη της Μεσοχώρας στην Κεντρική Ελλάδα). Η πρώτη τεχνική είναι αυτή του μηνιαίου υδατικού ισοζυγίου. Η δεύτερη αποτελεί σύζευξη των προσομοιωμάτων τήξης χιονιού και εδαφικής υγρασίας της Εθνικής Μετεωρολογικής Υπηρεσίας των ΗΠΑ που εφαρμόστηκαν με εξάωρο και ημερήσιο χρονικό βήμα αντίστοιχα. Η προσομοίωση με το μικρότερο χρονικό βήμα ανάλυσης παρήγαγε ηπιότερες υδρολογικές αποκρίσεις (όχι μεγάλες μειώσεις το θέρος, όχι μεγάλες αυξήσεις τον χειμώνα) σε σύγκριση με εκείνες της προσομοίωσης με το μεγαλύτερο βήμα.

INTRODUCTION

While physical models are appropriate as regards their structure for investigating the sensitivity of water resources to climate processes, their implementation poses the main problem relating to the different scales of hydrological processes. Depending on the space and time scale of a hydrological investigation, different models and modelling approaches may be applied. If the fundamental equations of mass, energy and momentum conservation are applied to the modelling of the hydrological land-surface processes, they can only conserve a real-world validity on a micro- and meso-spatial scale (for reasons of continuity, homogeneity, etc) in relation to hourly-and daily temporal scale (Becker & Nemec 1987, Sunada 1993).

The requirement of space-time linkage on the appropriate scale is because the meteorological-hydrological processes (e.g. rainfall-runoff) are highly nonlinear, while subprocesses such as infiltration and evapotranspiration, which play major roles in determining the runoff yield of a catchment, depend strongly on the storage and movement of water within the soil column during storms, as well as the soil moisture condition at the onset of storms (Panagoulia 1991, 1992a).

This paper reflects the importance of the appropriate space-time scale connection in hydrological modelling when the catchment responses to global climate changes are to be interpreted. For this purpose, two modelling approaches with different time resolution were considered for the same catchment. The first approach was a monthly water balance model used by Mimikou et al (1991) and the second one was the daily (or six-hourly) US National Weather Service (US NWS) snowmelt and rainfall-runoff models applied by Panagoulia (1991, 1992a,b, 1993). The hydrological responses to hypothetical and GISS-modelled climate changes for both modelling approaches are presented on a monthly basis (GISS stands for Goddard Institute for Space Studies).

HYDROLOGICAL DESIGN OF DIFFERENT APROACHES

The Mesochora catchment of the Acheloos River in Central Greece has been selected by Mimikou et al (1991), as well as Panagoulia (1990, 1991, 1992a, 1993) for an analysis of the hydrological responses to global climate changes due to the partial diversion of the river for irrigation and hydropower purposes. The network of meteorological stations (precipitation, temperature, sunshine, humidity and wind gauge stations) is relatively dense, but missing daily values, particularly in precipitation and min-and-max temperature time series for the 15-year study period (1972-1986), were noticed.

The catchment area is about 633 km^2 belonging to catchment space scale (100 - 1000 km^2, Becker & Nemec 1987, Lettenmaier & Gan 1990) and its hydrology is controlled by snowfall and snowmelt due to its high mean elevation (1390m). A detailed description of the catchment has been presented by Panagoulia (1992b).

For this catchment we summarize the methodologies used by the aforesaid authors, as well as their model calibration procedures for historical and altered climate inputs.

Mimikou et al (1991) used a monthly water balance model with a first order memory (Thornthwaite & Mather 1955, 1957) to simulate the surface runoff and soil moisture of the Mesochora catchment. The model included a snowmelt variable determined empirically according to monthly average temperature. Main inputs to the model were the monthly precipitation and temperature averaged over the catchment, as well the monthly evapotranspiration which was computed by the Blaney-Criddle method. The calibration period was 15 hydrological years (1971/72 - 1985/86). Regarding the calibration accuracy, the Nash parameter *NTD* (Nash & Sutcliffe 1970) was used for each year. The average value of the Nash criterion for the study period was 0,864 (on maximum value of 1,0). For detailed description of the model and its calibration, see Mimikou et al (1991).

The methodology of clearly conceptual simulation was adopted by Panagoulia (1991, 1992a,b, 1993) to represent the detailed hydrological regime of the Mesochora catchment. Two hydrological models were used: the *snow accumulation and ablation model* (Anderson 1973) and the *soil moisture accounting model* (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 runoff model accounts for the flux of soil moisture between five conceptual storages zones. Although it is not possible to relate the contents of the individual soil moisture zones directly to physical parameters, the sum of all the soil moisture contents is expected to correspond to moisture storage in the soil column (Lettenmaier & Gan 1990, Gan & Burges 1990). Based on this consideration we compare herebelow the soil moisture estimated from the water balance model and the cumulative soil moisture from the five conceptual zone contents.

The runoff model accepts as inputs the snowmelt model output "daily rain plus melt" and long-term average monthly potential evapotranspiration *(PET)* which is disaggregated by the model to daily increments. In this study the *PET* was estimated through the Penman method on monthly basis. For better performance of the snowmelt models, the catchment was divided into three elevation zones and the daily rain plus melt was averaged over the elevation zone areas. The models were manually calibrated over the 15-year period (1972-1986) through a trial-and-error approach, which was carried out concurrently for both models. Details of the development, calibration and statistical verification of the models are presented by Panagoulia (1992b).

In order to compare the calibration accuracy between the two different approaches we also computed the *NTD* parameter criterion for the series simulated through US NWS models. The aforesaid efficiency measure took the mean value 0,872 (see Appendix) which shows that the US NWS models are *better calibrated*. The historical input data for both approaches were adjusted to reflect the altered climates simulated through, primo, fifteen combined hypothetical scenarios of 1, 2, 4°C temperature increases (denoted by ΔT), and secundo 0, ±10, ±20% precipitation changes (denoted by ΔP). Yet, GISS-predicted monthly precipitation and temperature changes were applied to the historical inputs of US NWS models (Panagoulia 1992a). The GISS mean monthly temperature increase was 3,94°C, while precipitation rose by 8,3%, both values approximating the 4°C temperature increase and 10% precipitation increment of hypothetical scenarios. Therefore, the GISS monthly changes scenario (as better represented) will be also used as a comparative measure during the results analysis.

For the conceptual simulation only, the potential evapotranspiration was adjusted for both hypothetical and GISS-predicted monthly precipitation and temperature changes (Panagoulia 1992a).

HYDROLOGICAL PROCESSES: TEMPORAL SCALE EFFECTS

Eight catchment hydrological processes were simulated through the US NWS models for 15 years and 17 alternative climates (one is the base case and the other is the GISS condition) on daily and monthly basis. These processes are: average snow water equivalent, runoff, evapotranspiration and soil moisture storages in five model zones (the cumulative soil moisture will be used in the analysis of results). The water balance model simulated the monthly catchment runoff and soil moisture for 15 years and 16 alternative climates. For comparison reasons we restrict the analysis of results on monthly mean catchment runoff and monthly mean catchment soil moisture.

Runoff

Table 1 shows the monthly changes (in percent) of Mesochora catchment runoff for all 16 climate change scenarios and both modelling approaches (the values in the shaded areas were generated through the water balance method). The analysis is expressed according to the associated scenarios of $\Delta T = 1, 2, 4$°C.

The combined scenarios of $\Delta T = 1$°C and all ΔP changes produced larger reductions and lesser increases in runoff during the wet period (January-February-March) for the US NWS models. During the dry period (June to September) the same climate cases yielded a reversal profile (lesser reductions and larger increases in runoff) for the aforesaid models. In the transition period from winter to summer and no significant trend in runoff changes can be distinguished between the two modelling approaches.

The associated scenario of $\Delta T = 2$°C with all ΔP changes generated generally the same image of runoff changes as that of $\Delta T = 1$°C. A certain difference is noticed in spring changes which tend to make longer the wet period's profile (larger reductions, lesser increases).

The warmest scenario of $\Delta T = 4$°C linked to all ΔP changes produced the most clear results. During the year, three periods with different change profiles were distinguished: the wet period (January to May) with larger runoff reductions and lesser runoff increases for the US NWS models, the dry period (June to September) with larger runoff increases and lesser runoff reductions for the same models and the autumn period which had similar runoff changes image as that of the wet period. Also, Table 1 reflects the fact that the runoff changes simulated through US NWS models for $\Delta T = 4$°C and $\Delta P = 10\%$ are approximated from runoff changes yielded by the same models and GISS monthly climate cases.

Soil Moisture

The monthly changes (in percent) of Mesochora catchment soil moisture for all 16 climate changes scenarios and both modelling approaches are presented in Table 2 (the values in the shaded areas were obtained through the water balance method).

For each modelling approach the fifteen combined scenarios of all ΔT increases and all ΔP precipitation changes produced similar interannual profiles of soil moisture changes. During the wet period (January to April) all the combined climate changes yielded very similar (almost to zero) soil moisture changes for both approaches. In the dry period (May to September) the US NWS models generated significantly lesser soil moisture reductions than those of water balance model, which in August was a full 100% for the combined driest scenario ($\Delta T = 4$°C, all ΔP). During the autumn period (October to December) the US NWS models did not reflect significant changes (reductions and increases) in soil moisture than those of the water balance method. Furthermore, Table 2 reflects the fact that the soil moisture changes simulated through US NWS models for $\Delta T = 4$°C and $\Delta P = +10\%$ are approximated from soil moisture changes yielded by the same models and GISS cases.

CONCLUSIONS

The most significant result of the study was that the hydrological responses of a catchment scale area to global climate changes were strictly related to temporal scale inputs and operation. Although the hypothetical climate changes were roughly represented, the adoption of finer time resolution in hydrological modelling produced:

TABLE 1. Percent change in monthly runoff simulated through (a) water balance model (shaded areas) and (b) US NWS rainfall - runoff model for fifteen hypothetical (ΔT, ΔP) and GISS-predicted climate changes.

ΔT	ΔP	JANUARY		FEBRUARY		MARCH		APRIL		MAY		JUNE		JULY		AUGUST		SEPTEMBER		OCTOBER		NOVEBER		DECEBER	
°C	%	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
1	-20	-21	-18	-14	-16	-16	-23	-30	-30	-51	-55	-48	-38	-50	-33	-49	-34	-39	-39	-33	-37	-32	-36	-34	-31
1	-10	-3	-3	1	-2	-4	-12	-18	-18	-41	-43	-37	-28	-39	-24	-39	-24	-29	-25	-20	-22	-18	-20	-14	-13
1	0	14	12	16	11	9	-1	-6	-6	-30	-29	-26	-18	-28	-15	-27	-14	-18	-10	-3	-4	-2	-1	4	5
1	10	31	27	31	23	21	10	6	6	-17	-16	-14	-7	-15	-5	-15	-4	-6	6	14	15	19	19	23	23
1	20	47	40	45	35	33	21	18	18	-5	-1	-1	5	-2	4	-2	7	6	24	32	36	44	41	40	42
2	-20	-11	-12	-2	-11	-17	-24	-43	-40	-67	-66	-56	-46	-59	-42	-58	-42	-45	-44	-34	-40	-33	-38	-34	-30
2	-10	8	6	15	3	-3	-12	-32	-27	-50	-59	-47	-37	-50	-33	-49	-33	-36	-31	-22	-24	-20	-22	-14	-11
2	0	27	22	31	17	11	-1	-21	-15	-41	-50	-38	-28	-41	-25	-40	-24	-26	-18	-5	-7	-4	-4	5	8
2	10	45	38	48	30	24	11	-10	-2	-32	-40	-29	-19	-32	-17	-31	-16	-17	-3	12	12	16	16	23	27
2	20	63	53	63	43	37	22	1	10	-23	-30	-19	-9	-22	-9	-21	-6	-7	14	29	32	39	37	41	46
4	-20	-8	-6	3	-6	-31	-33	-51	-57	-52	-73	-62	-56	-65	-52	-64	-52	-49	-51	-34	-44	-36	-42	-38	-33
4	-10	14	14	21	10	-17	-21	-41	-48	-51	-67	-54	-48	-58	-44	-56	-44	-40	-39	-24	-29	-22	-26	-19	-14
4	0	34	32	39	26	-4	-9	-32	-38	-48	-61	-46	-40	-50	-37	-49	-36	-32	-27	-8	-12	-7	-9	1	6
4	10	53	51	56	41	10	3	-22	-28	-40	-55	-38	-32	-41	-30	-40	-29	-23	-13	8	6	10	10	20	26
4	20	72	69	73	56	23	15	-12	-19	-31	-48	-29	-24	-33	-23	-31	-21	-14	2	25	25	32	31	37	46
GISS			44		18		-3		-31		-58		-37		-32		-32		-27		68		42		40

TABLE 2. Percent change in monthly soil moisture simulated through (a) water balance model (shaded areas) and (b) US NWS rainfall - runoff model for fifteen hypothetical (ΔT, ΔP) and GISS-predicted climate changes.

ΔT	ΔP	JANUARY		FEBRUARY		MARCH		APRIL		MAY		JUNE		JULY		AUGUST		SEPTEMBER		OCTOBER		NOVEBER		DECEBER	
°C	%	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
1	-20	0	-9	0	-5	-1	-4	-1	-6	-10	-8	-28	-17	-66	-19	-100	-22	-66	-25	-31	-25	-20	-23	-2	-17
1	-10	0	-4	0	-1	-1	-1	-1	-3	-6	-5	-21	-12	-53	-14	-93	-16	-49	-17	-19	-17	-11	-13	-1	-9
1	0	0	1	0	2	-1	2	-1	0	-4	-2	-15	-8	-40	-8	-67	-9	-31	-9	-8	-8	-4	-4	0	-1
1	10	0	4	0	5	0	4	0	2	-2	1	-10	-4	-23	-3	-39	-3	-4	-2	4	1	1	5	1	6
1	20	0	8	0	7	0	6	0	4	-1	3	-5	0	-7	2	-3	3	30	6	18	11	4	14	1	12
2	-20	0	-9	0	-4	-1	-3	-3	-6	-16	-12	-40	-21	-85	-25	-100	-29	-70	-31	-35	-31	-22	-26	-2	-19
2	-10	0	-4	0	0	-1	0	-2	-3	-12	-8	-33	-17	-71	-19	-100	-22	-54	-24	-22	-22	-13	-16	-1	-11
2	0	0	1	0	3	-1	2	-2	-1	-10	-5	-27	-13	-56	-14	-96	-16	-37	-17	-12	-14	-6	-7	0	-3
2	10	0	5	0	6	-1	5	-1	1	-7	-3	-20	-9	-41	-9	-64	-10	-18	-9	-1	-5	0	2	1	4
2	20	0	8	0	9	0	7	0	3	-5	0	-15	-6	-27	-5	-37	-4	12	-2	13	4	3	10	1	11
4	-20	0	-11	0	-4	-1	-3	-5	-10	-21	-18	-54	-27	-97	-32	-100	-37	-77	-40	-41	-38	-26	-30	-3	-22
4	-10	0	-5	0	0	-1	0	-4	-7	-17	-14	-46	-23	-92	-27	-100	-31	-64	-33	-28	-30	-16	-21	-1	-14
4	0	0	-1	0	4	-1	3	-3	-4	-14	-11	-39	-19	-84	-22	-100	-25	-48	-27	-17	-22	-8	-13	0	-6
4	10	0	4	0	7	-1	6	-2	-2	-11	-9	-33	-15	-71	-17	-100	-20	-31	-20	-7	-14	-2	-4	0	1
4	20	0	7	0	10	-1	8	-2	0	-9	-7	-28	-12	-57	-13	-90	-14	-14	-13	3	-6	1	5	1	8
GISS			7		7		3		-3		-10		-17		-20		-20		-21		-20		14		11

1) Larger reductions and lesser increases in winter runoff
2) Lesser reductions and larger increases in summer runoff
3) Separation trend of interannual runoff image in two distinct situations as the temperature was increasing: one is described by case (1) and the other by case (2).
4) Lesser reductions in late spring and summer soil moisture and none significant change in winter soil moisture.

The above cited conclusions reflect the fact that the finer temporal scale can yield a milder hydrological regime (no large reductions in summer, no large increases in winter) than that of larger scales under global climate change conditions.

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APPENDIX

MONTHLY RUNOFF ERROR [cm]

year	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	*NTD*
1972	-3,26	-2,36	-3,82	,67	-4,21	-0,32	-0,31	,05	-0,07	4,15	2,52	1,16	,8448
1973	,36	-5,66	1,02	-0,11	2,75	-0,68	,59	,51	,19	,67	,36	-1,54	,9358
1974	1,39	2,30	-0,05	,41	-0,45	-0,25	1,11	,81	1,24	-1,84	-1,65	1,76	,9693
1975	1,18	4,41	,79	-0,87	-4,86	-1,08	-0,62	-0,56	-0,63	,06	,54	-0,02	,7527
1976	3,84	4,22	1,04	2,17	-5,10	-0,69	,00	-0,08	-0,18	-0,33	1,00	6,72	,7572
1977	1,21	2,60	4,26	1,31	-1,77	,00	-0,25	-0,20	,69	-0,02	4,12	-2,46	,7340
1978	,91	-2,39	,98	-1,36	3,71	,20	1,04	,28	2,42	-0,39	-0,76	-4,14	,9490
1979	-9,26	,73	4,08	-3,59	3,27	1,79	,62	,76	,12	1,61	,45	2,43	,9194
1980	-2,59	3,12	2,97	-2,54	-1,16	-3,40	,17	,88	,30	1,88	-3,17	2,36	,9409
1981	1,60	-2,88	-7,65	-3,05	-1,70	-1,11	,49	1,01	,18	1,66	,36	-9,47	,9141
1982	-0,19	3,31	4,20	-2,53	2,18	-0,39	,39	,13	,33	,54	2,22	-0,56	,9530
1983	2,73	2,86	,29	-0,96	-2,49	-2,54	-2,08	-0,48	-0,54	-0,28	-1,92	-1,27	,8331
1984	-6,57	3,72	4,51	1,58	,31	-1,36	,96	,46	,55	-0,51	-0,34	,43	,9087
1985	2,73	2,58	7,49	4,80	-0,74	-0,47	,73	,74	,23	,78	-2,92	,78	,8320
1986	9,06	4,27	-0,86	5,93	-2,07	-1,47	-0,20	,17	-0,16	1,00	-0,37	-1,11	,8277
mean	3,15	20,84	19,26	1,85	-12,34	-11,77	2,64	4,49	4,67	8,98	,45	-4,95	,8715