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IIASA Working Paper

WP-95-048

June 1995

Kaczmarek, Z., Niestepski, M. and Osuch, M. (1995) Climate Change Impact on Water Availability and Use. IIASA Working Paper. WP-95-048 Copyright © 1995 by the author(s). http://pure.iiasa.ac.at/4544/

Working Paper

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Introduction

An assessment of potential water resources impacts associated with climate change, and the evaluation of possible water management strategies deserves an increased attention of the world's community. Although "No global crisis is likely to shake the world the way the energy crisis of the seventieth did" [Sandra Postel, 1992], the global and regional food supply and economic development may be affected by climate-induced changes in water availability in crop-producing regions and in large urban agglomerations. The assessment of climate change impacts on water resources management attempts to portray how the range of possible changes in temperature, precipitation and runoff is likely to affect the range of water uses and their socio-economic implications.

The biggest current pressure on water resources is caused by high population increase in some parts of the world, and by progressing concentration of economic activities in urban areas. Following the concept of a *water stress index* of Falkenmark & Widstrand (1992), based on an approximate minimum level of per capita water requirement, Engelman & Roy (1993) suggest that while in the year 1990 about 20 countries with population of 335 million experienced chronic water scarcity (less than 1,000 m^3/capita yearly), about 30 countries with 880 million inhabitants may fall into this category by 2025 only because of the expected population growth. About 65% of those people live in Africa, and 33% in Asia. This predictions do not take, however, into account possible consequences of climate change on water supply. The aim of this paper is to evaluate, for selected countries in the Euro-Asiatic region, the possible joint implications of population growth and climate change on per capita water availability in the years 2020 and 2050.

The fundamental questions are: what may be an impact of expected climatic perturbations on *regional* water supply and demand, and what kind of adaptive measures may be applied to cope with possible negative consequences of these perturbations? The answer is not simple because of uncertainties still accompanying the climate change issue. In the framework of the IPCC activity (Kaczmarek *et al*, 1995) an analysis of vulnerability of water systems in a number of countries to changes in climate was done based on three scenarios. For example, in the South African Republic the current available water supply was estimated to be 1,320 [m^3/year,cap]. The following values were obtained for the mid of next century due to demographic and climatic processes, based on three transient climate scenarios:

• no climate change:	540 m^3/year, cap
• GFDL model:	500 "-"
• Hadley-Center model:	150 "-"
• Max Planck-Institute model:	330 "-" .

The differentiated results demonstrate how difficult would be to initiate adaptation actions based on the currently available methods of climate predictions. At least for the coming decades the non-climatic factors will probably dictate what kind of measures should be undertaken to secure sustainable water supply. Climate change predictions will, however, add a new highly uncertain component to the challenge of managing water resources.

Not only hydrologic processes, but also water demands may be affected by changed climatic characteristics. Few reported in literature studies on domestic water use lead to conclusion, that *per capita* water requirements will probably change insignificantly in a warmer climate. Also amount of water needed for technological processes is rather insensitive to changes in temperature and precipitation, with the exception of increased demand of water for cooling purposes. Much more serious problems may arise in agriculture.

At present about 250 million hectares of land is irrigated, roughly half of it in Asia. As world population will grew during the next century, the share of irrigated croplands may increase to guarantee the global food security. Moreover, some recent studies indicate that for 1^{0}C increase of air temperature one may expect 12 to 25 percent increase in spray irrigation demands. Another case study, based on a modified Thornthwaite water balance model, shows that for a broad range of prescribed temperature rise and changes in precipitation, annual irrigation demand increases even with a 20 percent increase in precipitation. On a global scale the amount of water needed for agriculture may easily more than double by middle of the next century. This, in turn, may largely extend number of countries suffering chronic water scarcity. It is important to emphasize that the ultimate effect of global warming on irrigation water demands depends significantly on changes in global agricultural policy, food prices and more equitable distribution of food among nations.

The key problem in responding to possible consequences of man-induced global warming is to decide *when* and *what kind* of adaptive measures should be undertaken to assure water supply reliability. Concrete decisions will depend on local hydrologic conditions, economic situation, and national priorities. There is no reason to apply sophisticated decision making techniques for river systems abundant of water, when the results of any climate impact assessment will be trivial. On the other hand even limited climatic disturbances may lead to serious worsening of water situation in arid and semi arid regions.

Three approaches are possible in dealing with adaptation of water systems to changed climatic conditions. Firstly, a *"wait and see"* or *"business as usual"* strategy, what means to postpone decisions on adaptation measures until more reliable information on global atmospheric processes will become available. Existing water schemes remain unchanged, and the new ones will be planned and implemented according to standard analytical procedures. Because in case of large hydraulic schemes time needed for planning and implementation is usually very long, this approach may cause undesirable delays in taking necessary decisions.

Secondly, a *"minimum regret"* approach, when decisions will be taken to solve current problems in the best possible way, and at the same time to prepare water systems to possible changes and shocks by making them more robust, resilient and flexible for any future. Finally, the third approach assumes that optimality rules should be applied to a range of climatic scenarios. Final decisions may be taken by comparing costs, benefits and losses for each scenario, and on somewhat subjective interpretation of results.

Sensitivity of Water Availability to Climate Change

The growing interest in possible consequences of man-induced climate change on regional water resources has given rise to a wealth of studies on the sensitivity of water balance to climatic variables (Kaczmarek, 1990; Kaczmarek *et al*, 1995; Lang *et al*, 1995;

Schaake, 1990). Assuming that available regional water supply is represented by catchment runoff R dependent on precipitation P and temperature T, the impact of climate change on water resources may be approximated by:

$$\Delta R = \frac{\partial R}{\partial P} * \Delta P + \frac{\partial R}{\partial T} * \Delta T \tag{1}$$

where the partial derivatives characterize the sensitivity parameters. For example, Figures 1 and 2 show the sensitivities of mean annual runoff to changes in mean annual temperature and annual sum of precipitation, based on Turc (1954) relation between runoff and these climatic characteristics:

$$R = P * \left[1 - \frac{1}{\sqrt{1 + \frac{P^2}{PET^2}}} \right] \tag{2}$$

where the approximate relation among annual sum of potential evapotranspiration and air temperature has the form:

$$PET = 300 + 25T + 0.05T^3 \tag{3}$$

Although equations 2 and 3 were tested for river catchments with differentiated climatic conditions, their empirical nature should be taken into account when evaluating the results. In particular it seems that the sensitivity of Turc's potential evapotranspiration is slightly higher than e.g. in case of Penman's PET.

Comparing results shown on Figures 1 and 2 with runoff values responding to the same values of T and P, it can be seen that water availability in arid regions with high temperature and low precipitation may be more affected by climate change than river basins abundant in water. It should be added that very often the climate sensitive arid and semi-arid regions are also densely populated with a tendency for high population growth. Such regions may become particularly vulnerable to change in precipitation and potential evapotranspiration.

Future Water Availability in Selected Countries

Twenty-six countries (see Table 1) from regions defined by IIASA's *Environmentally Compatible Energy Strategies* Project were chosen for the purpose of the Study. The criteria for selection are mostly based on the present-day (year 1990) per capita water availability. In each region countries with relatively scarce water resources were analyzed, and those were chosen for which reliable hydrologic data are obtainable. For example, for the whole WEU region more than 5,000 m^3 of water per capita is available during an average year, while for the nine selected countries the respective figure is only 2790 m^3/cap. But in some regions (e.g. in Pacific Asia) the present-day water resources are generally much higher than required to meet domestic, agricultural and industrial demands.

Water resources for countries used in the Study were estimated on the basis of various sources (e.g. Engelman & LeRoy, 1993; Lvovitch, 1974). From 20 to 40 per cent of "transit" runoff was added to resources originated on the territory of a given country. Population data for year 2020 are based on UN Medium Projection (Engelman & LeRoy, 1993), and for the year 2050 on the IPCC socio-economic predictions of regional trends of the population growth.

Three transient-type Global Circulation Models (GCMs) were applied to assess changes in air temperature and precipitation patterns for the years 2020 and 2050, developed by:

- Geophysical Fluid Dynamic Laboratory, Princeton,
- the Hadley Centre, UK Meteorological Office, Bracknell,
- Max_Planck Institute for Meteorology, Hamburg.

Each country was divided into a certain number of grid cells, for which T (mean annual temperature) and P (annual sum of precipitation) were estimated from the IPCC climatic data. These values were used to calculate partial derivatives (sensitivity parameters) in equation (1). As the next step changes in temperature ΔT and precipitation ΔP for the years 2020 and 2050 were found for each grid cell for the above mentioned climate scenarios. Finally, change of runoff in mm per unit area was calculated for each grid cell, and after integration - in km^3 for the whole territory of the country. An example of results obtained for Ukraine (for year 2050) is shown in Table 2.

It should be stressed that expected changes in climatic and hydrologic characteristics may highly variate over the whole territory, particularly for large countries. For example, Figure 3 presents the expected runoff change in Poland, calculated by means of equation (1) for the year 2050, by using the Hadley Centre (HC) transient climate scenario. This result may be compared with the highly differentiated picture obtained for the same year for China (Figure 4) by means of GFDL scenario.

After calculating possible changes in annual runoff for each country, for selected years (2020 or 2050) and three transient climate scenarios, the per capita water availability was estimated taking into account the expected population growth. The results are summarized for individual regions in Tables 3 to 8. The following observations can be made:

(a) In some regions they differ substantially depending on the climate scenario;
(b) For the less developed parts of the world the population growth will be the decisive factor in shaping future water conditions;
(c) In some cases the perturbed climate may increase the availability of water, while in others one may expect a worsening of water management conditions.

The above emphasized conclusions are even more visible on figures 5 to 10, where a bar showing the sole impact of population growth on per capita water availability is included. It can be seen that for the CPA (Centrally Planned Asia & China) and for SAS (South Asia) all three climatic scenarios lead to improvements in meeting water demands in comparison with the "no climate change" conditions. The reason is that for the Asian continent, according to scenarios obtained for all three models considered, a significant increase of precipitation may be expected.

These conclusion are, however, based on rather simplified methodology and should therefore be taken with necessary caution. Such an uncomplicated sensitivity analysis based on equations (1) - (3), although takes into account the spatial distribution of hypothetical changes of climatic variables, is not able to reflect the temporal changes of water balance components. More complex hydrologic models, based *inter alia* on extensive data collection are needed to assess possible changes in the intraannual distribution of flood and drought periods.

How Can We Improve our Predictions

To assess the impact of climate on water resources some kind of models of hydrological processes must be used. There is a range of possible model types, from simple empirical relationships, like the Turc formula, to complex conceptual models with certain number of parameters which need to be identified by means of a calibration procedure, or eventually estimated from empirical relationships with measurable catchment properties. Conceptual hydrologic models are representations of the processes involved in the hydrological cycle, based on a particular concept how the catchment works. The physical background of such models (e.g. the mass conservation law) induces that the implied sensitivity of water balance to climate change is not as dependent on past data, as in the case of purely empirical methods.

Authors of most climate change impact studies apply conceptual hydrologic models for small or meso-scale river catchments. They are unfortunately of little value for the large scale regional analysis, mostly because of very demanding data requirements for hundreds of middle-size river basins covering the region under consideration. For example, a detailed climate impact study implemented recently in Poland by means of a conceptual model CLIRUN3 (Kaczmarek, 1993) was done for 32 river catchments, for which 40-years long series of several climatic and hydrologic variables were available.

A Concluding Remark

There are still large uncertainties that are propagated through the numerous levels of analysis as one moves from multiply CO_2 scenarios; through the comparison of different GCM outputs; transference of climatic data to runoff and other hydrologic characteristics; impacts on each water sector and water management decisions; and finally on the socioeconomic and incremental impacts of response measures. In addition, incremental impacts due exclusively to climate change should be differentiated from changes (sometimes also highly uncertain) that would occur in the absence of climate change.

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Tables

Table 1. Countries selected for analysis.

Region	Country	Area		Available water
		km^2	in km^3/year	1990 - mln
WEU	Belgium	30,500	16.9	10.0
	Cyprus	9,300	0.9	0.7
	Denmark	43,100	15.1	5.1
	France	547,100	232.0	56.4
	Germany	356,500	113.0	79.5
	Malta	300	.03	0.3
	Spain	504,800	129.0	39.0
	Turkey	779,500	172.0	56.0
	U.K.	244,100	152.0	57.4
CEU	Bulgaria	111,000		34.8
	Hungary	93,000	14.6	10.5
	Poland	312,700	56.3	38.2
FSU	Byelorussia	207,600	56.0	10.3
	Kazakhstan	2,717,300	125.0	16.7
	Ukraine	603,700		210.0
CPA	China	9,600,000	2,880.0	1153.5
	North Korea	120 000	67.0	21.8
	Vietnam	329,600	459.0	66.7
SAS	Afghanistan	652,100	75/0	16.6
	India	3,287,600	1,633.0	846.2
	Pakistan	796,100		107.0
PAO/PAS	Japan	377,800	396.0	123.5
	Malaysia	329 700	486.0	17.9
	Philippines	303 000	390.0	62.4
	South Korea	99,000	60.0	43.4
	Thailand	513,100	185.0	54.7

Table 2. Runoff changes [mm/a] in the Ukraine for three climate scenarios (year 2050).

grid	coordinates	GFDL-tr	HC-tr	MPI-tr
1	32°E - 52°N	-4.9	-51.6	-45.0
2	34°E - 52°N	2.5	-37.1	-47.1
3	24°E - 51°N	-21.0	-39.4	101.8
4	26°E - 51°N	-16.5	-46.5	98.5
5	28°E - 51°N	-8.1	-44.8	82.9
6	30°E - 51°N	-0.2	-56.8	11.8
7	32°E - 51°N	3.2	-64.8	-14.1
8	34°E - 51°N	6.2	-50.9	-20.2
9	24°E - 50°N	-37.3	-43.7	105.4
10	26°E - 50°N	-28.2	-55.6	103.6
11	28°E - 50°N	-19.3	-66.1	97.6
12	30°E - 50°N	-7.9	-75.7	47.0
13	32°E - 50°N	-7.9	-84.1	9.3
14	34°E - 50°N	-1.0	-70.3	-0.4
15	36°E - 50°N	15.0	-55.8	22.7
16	38°E - 50°N	36.4	-58.9	47.6
17	30°E - 48°N	-14.4	-108.1	113.0
18	32°E - 48°N	-10.8	-101.4	56.6
19	34°E - 48°N	-6.8	-88.6	37.1
20	36°E - 48°N	8.0	-81.2	71.7
21	38°E - 48°N	21.0	-85.3	115.3
22	40°E - 48°N	6.3	-84.4	121.0
23	34°E - 46°N	-2.8	-62.1	40.9
24	34°E - 45°N	-9.7	-69.7	34.2
average	-------	-4.1	-66.0	50.9

Remark: For the Ukraine, 1.0 mm/a corresponds to a runoff change of 0.604 km^3/a.

Table 3. Estimated per capita water availability for Western Europe (selected countries).

Country	Population [mln]			WR/c[a]	WR/c (2020)			WR/c (2050)		
	1990	2020	2050	1990	GFDL	HC	MPI	GFDL	HC	MPI
Belgium	10.0	9.9	9.9	1695	1499	1374	1440	1521	1390	1547
Cyprus	0.7	0.9	1.1	1286	787	837	1679	644	619	852
Denmark	5.1	5.1	5.1	2938	3016	3081	2343	2926	3292	2871
France	56.4	60.2	64.1	4111	3358	2607	3134	2875	2509	2965
Germany	79.5	83.2	87.2	1422	1121	1013	9854	1061	938	1344
Malta	0.3	0.4	0.5	86	69	67	79	52	52	64
Spain	39.0	40.4	41.8	3311	2988	2453	2705	1822	2202	2202
Turkey	56.0	88.3	139.2	3072	1595	986	2787	890	699	1915
U.K.	57.4	59.9	62.5	2649	2427	2468	2386	2393	2516	2192
Region	297.9	348.3	411.5	2789	2106	1680	2346	1564	1441	2027
Mean (for 3 scenarios)					2044			1677		

[a] Water resources per capita in m^3.

Table 4. Estimated per capita water availability for Central and Eastern Europe (selected countries).

Country	Population [mln]			WR/c[a]	WR/c (2020)			WR/c (2050)		
	1990	2020	2050	1990	GFDL	HC	MPI	GFDL	HC	MPI
Bulgaria	9.0	8.8	8.8	3867	3409	2545	3807	3000	2545	4659
Hungary	10.5	10.4	10.4	1390	1087	750	1385	788	760	2288
Poland	38.2	43.8	45.0	1474	1135	1005	1279	1029	978	1858
Region	57.7	63.0	64.2	1832	1444	1178	1649	1260	1157	2312
Mean (for 3 scenarios):					1424			1576		

[a] Water resources per capita in m^3.

Table 5. Estimated per capita water availability for the former Soviet Union (selected countries).

Country	Population [mln]			WR/c[a]	WR/c (2020)			WR/c (2050)		
	1990	2020	2050	1990	GFDL	HC	MPI	GFDL	HC	MPI
Byelorussia	10.3	11.4	12.1	5437	4430	4649	5079	4322	4636	4661
Kazakhstan	16.7	21.8	26.1	7485	7041	2885	7468	5870	3253	7257
Ukraine	51.8	56.7	60.3	4054	3713	2892	3524	3447	2827	3998
Region	78.8	89.5	98.4	4962	4631	3128	4898	4197	3163	4944
Mean (for 3 scenarios):					4153			4101		

[a] Water resources per capita in m^3.

Table 6. Estimated per capita water availability for centrally planned Asia and China (selected countries).

Country	Population [mln]			WR/c[a]	WR/c (2020)			WR/c (2050)		
	1990	2020	2050	1990	GFDL	HC	MPI	GFDL	HC	MPI
China	1153.5	1477.0	1767.0	2497	1986	1981	2027	1548	1779	1760
N. Korea	21.8	31.3	39.8	3073	2217	2061	2454	1668	1510	1920
Vietnam	66.7	108.0	154.4	6882	4260	4437	4400	3142	2683	2964
Region	1142.0	1616.3	1961.2	2742	2143	2147	2193	1676	1845	1858
Mean (for 3 scenarios):					2161			1793		

[a] Water resources per capita in m^3.

Table 7. Estimated per capita water availability for South Asia (selected countries).

Country	Population [mln]			WR/c[a]	WR/c (2020)			WR/c (2050)		
	1990	2020	2050	1990	GFDL	HC	MPI	GFDL	HC	MPI
Afghanistan	16.6	39.5	50.2	4518	1876	1597	1914	1420	1424	1606
India	846.2	1298.0	1553.1	1930	1340	2010	1495	1259	1420	1058
Pakistan	118.1	232.0	294.6	1050	603	813	522	461	817	427
Region	980.9	1569.5	1897.9	1870	1246	1824	1363	1140	1328	985
Mean (for 3 scenarios):					1477			1151		

[a] Water resources per capita in m^3.

Table 8. Estimated per capita water availability for Pacific Asia (selected countries).

Country	Population [mln]			WR/c[a]	WR/c (2020)			WR/c (2050)		
	1990	2020	2050	1990	GFDL	HC	MPI	GFDL	HC	MPI
Japan	123.5	126.5	129.6	3206	3564	3633	3334	3468	2941	3100
Malaysia	17.9	28.9	35.6	27151	18080	18467	16910	15121	12242	13584
Philippines	62.4	97.6	120.3	6250	4701	3313	4448	3495	2421	34734
S. Korea	43.4	49.3	53.9	1382	1227	1083	1578	1009	892	1397
Thailand	54.7	69.5	83.1	3382	3335	2196	4068	3073	590	2065
Region	301.9	371.8	422.5	5025	4638	4095	4586	4066	2852	3669
Mean (for 3 scenarios):						4440			3529	

[a] Water resources per capita in m^3.

Figures

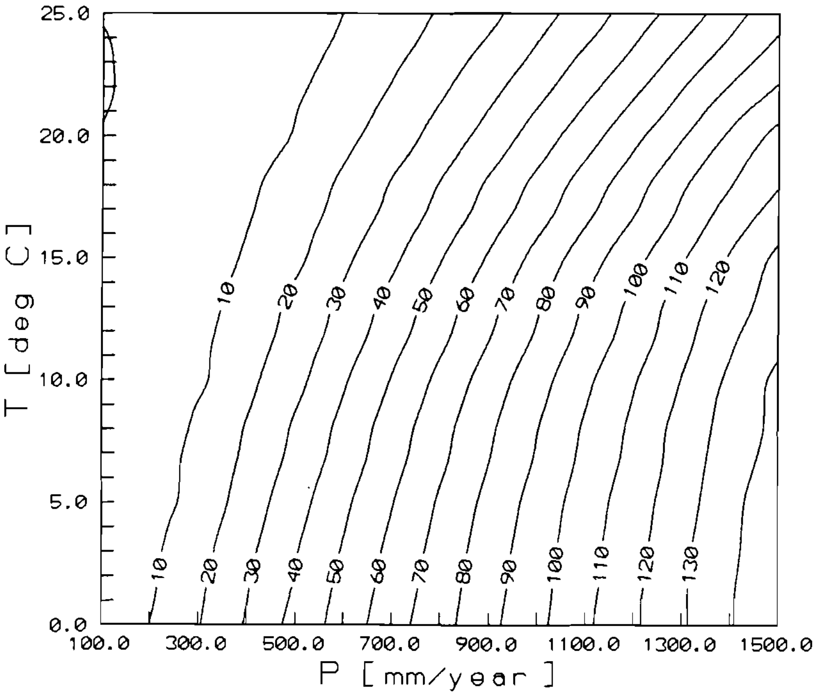

Figure 1. Runoff change [+/- mm/year] for +/-10% change of precipitation (constant air temperature).

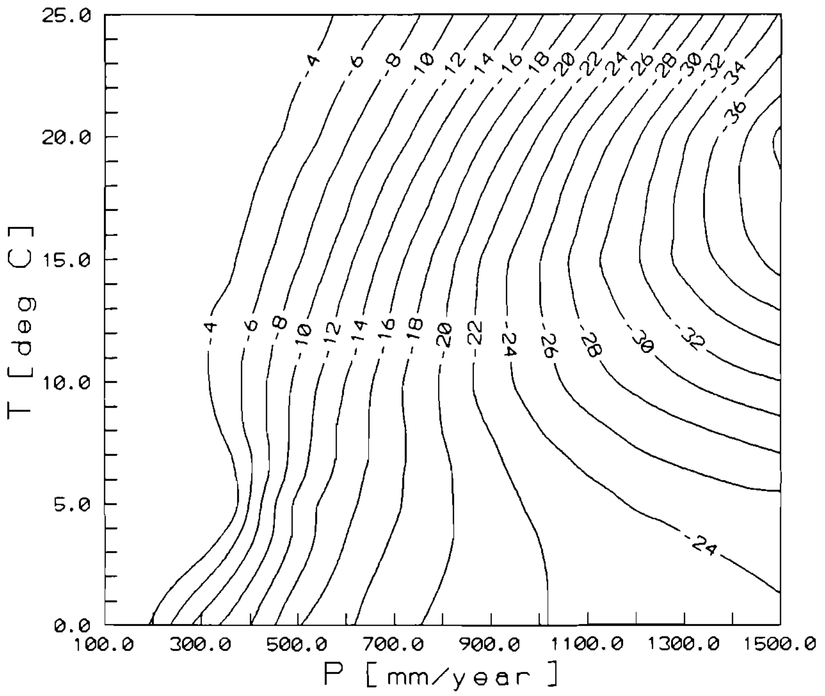

Figure 2. Runoff change [mm/year] for 1°C increase of air temperature (constant precipitation).

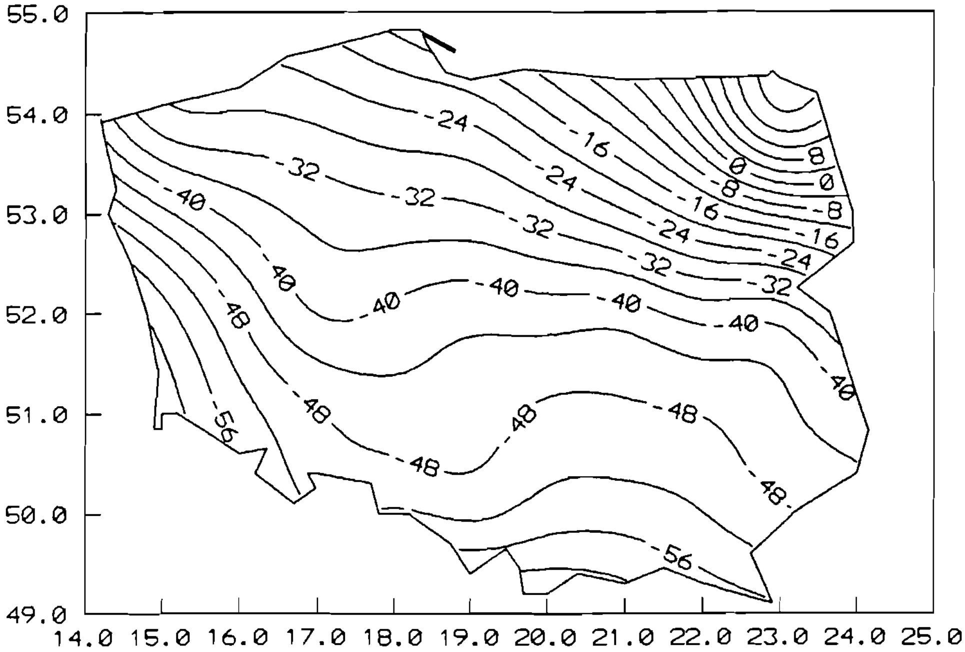

Figure 3. Runoff change (mm/year) in Poland for the Hadley-Center transient climate scenario: year 2050.

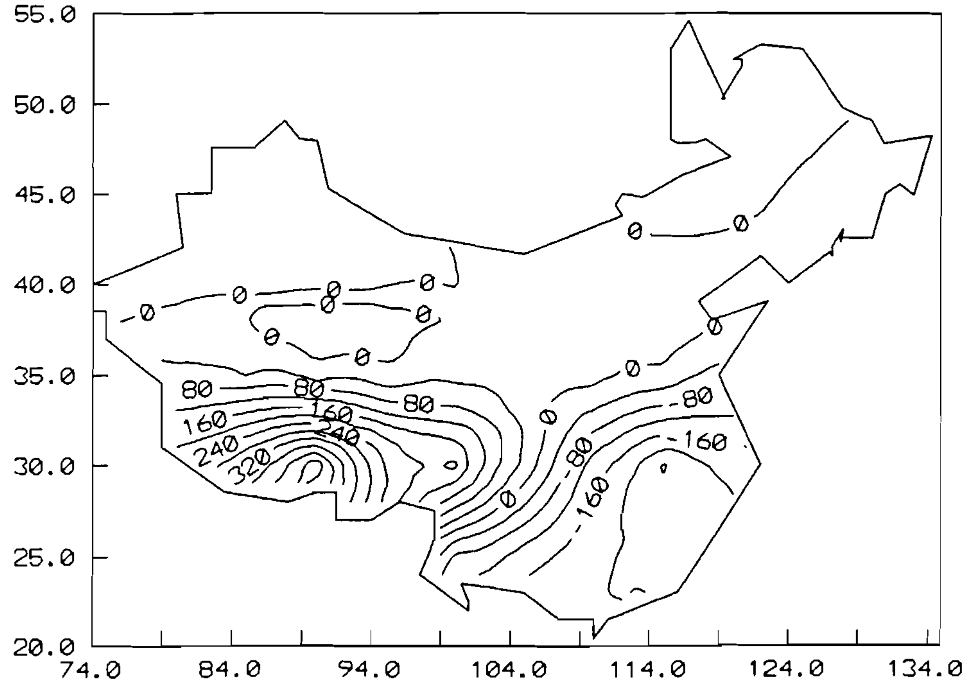

Figure 4. Runoff change (mm/year) in China for the GFDL transient climate scenario: year 2050.

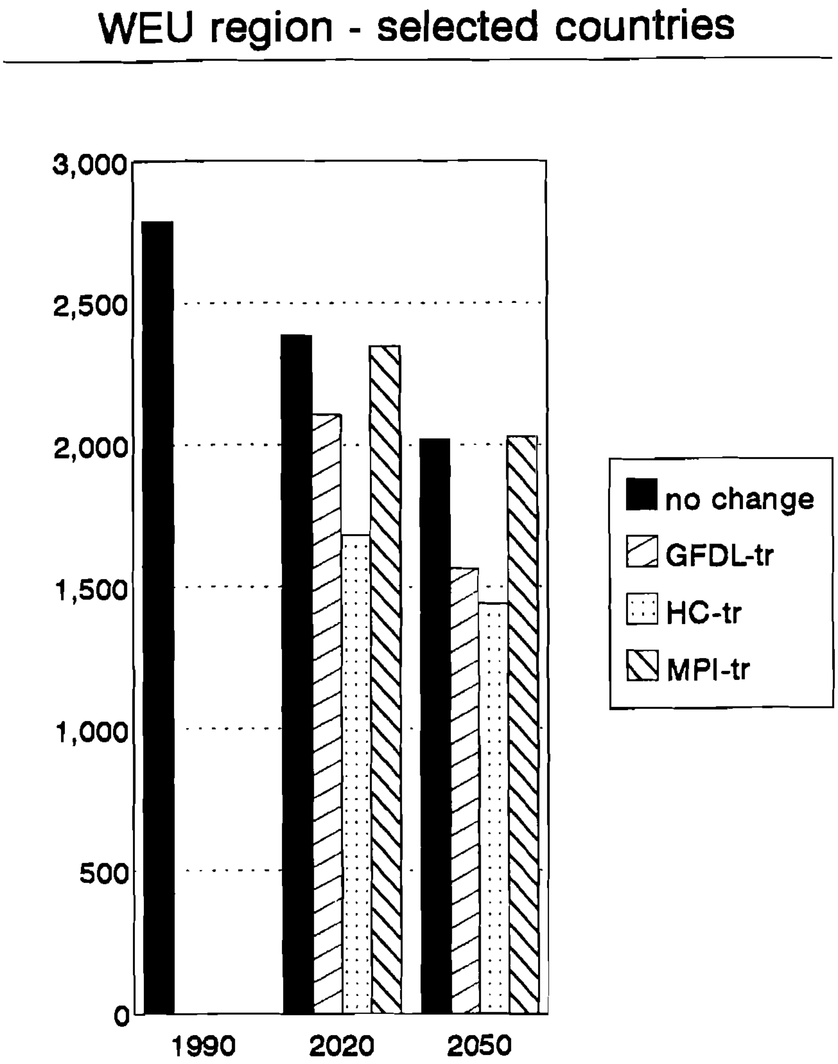

Figure 5. Per capita water availability (m^3) for current climate (no change) and three transient climate scenarios.

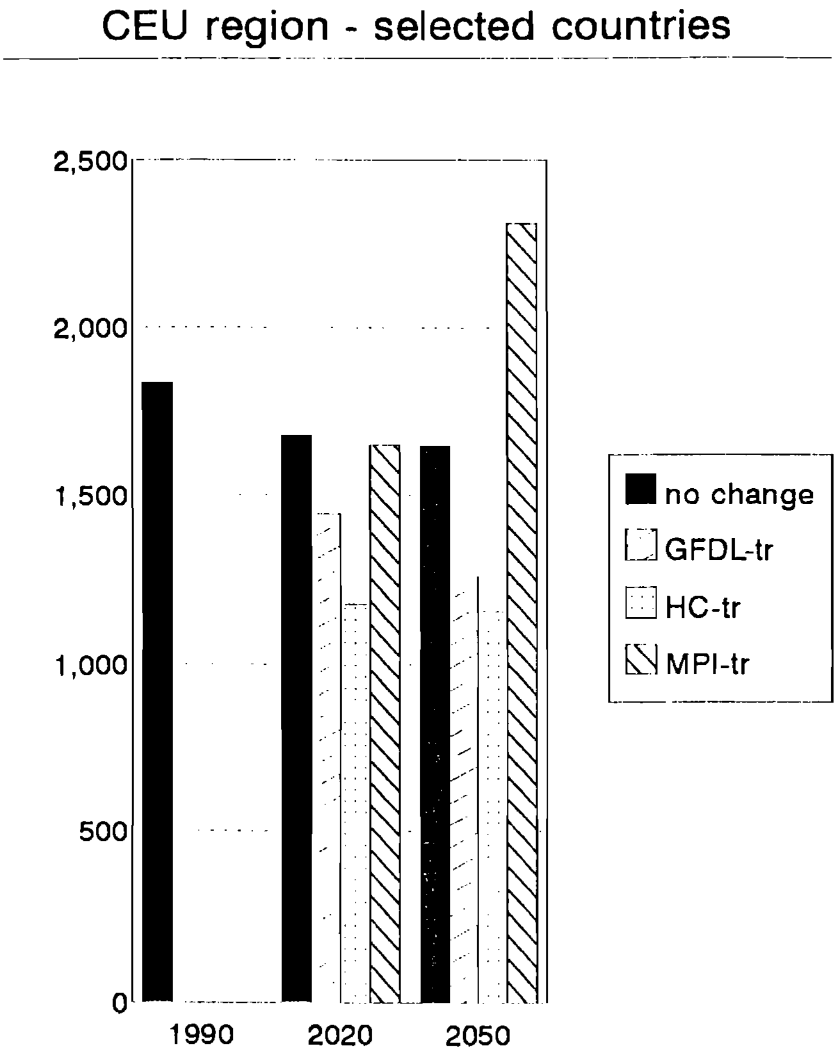

Figure 6. Per capita water availability (m^3) for current climate (no change) and three transient climate scenarios.

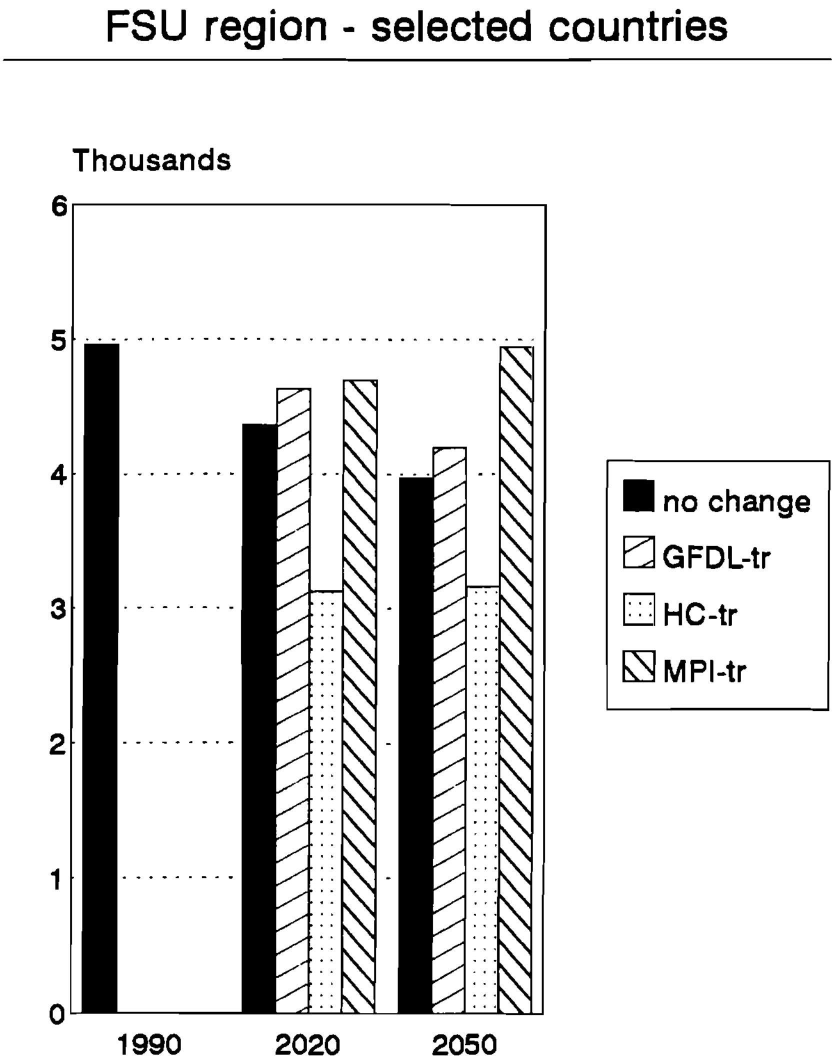

Figure 7. Per capita water availability (m^3) for current climate (no change) and three transient climate scenarios.

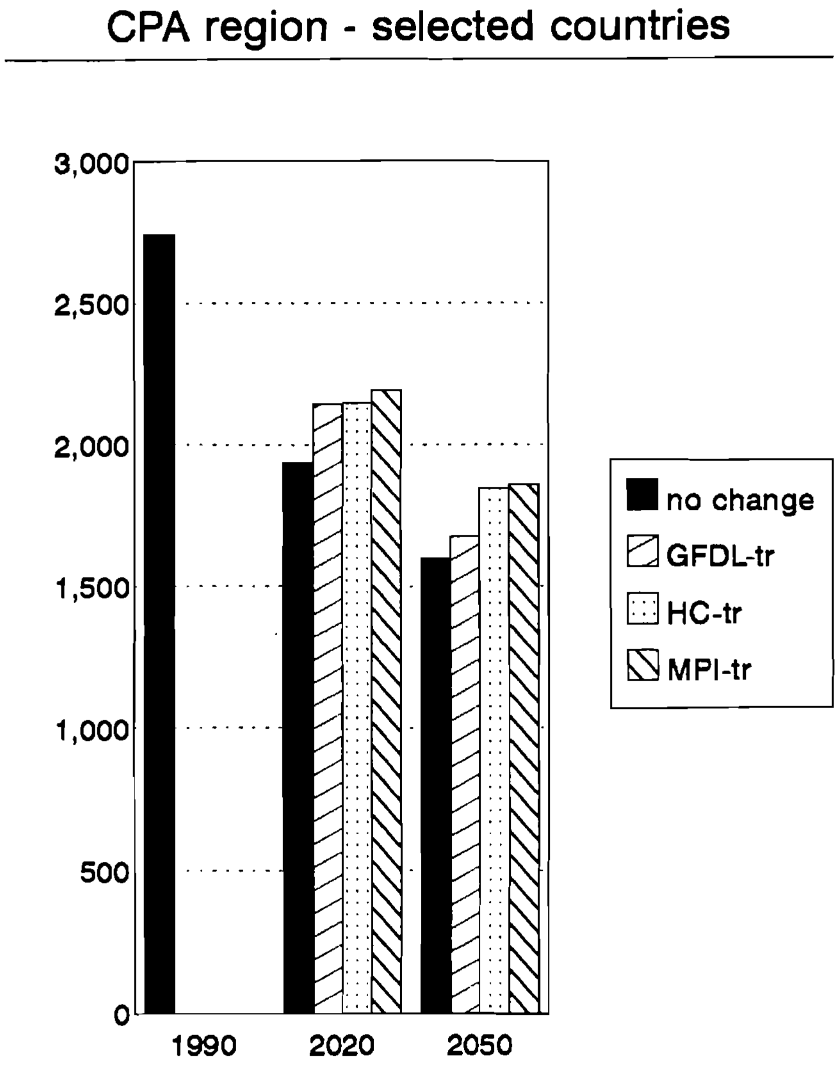

Figure 8. Per capita water availability (m^3) for current climate (no change) and three transient climate scenarios.

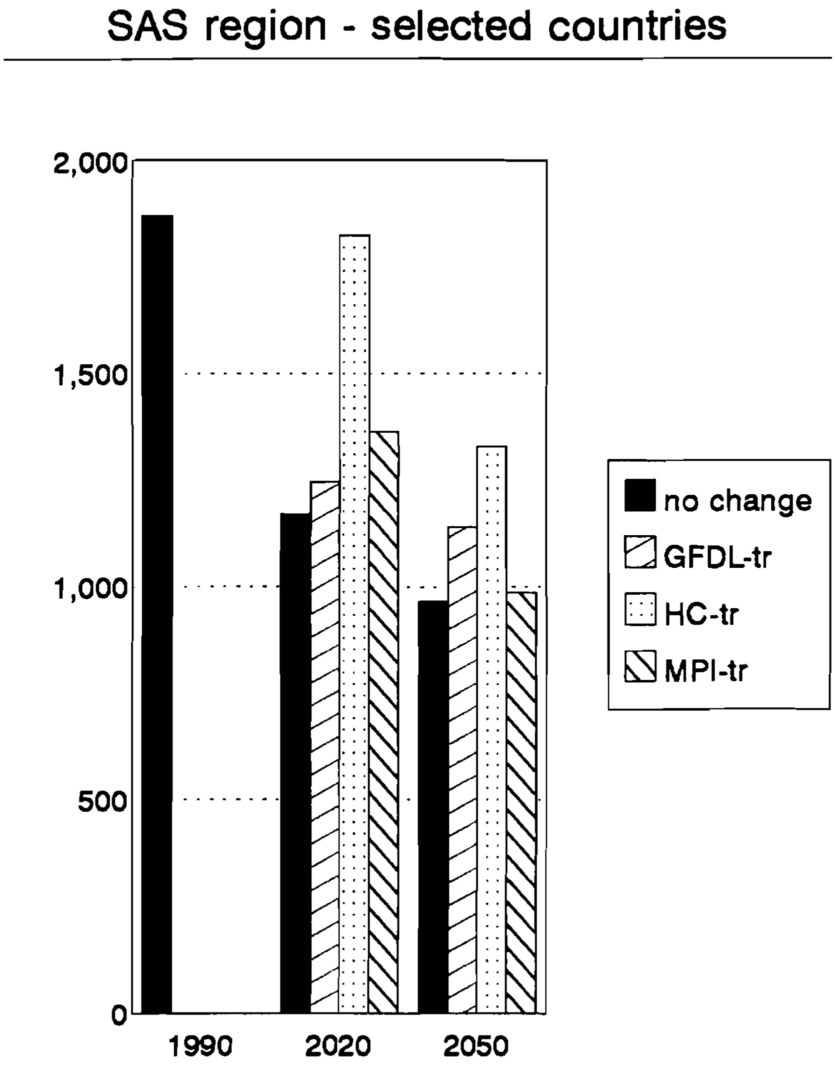

Figure 9. Per capita water availability (m^3) for current climate (no change) and three transient climate scenarios.

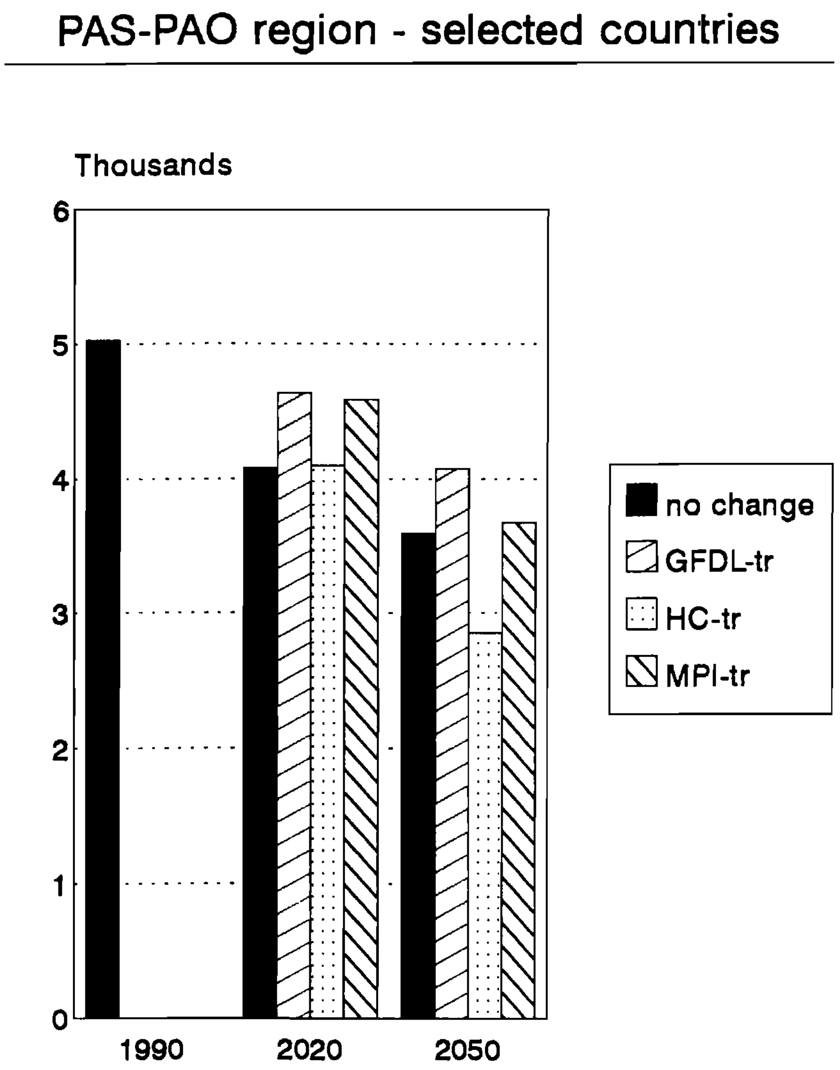

Figure 10. Per capita water availability (m^3) for current climate (no change) and three transient climate scenarios.