9 SUMMING UP EUROWASSER: AN INTEGRATED ASSESSMENT OF CLIMATE CHANGE IMPACTS ON EUROPE'S WATER RESOURCES

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9.1 Introduction

Water is a vital need of society, but it is not an easy need to satisfy. In particular, the fluctuation of precipitation from season-to-season and year-to-year means that there is often either too little water for its needs or too much to contain within the banks of a river. But over the scale of several decades both society and aquatic ecosystems are usually adapted fairly well to expected fluctuations, in that towns are usually built above the elevation of frequent floods and the sources of water supply do not frequently run dry. Of course society also uses many other strategies to cope with "normal" climate fluctuations such as by storing water in reservoirs, or constructing dikes to protect cities from periodic floods.

But climate change related to greenhouse gas emissions has changed the situation. Now it is conceivable, if not likely, that the build-up of greenhouse gases in the atmosphere will lead to major shifts in the spatial and temporal patterns of precipitation and temperature in Europe and elsewhere in the world over the next several decades. Figure 4.1 in this report shows, as an example, the changes in annual average precipitation in the 2020s and 2070s according to two different credible scenarios compared to the "climate normal" period (1961-90). Here annual average precipitation changes from about –25% to +25% depending on location. Climate modeling results also show that it is likely that climate change will alter the fluctuation of rainfall and other climate variables, that is, a change in the frequency or intensity of dry and wet periods (IPCC, 2001).

In the light of these climate changes, Europe needs to re-examine its current strategies for dealing with the fluctuations of climate. Important questions are: In which regions will average changes in water withdrawals and water availability significantly increase water stress? And in which "critical regions" of Europe might changes in the frequency and intensity of droughts and floods require new adaptive measures? These questions are addressed by the "EuroWasser" project whose findings are given in this report. EuroWasser was carried out by the Center for Environmental Systems Research at the University of Kassel, Germany and was financially supported by the Ministry of Education and Research of the Federal Republic of Germany.

In this chapter we review the main findings of the project.

Compared to other studies, the EuroWasser project has several unique features:

- Previous climate impact studies have focused either on the impacts of changes in the occurrence and intensity of extreme climate events such as droughts and floods over small areas, or the impact of average changes over large areas (as in the case of the ACACIA study; Parry, 2000). In this study we examine the impacts of changes in extreme climate events over a large area, namely continental Europe with about 10.5 million km^2.
- Studies up to now have usually focused on the impact of too little water (drought) or too much (floods), whereas in this study we examine changes in frequency and intensity of both. This study presents the first continental estimates of changes in intensity and frequency of droughts and floods under climate change and under changes in water withdrawals.
- Most studies have focused either on the impacts of climate change on water availability or the impact of changes in society on water use. Here we examine the impacts of both on Europe's water resources.

9.2 What is the approach of the project?

This study takes an "integrated assessment approach", meaning that information from various disciplines is drawn together and linked in a unified analysis. Furthermore, integrated assessment implies a link between science and policy, and we make this link by pointing out the regions in Europe where new adaptive policies may be needed to contend with climate-related changes in water resources. Scenario analysis is also used to evaluate "if – then" propositions – If climate changes according to a particular climate scenario, then how might the occurrence of droughts and floods change?

Another key aspect of our approach is that we use a global water assessment model called "WaterGAP" for obtaining a synoptic, long-term view of changes in Europe's water resources. The WaterGAP model provides quantitative estimates of water withdrawals and water availability (defined as the sum of annual average river discharge and groundwater recharge) for Europe with a spatial resolution of 0.5° latitude by 0.5° longitude (in Europe approx. 30 km by 50 km), and over a long time horizon (1901 to 2100). The model consists of two main components – a Global Water Use Model and a Global Hydrology Model – which are applied to compute water use and availability on the river basin level. The Global Water Use Model consists of domestic, industry and agriculture sectors. The domestic and industry sectors take into account the effect of structural and technological changes on water intensity, while the agriculture sector accounts especially for the effect of climate on irrigation water requirements. Total withdrawals are computed for each country and then downscaled to the grid- and watershed-level using population density and other indicators.

The Global Hydrology Model calculates surface runoff and groundwater recharge based on the computation of daily water balances of the soil and canopy. A water balance is also performed for open waters, and river flow is routed through a global flow routing scheme. The Global Hydrology Model provides a testable method for taking into account the effect of changed climate and land cover on runoff. The model includes a 0.5° drainage direction map and divides Europe into more than 550 first order watersheds.

As part of the EuroWasser study we have shown that the model gives reasonable estimates of the occurrence of low monthly discharge (see Chapter 7) and high monthly discharge (see Chapter 6), and can therefore be used to make first estimates of the occurrence of droughts and floods throughout Europe. Further details of the WaterGAP model are given in Chapter 2.

9.3 What is the current situation of water stress in Europe's rivers?

The concept of "water stress" is commonly used to obtain a synoptic first estimate of the state of water resources relative to its use. Generally speaking, the more often water is withdrawn, used, and discharged back into a river, the more a river is degraded or depleted, and the higher is its water stress. The higher the water stress, the stronger the competition between users, and the greater the barriers to its use downstream and to a future expansion of its use. A typical measure of this stress is the "withdrawals-to-availability ratio" (w.t.a.); where the higher the ratio, the higher the stress. The w.t.a. has the advantage of being transparent and computable for all river basins, although it is obviously a gross simplification of the processes of water scarcity (see Box 9.1).

To compute the w.t.a ratio for Europe we first estimate average annual water withdrawals and availability on the river basin scale using the WaterGAP model. Both water withdrawals and availability vary widely within Europe. Water withdrawals (in terms of the volume of withdrawals per unit river basin area) differ by a factor of 200 or more from watershed to watershed because of differing economic and population levels, and related levels of domestic, industry and agriculture water use (see Figure 5.1). Water withdrawals by industry (including power plants) dominate the use in most of Europe, but water for irrigation is very important in Southern and South-Eastern Europe. Of the estimated 415 km^3 withdrawn in 1995 slightly more went to industry than agriculture (see Tables 5.1 and 9.1).

Table 9.1: Total European water withdrawals.

Sector	Current (1995)		Baseline-A (2020s)		Baseline-A (2070s)	
	km^3/yr	%	km^3/yr	%	km^3/yr	%
Domestic	66.0	15.9	143.4	21.2	154.6	23.4
Industry	207.4	50.0	386.9	57.4	359.4	54.4
Agriculture	141.3	34.1	144.1	21.4	146.3	22.2
Total	**414.7**	**100.0**	**674.4**	**100.0**	**660.3**	**100.0**

Water availability also varies greatly from river basin to river basin in particular because of differences in precipitation in the upland areas. Annual availability ranges from above 1000 mm/yr along rainy stretches of the Norwegian and English coasts to below 100 mm/yr in parts of Spain, Sicily, Turkey and Southern Russia. Combining data on water availability with water withdrawals gives a highly variable picture of the level of water stress in Europe (see Figure 5.2). Different thresholds are used to estimate watersheds with "low", "medium", and "severe" water stress (see Box 9.1). Today, roughly one-fifth of Europe's river basin area falls in the "severe" water stress category, including many of Europe's largest or most important basins such as the Don, Meuse, Thames and Seine. Also, most river basins from Southern Spain to Turkey are in this category. The causes of severe stress differ from river basin to river basin, ranging from large industrial withdrawals on the Thames to irrigation withdrawals in Southern Spain.

Box 9.1: Thresholds for categories of water stress.

In this study we employ common thresholds for different categories of water stress, previously used, for example, by the World Water Commission (Cosgrove and Rijsberman, 2000) and a Consortium of U.N. organizations (Raskin, 1997). These are (based on the withdrawals-to-availability ratio "w.t.a."): "low stress" when w.t.a. ≤ 0.2, "medium stress" when $0.2 <$ w.t.a. ≤ 0.4, and "severe water stress" when w.t.a. > 0.4. It should be noted that the effects of severe water stress are very different between countries with a high economic level as compared to those with economies "in transition". Industry in richer countries tends to more intensively recycle its water withdrawals, and wastewater is more frequently treated before being sent on to downstream users. For these and other reasons countries that are more economically advanced can often intensively utilize their water resources without experiencing scarcity. By contrast, in countries with economies in transition, the level of water recycling and wastewater treatment is much lower and so the intensive use of available water resources (as indicated by w.t.a. ratios of greater than 0.4) can cause severe degradation in water quality and severe competition between water users (e.g. periodic disruptions in municipal or industry water supply).

9.4 How will water stress change in the future?

It is very likely that the level of water stress will change in Europe's rivers because of expected changes in both withdrawals and availability. Water availability is likely to change along with changes in long-term precipitation and temperature caused by greenhouse gas emissions. The location and intensity of withdrawals will change along with changes in European income, population and other factors as explained below. Although we must rely upon an inherently uncertain model to make these future estimates, the model does consider important factors such as the growth of household water use per person with income up to a saturation point. Also taken into account are the efficiency improvements that tend over time to lower the volume of water used per person, or per unit industrial output, or per hectare of irrigated land.

As assumptions of the driving forces for water withdrawals we use data from the “Baseline-A” scenario, developed for Europe and other world regions by the National Institute of the Environment, The Netherlands (Alcamo et. al, 1998). Driving forces for Baseline-A, in turn, were based largely on the driving forces of an intermediate scenario (“IS92a”) of the Intergovernmental Panel on Climate Change (IPCC, 1992). This scenario is also well within the range of marker scenarios of the updated IPCC scenarios (the so-called “SRES” scenarios documented in IPCC, 2000). Under Baseline-A, population and economic growth will continue in Europe, but at a slower pace than today. According to this scenario there will be large regional differences in growth as in the case of the much larger relative increases in the economy and electricity production in Eastern Europe and Russia as compared to Western Europe (see Table 5.1).

9.4.1 Changes in water withdrawals

Changes in driving forces lead to a very variable picture of changing withdrawals in different water use sectors and in different parts of Europe (see Figure 5.4 and Table 5.1). Over a large part of Northern and Central Europe, small increases in income tend to increase water use per person in the domestic sector but this is negated by even faster improvements in water use efficiency. This effect, together with the stabilization of population, leads to a long-term decrease in withdrawals in the domestic sector. Elsewhere in Europe, the growth in income leads to a larger growth in the amount of water withdrawn per household in order to satisfy the requirements for new water-using appliances such as washing machines and dishwashers, or water needed to irrigate larger lawns or to wash a greater number of vehicles per household. Improvements in water efficiency slow down but do not reverse these trends in Central, Eastern, or Southern Europe. An increase in population here has a strong effect as the increase in water use per household is multiplied by the increasing number of households. The net result is a large increase in water withdrawals over the long run (compare Table 5.1).

Meanwhile in the industrial sector, the volume of water withdrawn per unit electricity generated slowly sinks in Western Europe because of efficiency improvements. This effect, together with the slowing of the growth of electricity production and manufacturing, leads to an overall significant decrease in water withdrawn for industry. By contrast, economic growth in Eastern Europe and Russia boosts electricity production, and this is the main factor for the large growth in water withdrawals for industry in this region over the long run (compare Table 5.1).

Changes in water use for irrigation will be influenced by the future area and type of irrigated land and the number of farm animals, by improvements in irrigation efficiency, and also by changes in climate. In the Baseline-A scenario we leave the area of irrigated land and number of farm animals constant at their current values since further study is required to develop a credible long-term scenario of these factors. However, we take into account the effect of climate on the water required for irrigation, and we assume that the efficiency of water use on irrigated farms will continue to improve. The effect of changes in temperature and precipitation on increasing or decreasing the requirements for irrigation water per hectare are considered by using climate scenarios from global climate models (see below). In some parts of Europe where irrigation is important (for example, the Southern Iberian Peninsula, Italy, Greece and Turkey), the improvement in water use efficiency is more important than changes in climate, and there is a decrease in water withdrawn for irrigation. However, over much of the rest of Europe (except in Northern Europe where irrigation is not a big factor in agriculture) irrigation requirements moderately increase because of unfavorable climate conditions (compare Table 5.1).

Adding together the trends in different water use sectors we compute a significant decrease in annual water withdrawals between today and the 2070s in Western Europe, but a simultaneous sharp increase in Eastern Europe (see Figure 5.4 and Table 5.1). In particular, the increase in water withdrawals for industry is most important in Eastern Europe and Russia, while this type of withdrawals decreases in Western Europe.

9.4.2 Changes in water availability

While water withdrawals change along with demographic and economic changes, water availability changes because of modifications of Europe's climate. Here we have used climate projections for the 2020s and 2070s from the ECHAM4 model (Max Planck Institute of Meteorology, Hamburg, Germany; Röckner et al., 1996, 1999) and the HadCM3 model (Hadley Centre for Climate Prediction and Research, Bracknell, UK; Gordon et al., 1999). These projections are based on an average increase in greenhouse gas emissions that is consistent with the assumptions of the Baseline-A scenario. Precipitation and temperature data from the climate models are input to the hydrology model of WaterGAP to compute future river discharge.

We use climate scenarios from two different models because state-of-the-art climate models continue to give different estimates of future climate. Indeed, when we compare future availability using climate data from the two models we find that water availability changes differently or even in the opposite direction in parts of Europe (i.e. water availability increases when climate data is used from one climate model, and decreases when the other is used, see e.g. the Iberian Peninsula in the 2020s, Figure 5.3). On the other hand, results using climate data from both models are generally consistent in leading to an increase in availability through much of Northern Europe, and a decrease in much of Southern Europe (see Figure 5.3).

In Northern Europe the changed climate leads to contradictory tendencies in water availability. On the one hand, warmer temperatures tend to increase evapotranspiration (the loss of water by evaporation plus the passage of water vapor through the pores of vegetation) and hence reduce water availability. On the other hand, the increase in precipitation more than compensates for this, so that there is a net large increase in annual water availability. Climate data of the 2070s from both models give an increase in availability exceeding 10% over much of North-Eastern Europe, and 25% in its northernmost areas (see Figure 5.3). Of course, whether this increase in annual availability will actually augment the available water supply in a river basin depends on many factors, including when in the year the additional river discharge occurs or whether it can be stored.

In Southern Europe the combined warmer temperatures plus decreased precipitation lead to significant decreases in annual water availability. Data of the 2070s from both models suggest that annual water availability could decrease by more than 25% in parts of the Iberian Peninsula and Turkey (see Figure 5.3). These decreases will be especially unwelcome in these already arid areas.

We note at this point, however, that these estimates are based on only one reference scenario of changing greenhouse gases, whereas other equally valid scenarios would give stronger or weaker changes in water availability.

9.4.3 Changes in water stress

Using the computed trends in withdrawals and availability we can now compute the expected changes in water stress for European water resources. On the one hand, changes in Europe's socio-economic indicators will alter the pattern of water withdrawals, while on the other hand, climate change will alter the situation of water availability. Combining the two effects gives quite surprisingly different regional trends in water stress between now and the 2070s (see Figure 5.5). According to this scenario, water stress will level off or even significantly decrease over much of Northern and Western Europe because of increasing water availability and decreasing water withdrawals. Yet in some parts of Western Europe (e.g. over large areas of the Iberian Peninsula, France and Italy) withdrawals decrease but the decrease in water availability is even sharper, leading to a significant increase in water stress. Meanwhile, over most of Eastern and South-Eastern Europe, domestic and industrial withdrawals sharply increase and water availability either decreases or remains the same. As a result water stress increases by 50% or more and enters the “severe“ category (see Figure 6). These regions may be called Europe's “critical regions” of water stress, and under this scenario the largest water resource problems in Europe may arise here in the coming decades.

9.5 Will droughts occur more often?

Up to now we have examined changes in the long-term average water stress levels in Europe by examining changes in annual averages of water withdrawals and availability. But we noted above that climate changes are likely to include changes in the frequency and intensity of dry and wet periods. Here we address the question of whether changes in dry periods will affect the frequency and intensity of droughts.

Although they occur infrequently, droughts often have a heavy impact on society. For instance, a severe drought in the early 1990s was estimated to cost Spain several billion Euro (Garrido and Gomez-Ramos, 2000). Droughts can also affect many countries at the same time, as in the case of the European drought of 1976 which affected an area from Spain over France, Germany and Britain to Scandinavia.

Just how much will climate change affect the occurrence of droughts in Europe? Before answering this question we must address the more basic question of how to define drought? Alternatively, drought could be a deficit in precipitation, soil water, groundwater, or river discharge, or a shortage of water relative to demands for water. In this study we use the concept of "hydrological drought", which is defined as a deficit of river discharge. This definition has the advantage of giving an integrative view of deficits of precipitation, soil moisture, and groundwater, since they are reflected in the resulting discharge. With this concept we compute drought "deficit volumes" as an indicator to estimate the occurrence and intensity of drought events related to how long and how much a river discharge is below a reference minimum river discharge. To test this indicator for Europe, we have computed its values for historical flow conditions and found that it gives results consistent with what is known about past European droughts (see Chapter 7).

We next compared frequencies of drought occurrence under current and future climate conditions (using the climate scenarios above). One indicator was the change in the intensity of a drought with a particular return period (here "intensity" is defined by the deficit volume: i.e. the longer the discharge is below a defined threshold value, or the more it is below this value, the higher the intensity of the drought). Figure 7.9 compares the intensity of the 100-year drought (the drought with a statistical return period of 100 years) under current and future climate conditions (in the 2070s). Mainly because of increased rainfall, the 100-year drought becomes less intense over much of Northern Europe.

In other parts of Europe, in particular Southern and South-Eastern Europe, the intensity of the 100-year drought increases by more than 25% because of a combination of lower rainfall, warmer temperatures (which increase evapotranspiration) and greater water consumption. An important result of our study is that increased human consumption of water is an important factor in depleting river discharge. This increase can be explained by the rapid economic growth assumed as part of the Baseline-A scenario which stimulates greater consumption of water in households and industry.

An alternative way of analyzing the impact of climate change on drought is to assess if the current 100-year drought will become more or less frequent under climate change. The reasoning for this point of view is that usually society does not consciously prepare for very seldom drought events. But under climate change a rare but serious drought may become more frequent. In Figure 7.11 we see that over a large part of Southern and South-Eastern Europe the current 100-year drought will occur perhaps every 40 or 50 years, or even more often. What now occurs once a century might in the future occur every one or two generations. These results should be interpreted to mean that under climate change, the intensity of infrequent but inevitable droughts will be greater, and that current emergency plans and engineering structures (e.g. reservoirs) to deal with these events may be inadequate in parts of Europe. These "critical regions" are Southern and South-Eastern Europe.

9.6 Will the potential to generate hydroelectricity be affected by climate change?

Droughts in Europe place unusual pressure on municipal water supplies, water withdrawals for manufacturing, water needs of irrigation and the many other water requirements of European society. One specific and important impact examined in this study is the impact of climate change on hydropower potential in Europe. Hydropower now makes up a significant percentage (about 20%) of the total installed capacity for electricity generation in Europe (European Commission, 2000), and there is strong motivation to expand this capacity especially in Southern and Eastern Europe to provide electricity for economic growth.

Here we make a first order estimate of how climate change can alter the potential of generating hydroelectricity. Our analysis addresses the two questions, if river discharge was to change because of climate change, (i) how would the "gross hydropower potential" change (i.e. the potential if all runoff at all locations were to be transformed into energy), and (ii) how would the "developed hydropower potential" of current hydroelectric power plants change?

The gross hydropower potential, a highly theoretical value, is defined as the annual energy that is potentially available when all natural runoff at all locations could be harnessed down to sea level without any energy losses (regardless whether there is a power station or not). Of even greater interest would be the expected change in the so-called "technical", "economic", or "exploitable" potentials of Europe, but these estimates would require an extensive amount of additional data that were not available in our study.

With given elevation data and estimates of river discharge computed with WaterGAP, we first computed the current gross hydropower potential in order to set a benchmark to compare future changes under climate change. As expected, the highest potential is found in the wettest and most mountainous regions of Europe such as in the Alps and along the Norwegian coast (see Figure 8.1). For the whole of Europe the gross hydropower potential is estimated at 2500 TWh/a. Applying the results of the HadCM3 climate model (see above) for the 2070s, the change in discharge would lead to a reduction of the European gross hydropower potential to about 2400 TWh/a.

For the second assessment we consider only the developed hydropower potential of power plants that currently exist. It can be argued that it is unrealistic to assume that future plants will remain at their current location if climate change significantly alters river discharge. On the other hand, although this is conceivable, it is not particularly likely because it would be difficult to find new locations for hydroelectric plants owing to the public opposition to new plants, and because of the presence of settlements and other competing land uses at prospective new sites. Moreover, many hydroelectric plants are already located where the topography (i.e. the arrangement of hills and valleys, and the river slope) is best suited for exploiting hydroelectricity. Hence, it is of great interest to power producers to find out if the river discharge at their *current* location will change.

To carry out this analysis it was first necessary to develop a new database about the location, physical setting and operational characteristics of hydroelectric power plants in Europe (see Chapter 8). With these data, and employing discharge calculations of WaterGAP for today and for future scenarios, the changes of developed hydropower potential of about 6000 European power plants were assessed. Since the developed hydropower potential is strongly related to river discharge (the greater the discharge the more electricity produced by the plant's turbines) the change in future discharge (see Figure 8.3) indicates the change in future potential. By the 2070s we estimate an increase in potential over large areas in Northern Europe. During the same period there is a decrease of 25% or more in the developed hydropower potential of facilities throughout much of Southern and South-Eastern Europe.

Summing up the calculations on a country basis (see Table 8.2), shows that 22 European countries (out of a total of 40 examined) will have a net decrease in the developed hydropower potential at current hydroelectric facilities; 14 of these countries will experience a decline of more than 25% (according to at least one climate model).

This means that for many hydroelectric plants in Europe a decrease in discharge could endanger their long-term electricity output. Moreover, according to the Baseline-A scenario examined in this study, the need for electricity will increase sharply between now and the 2070s in Eastern and South-Eastern Europe, and it is logical to assume that part of this electricity production would be needed from the expansion of hydroelectric facilities. In other words, while hydroelectric plants in these regions are under pressure to expand their output, climate change may at the same time hamper their capability to produce electricity.

9.7 Will floods become more frequent?

We noted above that some regions are likely to suffer less often from droughts because of increased precipitation. While this may be true, our analysis has also shown that some of these areas could also experience more intense and frequent floods. By floods we mean an infrequent event of high river discharge, which depending on local topography and the extent of flood defenses, could inundate normally dry land. As in the case of droughts, society has more or less adapted to regular and frequently occurring high river flows but not to the more seldom and serious events. Therefore, here we examine different indicators of infrequent but potentially damaging river flows.

One change to be expected is that the month of the highest flows may significantly switch over much of Europe. Figure 6.6 shows that in the colder areas of Northern and Central Europe the highest river discharges occur each year during the snowmelt period of spring to early summer. In contrast, river basins in the more maritime influenced rest of Europe have their highest discharges during pronounced precipitation periods in winter. The simulation of the 2070s, however, shows that for the snow-dominated areas warmer temperatures bring on earlier snowmelt and thus maximum river discharges occur earlier in the year. One implication of this shift in high discharges is that flood emergency authorities may have to modify their plans for dealing with floods.

To identify the critical regions for changes in flood frequency we first examine the change in the magnitude of the 100-year flood. We focus on this return period because engineers often use the 100-year flood as a reference point for designing flood protection works. The "critical regions" (as defined as river basins having a 25% or more increase in the magnitude of the 100-year flood) cover much of Sweden, Finland, the Baltic States, and Northern Russia. These are generally the areas least affected by increasing drought as noted above, but most affected by stronger floods. Depending on the applied climate scenario and time slice, also parts of the Iberian Peninsula show an increase in the magnitude of the 100-year flood; this is most likely due to rise in discharge in one or a few months of the year, whereas the total sum of discharge over the year decreases.

As we reported for droughts, another perspective for identifying critical regions regarding floods is the change in the frequency of the 100-year flood. Here the critical regions can be defined as river basins where the current 100-year flood will statistically return at least every 40 or 50 years because of climate change. This leads to basically the same areas as described above.

Comparing the simulation results for 2020s and 2070s also showed important changes with time. For example, climate data from the HadCM3 model produced an increase in flood frequency for much of Southern Europe in the 2020s, but a decrease in the 2070s (see Figure 6.9). These dynamic effects of a changing climate could make it especially difficult for flood emergency planners in these parts of Europe to estimate flood frequencies based on measured year-to-year discharges.

9.8 Uncertainties and future work

At the beginning of this chapter it was pointed out that estimates presented here are based on modeling and scenario analysis. While these techniques help us maintain consistency in thinking about the future, they cannot avoid the uncertainty that inherently comes from making estimates about the future. In these estimates, there are particular areas of uncertainty that need to be addressed:

- **The uncertainty of climate scenarios**. Climate scenarios used in this report are based on *global* climate models that have a rather crude spatial resolution (about 200 km x 200 km) relative to the actual differences that are observed from place to place in precipitation and other climate variables. A better representation of the actual spatial details of climate variables are given by a new generation of *regional* climate models, and it is recommended to use these models in further assessments of climate impacts on Europe's water resources.

- **The uncertainty of river discharge calculations.** The model used to compute river discharges in this study also has a coarse spatial resolution, although not as crude as the global climate models. Within this report (Chapters 3, 6 and 7) we tried to evaluate the accuracy of the model by comparison to more finely scaled models and to measured data. The results are promising, but much work needs to be done in improving the model's ability to compute very low and high river discharges, especially in arid areas where transpiration from plants and evaporation play an important role in the local water balance or in snow dominated areas where snowmelt is a dominant factor in causing floods.

- **The need for scenario analysis.** In our study we have pointed out the significant and varying changes that could occur in Europe's water resources under changes in society and climate. Although these changes could have many different directions, in this study we have examined only one of many possible driving force scenarios. An urgent task is to carry out a more comprehensive analysis of different scenarios of changes in water withdrawals and availability. These scenarios should represent a credible range of possible trends in population, economy, climate and other variables in the coming decades. A requirement of these scenarios is that the socio-economic and climatic driving forces should be internally consistent. For this reason, the scenario analysis could use the driving forces and resulting climate scenarios of the recently developed "SRES" scenarios of the Intergovernmental Panel on Climate Change (Nakicenovic et. al, 2000). These scenarios provide regional estimates of economic growth and demographic change that can serve as input to withdrawal calculations. The greenhouse gas emission scenarios have been used by various global climate modeling groups to produce climate scenarios that can be input to availability calculations.

9.9 Final conclusions and recommendations

In this report we have assessed the possible impact of climate change on Europe's water resources. We have also included the complicating factor of growing water withdrawals and their influence on water stress. Since there is no standard yardstick to measure these impacts, we use the concept of "critical regions", meaning regions where the extent of changes to water resources (according to different measures) is larger than in other European regions. The thinking behind this concept is that the regions facing the most rapid changes (in the direction of higher risk) may have to devise the most drastic adaptation measures. Conversely, regions with slower changes may be able to gradually, and without special effort, adapt to the changes in their water resources.

As the basic spatial unit of our analysis we have taken the river basin and grid cell because water withdrawals, availability, or drought and flood frequencies cannot, in our opinion, be meaningfully averaged over larger scales like countries. Within each of the approximately 550 first order river basins and 6500 grid cells making up Europe, we have estimated several measures of changes in water resources because it is unclear which measure is best suited for assessing impacts on society and ecosystems. Indeed, an urgent task for the research community is to identify relevant and measurable indicators of impact. This task requires multi-disciplinary studies of the vulnerability of society to changes in water resources, and such studies must in particular include social scientists who up to now have played only a small role in water resource studies. Despite the challenge of this task, it needs to be done.

As one measure of changes in water resources we have examined the change in "water stress" – here taken as an indicator of the pressure put on water resources by water withdrawals. We have shown that today's severe water stress regions in Europe include not only expected areas such as arid Southern Europe, but also heavily populated watersheds of North-Western and South-Eastern Europe because of their high water withdrawals. Under future changes in population, economy, and climate change we have shown that Eastern Europe will be an especially critical region for water stress because of the sharp increase in water withdrawals for households and industry, but also because of climate-related decreases in water availability. As compared to other regions, the pressure on aquatic ecosystems may increase faster, and the competition between water users may be greater. The need for intensive river basin management is likely to increase.

Another measure of change is the change in the frequency of drought. The critical drought regions (defined as a decrease in the return period of the current 100-year drought to 50 years or less) include much of Southern Europe and parts of Central Europe. In these calculations the increase in water consumption in the domestic and industry sectors again play an important role, especially in South-Eastern Europe. During periodic dry spells, this water consumption will deplete river discharge to a level below a critical reference flow. Drought planning in these critical regions may need to be revised in the light of these impacts and additional adaptive measures may be needed.

Consolidating the results for water stress and drought frequencies, Figure 9.1 shows that South-Eastern Europe might be the area with the greatest increase in pressure on its water resources in the coming decades. Here large areas fall under the critical regions definition regarding both water stress and drought frequencies, in total accounting for about a quarter of Europe's land area. This region might require the highest degree of adaptive measures to ensure adequate water supply and protection of aquatic ecosystems.

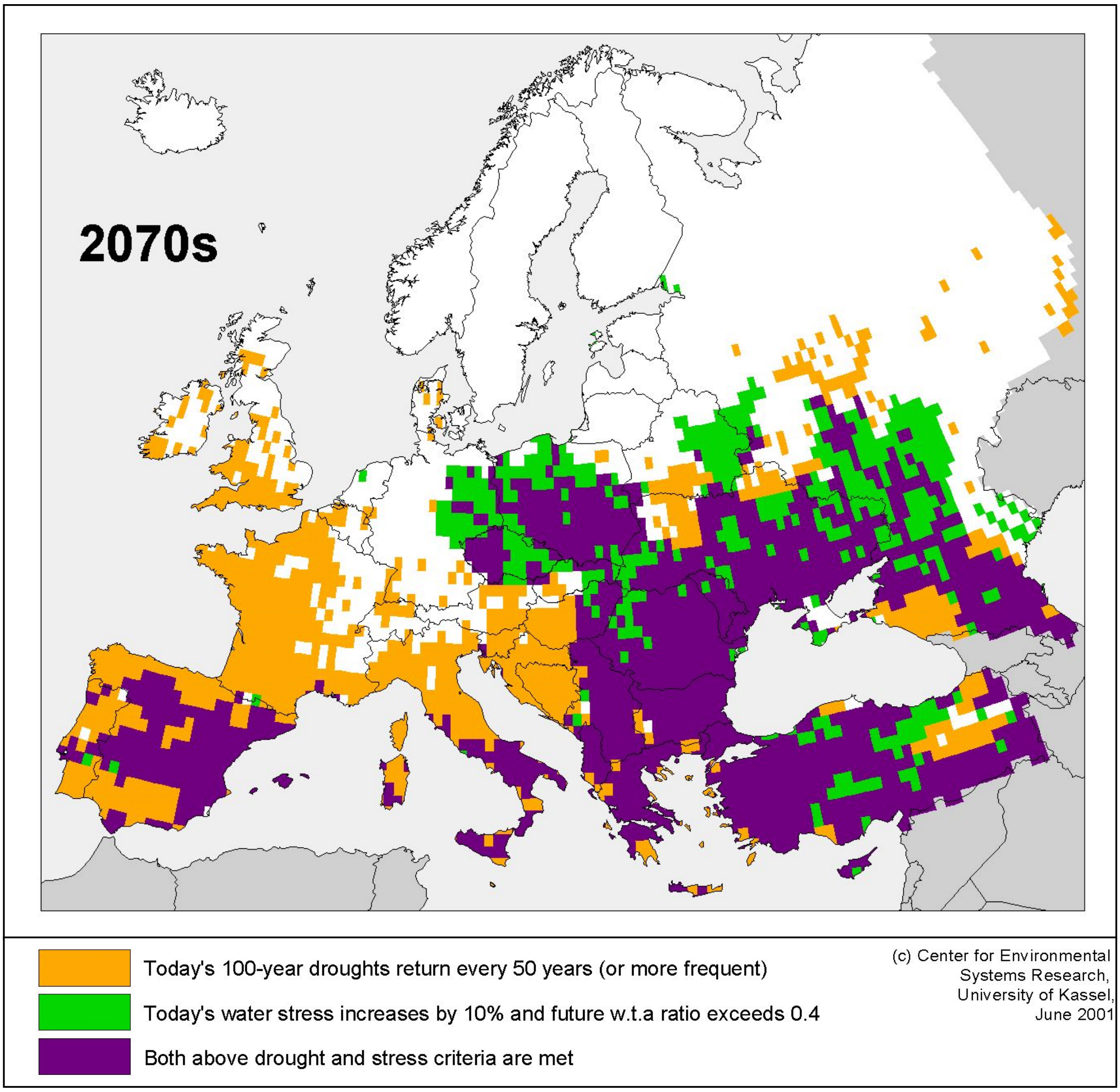

Figure 9.1: Critical regions as referred to (i) a decrease in the return period of the current 100-year drought to 50 years or less and (ii) an increase of today's water stress by 10% which leads to a future w.t.a. ratio greater than 0.4. Calculated with WaterGAP 2.1 applying the HadCM3 climate model and Baseline-A water use scenario for the 2070s.

Future changes in the occurrence of low flows and droughts may also affect the output of hydroelectric power plants. To address this issue we have computed both an indirect measure of this impact, namely the change in the gross hydropower potential (i.e. the potential if all runoff at all locations were to be transformed into energy) and a more realistic measure, namely the developed hydropower potential of current hydroelectric facilities. For the latter analysis we assumed that most of Europe's future hydroelectricity will be generated at current hydroelectric sites because they are already good sites, and because it is difficult to develop new sites in Europe. Under these assumptions, the critical regions (defined as where the developed potential of hydroelectric facilities will drop by 25% or more) will be similar to the critical regions for drought of Southern and South-Eastern Europe noted above. But not all countries are equally affected because some are more reliant on hydroelectricity than others. Of the 40 European countries investigated, 14 will experience a decline of more than 25% in developed hydropower potential. Nine of these countries are in Eastern Europe and they may be particularly affected by the decrease in hydroelectric potential because they are undergoing a rapid increase in the demand for electricity.

Although we have emphasized the negative impacts of climate change, it is also notable that 15% of Europe will have decreasing water stress under the long-term scenario investigated in this study. Where water stress decreases, water quality may improve (depending on the degree of wastewater treatment and many other factors), and aquatic ecosystems and biodiversity may recover. Also, according to this scenario, the current 100-year drought will occur less frequently in approximately half of Europe's land area, implying less frequent water shortages. In addition, the potential for generating hydroelectricity will increase in about the same areas, along with its evident economic benefits.

But the above benefits have an important caveat – although increasing precipitation could bring positive effects, it could also bring more intense and frequent floods. Critical flood regions (defined here as a decrease in the return period of the current 100-year flood to 50 years or less) include much of Northern Europe, and smaller parts of Central and Southern Europe. These regions cover many of the same areas that may benefit from decreased occurrence of drought. Here new strategies may be needed to prevent an increase in damaging river flooding. Preliminary modeling results indicate that some parts of Southern and Central Europe may even be in a special category where both droughts and floods become more frequent, e.g. the Wisla basin in Poland. This may be due to a change in the seasonal variability of precipitation and temperature in these areas, but the results are still very preliminary.

In Figure 9.2 we compare critical flood regions in blue, with critical drought regions in yellow. Here the two sides of the climate change coin becomes evident. Critical regions of either floods or droughts (or both) cover a total of two-thirds of Europe's land area. This result suggests that adaptation to more frequent extreme climatic events should be a major concern of European water resources management.

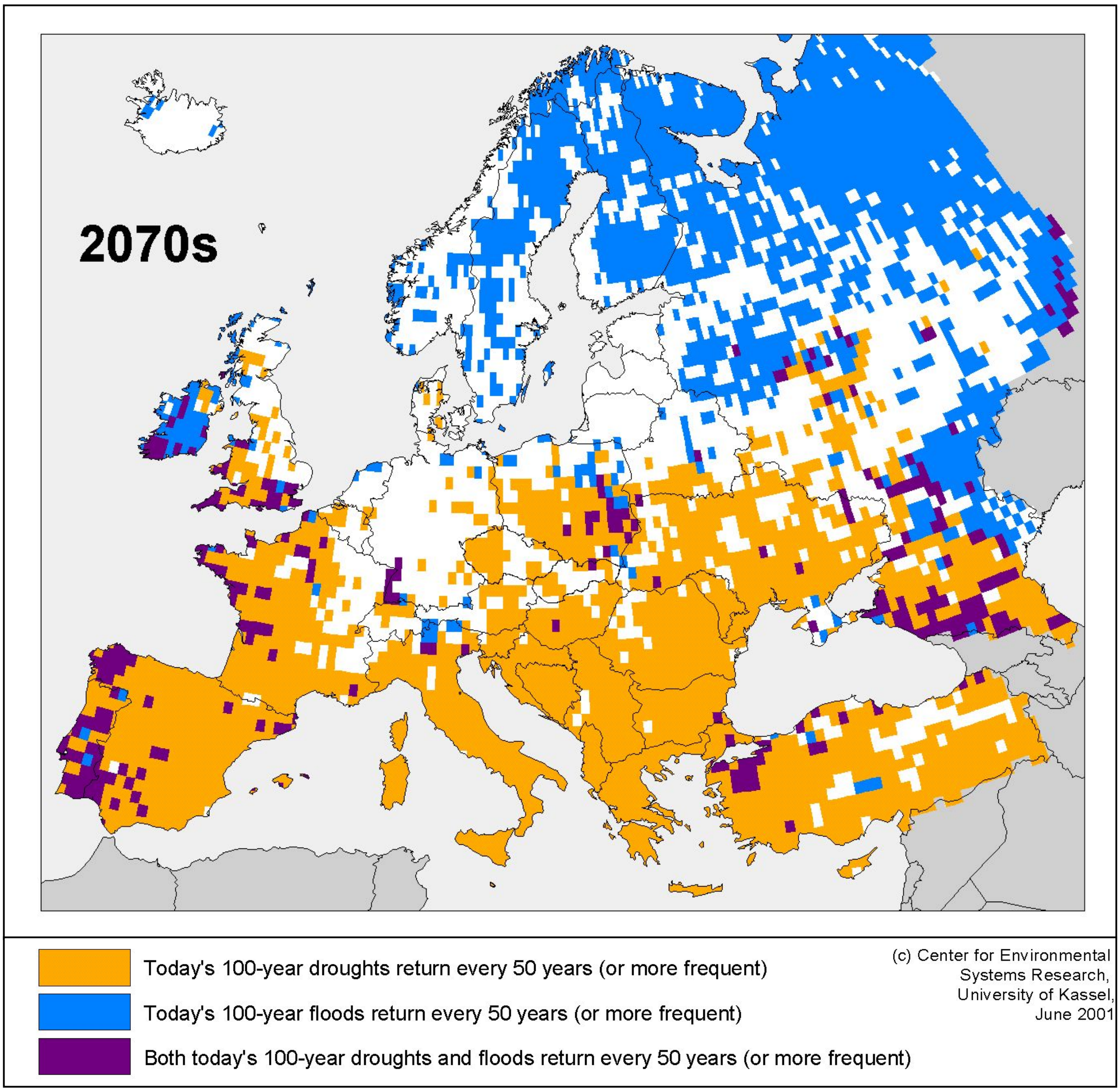

Figure 9.2: Critical regions as referred to (i) a decrease in the return period of the current 100-year drought to 50 years or less and (ii) a decrease in the return period of the current 100-year flood to 50 years or less. Calculated with WaterGAP 2.1 applying the HadCM3 climate model and Baseline-A water use scenario for the 2070s.

But what should the adaptation measures be? The long list of possibilities can be clustered into two categories:

- "demand side" measures that aim to reduce exposure to the impacts of climate change, and
- "supply side" measures in which actions are taken to directly counteract these impacts.

An example of a demand side measure is the reduction of water use through conservation or through changes in lifestyle or economic activity, which reduces the dependence of society on large volumes of water during periodic water shortages. Another demand side measure is reducing society's exposure to flooding by prohibiting development in flood plains.

An example of a supply side measure is counteracting more frequent or intense droughts by improving reservoir management or altering water distribution systems. Another supply side example is adapting to more frequent floods by creating natural inundation areas or by building dikes. These are just a few of the many adaptive measures available to European water managers in the face of increasing impacts of climate change.

The selection of these measures will depend on the type of new risks, the current adaptive measures being taken, the costs of new measures, the availability of land, and many other factors. Since these and other factors are mainly specific to the country and river basin, it is appropriate to evaluate these measures on these scales.

Yet although action should be taken on the national and river basin level, some intervention is also justified on the European Union level because of the large total European area that may experience either more frequent droughts or floods. It is also consistent with the findings of this study that droughts or floods could occur more often in different parts of Europe within a relatively short time of each other – Among other impacts, this could lead to the overtaxing of European emergency relief services. It is also conceivable that the financial burdens of dealing with two catastrophes within a short time span could lead to cascading financial problems between the tightly-knit economies of Europe. In any event, we recommend that the European Union review the adequacy of its planning for coping with water-related catastrophes in the face of climate change.

In conclusion, this study has shown that climate change will have mixed positive and negative effects on water resources in different parts of Europe, but that we should be especially alert to where it may cause new risks and require new adaptive strategies.

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