CLIMATE-INDUCED WATER AVAILABILITY CHANGES IN EUROPE

FLOOR BROUWER*

Research Scholar, Environment Program, International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria

and

MALIN FALKENMARK

Professor of International Hydrology, Swedish Natural Science Research Council, S-11385 Stockholm, Sweden

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Abstract. Water availability changes in Europe are discussed in this paper, as seen in a perspective of climatic change. Such changes will be assessed in terms of the shifts in the watering of terrestrial ecosystems, as well as the shifts in the availability in terrestrial freshwater systems. A changing climate will have a major impact on the availability of water. Both wetter and drier conditions will have major implications for societal activities and land use patterns (e.g., agriculture, urban activities, waste water disposal, etc.).

Some future research and monitoring activities are proposed by the authors to assess linkages in hydrological shifts to changes in land use patterns.

1. Introduction: Water and Environmental Change

Man lives in the natural environment, which provides him with food to eat, fodder for his cattle, timber for his houses, fuel for heating, water for drinking and washing, and other beneficial resources. Water is a main determinant of life, its ubiquitous presence distinguishing Planet Earth from other planets. It is one of the key resources: (i) it is essential for crop growth and wood production; (ii) numerous species live in water, and (iii) the hydrological cycle of evaporation, precipitation and runoff plays a central role in the biogeochemical cycles of, among others, carbon, nitrogen and phosphorus. Disturbances of water chemistry and/or water flows, caused by pollutants or by intervention with soil and vegetation, therefore tend to produce many secondary effects on flora, fauna and human health.

Water is continuously circulating through the biosphere, where life is based on myriads of water flows through plants, animals and human bodies. The amount of water that circulates annually between oceans, atmosphere and continents is only a minor part of the overall global water volume which amounts to about 1400 million km^3 (UNESCO, 1978). The major part of that, about 98%, exists either as water in the oceans (about 96.5%), or as ice/snow in ice caps and permanent snow cover (about 1.5%). These two major components of the global water cycle have a very long residence time, amounting to between a few thousand and several hundreds of

* Present address: Agricultural Economics Research Institute, P.O. Box 29703, 2502 LS The Hague, The Netherlands.

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thousand years. Continental ice caps for example, contain ice that is 100 000's of years old. The remaining 2% of global water volume is available either as groundwater (about 1.5%), as soil moisture, in rivers and lakes, or as water vapour in the atmosphere. Those parts of the global water cycle have residence times of between a week and a few centuries.

The atmosphere wettens the land through precipitation, but gains water back by evapotranspiration from vegetation and wet surfaces. As seen from an overall perspective, water reaching the ground is partitioned into two main water flows: the upward return flow, which is part of the plant production process, and the recharge of terrestrial waters, producing the flow in aquifers and rivers. The recharge in the root zone in relation to the water attraction capacity of the atmosphere determines, besides the air temperature, the length of the growing season.

The water in the terrestrial water systems can be used while passing through a country. The amount locally accessible can be increased by the development of water resources (e.g., wells, storage reservoirs, distribution channels and networks, etc.).

From a human perspective, water has a number of functions:

(–) it is necessary to sustain life. Crop production is operated by a water flow, passing in through the roots and out through the leaves. Plant production may be very vulnerable to lack of available water in the root zone. When the soil moisture goes below a certain threshold (wilting point), plant production stops altogether. This vulnerability is reflected by the fact that 80% of the fresh water consumed globally is used for irrigated agriculture (Pimentel, 1986). In Europe, about 40% of the consumed water is used for agriculture, and irrigated agricultural land covers over 15 million ha during the 1980s (not including the USSR);

(–) it is used for household supply and for a multitude of other (mainly socio-economic) purposes, such as in industry and for energy production. Between 40 and 50% of the total European water use is for industrial purposes (Chernogaeva, (1971);

(–) it is active in generating environmental feedbacks by propagation of physical and chemical disturbances onwards in the water cycle. A large amount of nitrogen and phosphorus fertilizers may enter surface waters by runoff, especially in areas of intensive agricultural practice.

In addition to the above mentioned functions that water may have from a human perspective, water systems may also be affected by environmental pollution (e.g., eutrophication, toxification) which degrades the aquatic ecosystems.

These different functions have to be balanced into a well-functioning, and preferably well-integrated, land and water management system. Experience, however, indicates that there exists in fact a 'water barrier' (Falkenmark, 1986), limiting the size of the population that can be supported from each flow unit of water. That limit depends on water demand patterns (including water for irrigation in agriculture, and other activities), access to technology (for storage, redistribution, recycling of waste water), administrative capacity (to coordinate all sectors related to water), and the geographical scale of a country (possibility to organize sequential, multi-purpose recycling of water). On the whole, water management problems tend to increase in complexity with increasing level of water competition (in terms of the number of people that need to be supported from a flow unit of water), increasing aridity (agricultural demands for irrigation), and increasing scale of a country.

This paper focusses on the issue of *water availability in Europe*, i.e. on the amount of water that is moving through the landscape, as seen in a perspective of climate change. We shall distinguish between its two main components: the root zone water availability, i.e. the watering of terrestrial ecosystems on the one hand, and the availability in terrestrial freshwater systems on the other.

The large-scale climatic change that results from the accumulation of greenhouse gases in the atmosphere will affect humankind primarily through the water cycle (e.g., through changes in soil moisture levels), as well as through numerous phenomena that are closely related to the water cycle and related processes (such as the occurrence of flooding or droughts). The issue of water availability might become more important in Europe over the next decades, especially in those regions that will be affected by a decrease in precipitation levels and/or an increase in temperature.

2. Present Hydrology of Europe

2.1. Introduction

The water cycle is a crucial system in the biosphere, since it:

(1) circulates water between atmosphere, lithosphere and world oceans;

(2) provides water to the soils and feeds terrestrial ecosystems; and

(3) feeds the terrestrial freshwater systems (with runoff being the difference between precipitation and evaporation).

The water cycle is also one of the major sources that determine regional climatic conditions, exchanging heat and water vapour from tropical latitudes to middle and high latitudes. That phenomenon is one of the main factors that are critical to the climatic conditions of Europe. In addition to that, Northern Europe is warmed by the ocean circulation system through heat that is released from the surface waters of the North Atlantic (Broecker, 1987).

The water balance for each of the continents is summarized in Table I. The water balance in this table is based on average values with a considerable variation both in space and time. This is reflected by the fact that water availability in Africa for example, is having a considerable level at the continental scale, although it is reaching minimum levels in the Sahara and Kalahari deserts. Precipitation and evaporation in Europe are slightly less than the global averages, while runoff is about the global average. The total amount of available runoff is critical to meet the water requirements for society in large areas of the world, while the extremes in runoff (in terms of the temporal variation over the seasons) are critical to the occurrence of floods and droughts. This table also includes information on the availability of water resources for human uses as seen on a per capita basis, showing the already limited amount of water available in Europe compared to other continents (WHO/UNEP, 1987).

TABLE I

Water balance (in mm y^{-1}) and water availability (per capita, in m^3, ca 1970) on the continental scale. (*Source:* Lvovich, 1979.)

Continent	Precipitation	Evaporation	Runoff	Availability
South America	1648	1065	583	54400
Europe	734	415	319	4800
Asia	726	433	293	6550
North America	670	383	287	19000
Africa	686	547	139	12000
Australia	440	393	47	n.a.
Average	834	540	294	–

In response to the hydroclimate, European land has developed its present pattern of soil wettening, of returning evaporated water to the atmosphere, and of recharge of groundwater and river systems. Basically, there are five main types of water balances in Europe (Chernogaeva, 1971), principally distinguished by differences in hydroclimate [1] as well as differences in topography and soil permeability:

(1) heavily moistened mountain regions of the Alps, Pyrenees and the mountain regions of northern Europe (aridity index between 3 and 4);

(2) normally moistened lower mountain regions of Great Britain, the Apennines, Carpathians and the lower mountains of Central Europe (aridity index between 2 and 3);

(3) mountain-plain complexes of Central Europe and heavily moistened plains of Great Britain, France, Germany, the Netherlands and Denmark (aridity index between 1 and 2);

(4) moderately moistened plains in the lowlands of Poland, GDR and Czechoslovakia (aridity index around 1); and

(5) arid plains in major parts of the Mediterranean region, southern part of the USSR and the coastal lowlands of the Danube catchment (aridity index less than 1).

We have no map of such indices, but runoff (as the difference between precipitation and evaporation) is closely related. Figure 1 shows the regional overall patterns of runoff in Europe, based on long-term mean annual values. Annual runoff values are in the range between over 1000 mm in the mountain regions, and about 10 mm in parts of the Mediterranean area and bordering the Black Sea.

The river flow discharge (and similarly, the amount of water that is moving through the landscape) is also characterized by large interannual and interseasonal variations. Figure 2 for example, shows the distribution of the monthly average discharge values (in m^3 per second) for catchment areas of five rivers in several parts of Europe. The figure shows the range of monthly average discharge values for approximately a 50 years period, respectively in Finland, Romania, Spain, Austria,

[1] In terms of an aridity index, with annual precipitation expressed as a multiple of water attraction capacity of atmosphere (potential evapotranspiration).

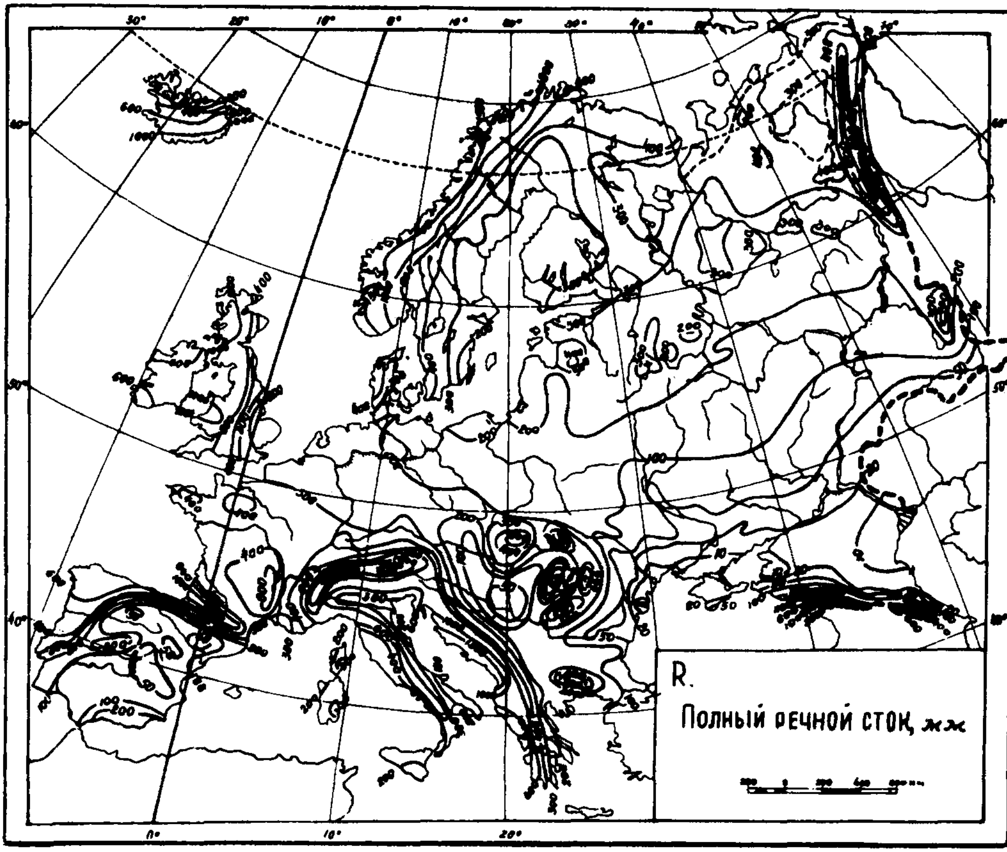

Fig. 1. Runoff generation in Europe. (*Source:* Lvovich, 1979.)

and France. The line drawn for each of the catchment areas represents the long-term mean monthly discharge. The figure also shows the first and fourth quartiles of the monthly average discharge values, and this statistic already indicates the large variation during the observed period, with maximum values sometimes being several orders of magnitude larger than the minimum values.

2.2. Water availability in terrestrial freshwater systems

This is the total amount of runoff that is moving in aquifers and rivers, produced either from local precipitation over the country itself, or by water that enters rivers and regional aquifers.

The per capita amount of water available for socio-economic development is being pushed towards more critical levels in semi-arid countries, with limited amounts of water available from the global water cycle and increasing water needs for the growing population and the irrigation of agricultural land. As indicated earlier, the number of people that a society can support on a certain flow unit of water depends on a number of supply and demand factors. Under optimal conditions in a well-organized, small-scale advanced country like Israel, for example, sophisticated water

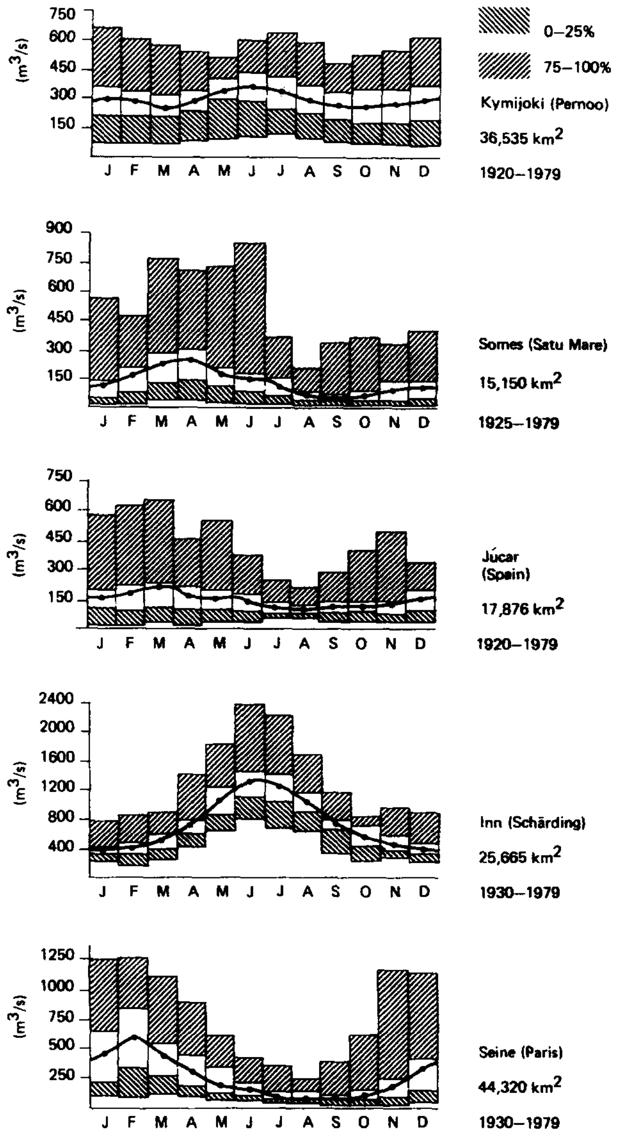

Fig. 2. Range of monthly average discharge (in $m^3 s^{-1}$) for five river basins in Europa (Finland, Romania, Spain, Austria and France) during approximately a fifty years period.

management and demand control policies, may enable 2000 individuals to be supported on one million $m^3 y^{-1}$ (equivalent to a per capita level of 500 m^3). This may in fact be close to the barrier of what a modern society is able to manage with advanced technology and advanced administrative capacity (Falkenmark, 1986; Falkenmark *et al.*, 1987). Larger countries with a less advanced water-management would be expected to have massive water-related problems at considerably lower levels of water competition index.[2] On the whole, water management problems tend to increase with increasing water competition index, increasing aridity, and increasing geographical scale.

The water balance components also have a wide spatial variation over Europe, and this will be further explored in terms of the amount of water that is available in each country from the natural flows. Table II shows the amount of water (in $km^3 y^{-1}$) in relation to the population (in million people), that is available in Europe for each country for household supply, agriculture and other socio-economic activities.

TABLE II

Water availability for human use in Europe. (*Source:* Forkasiewicz and Margat, 1980.) Population data for 1980 originate from United Nations (1986)

country	population (million)	available water		number of people per flow unit
		national (km^3)	per capita (m^3)	
Albania	2.7	27.5	10200	100
Austria	7.5	90.0	12000	85
Belgium	10.2	12.5	1200	835
Bulgaria	8.9	197.0	22100	45
C.S.S.R.	15.3	90.0	5900	170
Denmark	5.1	12.9	2500	400
Finland	4.8	104.0	21700	45
France	53.7	180.0	3400	295
Germany, F.R.	61.6	160.0	2600	385
G.D.R.	16.7	26.2	1600	625
Greece	9.6	55.0	5700	175
Hungary	10.7	120.0	11200	90
Ireland	3.4	43.7	12900	80
Italy	57.1	167.0	2900	345
The Netherlands	14.1	90.5	6400	155
Norway	4.1	388.0	94600	10
Poland	35.6	58.8	1700	590
Portugal	9.9	87.5	8800	115
Romania	22.2	192.0	8600	115
Spain	37.4	110.0	2900	345
Sweden	8.3	183.0	22000	45
Switzerland	6.3	50.0	7900	125
United Kingdom	55.9	162.7	2900	345
Yugoslavia	22.3	244.0	10900	90

[2] In terms of the number of individuals that need to be supported on an annual flow unit of 1 million m^3 of water.

The table also shows the number of people that need to be supported from a unit of 1 million m^3 of water.

Table III relates the total water demand in the different countries to the per capita availability. It is clear when combining both tables that the most water-stressed countries under present climatic conditions are Belgium, G.D.R., and Poland. These countries have a per capita water availability in the range between 1200 and 1600 m^3, which means that about 600–800 individuals need to be supported from each flow unit of one million m^3 of water.

TABLE III

Per capita water demand and water availability for human use (in m^3 y^{-1}). (*Source:* Forkasiewicz and Margat, 1980.)

water availability per capita	Water demand per capita				
	<100	100–300	300–500	500–800	>800
1 000–2 000			GDR, Poland		Belgium
2 000–3 000		Denmark	UK	FRG, Italy, Spain	
3 000–5 000				France	
5 000–10 000			CSSR, Greece, Switzerland	Portugal	Netherlands
10 000–50 000			Austria, Yugoslavia	Hungary, Ireland, Sweden	Finland
>50 000			Norway		

2.3. Water availability for plant growth

In this section we shall focus on the moisturization of the soils and the storage of soil moisture in the European environment. The terrestrial ecosystems are primarily driven by energy and water, and controlled by soil conditions and the management of cultivated land. Soil moisture in Summer is a critical factor for crop growth, because it has to supply enough water to the plants to compensate for their water loss through evapotranspiration. The major climatic factors that influence crop growth are based on temperature and moisture conditions. Moisture conditions are a major limiting factor for growing crops in the southern part of Europe. This can be seen by comparing Figures 3 and 4 (the maps of Europe in this report are all based on grids of size 0.5° latitude by 1° longitude, which corresponds to grids of about 60 km in the North-South direction and between 90 to 40 km in the East-West direction).

Figure 3 shows the period of the year (in number of days) that the average temperature is over 5 °C (the figure is based on data from weather stations with monthly averages for a thirty year period from 1931–1960, and they originate from Müller, 1982). The threshold of 5 °C is considered to be a critical level for crop

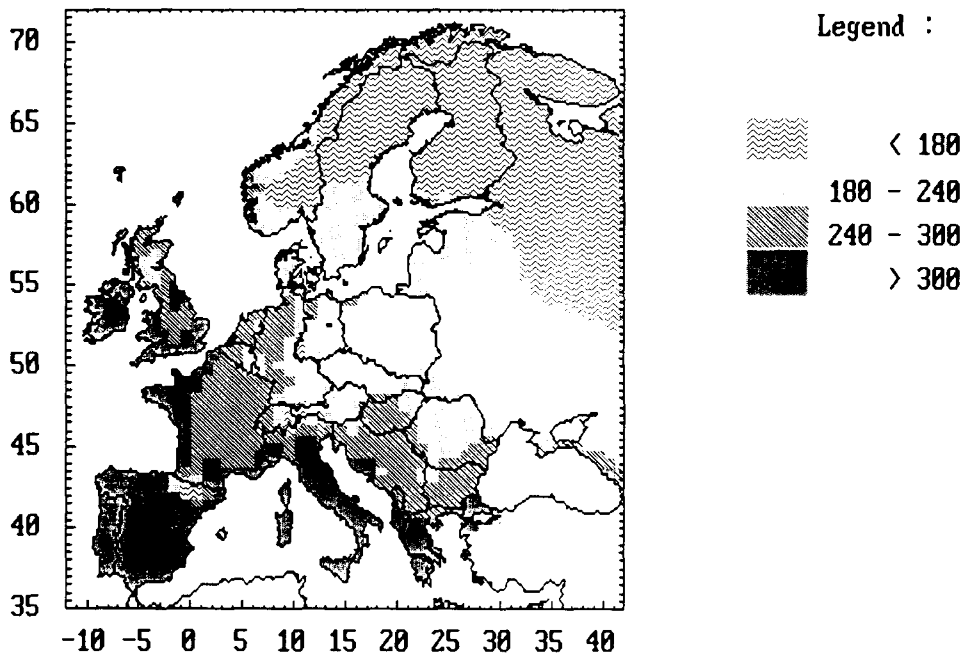

Fig. 3. Number of days in Europe with mean monthly temperature over 5 °C.

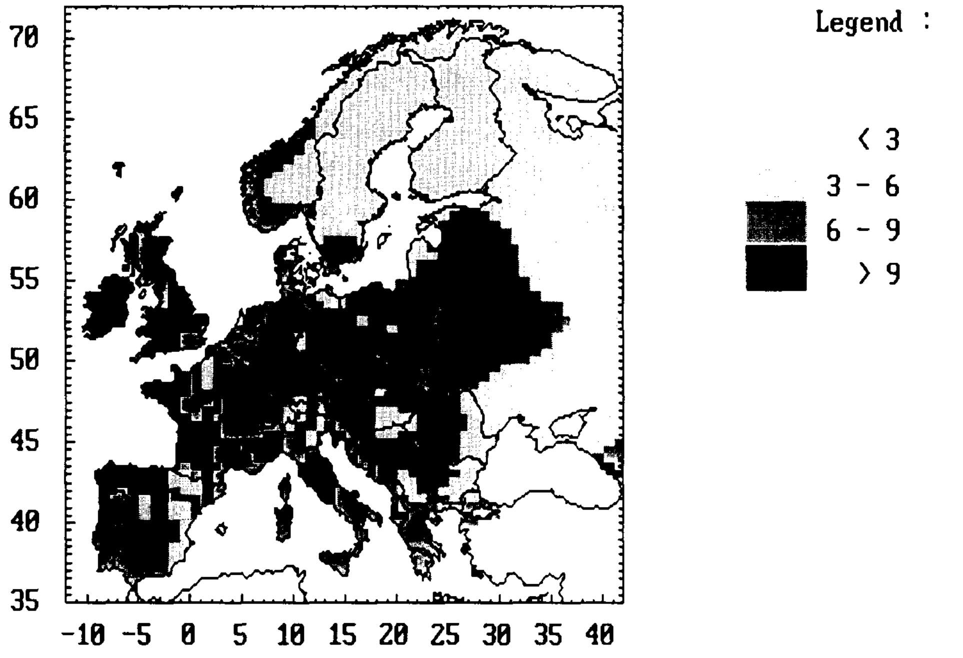

Fig. 4. Growing period in Europe (in months).

growth. Winter wheat for example, requires a period of some 180–210 days with an average temperature of at least 5 °C (Verheye, 1988), and rainfall during the growing period of some 600–800 mm. Limitations in production are expected to occur otherwise.

The growing period is also controlled by availability of soil moisture, and is defined as the period of the year (in months) that the long-term mean temperature is above 5 °C and the period during which long-term mean precipitation exceeds half of the potential evapotranspiration (Verheye, 1986). Figure 4 shows the growing period of Europe.

Comparison of Figures 3 and 4 shows that soil moisture is a major critical factor for crop growth in the southern part of Europe, since the growing period is largely limited by soil moisture conditions. This is particularly true in May-August since this part of Europe is characterized by a Mediterranean climate with maximum rainfall in Autumn or Winter period, and minimum amounts during the Summer period. Although soil moisture deficits are recharged during Winter and soil moisture storage can meet moisture demand during short periods when evapotranspiration exceeds precipitation, soil moisture deficits soon restrict transpiration and the rate of dry weight increment is reduced. The average January temperature in this part of Europe is over 5 °C with only occasional occurrence of frost, while the monthly average July temperature is over 20 °C. The critical climatic factor for growing crops in the northern part of the continent is however temperature. The growing period in this part of Europe is between 3 and 6 months, which is primarily determined by temperature. The limitation to plant growth is not affected by lack of soil moisture in a major way.

3. Climatic Change in Europe

Climate is expected to change on a global scale due to increasing concentrations of atmospheric greenhouse gases (carbon dioxide, chlorofluorocarbons, nitrous oxide, methane and ozone). The last hundred years have already seen an increase in global mean temperature of between 0.3 and 0.7 °C. Although a direct relationship among changes in the concentrations of greenhouse gases and temperature is complicated by numerous factors (such as atmospheric blocking phenomena, and effects of oceanic thermal inertia on atmospheric circulation), this rise in global temperature is consistent with the observed increasing concentrations of carbon dioxide and the other greenhouse gases.

Recent estimates, based on general circulation models (GCMs) with a doubling of atmospheric CO_2 concentrations, suggest an annual global warming of between 1.5 and 4.5 °C (World Climate Program, 1985). A doubling of carbon dioxide could occur before the middle of the next century. This scenario of increasing CO_2 depends on (uncertain) long-term projections of fossil fuel consumption. However, the magnitude and order of variation of the climatic change as well as the changes over the seasons will vary with latitude. Largest increases in temperature are expected to occur in high latitude regions (above 60° latitude).

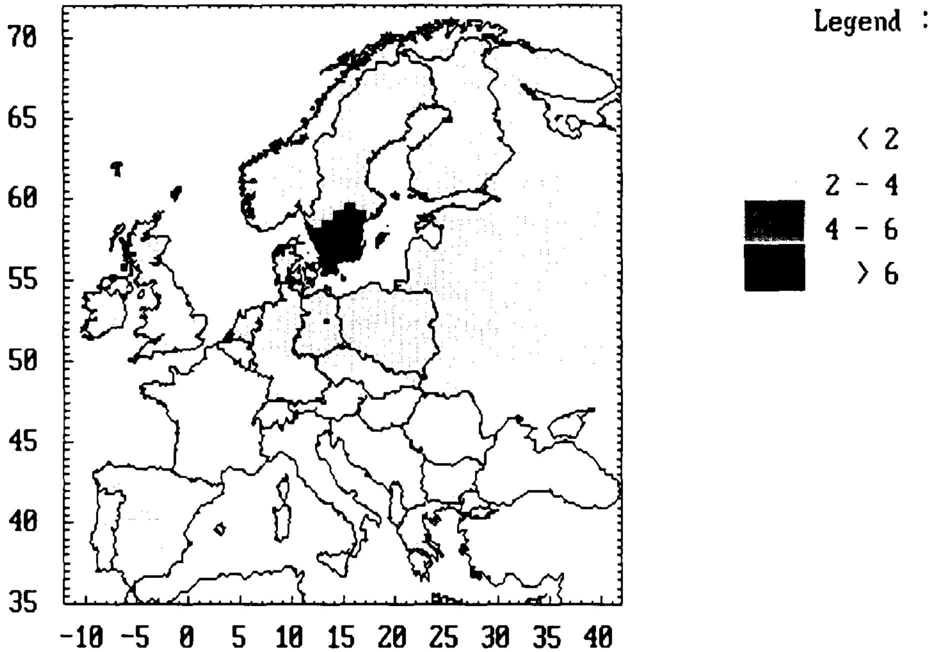

Fig. 5a. Changes in mean annual temperature (in °C) (UKMO scenario).

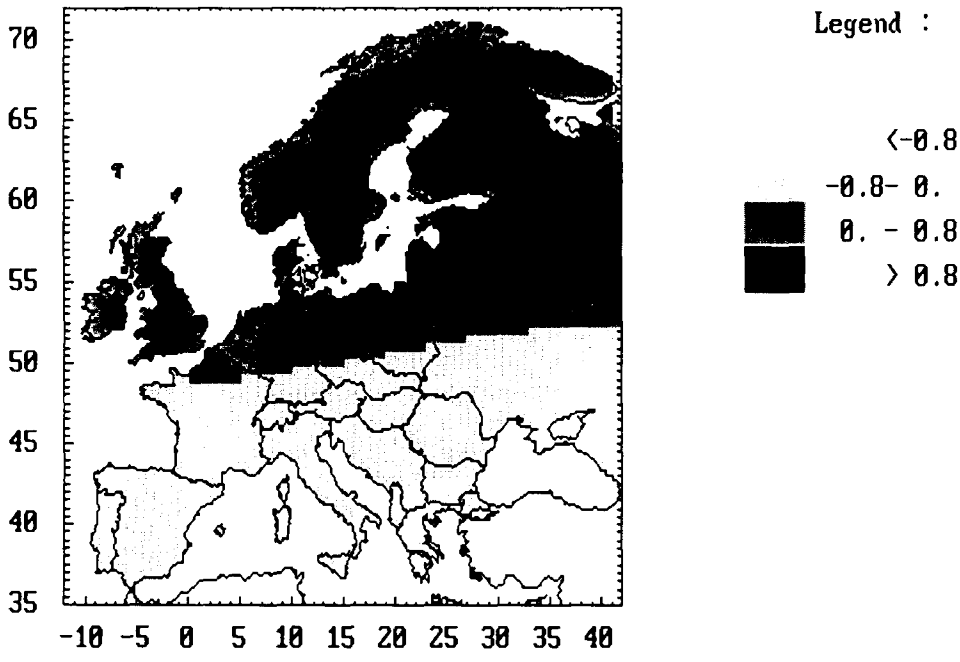

Fig. 5b. Changes in mean annual precipitation (in mm day^{-1}) (UKMO scenario).

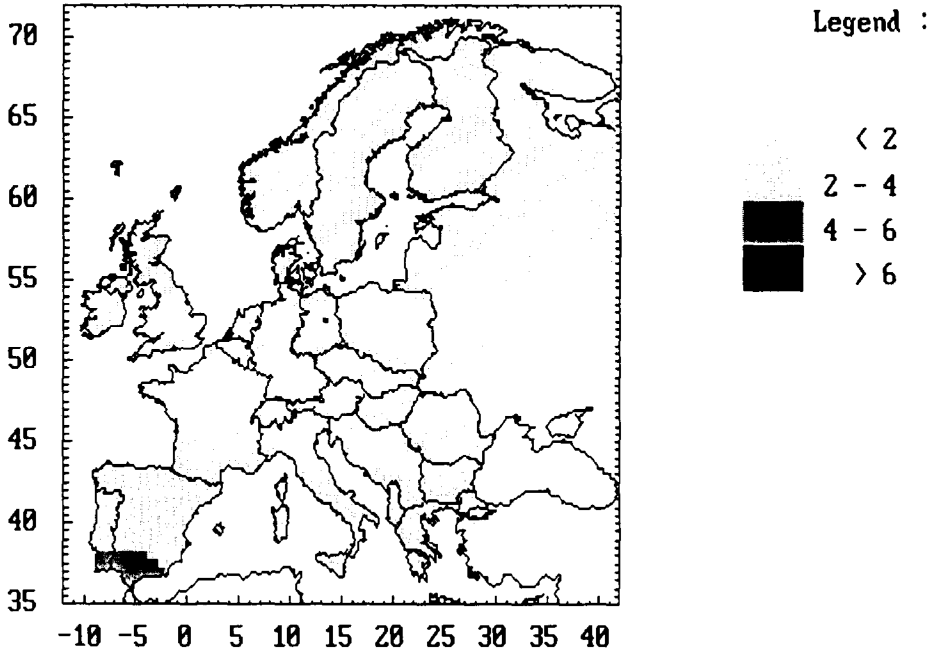

Fig. 6a. Temperature increases in Summer (in °C) (UKMO scenario).

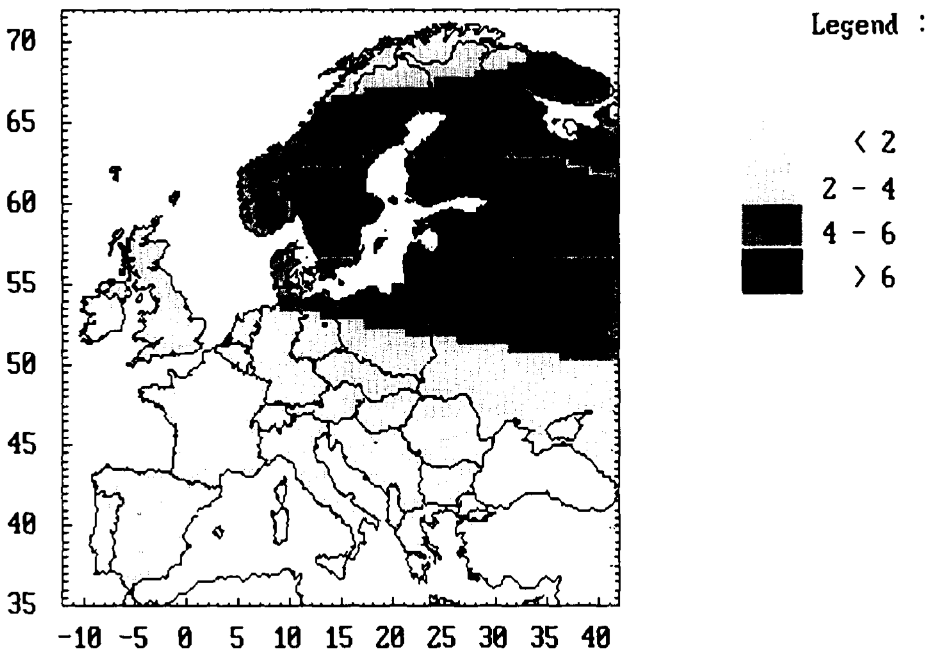

Fig. 6b. Temperature increases in Winter (in °C) (UKMO scenario).

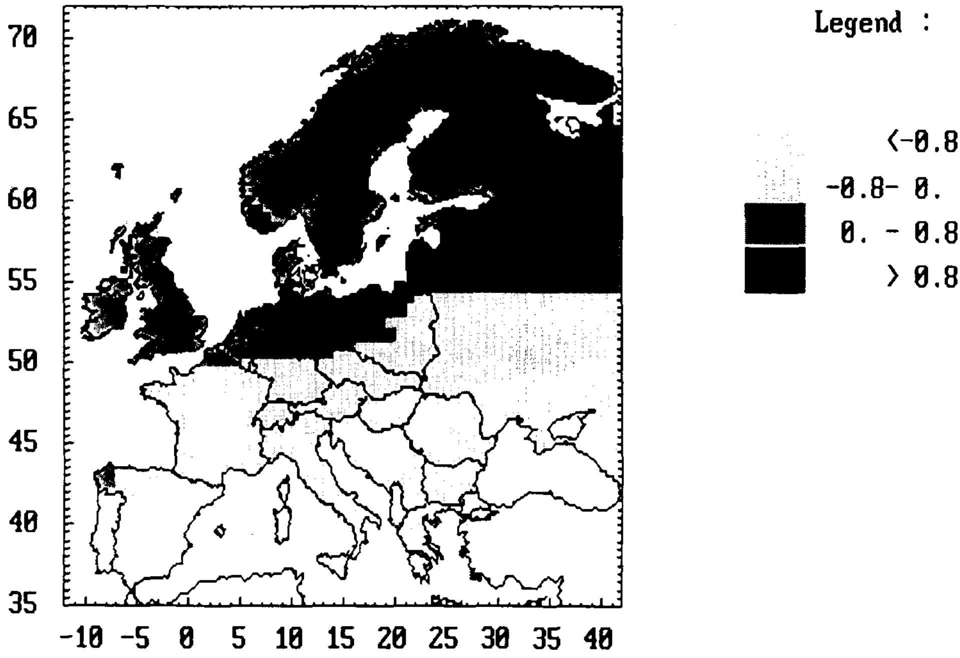

Fig. 7a. Precipitation changes in Summer (in mm day^{-1}) (UKMO scenario).

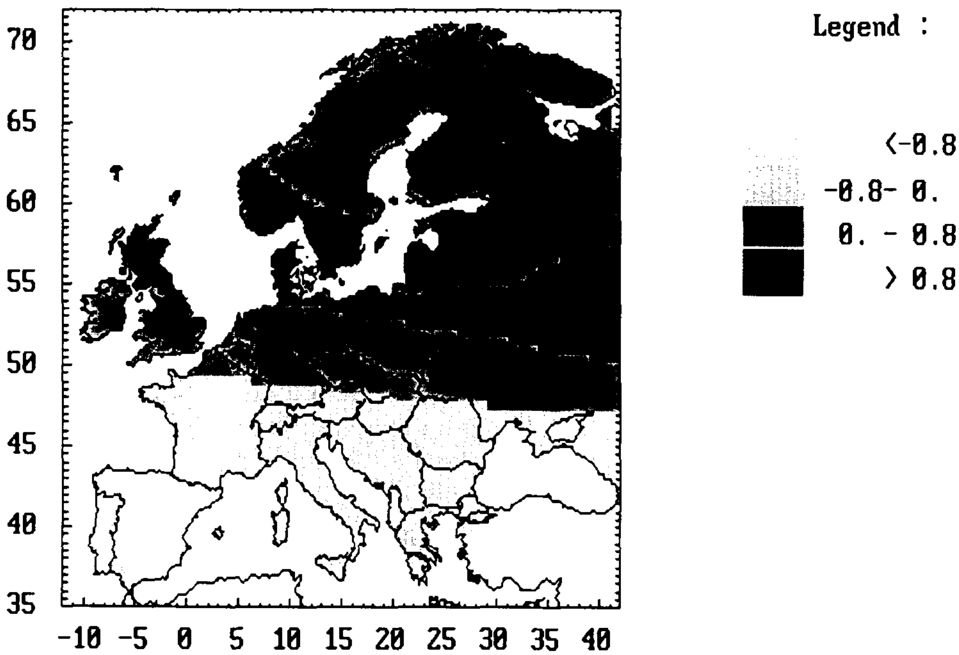

Fig. 7b. Precipitation changes in Winter (in mm day^{-1}) (UKMO scenario).

The climate model that will be used here is from the United Kingdom Meteorological Office based on a doubling of atmospheric carbon dioxide compared to pre-industrial levels (hereinafter referred to as the UKMO), and an equilibrium response in climate (see also Mitchell, 1983). Figure 5 shows the changes in mean annual temperature and precipitation in this scenario, compared to present climatic conditions. The increase in mean annual temperature is between 2 and 4 °C for most of Europe, with largest increases in the southern part of Sweden. The mean annual precipitation roughly shows an increase north of around the 50° latitude and a decrease to the south. Largest decreases in mean annual precipitation are projected in the south-eastern part of Europe.

The Summer and Winter scenarios project warmer temperature all over Europe (Figure 6) as a result of a doubling of carbon dioxide, with largest increases in the Winter period. Summer temperature increases by less than 2 °C for most of Europe, while an increase of more than 4 °C is projected during the Winter period over Scandinavia and northern USSR. The increase in Winter temperature could be as much as over 6 °C in parts of northern Europe. The Summer and Winter scenarios (Figure 7) project increased precipitation over the northern half of Europe, and less precipitation over much of southern Europe. Largest decreases in Summer precipitation (of more than 0.8 mm day^{-1}) are projected in the region bordering the Black Sea, and an increase in Winter precipitation (of more than 0.8 mm day^{-1}) is projected in large areas of Great Britain, Norway, Sweden, Denmark, Poland and the USSR.

4. Hydrological Shifts in Europe Due to a Changing Climate

A climate change will have a major impact on the availability of water, in terms of feeding the terrestrial ecosystems as well as the freshwater systems (the available methods and models to assess the impacts of climatic change on water resources have been surveyed by Beran, 1986). In the following, we shall present some of the major hydrological shifts in Europe due to a changing climate, again described in terms of its consequences for feeding the terrestrial ecosystems and the freshwater systems.

Figure 8 indicates the length of the growing period based on the UKMO scenario. Comparing Figures 4 and 8 shows that the greatest increases are projected in northern Europe (due to an overall rise in mean seasonal temperature) and the largest decreases are projected in southern Europe where increasing soil moisture deficit limits crop production. Water consumption for irrigation of cultivated land might increase accordingly in this part of the continent.

A more detailed seasonal analysis of changes in growing period is shown in Figure 9 for a few climate stations in Europe. Figure 9a shows the present and projected conditions of precipitation and potential evapotranspiration (mean monthly values, represented by bars) and temperature (mean monthly values, represented by a line). The left side of the figure shows the present conditions, and the projected ones under a climate change are depicted on the right side. The resulting growing period

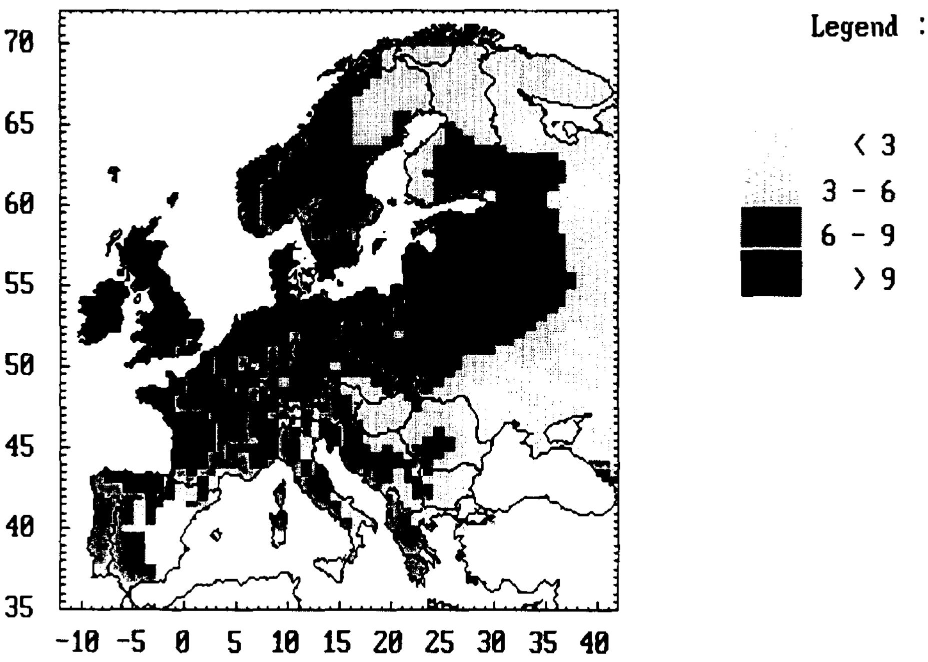

Fig. 8. Growing period (in months) (UKMO scenario).

(Figure 9b) indicates the period of the year that climatic conditions are not critical to crop growth. The figure shows that the climatic conditions such as the one around Stockholm, are affected by a short period of soil moisture deficit during early Summer. This is projected to change due to an increase in precipitation. The growing period during the Spring and Summer period is projected to decrease in the remaining climate stations considered due to an increase in soil moisture deficit, because of the increase in temperature and changing precipitation patterns.

The climate change scenario also considers a sea level rise over the next 70 years of between 40 and 160 cm (UNEP/WMO/ICSU, 1988). This is particularly important for the coastal lowlands of Western Europe (in France, Belgium, The Netherlands), and part of the Mediterranean coastal areas (in Italy). Salt intrusion of groundwater and surface water may affect agriculture and the quality of drinking water as a result of sea level rise in these areas.

Various kinds of soil degradation factors may be aggravated over the next several decades due to changes in hydroclimatic factors. The expected increase in soil moisture deficit in the Mediterranean area, already mentioned, might result in changing fertilization patterns, such that more fertilizers are added to the soils to maintain land productivity, which again may result in an increase in losses of nutrients from leaching. In addition, the depletion of nutrients and organic matter

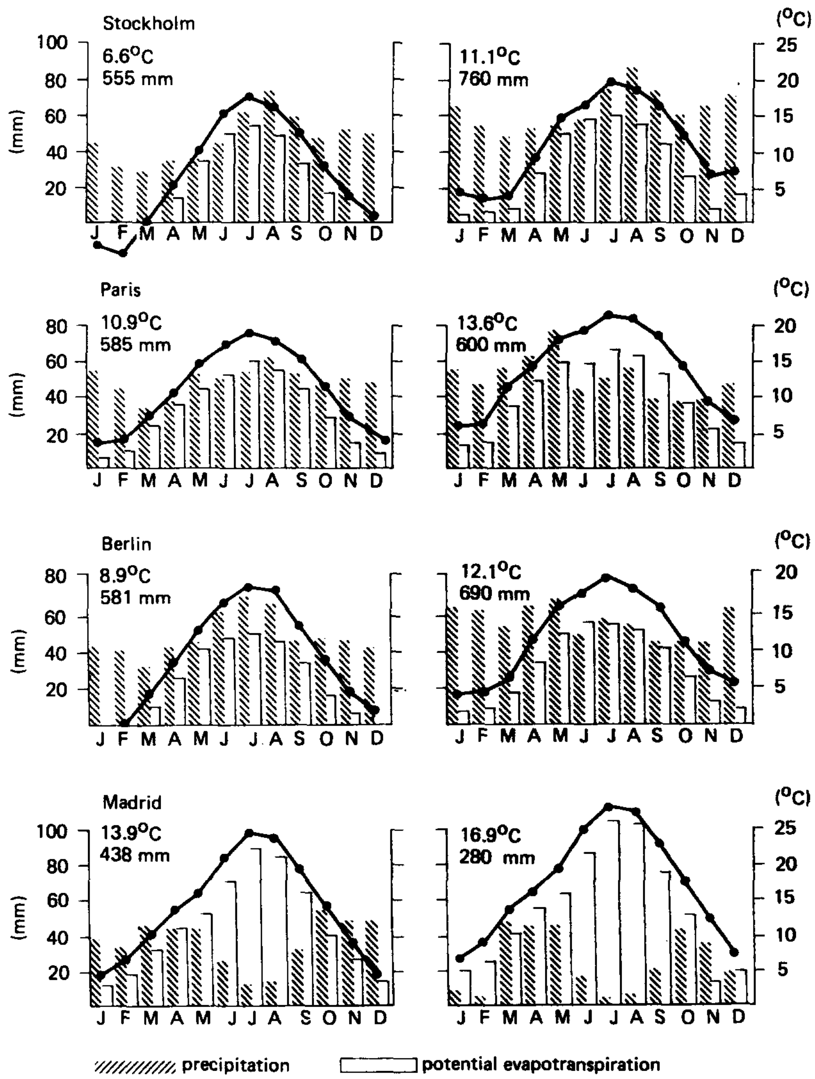

Fig. 9a. Mean monthly temperature, precipitation and potential evapotranspiration for four weather stations under present and a projected climate.

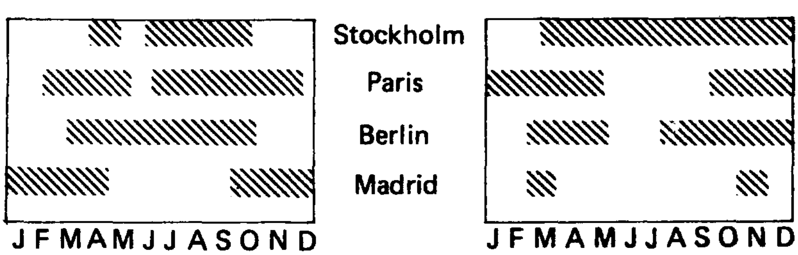

Fig. 9b. The resulting growing period (in months) under present and a projected climate.

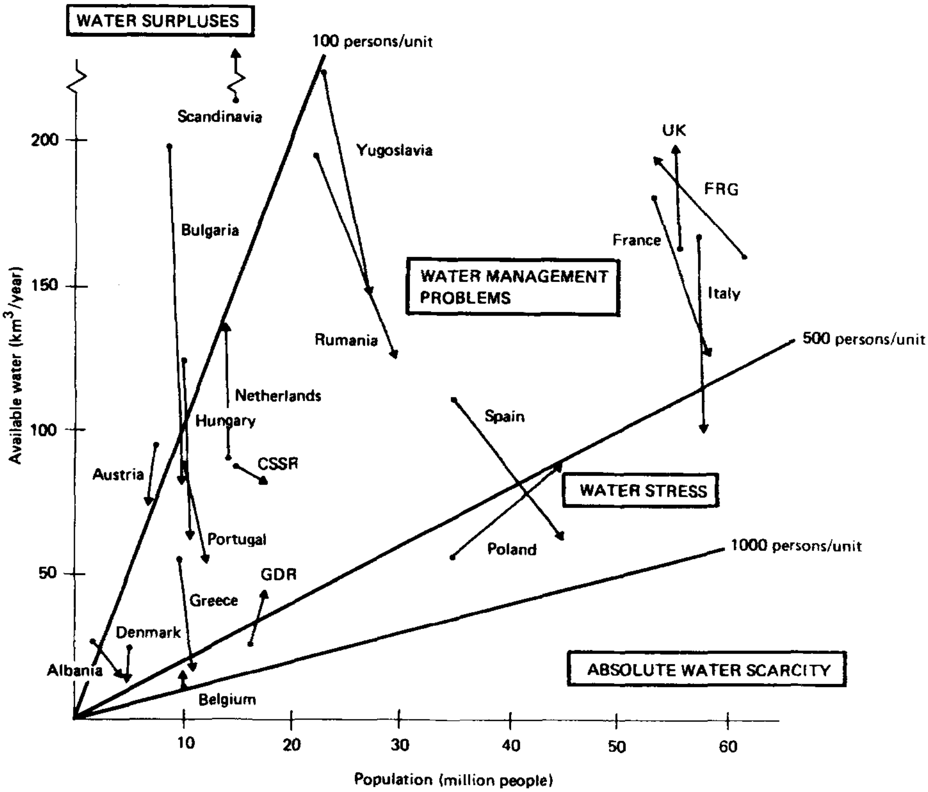

Fig. 10. Indicative hydrological shifts due to a changing climate for the European countries based on the UKMO (1 unit corresponds to a flow of 1 million m^3 water per year).

may accelerate in areas of increased precipitation due to leaching (particularly in northern Europe).

Figure 10 shows the direction of changes in water availability in relation to population for the European countries, compared to the actual levels shown in Table II. The figure has been divided into four areas, that, in order of increasing water scarcity, are: water surpluses (less than 100 people unit^{-1}); water management problems (between 100 and 500 people unit^{-1}); water stress (between 500 and 1000 people unit^{-1}); and absolute water scarcity (more than 1000 people unit^{-1}). The changes in water availability should be considered as a first approximation only. The water availability was based on the climate scenario discussed above and determined simply by subtracting future evapotranspiration from the future precipitation in a model determining the former as a function of the latter (Kovacs, 1987; Olejnik, 1988). The population trend is from the United Nations, medium projections (United Nations, 1986).

The total amount of available water may decrease in 13 European countries: Albania, Austria, Bulgaria, CSSR, France, Greece, Hungary, Italy, Portugal, Roma-

TABLE IV

Implications of water-related disturbances

		Land			Rivers and Lakes			
	wetter = + drier = –	soil moisture	groundwater	surface water	flow-related uses	carrier of effluents	use of water bodies	use related to water depth
Societal activities concerned		• agriculture • forests • buildings • roads	• rural water supply • local irrigation	• urban activities	• water supply • hydropower • irrigation	• sanitation • industrial waste water disposal	• fishing • recreation	• navigation
Problems encountered	+	• reduced fertility	• water logging • building damages	• urban storm runoff • erosion	• failing flow control • floodings		• erosion/ sedimentation • increasing currents • flushing of lake phosph.	• floodings, inundations
	–	• droughts • crop failures	• drying wells • pumping costs • foundation problems • subsidence		• water deficiencies • reduced hydropower production	• reduced dilution • aeration problems • unsafe for bathing	• changing fish population • reduced water removal	• collapsing navigation systems • reduced traffic
Engineering measures to mitigate	+	• drainage	• drainage	• urban drainage	• flow control		• river training	• increased levee height • reservoirs
	–	• irrigation	• deeper wells		• water transfer schemes	• flow control • waste treatment • aeration	• dredging	• flow control • barrages • sluices • dredging

nia, Spain, Switzerland, and Yugoslavia. Large decreases in water supply may be experienced in countries including Bulgaria, France, Greece, Hungary, Italy, Portugal, Romania, Spain and Yugoslavia. The amount of water that is available in Belgium, the GDR and Poland, being water-stressed under the actual climatic conditions, shows an increase because of an increase in precipitation with the simulation results of the UKMO. The total runoff may also increase in these countries (Olejnik, 1988). This analysis on water availability is based on annual flows. The variation over the seasons and the years is also of considerable importance, as illustrated in Figure 2 by showing river discharge for some river basins in Europe. This wide seasonal and interannual variation indicates one of the major difficulties in projecting changes in water availability due to a climatic change.

The water shortage is expected to aggravate in the Mediterranean region, because of the drier and warmer summers. Soil moisture during Summer in southern Europe may decrease by between 20 and 50%, whereas soil wetness may increase over large regions of Europe, particularly in middle and high latitudes (Manabe and Wetherald, 1986). Gleick (1987) made an assessment on the effects of climatic change on seasonal runoff for the Mediterranean-style climate of the Sacramento River in California. He concluded that changes in seasonal temperature and precipitation of the magnitude of the UKMO might result in large changes in regional water availability. An increase of 4 °C in Summer temperature and a 20% reduction in precipitation resulted in a reduction of runoff of nearly 75%. An increase of 4 °C in Winter temperature with a 20% increase in precipitation would result in a 75% increase in runoff.

5. Related Issues: Consequences for Water-related Disturbances

5.1. Introduction

Changes in water conditions as described in this paper will affect society in a major way. The major implications are exemplified in Table IV, listing the main problems to be expected and engineering measures needed to mitigate the effects of such changes. The table lists the multitude of societal sectors that will be concerned. The water-related disturbances have been structured into two main groups: disturbance of land-based water uses, and disturbance of river-based water uses, respectively. The table also distinguishes different functional uses of river water: flow-related uses, use as carrier of effluents, use of water bodies as such, and use for activities related to water depth.

Based on the discussions on the major hydrologic trends, we recommend three important issues for future research and monitoring activities in the area of linkages between water availability and its fluctuations in time and space to vegetation, soil fertility, land use and societal activities in general. In Section 5.2, we shall describe the importance of variability changes of climatic and hydrological factors. An environmental assessment to link hydrological shifts to changes in land use patterns

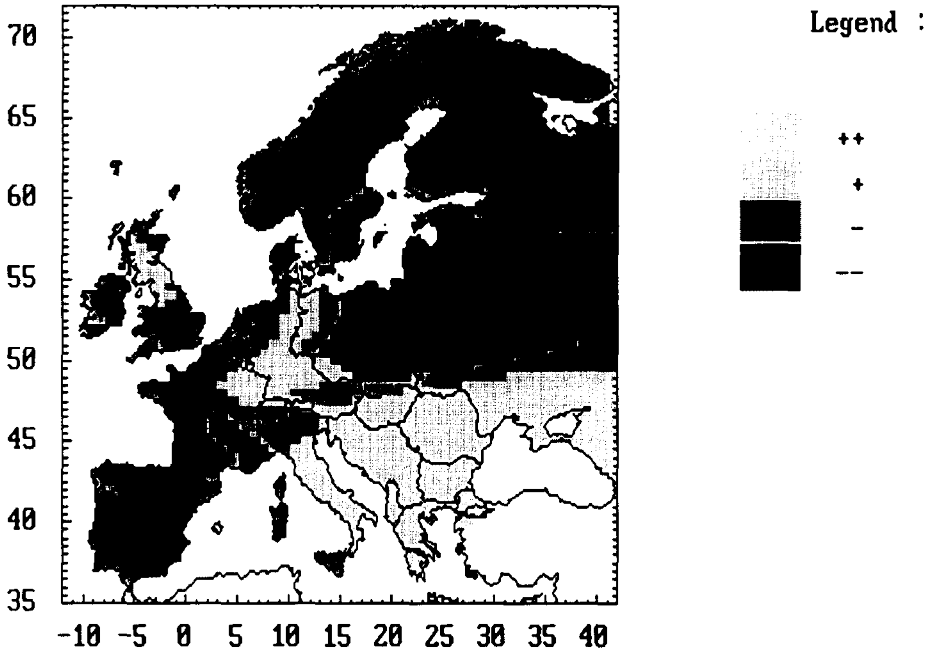

Fig. 11. Changes in the interannual variability of precipitation in Summer due to a climatic change (source: Lough *et al.*, 1983) (+ + = significant (5% level) increase in variability; + = increase in variability; − = decrease in variability; − − = significant (5% level) decrease in variability).

will be described in Section 5.3, to be followed by a proposed comparative historical study on the factors determining changes in water availability (Section 5.4).

5.2. CHANGES IN CLIMATIC VARIABILITY AND THE IMPACTS ON HYDROLOGICAL SHIFTS

Climatic factors such as temperature and precipitation are characterized by large interannual variation. Western Europe was during the Summer of 1976 affected by extreme droughts, which resulted in large soil moisture deficit, and a reduction of yields of as much as 30% in countries as Belgium and France and widespread problems over Europe: rural wells running dry, problems with municipal and industrial water supply due to exhausted water reservoirs, high levels of pollution in overloaded water courses, etc.

The frequency of extreme climatic events is expected to increase under climatic change (see for example Lough *et al.*, 1983). An important characteristic of the occurrence of extreme climatic events is the interannual variability of precipitation and temperature, which is expected to change in Europe. Figure 11 shows a scenario for changes in the interannual variability of precipitation in Summer due to climate change.

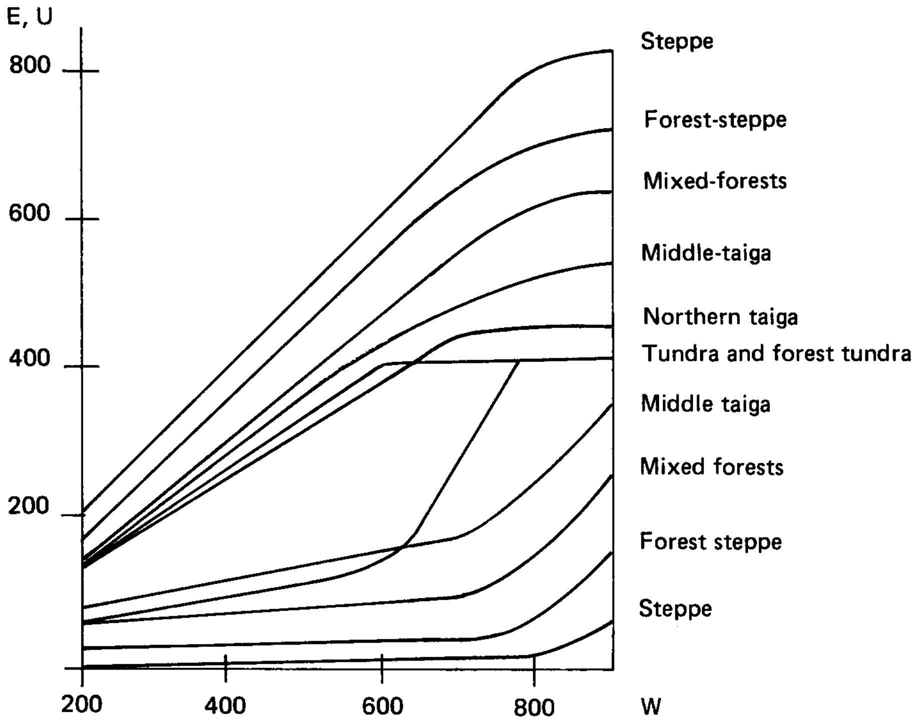

Fig. 12. Zonal regularities of the water balance elements in Eastern Europe according to Chernogaeva (1971). Diagram shows relation between evapotranspiration (E), upper set of curves, and groundwater recharge (U), lower set of curves, with land moisturization (infiltration, W) (in mm).

The interannual variability of precipitation in Summer might decrease in large areas of Europe with the exception of the south-eastern part of Europe, and parts of Central Europe. The largest increases in the interannual variability of precipitation are expected to occur during the Spring and Autumn season (Lough *et al.*, 1983).

The variability in climate components is reflected in the hydrological components, such as river flow, which is characterized by large interannual and interseasonal variations as was illustrated in Figure 2 for some river basins in Europe. The present rainfall/runoff models are not sufficient to incorporate interannual variability of runoff and (potential) evapotranspiration at the level of continents. In addition, the transfer function that links climatic factors with water balance components would also most probably alter under a changing climate. For example, changes in soil surface conditions as well as in vegetation will alter this function (RIVM, 1988).

5.3. Hydrological shifts and changes in land use due to a climatic change

Hydrological shifts are expected to produce major effects on both terrestrial ecosystems and water-related phenomena. To develop methods to assess these shifts will be an important task for future research. One rather crude way of addressing this issue might be to use empirical relationships between water balance elements and terrestrial ecosystems in ecological zones of Europe (Figure 12). In a long-term perspective, the relations would, of course, change as a result of new ecosystems developing in response to changed soil water infiltration, and changes in evapotranspiration. Early changes could, however, possibly be seen as perturbations in the present zonality pattern, i.e., move along the curves for specific ecosystems. Higher precipitation would in other words produce more groundwater. Subsequent changes would probably cause shifts to neighbouring ecosystems. In the former example, persistently increased groundwater would favor development of ecosystems adapted to wetter conditions.

A climatic change and an altered availability of water will have a major effect on the use of European land over the next decades, as well as on degradation factors (such as erosion, leaching of soluble components, depletion of nutrients and organic matter, and salinization) that relate to changes in using cultivated land and hydroclimatic conditions.

A proper assessment to link changes in soil moisture deficit with land degradation factors at the level of continents is still missing. This assessment is complicated by the occurrence of threshold conditions in the soils. That means that soil conditions which can be characterised as being stable could suddenly switch to a state that would allow erosion in various forms to take place.

5.4. A COMPARATIVE HISTORICAL ASSESSMENT OF CHANGES IN WATER AVAILABILITY

A proper assessment on interannual variability of water balance components in relation to a change in climate would require the collection of long-term historical data for a representative set of countries. Such a comparative historical assessment of hydrological shifts would require information on temperature and precipitation at a monthly level, soil and vegetation types, surface runoff and geophysical information on the watersheds. The European areas that are projected to be most vulnerable to a change in climate and consequential changes in hydrological phenomena are the Mediterranean region (with increasing soil moisture deficit in Summer) and northern Europe (with enhancement of soil wetness because of the increase in precipitation).

6. Concluding Remarks

The issue of water availability is already important in some parts of Europe suffering from a seasonal soil moisture deficit and societal water stress. However, this issue could become even more important, as demonstrated by the analysis of changes in hydrological shifts due to a change in climate. The following items ought to be taken into account in further explorations on future trends in water availability and their socio-economical consequences at a European level.

(1) Water authorities in areas suffering increasing shortages would be interested in developing methods for the conservation and recycling of water, including water

storage alternatives and parsimonious irrigation. The total amount of available water that can be made accessible from different sources (groundwater, aquifers and rivers) has to be matched, in time and space, with water demand for different purposes. It is likely that the need for a national water authority with broad responsibilities will increase in water-stressed regions, where it will also play an increasingly important role in an integrated view on the conservation and management of land and water;

(2) stimulation of research in the field of biotechnology to grow more drought resistant crops could provide species able to adapt to poor local climatic conditions. This can be incorporated in a land-use policy to improve the marginal land and to maintain the socio-economic structure of rural areas, but it would further aggravate the current problems of agricultural surpluses; and

(3) water shortage for growing crops (as defined by soil moisture deficit) could be characterized by large interannual variations, as the frequency of extreme climatic events is expected to increase over the next decades. The occurrence of extreme climatic events (e.g., frequency of very dry years) could become more important in southern Europe, which means that there will be more years with extreme levels of soil moisture deficit.

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