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An Integrated Analysis of Changes in Water Stress in Europe

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ABSTRACT

Future changes in water availability with climate change and changes in water use due to socio-economic development are to occur in parallel. In an integrated analysis we bring together these aspects of global change in a consistent manner, and analyse the water stress situation in Europe. We find that today high water stress exists in one-fifth of European river basin area. Under a scenario projection, increases in water use throughout Eastern Europe are accompanied by decreases in water availability in most of Southern Europe – combining these trends leads to a marked increase in water stress in Europe.

Keywords: water stress, runoff, water use, integrated analysis, global change, climate change, scenario analysis.

1. INTRODUCTION

The problems induced by using and often 'over-using' water resources have recently received increased attention. Considerable stress on water resources systems exists throughout Europe and worldwide. Growing demand for water in the households, industry, and agricultural sectors has lead to increased withdrawals, and may lead to even higher withdrawals in the future. At the same time climate change may reduce water availability at some locations.

Several studies have provided first continental or even global assessments of the current and future situation of water resource systems. The European Environment Agency, for example, confirmed that high levels of water stress exist in many countries throughout Europe [1, 2]. Similarly, the World Resources Institute warns that more than two-fifth of the world's population lives in water-scarce river basins, and that this number is likely to increase [3]. Studies commissioned by the United Nations extrapolate changes in water demand and expect considerable increases in water withdrawals both world-wide and in Europe until 2025, amounting to 20 per cent and more above today's levels [4]. Conversely, under a Business-as-Usual scenario examined for the World Water Commission [5] water withdrawals are expected to decrease in Europe. But even in the latter assessment, decreases in water withdrawals are only seen in Western Europe while withdrawals increase strongly in Eastern Europe, thus leading to a net increase in area and population affected by severe water stress in Europe. The Intergovernmental Panel on Climate Change warns that, in addition to the increasing demand for water, climate change is bound to impact the water cycle as well, and could lead to further decrease of runoff and groundwater recharge in many regions that experience high water stress today [6]. The effects of climate change on water availability will certainly vary regionally and between scenarios, depending strongly on projected changes in precipitation. In Europe, runoff is likely to decrease due to climate change in Southern Europe, and to increase in Northern Europe [7, 8].

However, most studies concerned with impacts of global change upon the water sector have so far focused exclusively on either future changes in water demand due to socio-economic development or on future changes in water supply resulting from climate change. But effects of changing water demand and supply will enhance each other in some regions, and cancel each other out in others. Thus, a comprehensive assessment of future changes in water stress needs to analyse the implications of global change on both water withdrawals and water availability. This calls for an 'integrated' analysis of global change impacts, that takes into account projected changes in both water withdrawals and water availability. In this study we use a global water model (WaterGAP) to carry out such an integrated analysis of changes in water stress in European river basins. We assess both the current and future situation of water stress in Europe under a consistent set of baseline assumptions of socio-economic and climatic driving forces.

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2. METHODOLOGY : THE WATERGAP MODEL

The WaterGAP 2 model (*Water - Global Assessment and Prognosis*, version 2), a global model of water availability and water use, has been developed at the Center for Environmental Systems Research at the University of Kassel, Germany. The aim of this model is to provide a basis both for an assessment of current water resources and water use and for an integrated perspective of the impacts of global change on the water sector. WaterGAP comprises two main components, a Global Hydrology Model and a Global Water Use Model. The Global Hydrology Model simulates the characteristic macro-scale behaviour of the terrestrial water cycle to estimate water availability; in this context we define 'water availability' as the total river discharge, which is the combined surface runoff and groundwater recharge. The Global Water Use Model consists of three main submodels which compute water use for the sectors households, industry, and irrigation. Both water availability and water use computations cover the entire land surface of the globe, except Antarctica (spatial resolution 0.5, i.e., 66896 grid-cells). A global drainage direction map with a 0.5 spatial resolution [9] allows for drainage basins to be flexibly chosen; this permits the analysis of the water resources situation in all large drainage basins world-wide. In this study, we use the WaterGAP model to examine the situation in European river basins, and distinguish approximately 800 large basins and sub-basins. Below we present an overview of the model structure; for a more detailed description of the model see [10–12].

2.1. Global Hydrology Model

The Global Hydrology Model calculates a daily vertical water balance for both the land area and the open water bodies of each grid-cell. The total runoff of each cell is then routed laterally to compute river discharge, following a global drainage direction map.

The vertical water balance for the cell's land fraction consists of a canopy water balance and a soil water balance. These are calculated as functions of land cover (which is assumed to be homogenous within each cell, based on results from the IMAGE 2.1 model [13]), soil water capacity (based on [14, 15]), and monthly climate variables (i.e., temperature, radiation, and precipitation [16]; or future climate projections from general circulation models). The canopy water balance determines which part of the precipitation evaporates from the canopy, and which part reaches the soil as throughfall. The soil water balance then partitions the throughfall into evapotranspiration and total runoff. Applying a heuristic approach, total runoff from land is further partitioned into fast surface/subsurface runoff and slow groundwater runoff; a detailed description of this partitioning is given elsewhere [17]. Additionally, a vertical water balance of open water bodies is computed for lakes, reservoirs and wetlands (based on a global 1-minute wetlands, lakes and reservoirs map [18]), with runoff being assumed to be the difference between precipitation and open water evaporation. All runoff produced within a cell, plus the discharge flowing into a cell from upstream cells, is transported through a series of storages representing groundwater, lakes, reservoirs, wetlands, and the river. Finally, the total cell discharge is routed to the next downstream cell of the drainage basin.

For 724 drainage basins world-wide, the discharge is calibrated against measured values by adjusting a single basin-specific runoff coefficient within the soil water balance, such that the long-term average annual discharge is within 1 per cent of measured discharge [19]. These 724 basins cover half the global land area excluding Greenland and Antarctica – in Europe, the model has been calibrated for 126 drainage basins, covering 65 per cent of Europe's land area. For uncalibrated drainage basins runoff factors are regionalised by applying a multiple regression approach.

2.2. Global Water Use Model

The Global Water Use Model calculates both consumptive and withdrawal water use in the households, industry, and irrigation sectors. Withdrawal water use is the quantity of water taken from its natural location, while consumptive water use is the part of the water withdrawn that is used for evapotranspiration. Water use in households and in the industry sector is computed annually, while for the irrigation sector the model delivers results by month. Each sector's water use is computed as a function of a 'water use intensity' and a 'driving force.' Variables representing water use intensity are per-capita water use (households), water use per electricity produced (industry), and irrigation requirement per unit of irrigated area (irrigation). Over time, society is subjected to both 'structural change' and 'technological change' both of which lead to changes in water use intensity; these concepts are based on knowledge about long-term trends of technology and energy (see, for example, [20]). Structural changes here reflect the idea that water use intensity changes are driven by the development of economies and lifestyles (households), by the shifting mix of thermal and non-thermal power plants (industry), or by changes in climate or in types of crops grown (irrigation). Technological changes complement structural changes and usually lead to improvements in the efficiency of water use, and thus to decreasing water use intensities. An example of this technological improvement is the continuous development and dissemination of more water efficient appliances in households during the last decades (e.g., [21]). By combining the concepts of structural and technological changes it is possible to estimate developments in overall water use intensities.

For the households and industry sectors, historical structural change curves have been derived from data provided by Shiklomanov [4, 22, 23] for 26 separate world-regions. Where additional data were available, the parameters have been calibrated for individual countries (in the model's current version this was possible for USA, Canada, Japan, and Germany). In the households sector historical structural changes in water use intensities can be described as a function of income and follow a sigmoid curve, which implies a saturation at high incomes. In the industry sector the structural changes in water use intensity with income are approximated with a hyperbolic curve which already stabilises at relatively low incomes. These functions are found to give good first approximations of historical trend in many regions [11]. To derive scenarios of country-specific future water use, regional structural and technological change assumptions are then applied to country estimates for present-day water use by sector [3, 23]. These country-specific values are finally distributed to the grid-cells following the spatial distribution of population, as well as information on urbanisation and access to safe drinking water.

Estimates for the irrigation sector rely on an irrigation sub-model to calculate monthly irrigation water requirement by grid-cell, which reflects an optimal supply of water to irrigated crops. To compute net irrigation requirements (i.e., consumptive water use) first the cropping patterns and optimal growing seasons for each cell with irrigated land are modelled using a rule-based system, making use *inter alia* of data on long-term average climate conditions and total irrigated area by cell [24, 25]. However, only rice and non-rice crops are distinguished in the current version of the model. The net irrigation water intensities are then computed for each day of the growing season in an approach similar to the CROPWAT approach [26] as the difference between crop-specific potential evapotranspiration and the plant-available precipitation. Taking into account regionally-varying irrigation efficiencies, gross irrigation water intensities (i.e., withdrawal water use) are computed.

Once the water use intensities have been determined for each sector, total water use is obtained by multiplying water use intensities with the respective driving forces. The corresponding driving forces by sector are population (households), electricity production (industry), and irrigated area (irrigation). By this procedure, current and future estimates of water use at the grid-cell level are calculated.

3. THE BASELINE-A SCENARIO

Scenario analysis provides a useful tool in environmental assessments for evaluating dynamic changes in society and environment. One of the first definitions cites scenarios to be 'hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision points' [27]. By this, scenarios can lead to possible images of the future, but these should not be interpreted as predictions or forecasts. Rather, scenarios unfold their full potential when seen to enhance learning of complex systems, to highlight inter-connectedness of driving forces, to raise questions, and to identify critical issues. To guarantee meaningfulness, scenarios should be based on a coherent, internally consistent, reproducible and plausible set of assumptions and/or theories of the key relationships and driving forces of change [28]. For this paper we conduct a long-term scenario analysis with a focus on the water sector by combining both socio-economic and climatic driving forces to describe developments between the base-year 1995, further referred to as 'today,' up to the 2020s and 2070s.

To embed our analysis into a wider frame of global change assumptions, we use the same driving forces used in a published scenario generated with the integrated IMAGE 2.1 model from the Dutch National Institute of Public Health and Environment (RIVM) [13]. Their scenarios are considered to be 'integrated' scenarios, as they give '*an integrated picture of global developments spanning a wide range of global change indicators, each of which are explicitly coupled*.' In effect, with this study we extend their analysis by highlighting implications for the water sector under their intermediate scenario 'Baseline A.' This Baseline A scenario is largely consistent with the no-climate-policy 'IPCC-IS92a' scenario estimates of the Intergovernmental Panel on Climate Change [29], which imply an average annual increase of global carbon dioxide emissions by one per cent per year until 2100. This global emissions pathway is also within the range of marker scenarios of the updated IPCC-SRES scenarios, and slightly above that of an intermediate scenario 'IPCC-SRES-A1B' [28]. Although socio-economic driving forces differ considerably on the global scale between the IPCC-IS92a and IPCC-SRES-A1B scenarios, they display rather similar trends for European countries (but with a somewhat higher economic growth assumption in Eastern European countries under IPCC-SRES-A1B). Yet, even with similar driving forces, climate projections, and especially precipitation estimates, vary considerably between general circulation models (GCM) – not only in magnitude but sometimes even in the direction of changes [6]. We therefore use climate projections calculated by two different state-of-the-art GCMs, the HadCM3 model [30], and the ECHAM4/OPYC3 model [31]. Appendix A describes how simulated climate data is scaled to match WaterGAP input requirements.

As far as possible, we rely on socio-economic driving forces and background as specified by the Baseline-A scenario. Where the WaterGAP approach requires additional input information (e.g., irrigated area), we borrow from the 'Business-as-Usual' scenario developed during the recent World Water Vision process [32]. This extended set of assumptions based on the Baseline-A scenario is further referred to here as the 'Baseline-A' scenario.

Under this scenario, population in Europe increases from 745 million in 1995 to 882 million in 2075. Income (given as

GDP per capita) grows at a slightly slower rate than historically, although GDP per capita still substantially increases in all European countries (between 1.7 and 4 per cent per year). Electricity production, as the main driving force for industry water withdrawals, follows very different trends in Western and Eastern Europe. In Western Europe, total electricity production rises in the first thirty years of the 21st century, but then drops back to today's levels before the end of the century. In Eastern Europe, total electricity production increases drastically, by a factor of five or more until 2100. The extent of irrigated area is assumed to remain constant throughout the century. And, finally, structural and technological change follow historical trends, as described above.

It should be noted that most scenario assumptions from the original Baseline-A scenario are provided at a rather coarse level of aggregation only, i.e., for thirteen separate world-regions (four of which contain European countries: Western Europe, Eastern Europe, Commonwealth of Independent States (CIS), Middle East). Consequently, these need to be 'down-scaled' appropriately for the WaterGAP approach. In Appendix A we describe the main socio-economic driving forces and how these have been derived in more detail.

4. THE WATER SITUATION IN EUROPE

A recent assessment of Europe's environment by the European Environment Agency warns that high levels of water stress, i.e., pressure on both quantity and/or quality of water resources, exists in many places throughout Europe and identifies several significant continuing pressures on water resources on the European scale [2]. Here we examine more closely the water stress situation in Europe with the WaterGAP model. First, the current situation of water availability and water withdrawals is compared, and resulting stress on water resources is characterised. Based on this description of the present-day state, the water sector related implications of the Baseline-A scenario are then discussed. We caution the reader that we present results from only one of many possible feasible scenarios. Nevertheless this scenario analysis does raise several critical issues.

4.1. The Current Situation

4.1.1. Water Availability

There is a large spatial variability in water availability (here: the annual long-term average renewable water resources) of river basins in Europe. Figure 1(a) shows that annual water availability ranges between well above 1000 mm (western Norway, Britain's west coast, southern Iceland) to below 100 mm (parts of Spain, Sicily, many regions of the Ukraine, southern Russia, large parts of Turkey). In most parts of Europe this reflects current patterns of precipitation – while in other parts runoff is carried through streams into more arid regions (Hungary, for example, receives most of its water from outside the country borders via the Danube). Note that this is accounted for in the WaterGAP model via a lateral routing scheme.

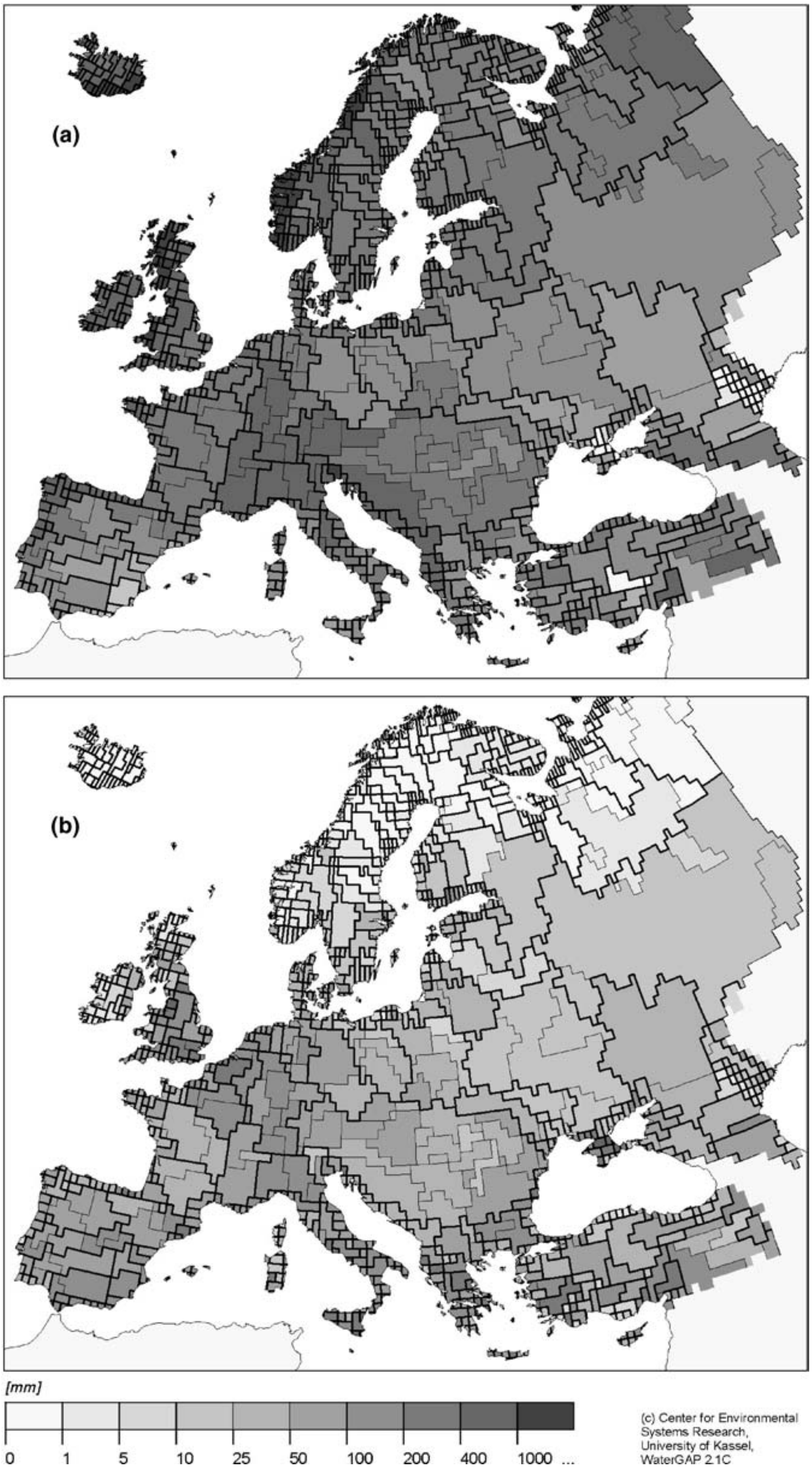
4.1.2. Water Withdrawals

During the last decades, total water withdrawals in Europe have in general increased. By 1995, a total of about 476 km^3 water was withdrawn annually – 45 per cent of this water is used for industry, 41 per cent for agriculture, and 14 per cent for domestic needs [4]. There is a huge difference between countries in how much water is withdrawn and for what purposes. The needs of industry dominate water withdrawals in most of Europe, while the share of irrigation is highest in Southern and South-Eastern European countries with low precipitation. Total withdrawals by river basin range from nearly zero (in the thinly populated areas of sub-polar Scandinavia and Russia) to well above 400 mm/a (in the most densely populated urban regions); see Figure 1(b).

4.1.3. Water Stress

To compare the level of water stress in different river basins we make use of the widely applied 'withdrawals-to-availability (wta)' ratio. A river (sub-)basin's wta ratio is defined by dividing annual water withdrawals (i.e., withdrawals within the basin itself plus withdrawals in all upstream (sub-)basins) by annual water availability. While this annual ratio does not capture inter-annual variability or seasonal droughts, it does give a first general approximation of the intensity of stress on water resources. In principle, the higher this ratio is, the more intensively water in a river basin is used, and hence the more stress is placed on water resources due to water extraction. We here employ commonly used thresholds [5, 33] to identify river basins under 'low' ($\text{wta} \leq 0.2$), 'medium' ($0.2 < \text{wta} \leq 0.4$) and 'severe' ($\text{wta} > 0.4$) water stress. Figure 2 presents an overview of the current situation utilising this common water stress indicator for European river basins, based on calculations from the WaterGAP model. River basins identified to be experiencing severe water stress are – among others – the Don, the Seine, the Meuse, the Thames, as well as most river basins in southern Italy, Spain, Greece, and Turkey. All in all, about one-fifth of European river basin area is classified as being under 'severe water stress.'

However, river basins may be in the severe water stress category for very different reasons. In southern Spain, for example, there are considerable amounts of river water extracted for irrigation purposes in rather dry regions with low water availability. In low-flow periods these relatively high levels of water consumption involve a threat of absolute water shortages. Conversely, very high demand of water for industrial use and in households may put a high pressure on both water quality and quantity in otherwise water rich river basins. Recent meteorological drought years in the Thames valley, for example, have prompted supply to fall below unrestricted demand, and thus lead to water shortages.



(c) Center for Environmental Systems Research, University of Kassel, WaterGAP 2.1C

Fig. 1. WaterGAP 2 computations for: (a) average annual water availability in European river basins based on a 30-year climate time series (1961–1990). (b) Average annual water withdrawals from European river basins in 1995. [Note that both water availability and water withdrawals in sub-basins within large river basins (with bold border-lines) have been accumulated along river networks.]

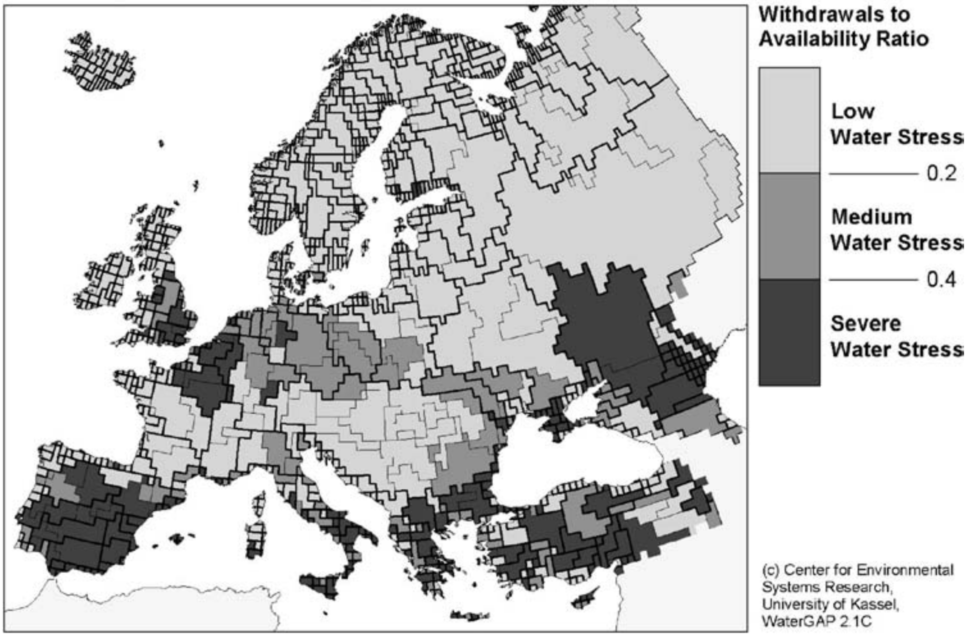


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Fig. 2. Water stress in Europe for today's situation. Water stress is given by the 'withdrawals-to-availability' ratio.

Although the wta indicator cannot distinguish these different aspects of water stress, it still gives a clear signal of severe water stress in both cases mentioned above. Thus, the wta indicator gives a good first impression of where water resource system are under notable pressure.

4.2. Future Changes – A Scenario Analysis

4.2.1. Water Availability

In its most recent assessment the IPCC warns that '*projected climate change could further decrease streamflow and groundwater recharge in many water-stressed countries*' [6]. Furthermore, the IPCC highlights that the effect of climatic changes on water availability will vary regionally and among scenarios, and in this largely follows projected changes in precipitation. As noted above, there are significant variations in the projected changes between different climate models, and therefore we here show the implications of temperature and precipitation changes from two different climate models (HADCM3 and ECHAM4) on water availability.

Figure 3 shows WaterGAP projections of mid-term (2020s) and long-term (2070s) changes in water availability. Relatively small changes are computed for most of Europe's river basins until the 2020s. Here, using climate output from different GCMs leads to contradictory results in some parts of Europe, with the most noteworthy contrast in southern Spain: Climate data from ECHAM4 suggests a decrease in water availability, whereas climate data from HadCM3 results in an increase. Notably, the trends for southern Spain under HadCM3 climate projections reverse in time, and by 2070 also lead to a decrease in water availability. In general, long-term changes in annual renewable water resources are found to be more pronounced – in some regions being as high as 50 per cent and more (both increases and decreases). Especially the Mediterranean region sees high decreases. Conversely, nearly all of northern Scandinavia and northern Russia (including the Volga basin) display an increased average annual water availability under both GCM realisations. Despite their differences, WaterGAP results based on both GCM projections agree that climate change will increase water availability in Northern and North-eastern Europe and decrease it in large parts of Southern and South-eastern Europe. In this overall tendency the results presented here agree with the findings of another recent study [8].

4.2.2. Water Withdrawals

The Baseline-A scenario leads to a marked difference in the development of water withdrawals between Western and Eastern Europe; Table 1 and Figure 4 highlight this development.

For most of Western Europe, the scenario leads to decreases in total withdrawals in the first half of the 21st century. Still, until the 2020s, small increases are seen in Ireland, France, and the United Kingdom. These increases result from assumed population growth in these countries which leads to an increased demand in the households sector. In the long-term (i.e., until the 2070s) these increases in the households sector are outweighed by decreases in industrial water abstractions, as water use intensity in the industry sector is reduced. For the rest of Western Europe, reductions in total water withdrawals are computed nearly everywhere. These reductions stem mainly from technological changes which continue to increase efficiency of water use in households and the industry sector.

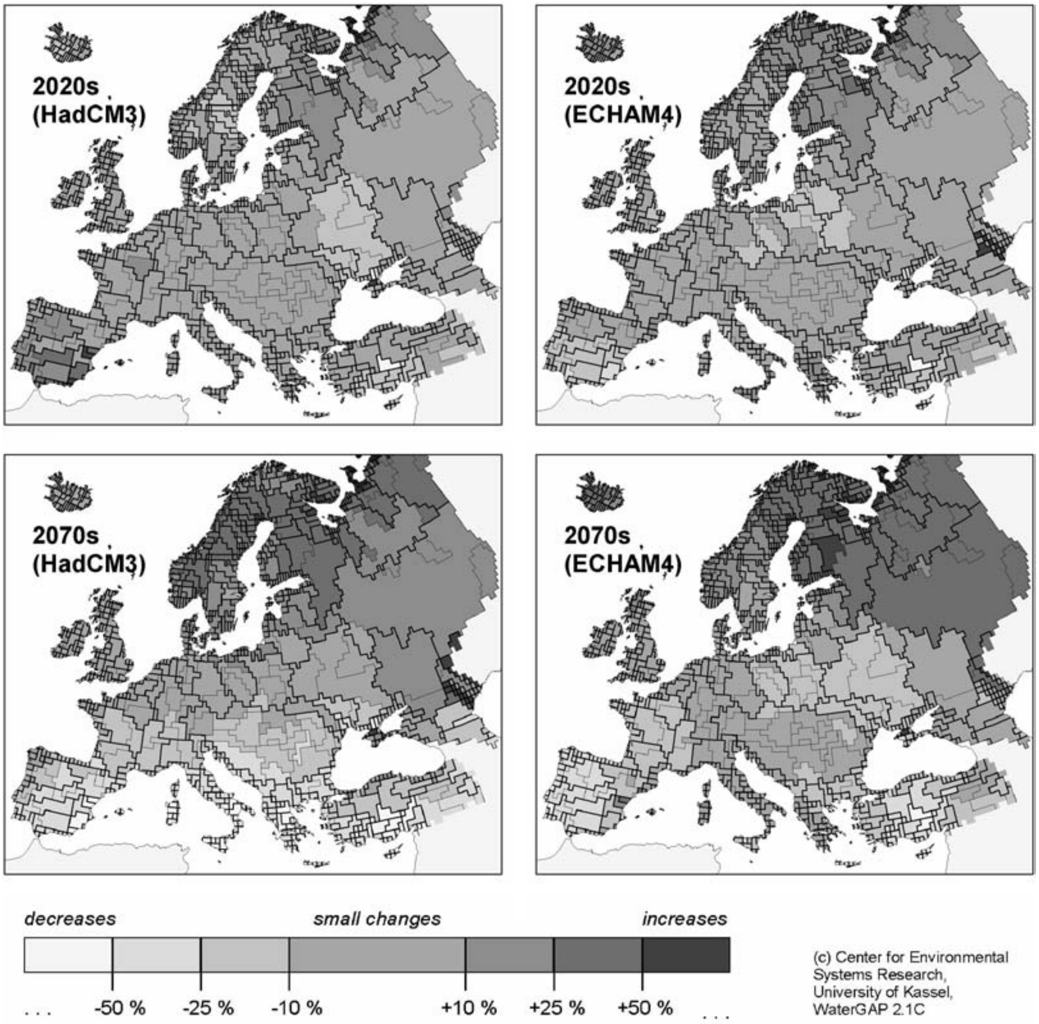

Fig. 3. Percentage change in average annual water availability for European river basins under the Baseline-A scenario assumptions compared to today's levels realised with two different GCMs (HadCM3 and ECHAM4) for the 2020s (upper row) and for the 2070s (lower row).

In Eastern Europe, however, the scenario assumptions lead to large increases in water withdrawals, as a consequence of high increases in demand for water in both the households and the industry sector. Especially abstractions for industrial purposes are assumed to rise sharply as a result of the large increases assumed in electricity

Table 1. Water withdrawals [km^3/a] in Europe by sector in 1995 and in the 2070s under the Baseline-A scenario.

World-region (*)	Withdrawals Today (1995)				Withdrawals Baseline-A (2070s)			
	Househo.	Industry	Irrigation	Total	Househo.	Industry	Irrigation	Total
Western Europe	42	118	76	236	48	69	74	191
Eastern Europe	10	32	33	75	27	164	36	227
European CIS	15	57	33	105	80	126	36	242
Europe	67	207	142	416	155	359	146	660

Note. (*) World-regions are here defined as follows: **Western Europe** comprises country-values from Belgium, Denmark, France, Finland, Germany, Greece, Iceland, Ireland, Italy, Malta, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom. **Eastern Europe** comprises country-values from Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia, Yugoslavia. **European CIS** comprises country-values from Belarus, Estonia, Latvia, Lithuania, Moldavia, Ukraine, and the European parts of the Russian Federation.

Note that figures for **Turkey**, while included on the maps displayed in this paper, are not included in this table (nor in the other tables presented in this paper). This is due to consistent historical and scenario driving force data not being available to the water use dynamics for neither the household nor the industry sector – thus reducing meaningfulness of this study's estimates in these sectors for Turkey considerably.

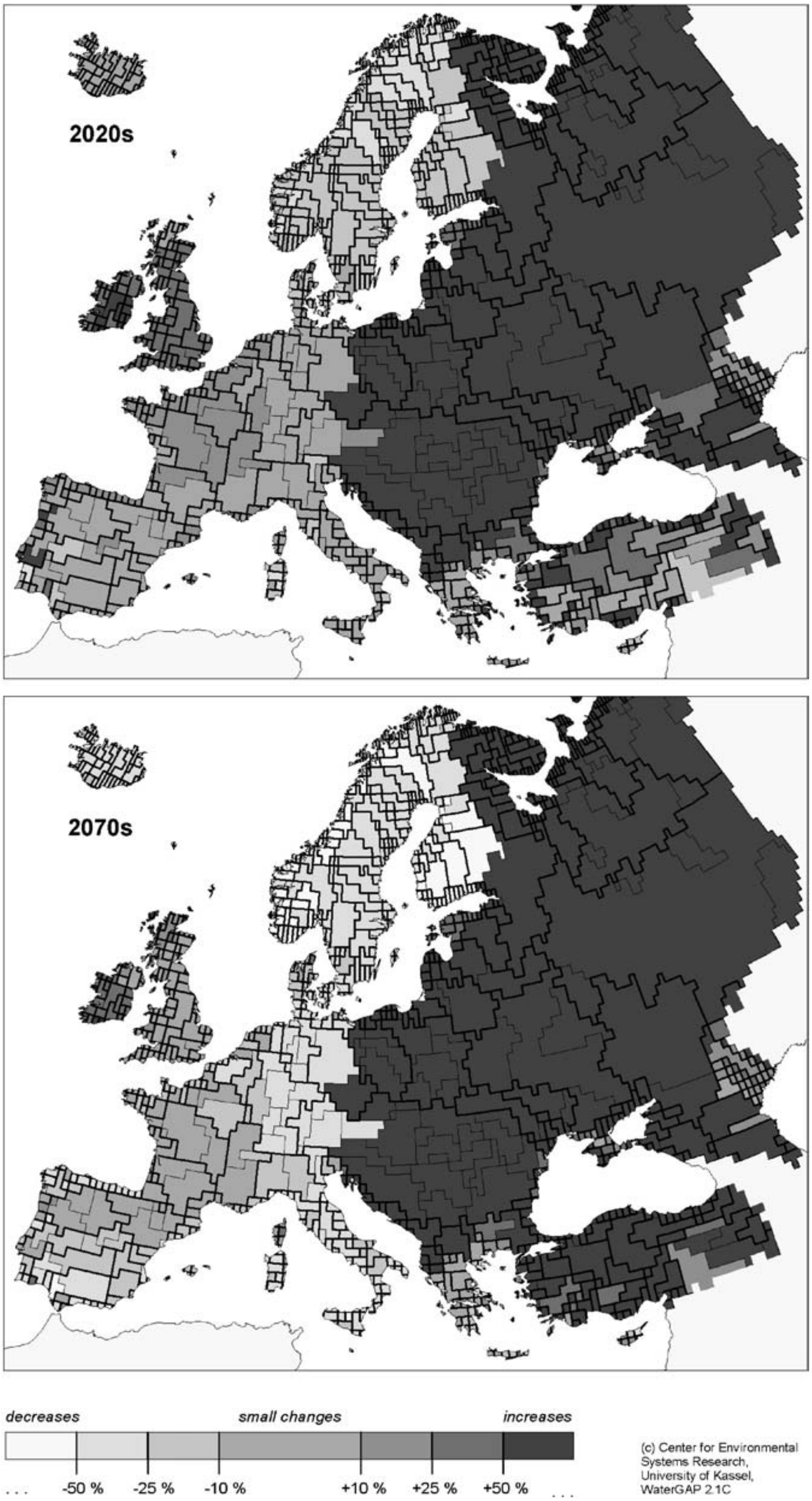

Fig. 4. Percentage change in annual total water withdrawals for European river basins under the Baseline-A scenario assumptions compared to today's levels realised for the 2020s and 2070s. [Note that water withdrawals for agriculture calculations are based on climate data from HadCM3.]

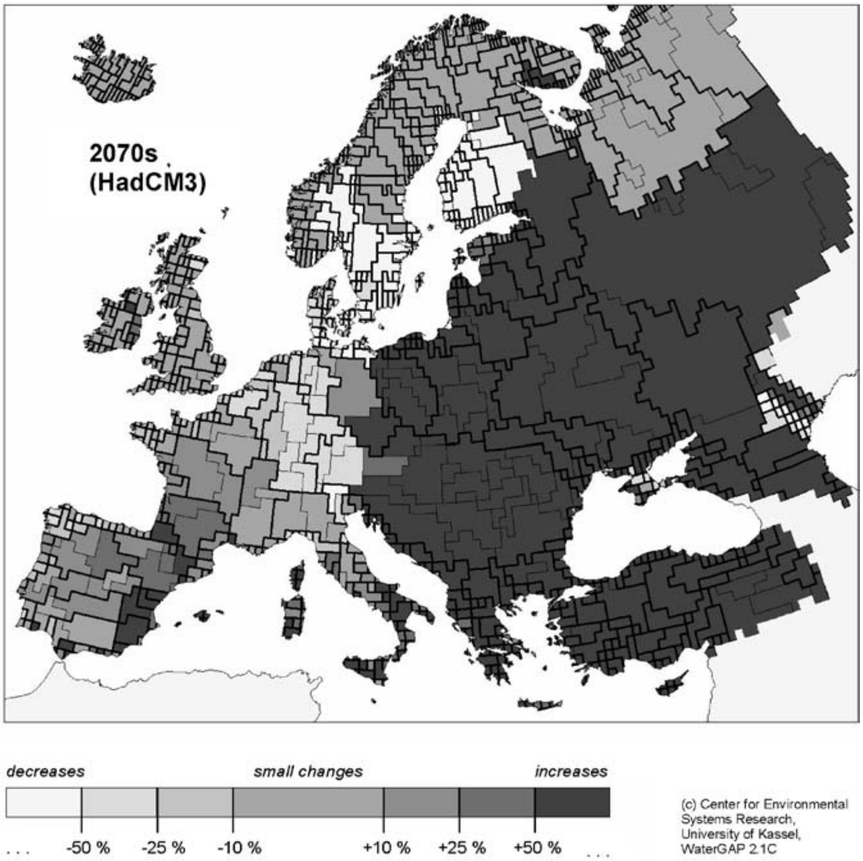

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Fig. 5. Long-term projection of changes in water stress in Europe under a Baseline-A (with climate data from HadCM3) scenario between today and the 2070s. [Note that combined changes in water availability and water withdrawals in sub-basins within large river basins have been accumulated along river networks.]

production (which is, as is noted above, assumed to grow by more than a factor of six in total). Withdrawals for the households sector are also computed to rise throughout Eastern Europe. In total, water withdrawals in Europe (excluding Turkey) are projected to rise from today's 416 km^3 to about 660 km^3 per year until the 2070s in the Baseline-A scenario. While annual total withdrawals in Western Europe decrease from 236 km^3 to 191 km^3, they rise considerably in Eastern Europe and the European CIS from 180 km^3 to 469 km^3.

The reader should be reminded that these projections are based on one feasible set of assumptions only. As this particular set of assumption presumes high increases in thermal electricity production in the East of Europe compared to today's level, increases in water withdrawals are computed to be very high. While this set of assumptions is as legitimate as any other projection of the development of socio-economic driving forces, we note that other equally feasible projections are possible, some of which may lead to somewhat lower water withdrawals in Eastern Europe. Still, even if the magnitude of changes may be contested, generally strong growth in water demand is likely to accompany economic and industrial development.

4.2.3. *Water Stress*

In discussing future levels of water stress, the effects of changing water availability due to climate change and changing water withdrawals have to be brought together, as they are bound to be complementary in some parts of Europe and contradictory in others. Figure 5 shows the combined implications of the Baseline-A scenario with HadCM3 climate projections. Results show decreasing pressure on water resources systems in large parts of the Scandinavian countries, due to combined effects of decreasing withdrawals and increasing availability. Also, most of the Benelux countries and Germany, and the North-western tip of Spain see decreasing water stress mainly due to reduced water withdrawals, as water availability is only slightly changed. Conversely, water stress increases in most of Spain and large parts of Southern France, often despite decreasing water withdrawals. In these river basins the effects of reduced water availability due to climate change dominate the overall trend. This may be particularly important, as many river basins on the Iberian peninsula are already regarded to be under severe water stress today. Also, most of Eastern Europe faces increases in the level of water stress, primarily because of projected growths in water withdrawals. In South-eastern Europe

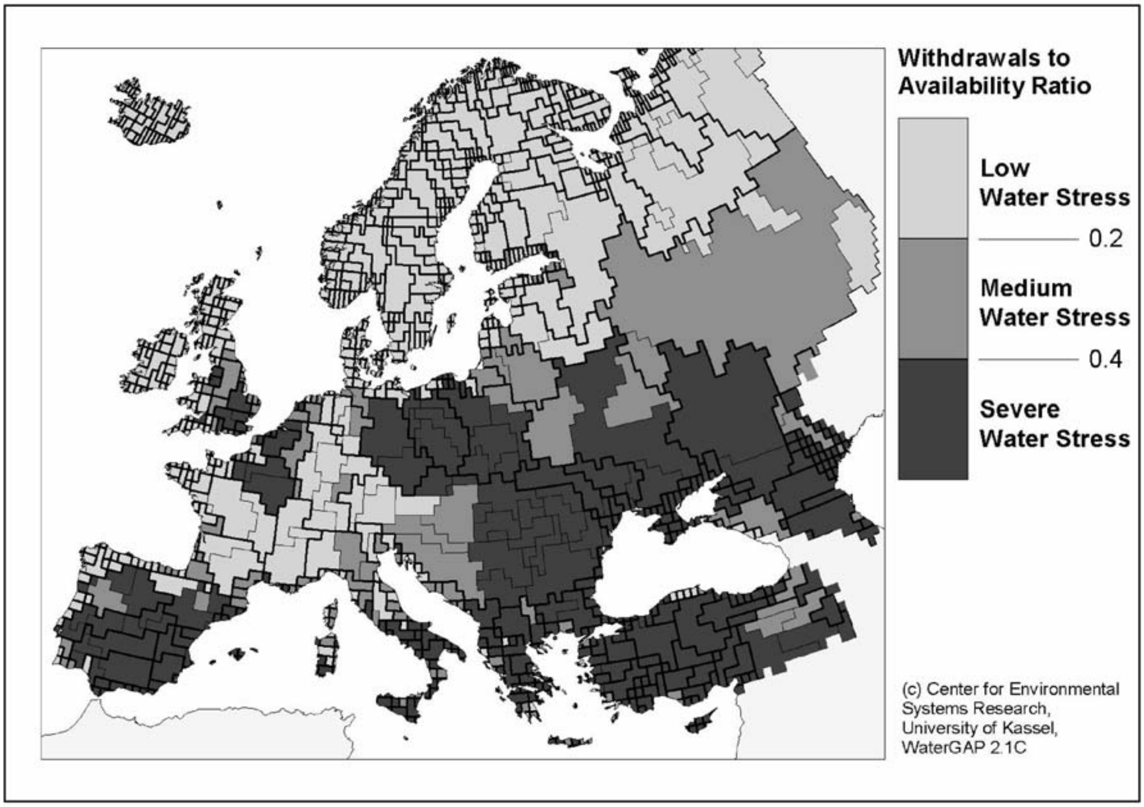

Fig. 6. Water stress in Europe in the 2070s under a Baseline-A (HadCM3) scenario. Water stress is given by the ‘withdrawals-to-availability’ ratio.

this growth in water demand is complemented by additional reductions in water availability due to climate changes. This combination enhances increases in water stress here.

In total, European river basin area in the severe water stress category increases from 19 per cent today to 34 to 36 percent by the 2070s (depending on the climate scenario). Figure 6 shows that most of the river basins regarded to be experiencing high levels of water stress remain in the highest stress category under the scenario projections. Additionally, many Eastern European river basins would then also be in the highest water stress category. As noted above, it should be kept in mind that these increases in water stress are rather sensitive to the assumption of a very high increase in the extraction of cooling water for thermal power generation throughout Eastern Europe. And although these results are based on one set of scenario assumptions only, they show that socio-economic development and industrial growth can have the same magnitude of impact on water stress as climate change.

5. CONCLUSIONS

With this study we present an ‘integrated’ analysis of global change impacts on European river basins, that brings together projected changes in both water withdrawals and water availability in a consistent manner. While preliminary, this study indicates several important trends that will influence future changes in water stress in Europe:

- Despite their differences, two different state-of-the-art climate models indicate that annual water availability generally increases in Northern and North-eastern Europe and decreases in Southern and South-eastern Europe. This overall trend is in agreement with the general findings of other recent studies [6, 8].
- Projected changes in water withdrawals strongly depend on the assumptions regarding economic and industrial growth. Following a common set of assumptions, we compute very different trends in water withdrawals for Western and Eastern Europe. Withdrawals tend to decrease in the long-term in Western Europe, mainly resulting from gains in the efficiency of water use. In Eastern Europe withdrawals are projected to increase strongly, particularly due to the critical assumption of growing demand for cooling water in thermal electricity production.
- When these trends in water availability and water withdrawals are combined, pressure on water resources increases sharply in most of Eastern Europe. This increase brings many Eastern European river basins into the high

water stress category. Additionally, those river basins in Western Europe under high water stress today remain in this category despite reductions in water withdrawals. In Europe as a whole, this leads to a notable increase in river basin area under high water stress, from one-fifth under present-day conditions to about one-third for the 2070s.

It should be noted that scenario results are very sensitive to the socio-economic driving forces assumed. Therefore using a different set of scenario driving forces for the households, industry, or irrigation sectors may lead to very different results for water use. For a more complete picture it is worthwhile to repeat this analysis with a wider range of scenario assumptions.

Also, projections for individual countries may differ strongly from the regionally based projections presented here. Nevertheless, in the absence of additional information, we assume that the regional trends in driving forces apply to all countries in that region. Particularly the currently implemented structural change curves for domestic and industrial water use appear to be very sensitive to the resolution of data used for model calibration. Additionally, the long-term data, that was available for the calibration of the structural changes curves may not capture in full the more recent developments that result from implementing market economies in Eastern Europe. This again may lead to too high increases in water withdrawals here. Further improvement of the water use model, however, will depend strongly on availability of differentiated water use data on the country-scale or at even higher resolutions.

Nevertheless, the assessment presented here confirms that the impacts of societal, economic, and industrial development on water resource systems may be of the same order of magnitude as changes in water availability due to climate change. Therefore the analyses of future global change impacts upon the water sector should take into account not only changes in climate but also changes in socio-economic driving forces.

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APPENDIX A – DRIVING FORCES UNDER THE BASELINE-A SCENARIO

Climate Driving Forces

In the WaterGAP approach, climate driving forces (i.e., radiation, temperature and precipitation) impact both on irrigation water use and water availability. With respect to climate we focus our analysis on three time-slices: Today's climate, future climate in the 2020s, and future climate in the 2070s. Today's climate is depicted by a 30-year time series (1961 to 1990) of observed monthly precipitation and temperature values on a 0.5° degree global grid from [16]. To derive appropriate future scenarios, today's climate is scaled by applying changes projected by general circulation models (GCMs). As the precipitation estimates vary considerably between GCMs – not only in magnitude but sometimes even in the direction of changes [6] – we construct different future climate projections as input to our model, based on calculations from two different state-of-the-art GCMs:

(i) The HadCM3 model from the Hadley Centre for Climate Prediction and Research (Bracknell, UK) with transient all-anthropogenic forcing integration (HC3AA) and greenhouse gas forcing similar to the IPCC-IS92a scenario [30].

(ii) The ECHAM4/OPYC3 model from the Max-Planck Institute for Meteorology (Hamburg, Germany) with transient greenhouse gas and sulphate aerosol integration and greenhouse gas forcing according to the IPCC-IS92a scenario [31].

First, by applying a simple interpolation procedure, the GCM results are interpolated from their original resolutions to a 0.5° degree grid. Then, for both GCMs, the decadal averages of mean monthly values of precipitation and temperature of the years 2020 to 2029 (for the 2020s) and 2070 to 2079 (for the 2070s) are determined. Also, to reflect the GCM calculations of present climate conditions, the averages of 1950 to 1979 (of the ECHAM4 model) and 1960 to 1989 (HadCM3) are computed. These GCM-based averages of future and present climate conditions are then used to scale the present-day 30-year time-series [16]. For temperature, the observed time-series are scaled by adding the respective difference between the future and present-day temperature as calculated by the GCM (Equation A1). For precipitation, observed precipitation time-series are scaled by multiplying them with the respective ratio between future and present-day precipitation as calculated by the GCM (Equation A2) – an exception to this rule is applied when present-day precipitation is zero or close to zero.

$$T_{\text{scaled future}} = T_{\text{CRU, present-day}} + (T_{\text{mean GCM future}} - T_{\text{mean GCM present-day}}) \tag{A1}$$

$$P_{\text{scaled future}} = P_{\text{CRU, present-day}} \cdot (P_{\text{mean GCM future}} / P_{\text{mean GCM present-day}}) \tag{A2}$$

with

T	average monthly temperature [°C]
P	average monthly precipitation [mm]
scaled future	monthly value in 30-year time-series representing future decade
CRU, present-day	monthly value in observed 30-year time-series (1961 to 1990)
mean GCM future	monthly average of future decade as computed by GCM
mean GCM present-day	monthly average of present-day climate as computed by GCM

Following this method, monthly climate time series are constructed for the 2020s and the 2070s for both GCMs. It should be noted that possible effects of climate change on the year-to-year variability are not taken into account.

Socio-Economic Driving Forces and Key Assumptions

The sectoral water use sub-models of WaterGAP rely on several socio-economic driving forces. Water use by sector is calculated as a product of water use intensities and the respective sectors' main driving forces, i.e., *population* (households), *electricity production* (industry), and *irrigated areas* (irrigation). Additional driving forces determine how water use intensities change due to structural and technological changes. In the households and industry sectors structural changes are represented as a function of *income*. Also, assumptions as to the type of mathematical function that describe *structural change* in water use intensity with income, need to be specified to match scenario assumptions. In the irrigation sector water use intensities depend on the types of crops grown, and on climatic conditions. Further driving forces that need to be detailed are the assumed future rates of *technological change* in the individual sectors, which represent improvements in the efficiency of water use.

Population

The assumed trends in population for the Baseline-A scenario have been derived from the United Nations 'medium' scenario, for which a time-series of population by world-region with five-year steps between today (i.e., 1995) and 2100 was given [23, 34]. To derive updated country-level population numbers consistent with these regional numbers, the country projections from the United Nations 1998 revision [35] were scaled to match the Baseline-A scenario's regional total population. The main reason for scaling the newer United Nations estimates to match the older regional values rather then implementing the newer projections, is to be consistent with the other driving forces derived from the Baseline-A scenario based on the older estimates. Also, the United Nations country projections only extend up to the year 2050. Thereafter, each country's share within its respective world-region is held constant, such that population by country develops relative

Table A.1. Total population in Europe[millions] following the Baseline-A scenario.

World-region (*)	1995	2025	2050	2075	2100
Western Europe	384	406	394	391	388
Eastern Europe	121	143	149	149	148
European CIS	180	193	186	185	184

Note. (*) Definition of World-regions as given in Table 1.

Table A.2. Average income [US$/cap] in Europe following the Baseline-A scenario.

World-region (*)	1995	2025	2050	2075	2100
Western Europe	19748	36271	54687	75392	96177
Eastern Europe	2037	7263	9977	13713	17500
European CIS	3526	11430	15480	21045	26687

Note. (*) Definition of World-regions as given in Table 1.

to the regional growth rates of the original Baseline-A scenario after the year 2050. Population distribution within countries is based on 'Gridded Population of the World – Version 1' data provided by the Center for International Earth Sciences Information Network (CIESIN). Table A.1 summarises the regional population figures of the applied scenario.

Income

For each of the thirteen world regions of IMAGE 2.1 assumptions on growth of income, (GDP per capita) are based on IPCC estimates until 2100. For most regions these estimates are lower than the historical trends. Nevertheless they lead to substantial increases in GDP per capita worldwide. Despite assumed higher annual growth rates in today's poorer regions, and thus a decrease in the relative gap between economies, the current large gap in absolute terms between Western and Eastern European countries will remain throughout the 21st century under the Baseline-A scenario.

In a preliminary step, the regional totals for GDP per capita given by IMAGE 2.1 are scaled such that they match present-day country income data [36]. For WaterGAP computations, the development of regional income then needs to be disaggregated to the country level. This disaggregating-procedure follows two criteria:

(i) We assume the incomes of individual countries within a specific world-region converges in the long-term, i.e., by the year 2100. By this, two countries within the same world-region which had a different income in 1995 (e.g., Spain, with 13,279 US$/cap, and Norway, with 31,550 US$/cap) would have the same income by 2100 (i.e., that of the respective world-region, in this case Western Europe with 96,177 US$/cap). The main reason for these criteria is to avoid an unreasonable widening of absolute income gaps *within* world-regions.

(ii) A time series is derived to bridge today's income and income assumptions for 2100. Therefore the income difference between individual countries and their corresponding world-region's average is assumed to reduce linearly with time. To complement the example given above: Spain's income in 1995 was 6,469 US$/cap lower than the West European average. Following this criteria, this gap would only be about half as wide by 2050 (i.e., 3,185 US$/cap), and close by 2100.

By applying this procedure, GDP per capita in Western European countries, for example, increases between 1.1 per cent (in today's richer economies) to 3 per cent (Greece and Portugal) per year. Table A.2 summarises the regional figures for income and the corresponding growth rates of the scenario.

Electricity Production

Country projections of electricity production are derived following an approach similar to the income projections. The IMAGE 2.1 model computes electricity production [MWh] for each of thirteen world-regions; current country level data on electricity production is based on United Nations data [36]. Similar assumptions are made for the change in future electricity intensity of economies [MWh/GDP] as were made for income above. Scenarios for country-scale electricity production are derived by combining the assumptions on future electricity intensity with scenarios of income.

For Western Europe this first leads to an increase, peaking in the 2020s at about two-thirds above today's level of electricity production. Thereafter, electricity production slowly decreases in the Baseline-A scenario, falling even slightly below today's total by the end of the 21st century. Conversely, in Eastern Europe and the CIS countries electricity continues to increase, reaching more than six-times today's levels. Table A.3 summarises the regional figures for electricity production and the corresponding growth rates applied in the Baseline-A scenario.

Irrigated Areas

As irrigation water use makes up a large fraction of total water use, the rate of expansion of irrigated area is one of the main driving forces of water use scenarios. Unfortunately, the IMAGE 2.1 model does not explicitly deal with changes in the extent of irrigated land. For this reason, and because the future of irrigation is unclear, we have here assumed no change in irrigated area in Europe.

Table A.3. Total electricity production [GWh] in following the Baseline A scenario.

World-region (*)	1995	2025	2050	2075	2100
Western Europe	2378	3945	3588	2728	2036
Eastern Europe	405	2048	2551	2718	2545
European CIS	902	2977	3575	4477	5164

Note. (*) Definition of World-regions as given in Table 1 above.

Structural Change

As noted above, the Water Use model assumes structural changes in the intensity of future water use. For the scenario analysed here, we follow the approach applied in the World Water Vision's 'Business-as-Usual' scenario [10, 32]. Future structural changes are thus assumed to follow curves consistent with historical trends. By this, water use intensities are approximated by a sigmoid function of income for the households sector and by a hyperbolic function of income for the industry sector, as described above. In the irrigation sector, no changes in the mix of crops irrigated (regarding rice and non-rice crops) are assumed. Still, modelled water use intensities in the irrigation sector are bound to change with changing climatic conditions.

Technological Change

Assumptions about future technological changes base on the assumptions of the World Water Vision's 'Business-as-Usual' scenario. In both the households and industry sectors, technological changes continue to reduce water use intensities all over Europe at the current estimated pace (about 2 per cent per year; see [21]) until 2005 when the pace is assumed to slow to 1 per cent per year following current trends in many areas of technology. After 2025 the pace is then assumed to further slow to then 0.5 per cent per year. Similarly, improvements in the water use efficiency in the agricultural sector continue to reduce water withdrawals by 0.3 per cent per year until 2025. In line with the assumptions made for other sectors, this pace halves to 0.15 per cent per year thereafter.