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Modelling Current and Future Pan-European Irrigation Water Demands and Their Impact on Water Resources

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1. Introduction

70% of the gross global water abstractions from water resources can be explained by water withdrawals for irrigation purposes (Portmann et al., 2010). This number even rises to 90% when considering the global water consumption (Siebert et al., 2010), which is also called net irrigation water use. Furthermore, the need of irrigating field crops highly correlates with climatic conditions, which leads to intense irrigation applications in warm and water scarce regions. In pan-Europe this especially holds true for the semi-arid regions in Mediterranean countries, such as in Spain, Israel, and Turkey (Aus der Beek et al., 2010). Therefore, it is important to analyze the impact of these water withdrawals on existing water resources in order to evaluate the consequences for sustainable water management.

Within this model experiment first the historic and current net and gross irrigation water requirements are being spatially explicitly calculated for pan-Europe. The next step includes integrating these irrigation water uses in a hydrological model on the same spatial and temporal domain. After the successful validation and verification of the model results, both for irrigation and hydrology, by comparing them to reported national irrigation sums and observed river runoff data, the model concept is being transferred to simulate potential future changes of and global change impacts on irrigation water use for the 2050s. Hereby, the effects of climate change and socio-economic change on future irrigation withdrawals and water resources are being evaluated separately. Socio-economic impacts on irrigation water withdrawals are mainly being expressed by increasing or decreasing spatial irrigated extents. Here, several factors, amongst others increases in food demand due to increasing world population (Lutz et al., 2008), changing human dietaries (Hanjra & Qureshi, 2010), biofuel production (Timilsina & Shresta, 2011), influence these future irrigated extents. Another important factor is climate change (Schlenker & Lobell, 2010; Olesen & Bindi, 2002), as it not only is able to reduce local yields due increasing air temperature and climate variability but also to increase local yields due to high atmospheric CO_2-concentrations (Long et al., 2006). Schaldach et al., (2011a) provide for the first time a separation of these influencing factors on future changes in irrigated areas and irrigation volumes for pan-Europe. In the here conducted study the same model set-up has been used to further analyze the impact of these factors not only on irrigation volumes but also on the consequences for pan-European water resources.

2. Material and methods

2.1 The study region

The pan-European study region has been developed within the EU-FP6 project SCENES which provides different pathways for the future of pan-European freshwater resources. It includes all European countries as well as their neighboring states, reaching from Northern Africa in South to the Near East in the South-East to the Russian Ural Mountains in the East (see Figure 1). The southern and eastern borders of the study region have been derived from river basin boundaries and are thus not concordant with political borders. An overview about the design of the study region and the contents of the SCENES project is given in Kamari et al., (2008). Based on the UN-classification the pan-European study region has been further divided into seven sub-regions to better allow for the analysis of regional differences: NA (Northern Africa), WE (Western Europe), NE (Northern Europe), SE (Southern Europe), EEc (Eastern Europe, central), EEe (Eastern Europe, eastern), and WA (Western Asia).

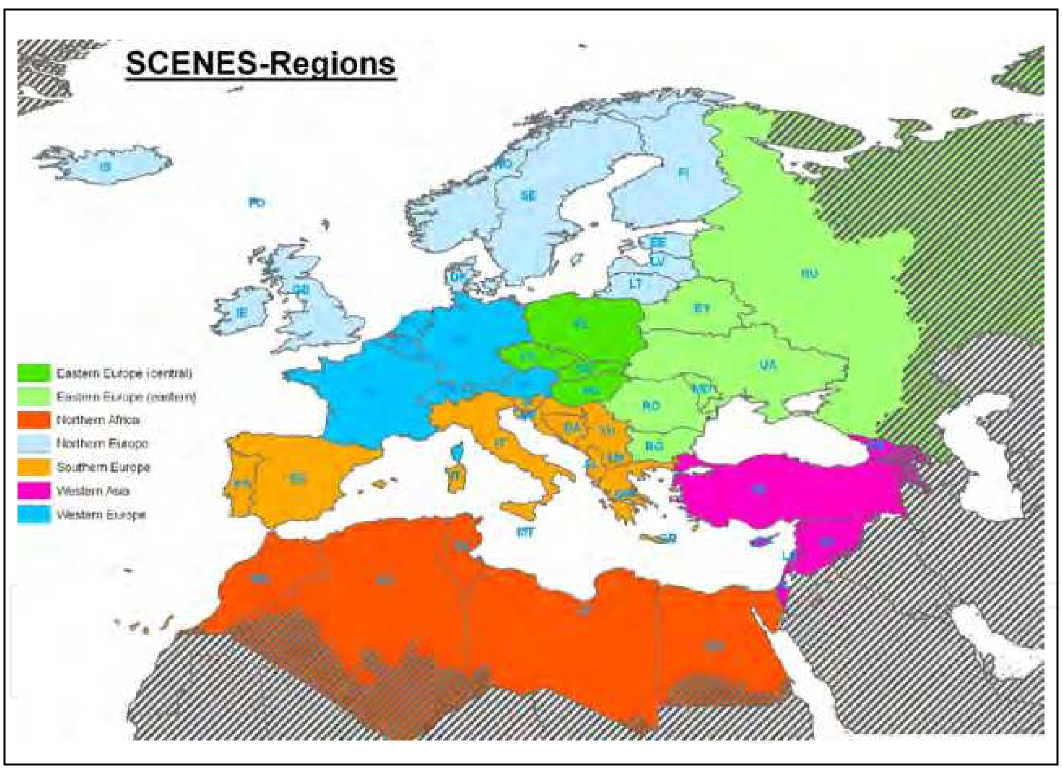


Fig. 1. Spatial extent of the study area and SCENES-regions.

2.2 The WaterGAP3 model

Within this integrated model study the well tested hydrology and water use model WaterGAP3 (Alcamo et al., 2003; Flörke and Alcamo, 2004; Verzano, 2009) is being applied to calculate irrigation water abstractions and their impact on pan-European water resources on a five arc minute grid (~6x9 km per grid cell). All irrigation and hydrology model runs are being conducted for the time period 1961 to 1990 (baseline) and 2041 to 2070 (scenarios 2050s). The calculation of future changes in irrigated areas based on socio-economic drivers (see chapter 2.3) is being conducted by the land use model LandSHIFT (Schaldach et al., 2011b) on the same grid. A detailed overview about the LandSHIFT model and the coupling procedure of LandSHIFT and WaterGAP within this study is given in Schaldach et al., (2011a).

First of all, based on expected population dynamics, food demand, etc. the crop-specific irrigated area maps are being generated by the LandSHIFT model and then fed into the irrigation module of WaterGAP3. The irrigation model then calculates net and gross irrigation demands as described is Aus der Beek et al., (2011):

The start day of the growing season is being calculated for each grid cell separately. For each grid cell the most suitable 150-day period within a year is ranked based on crop specific precipitation and air temperature criteria as given in Allen et al., (1998). The temperature criterion ensures continuous energy supply and optimal growing conditions, whereas the precipitation criterion promotes water supply and prevents cropping periods during droughts. If a day fulfils one of the two criteria, one ranking point is given. The growing season is then defined to be the most highly ranked 150-day period; in case of two consecutive growing periods the combination with the highest total number of ranking points is chosen (Döll & Siebert, 2002). If a second 150-day growing period is suitable, based on the crop specific precipitation and air temperature criteria, then a second cropping period within one year is added to the first period. However, in the current model set up it is not possible to change the crop type for the second period, as the crop-specific land use map provided by LandSHIFT only contains one crop type per grid cell. Therefore, double cropping is always being conducted with the same crop type, which holds true only for some crops in pan-Europe. Furthermore, the assumption of a growing period of 150 days is reasonable for crops such as vegetables, potatoes, pulses, wheat, barley, maize, rice and fruits, but underestimated for fibres and winter wheat, and overestimated for fodder plants (Smith, 1992).

Finally, the net irrigation requirements for each grid cell are being calculated, which are based on the CROPWAT approach published by Smith, (1992):

$$I_{net} = k_c * E_{pot} - P_{eff} \qquad \text{if } E_{pot} > P_{eff}$$
$$I_{net} = 0 \qquad \text{if } E_{pot} \leq P_{eff} \tag{1}$$

with

I_{net} = net irrigation requirement per unit area [mm/d]
P_{eff} = effective precipitation [mm/d]
E_{pot} = potential evapotranspiration [mm/d]
k_c = crop coefficient [-]

Aus der Beek et al., (2011) state further: Within the WaterGAP hydrology and water use modelling framework E_{pot} is consistently being calculated accordingly to Priestley & Taylor, (1972) as a function of air temperature and net radiation (Weiß & Menzel, 2008). K_C values feature a crop specific distinctive distribution curve throughout the growing period and are closely related to LAI development (Liu & Kang, 2007), as they mimic plant development. Each crop has three to four different development stages during its 150-day growing period: nursery (rice only), crop development, mid-season, and late-season.

Finally, the calculation of gross irrigation requirements I_{gr} for each grid cell is being conducted by taking into account net irrigation requirements I_{net} and national irrigation project efficiencies EF_{proj} (Rohwer et al., 2006):

$$I_{gr} = \frac{I_{net}}{EF_{proj}} \tag{2}$$

Irrigation project efficiency reflects the state of irrigation technology within each country. It is also more applicable than the often used irrigation field efficiency as it additionally considers conveyance losses, field sizes and management practices, while irrigation field efficiency mainly results from the irrigation practice (e.g. surface, sprinkler, micro irrigation). EF_{proj} typically ranges between 0.3 and 0.8, whereas 0.8 means that 80% of the water delivered to the crop is actually absorbed by it. Future changes in irrigation efficiency, have been derived by stakeholder meetings within the European research project SCENES. An overview of the performance of the WaterGAP3 irrigation module can be found in Aus der Beek et al., (2010), where its output has been compared to simulated gross irrigation requirements from a vegetation model and to reported values for all pan-European countries on a national basis.

Then, the calculated temporal and spatial explicit data sets on net irrigation requirements are being integrated in the hydrological module of WaterGAP3 (Alcamo et al., 2003; Döll et al., 2003) to assess the impact of irrigation on pan-European water resources. Here, within each irrigated grid cell they are abstracted from the internal water fluxes, and can thus alter river runoff. Also, by relating the amount of water which is being withdrawn for irrigation purposes to the amount of water that is naturally available on grid cell or river basin level, we are able to determine local water stress factors and the sustainability impact of the withdrawals. Furthermore, as WaterGAP3 also computes water withdrawals from other sectors, such as households, manufacturing industries, electricity production (Flörke et al., 2011), and livestock, we can provide an overview of locally dominant water use sectors in pan-Europe and their competition.

2.3 The scenarios

2.3.1 Socio-economic change

The SCENES project provides four different narrative socio-economic scenarios from which two opposing scenarios have been selected for this study, one reference scenario (Economy First) and one policy scenario (Sustainability Eventually). The aim of the scenarios is to provide a basis for the mid- to long-term development planning of pan-European freshwater resources. All scenarios have been designed by applying the story-and-simulation methodology (Alcamo, 2008) which iteratively links storyline revision with modeling exercises. The qualitative drivers for the scenarios have been developed in participatory international panel meetings and consider also environmental factors. The quantitative, i.e. numerical, drivers have been derived from modeling results, which are also influenced by the qualitative drivers, e.g. questionnaires filled out by panel participants (Schaldach et al., 2011a). Therefore, both scenarios offer a consistent set of environmental and socio-economic assumptions for the 2050s, which serve as a basis to study the potential future pathways of irrigation and hydrological developments in our analysis. Here, agricultural development, i.e. irrigated crop production and the impact of technological change, are the most important drivers. The two selected scenarios have been described by Schaldach et al., (2011a) as follows:

- *"Economy First"* (EcF): The economy develops towards globalisation and liberalisation, so innovations spread but income inequality, immigration and urban sprawl cause social tensions. Global demand for food and bio-fuels drives the intensification of agriculture. As the Common Agricultural Policy (CAP) is weakened, farms are abandoned where crop production is uneconomic. Until 2050 technological change allows potential increases of crop yields by 23% within the countries of the European Union (EEc, NE, WE, SE). Countries located in the other regions (EEe, NA, WA) only achieve a 14% potential increase. Total crop production is growing by 29% (from 981.890 kt to 1.266.157 kt). NA has the largest increase (+155%) followed by WA (+88%) and NE (+20%). Only for EEc a decrease of crop production by -4% is assumed. Future trends in population and economic activity show a further increase of population by 32.5% (348 million people) for pan-Europe until 2050. Here, highest growth rates are expected in NA and WA while the population increase in Europe is rather moderate. Economic activity continues to grow over the whole scenario period resulting in an 86% growth in GDP.
- *"Sustainability Eventually"* (SuE): Europe transforms from a globalised, market-oriented to an environmentally sustainable society, where local initiatives are leading. Landscape is the basic unit and there is a strong focus on quality of life. Direct agriculture subsidies are phased out and replaced by policies aimed at environmental services by farmers, such as support for farmers in less favourable areas with high-nature value farmland and accompanied by effective spatial decentralisation policies. Land use changes in general promote greater biological diversity. Crop yields are assumed to potentially increase by 50% until 2050 in all regions. Total crop production is increasing by 6.9 % (from 981.890 kt to 1.049.608 kt) with large regional differences. While crop production is doubling in NA, there is a decrease of --21% in EEe. Population is expected to increase by 13% (143 million people) in pan-Europe between 2000 and 2050. For Europe, a decrease in population is projected whereas for NA and WA the population continues to grow. Compared to EcF, SuE shows a lower total GDP development indicated by developing slower with an increase of 14% between 2000 and 2050.

2.3.2 Climate change

Both climate change scenarios are based on the A2 emission scenario of the IPCC SRES 4th assessment report and are combined in this study with both socio-economic scenarios. Within the A2 scenario the atmospheric CO2-concentration rises up to 492 ppm (IPCC, 2007). In order to include the variability of climate models, which are being employed to calculate climate data sets with the input from the IPCC SRES report, climate output for the A2 scenario from two diverging General Circulation Models (GCMs) have been selected for this study.

The MIMR GCM output has been provided by the MICRO3.2 model at the Center for Climate System Research at the University of Tokio, Japan. Here, the A2 scenario projects high air temperature increases over Europe in combination with low precipitation decreases to high precipitation increases. The MIMR climate data set can be considered as the "wetter" scenario of the two GCMs.

The IPCM4 GCM output has been generated by the IPSL-CM4 model at the Institute Pierre Simon Laplace in France. Here, the A2 scenario indicates higher air temperature increases for Europe than the MIMR GCM and only small changes in precipitation patterns. Thus, within this study the IPCM4 climate data set can be regarded the "dry" scenario of the two GCMs.

The GCM outputs have been downscaled from the original resolution of a T63 grid (1.875°x1.875°) to the 5′ grid of the WaterGAP3 model by applying a bilinear interpolation algorithm. Furthermore, the delta change approach (Henrichs & Kaspar, 2001) has been applied to scale the GCM model output with the observed climate data for the climate normal period (1961 – 1990) from CRU (see chapter 2.2) to include climate variability in this analysis.

3. Results and discussion

3.1 Irrigation

As this study focuses on the impact of irrigation on available water resources, we refer to Schaldach et al., (2011a) for a detailed description of changes in land use patterns and irrigated area extents.

A spatial overview of mean annual pan-European net irrigation water requirements for the baseline period is given in Figure 2. The water demand is highest in the Mediterranean countries, especially in Turkey, Spain, and Italy, which account with 92040 km² for about 55% of the total real irrigated area in Europe (Aus der Beek et al., 2010). Also, the riparian zones of the Nile River as well as its Delta are heavily irrigated, both in area and quantity, which can be explained by the concurring semi-arid to arid climate conditions and population pressures. The quantitative summary for each region is given in Table 1. As explained earlier the regions surrounding the Mediterranean Sea features the highest demands: Southern Europe (16.15 bil m^3), Northern Africa (15.6 bil m^3), Western Asia (13.44 bil m^3), followed by Eastern Europe, eastern (5.47 bil m^3), Western Europe (2.38 bil m^3), Northern Europe (0.47 bil m^3), and Eastern Europe, central (0.36 bil m^3). A country based evaluation of the goodness of these model results is given in Aus der Beek et al., (2010), who show that the deviation between modelled and reported irrigation requirements for Europe is about 1%.

Table 1 also summarizes the mean net irrigation requirements for the eight scenario model runs conducted within this study (see Chapter 2.3). The first two scenario model runs have been driven with the A2 model output from two GCMs, IPCM4 and MIMR. The socio-economic drivers, here summarized as land use, have remained in baseline conditions in order to solely analyze the impact of climate change on net irrigation water demands. Both scenarios lead to a small decrease in water demand (-1% and -5%), which is unexpected, as increasing air temperatures naturally cause an increase in evapotranspiration for most crops. Here, the decrease in irrigation water demands originates from the model structure which features a dynamic cell-specific cropping calendar. Based on the climate conditions of each modelled year the most suitable 150 day growing period, and thus the sowing day, is chosen. Therefore, changing climatic conditions shift the sowing dates to earlier or later periods to avoid high irrigation demands in July and August. A more detailed description as well as a graphic example for the Iberian Peninsula of this model algorithm can be found in Schaldach et al., (2011a). In general, this algorithm has rightly been implemented to mimic sowing date decisions from local farmers who would in reality also adapt to changing conditions in order to save expenses for irrigation water and also receive high yields. A model control run with sowing dates from the baseline for the IPCM4 scenario has shown that without these adaptation measures, the net irrigation demand increase by 15% to 61.85 bil m^3 instead of decreasing by 1%. An overview of the spatial distribution of all eight scenario model runs is given in Figure 3.

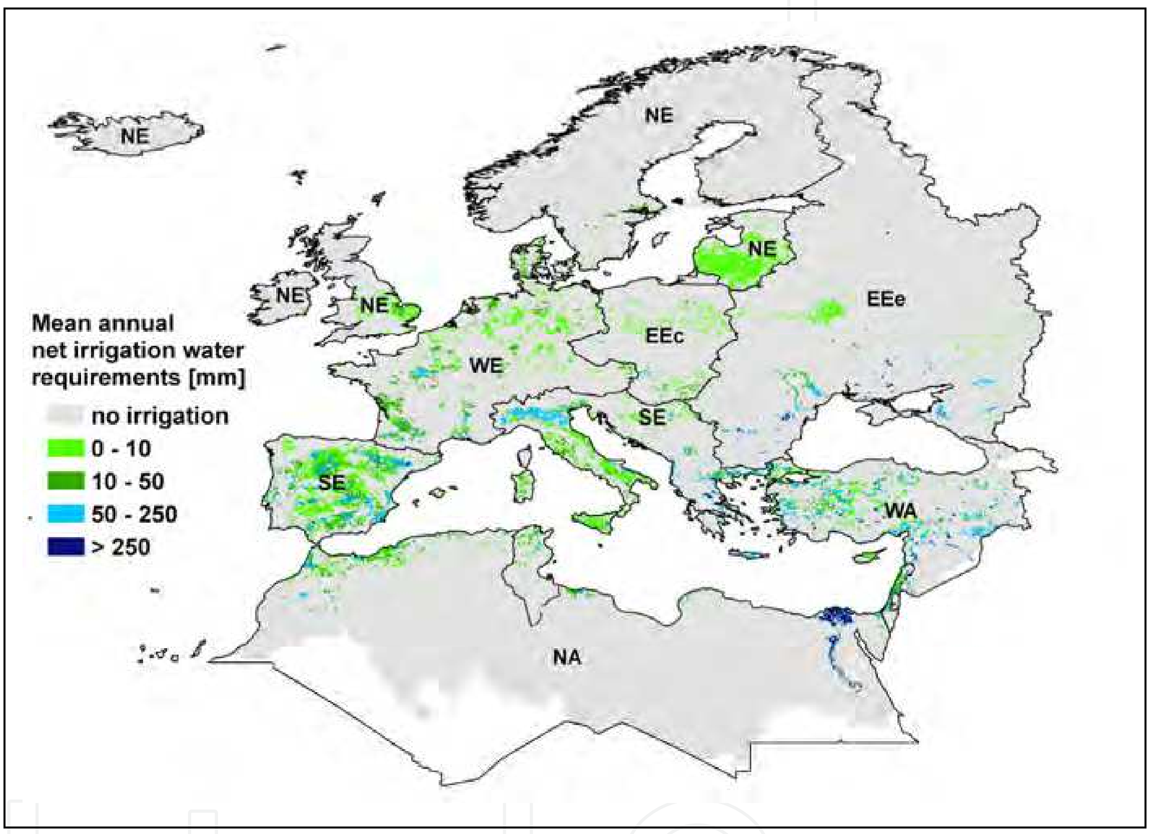


Fig. 2. Mean annual net irrigation requirements in [mm] for the baseline period (1961-90) as modeled with WaterGAP3 (EEc = Eastern Europe central, EEe = Eastern Europe east, NA = Northern Africa, NE = Northern Europe, SE = Southern Europe, WE = Western Europe, WA = Western Asia).

The next two scenario model runs have been conducted with climate input from the baseline but different socio-economic drivers, i.e. the opposing Economy First (EcF) and Sustainability Eventually (SuE) scenarios. Here, the model results show a completely different picture. Both scenarios imply an increase in net irrigation water demand, the optimistic SuE scenarios projects a minor increase of 2% for the 2050s whereas the pessimistic EcF scenario expects an increase of 48%. The differences in the spatial allocation of the water demand are also depicted in Figure 3a and 3b. Especially, in Southern Europe, namely Spain and Italy the opposing trends are evident which is also supported by Table 1 where under EcF conditions an increase of 51% and under SuE conditions an decrease of 11% occurs.

The last four scenario model runs have been conducted as combinations of the climate and socio-economic model drivers. Once again the socio-economic drivers dominate the future potential changes in irrigation water requirements. Under both "optimistic" SuE scenario model runs water demands are stable or decreasing, whereas under both "wetter" climate MIMR scenario model runs the trends are not consistent (-7% vs. +25%). As expected, the highest increase in irrigation water requirements can be observed when combing the "dry" IPCM4 scenario with the "pessimistic" Economy first scenario (+45%).

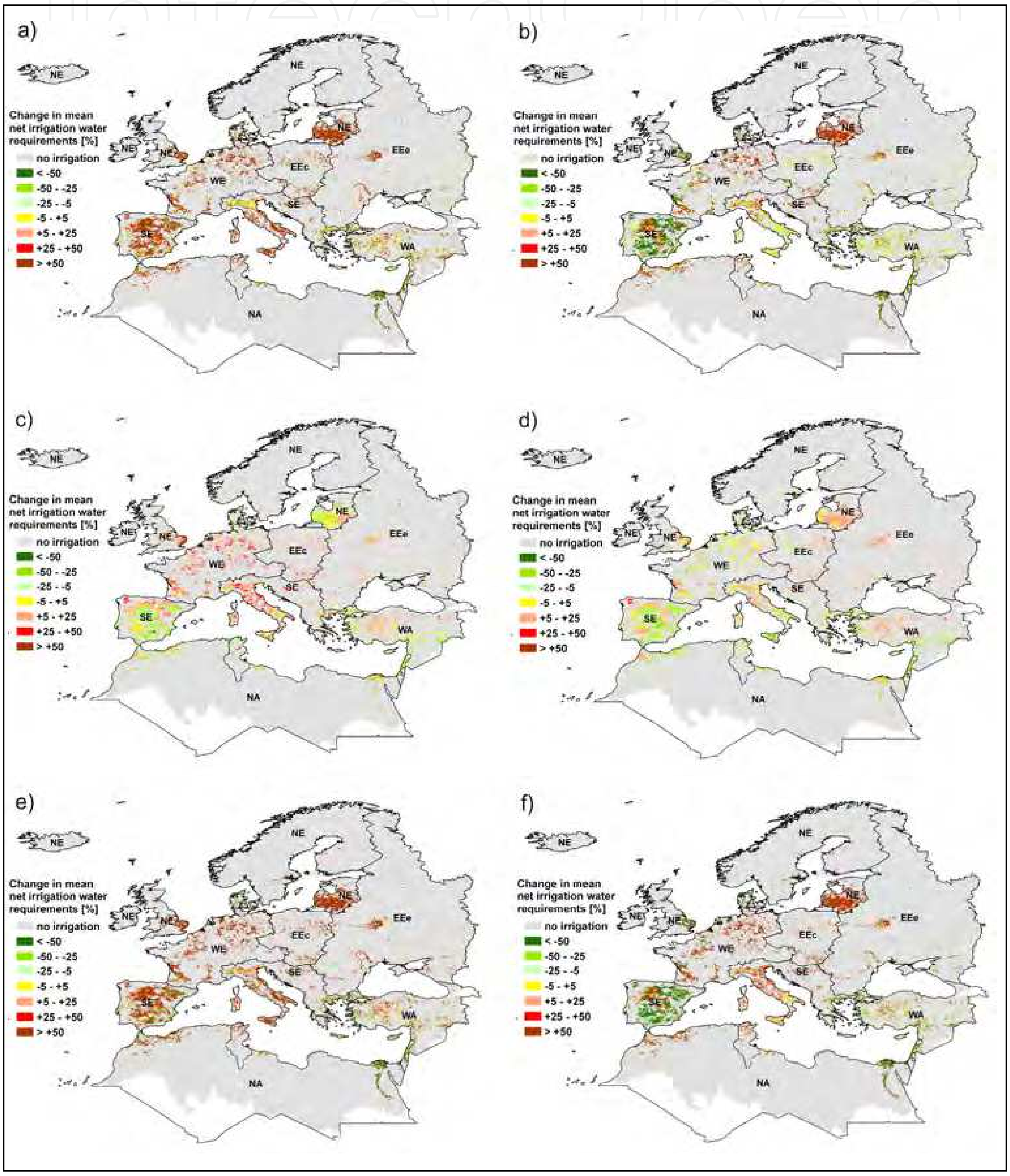
Climate forcing	**Base 61-90**	**IPCM4 2050**	**MIMR 2050**	**Base 61-90**	**Base 61-90**	**IPCM42050**	**IPCM4 2050**	**MIMR 2050**	**MIMR 2050**
Land use	**Base 2000**	**Base 2000**	**Base 2000**	**EcF 2050**	**SuE 2050**	**EcF 2050**	**SuE 2050**	**EcF 2050**	**SuE 2050**
Eastern Europe (central)	0.36	0.43 (+21)	0.41 (+13)	0.72 (+101)	0.40 (+12)	0.88 (+145)	0.49 (+37)	1.04 (+188)	0.56 (+57)
Eastern Europe (eastern)	5.47	5.93 (+8)	5.91 (+8)	7.39 (+35)	3.81 (-30)	8.12 (+49)	4.20 (-23)	7.32 (+34)	3.77 (-31)
Northern Africa	15.60	15.17 (-3)	14.35 (-8)	21.01 (+35)	19.48 (+25)	19.63 (+26)	18.41 (+18)	18.64 (+19)	17.40 (+12)
Northern Europe	0.47	0.49 (+5)	0.46 (-2)	1.20 (+157)	0.46 (-2)	1.34 (+187)	0.51 (+8)	1.09 (+134)	0.40 (-15)
Southern Europe	16.15	15.68 (-3)	14.90 (-8)	24.35 (+51)	14.43 (-11)	22.77 (+41)	13.97 (-14)	14.91 (-8)	11.49 (-29)
Western Asia	13.44	12.59 (-6)	12.83 (-9)	16.79 (+25)	12.50 (-7)	15.53 (+16)	11.66 (-13)	15.40 (+15)	11.53 (-14)
Western Europe	2.38	2.77 (+16)	2.37 (-0)	8.42 (+253)	4.03 (+69)	9.79 (+311)	4.69 (+97)	8.67 (+264)	4.82 (+103)
SUM	53.87	53.06 (-1)	51.23 (-5)	79.87 (+48)	55.11 (+2)	78.06 (+45)	53.92 (+0)	67.08 (+25)	49.98 (-7)

Table 1. Modeled mean net irrigation water requirements in billion m^3 under the IPCC-SRES scenario A2 with two GCMs (IPCM4 and MIMR) for 2040 – 2069 and two socio-economic land-use scenarios (Economy First (EcF) and Sustainability Eventually (SuE)). Numbers in parenthesis describe relative changes compared to the baseline (1961 – 1990), expressed in percent.

However, as the decreasing influence of the climate drivers also lowers the combined water demand due to the adaptive sowing date, it does not top the model run with baseline climate drivers and the EcF scenario (+48%), which can be regarded the worst case scenario. A graphic overview of the combined model run outputs is given in Figure 3e to 3h.

3.2 Hydrological impacts

Within this study the focus has been set on modelling irrigation water withdrawals and their impact on pan-European water resources. However, in order to reach this goal we also need to analyze and quantify the competition of the irrigation water use sector with other sectors. As WaterGAP3 is a state-of-the-art model it additionally considers the other water use sectors: households, electricity generation, and manufacturing industries (see Chapter 2.2). Thus, we have calculated all sectoral water uses on river basin level and ranked their impact for each basin separately. Figure 4 features a pan-European map with dominant water use sectors, where several trends are evident. In the majority of North European river basins the manufacturing sector, e.g. in Scandinavia, and the domestic sector, e.g. in the United Kingdom and Iceland, dominate the water uses. Only Denmark is an exception, as irrigation heads the ranking here. Western and Eastern Europe feature the electricity generation sector as the most used water sector. Southern Europe, Northern Africa, and Western Asia show the irrigation sector to be the most important water use sector due to unfavourable climatic conditions and high population pressures. The patchy composition of water use sectors in Northern Africa, i.e. Libya and Algeria, originates from the location of irrigable areas.



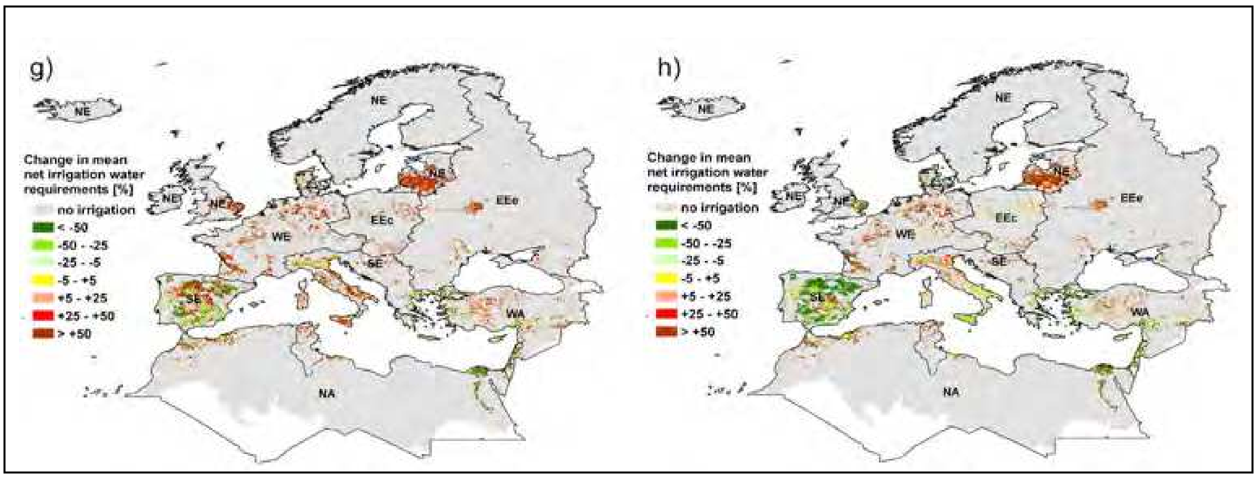


Fig. 3. Change in mean annual net irrigation requirements for the 2050s compared to baseline (1961 -1990) for different combinations of climate (CLIM: baseline; IPCM4; MIMR) and agricultural (AG: baseline; Economy First; Sustainability Eventually) scenarios. a) CLIM: baseline, AG: EcF; b) CLIM: baseline, AG: SuE; c) CLIM: IPCM4, AG: baseline; d) CLIM: MIMR, AG: baseline; e) CLIM: IPCM4, AG: EcF; f) CLIM: IPCM4, AG: SuE; g) CLIM: MIMR, AG: EcF; h) CLIM: MIMR, AG: SuE.

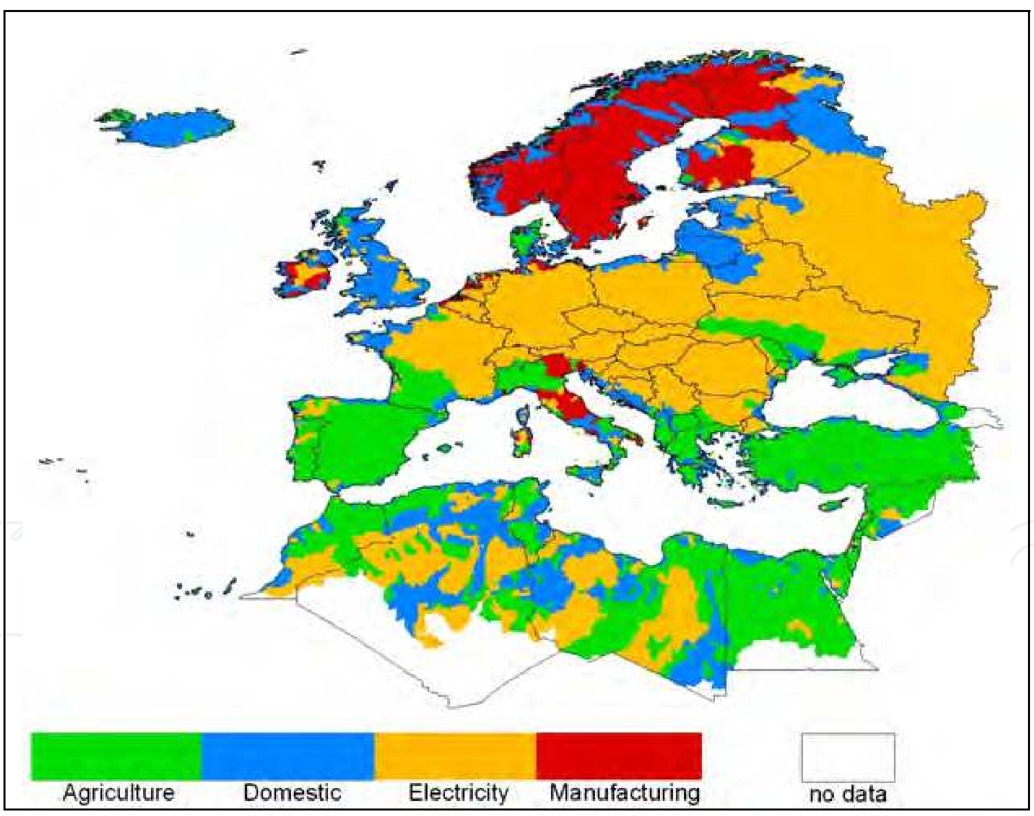
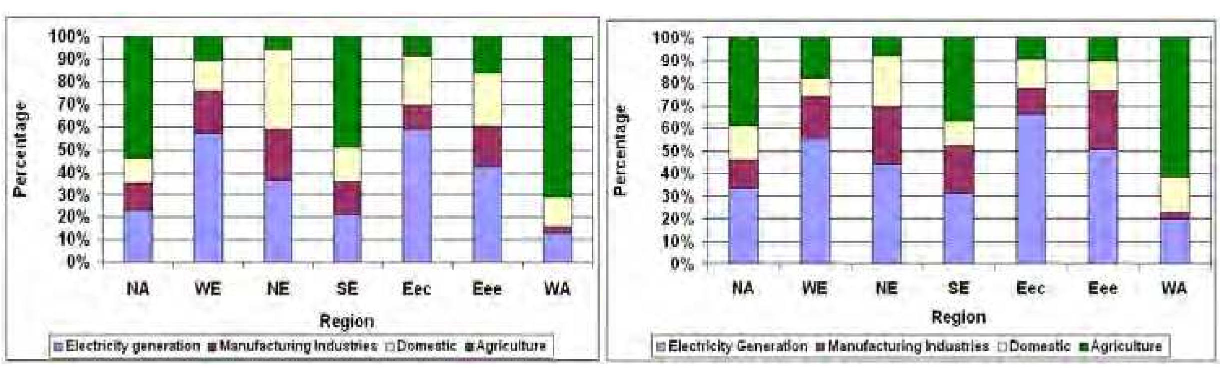


Fig. 4. Most dominant type of water use for the year 2005 on river basin level as modeled with WaterGAP3 for pan-Europe.

It needs to be mentioned that Figure 4 is an example for the year 2005. As our modelling runs are starting in 1961, the spatial as well as numerical patterns are changing within the modelling period. These patterns are influenced by a multifold of model drivers, such as climate, population numbers and allocation, power plant types and location, gross domestic product, etc., which all change with time.

To analyze the importance of irrigation water abstractions for current but also for future conditions we have summarized the shares of all water use sectors on a regional basis. The results for the year 2005 as well as exemplarily for one scenario combination are shown in Figure 5. The description of the spatial distribution of dominant water use sectors, as explained above for Figure 4, is well depicted in Figure 5a. Western Asia, Southern Europe, and Northern Africa feature with about 50% to 70% the largest irrigation water use share, followed by water used for electricity generation. Western and Eastern Europe use about 40% to 60% of their total water withdrawals for electricity generation, followed by households and manufacturing industries. Northern Europe features with about 35% equal shares for households and electricity generation. The results for the 2050s scenario driven with output from the IPCM4 climate model and socio-economic data from the Economy First set, is given in Figure 5b. Here, irrigation water withdrawals in the Mediterranean countries decrease from 50-70% in 2005 to 35-60%, whereas they remain stable or even slightly increase in the other pan-European regions. As climate change does not significantly affect future irrigation water requirements due to the adaptation measures (see Chapter 3.1), the decrease can be derived from two main factors. Firstly, the technical development of irrigation machinery has led to an improvement of the net-to-gross irrigation efficiency ratio (see Equation 2 in Chapter 2.2), reducing irrigation water withdrawals. For example, in Greece the efficiency increased from 0.57 to 0.65 and in Italy from 0.72 to 0.8. Secondly, population numbers for this scenario are decreasing in pan-Europe, except for Northern Africa and Western Asia. This trend is also well shown in Figure 5a and 5b, as water use shares in the household sector are consistently decreasing in mainland Europe. In all pan-European regions the electricity generation water use sector gains shares or its share remains constant, as for example in Western Europe. Similar patterns can be observed for the manufacturing industries water use sector.



a) b)

Fig. 5. Relative share of different water use sectors for pan-European regions as modeled with WaterGAP3: a) year 2005; b) scenario 2050s Economy First/IPCM4 (Eec = Eastern Europe central, Eee = Eastern Europe east, NA = Northern Africa, NE = Northern Europe, SE = Southern Europe, WE = Western Europe, WA = Western Asia).

The next step in this study is the assessment of the impacts of the irrigation water withdrawals explained above on pan-European water resources. Therefore, we have analyzed for all pan-European river basins how irrigation water abstractions affect water stress. As especially during summer time the irrigation water demand is highest, and an annual average stress indicator would mask seasonal streamflow variability, we have analyzed summer water stress induced by irrigation water abstractions, which is displayed in Figure 6. The irrigation WTA (withdrawal-to-availability ratio) indicator is a simple but effective tool to analyze water stress (Cosgrove & Rijsberman, 2000) as it divides irrigation water withdrawals by water availability on river basin level. If less than 20% of the available water resources in a river basin are being exploited, the status of this basin can be defined as low water stress and the abstractions in terms of water quantity can considered as sustainable. Medium water stress is occurring when WTA is between 20% and 40%. If more than 40% of the available water resources within a river basin are being abstracted from the system, the basin endures high water stress and the withdrawals can be considered as unsustainable. A high WTA also affects ecosystem services as environmental flow thresholds, which ensure water limits for flora and fauna, are often not being abode. Figure 6 shows the mean summer irrigation WTA for baseline conditions as well as for the two opposing scenarios combinations IPCM4/Economy Firs and MIMR/ Sustainability Eventually. The baseline results feature high irrigation induced summer water stress in Spain, Turkey, Israel, Greece, Morocco, Libya, and Algeria. Medium stressed river basins are located in Italy (e.g. Po River basin), France, and Morocco. Generally, these countries can be divided into two classes. First, semi-arid to arid regions which suffer low water availability due to climatic conditions, where already small water abstractions drastically increase water stress and water scarcity, as for example in Northern Africa and Western Asia. Secondly, semi-arid to humid regions which overexploit existing water resources, e.g. in Spain and Italy.

The "pessimistic" scenario combination IPCM4/Economy First for the 2050s increase irrigation induced summer water stress in several regions in pan-Europe (see Figure 6b). Here, most parts of France endure high water stress, except for the Rhone River basin, which experiences medium water stress. Also, in the Dniester River basin in the Ukraine water stress increases, as well as in Morocco, Algeria, Portugal, Italy, Germany, Sweden, and the United Kingdom.

The "optimistic" scenario combination MIMR/Sustainability Eventually yields an indifferent picture of pan-European summer water stress (see Figure 6c). In some river basins the water stress level decreases, as for example in Spain, Italy, and Ukraine, whereas other basins experience an increase in water stress, for example in France and Morocco. The reasons for these changes can be found in the high spatial variability of the climate change scenario data and the regional differences in the quantification of the model drivers of the socio-economic scenarios.

The next step in this study includes the impact analysis of water withdrawals from all water use sectors on water availability in pan-Europe. Therefore, we have calculated the mean annual water availability for baseline conditions after subtracting water uses, which is displayed in Figure 7a. High water availability of more than 300 mm per year occurs in Northern Europe, in the alpine basins including the Rhine, as well as in the Balkan Mountains. Medium water availability of 100 mm to 300 mm can be observed in Eastern Europe from Poland to Russia, in Spain, as well as in the countries adjacent to the Black Sea. Low water availability of less than 100 mm per year can be found in Northern Africa.

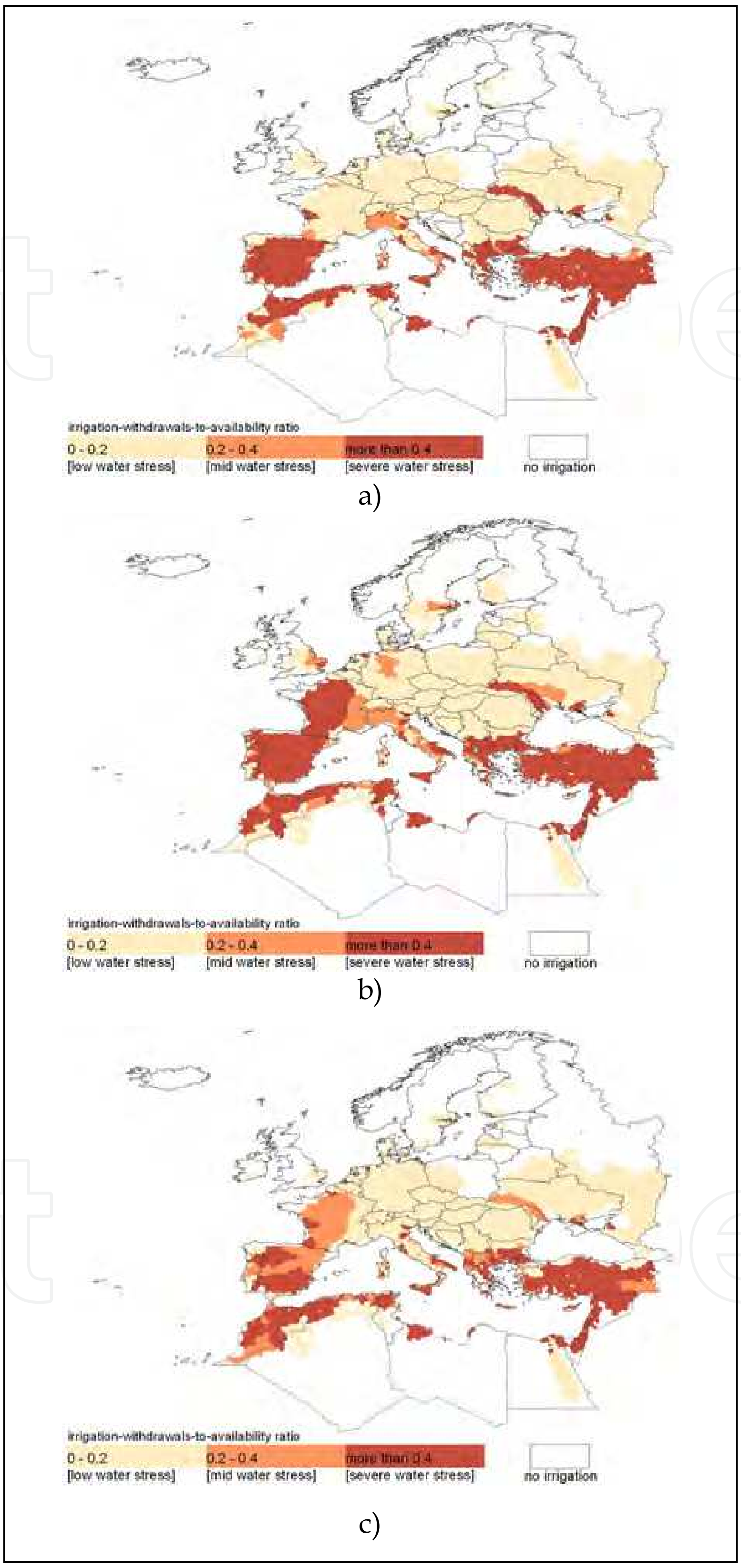


Fig. 6. Irrigation water stress in summer on river basin level for pan-Europe as modeled with WaterGAP3: a) baseline; b) scenario IPCM4/Economy First; c) scenario MIMR/Sustainability Eventually.

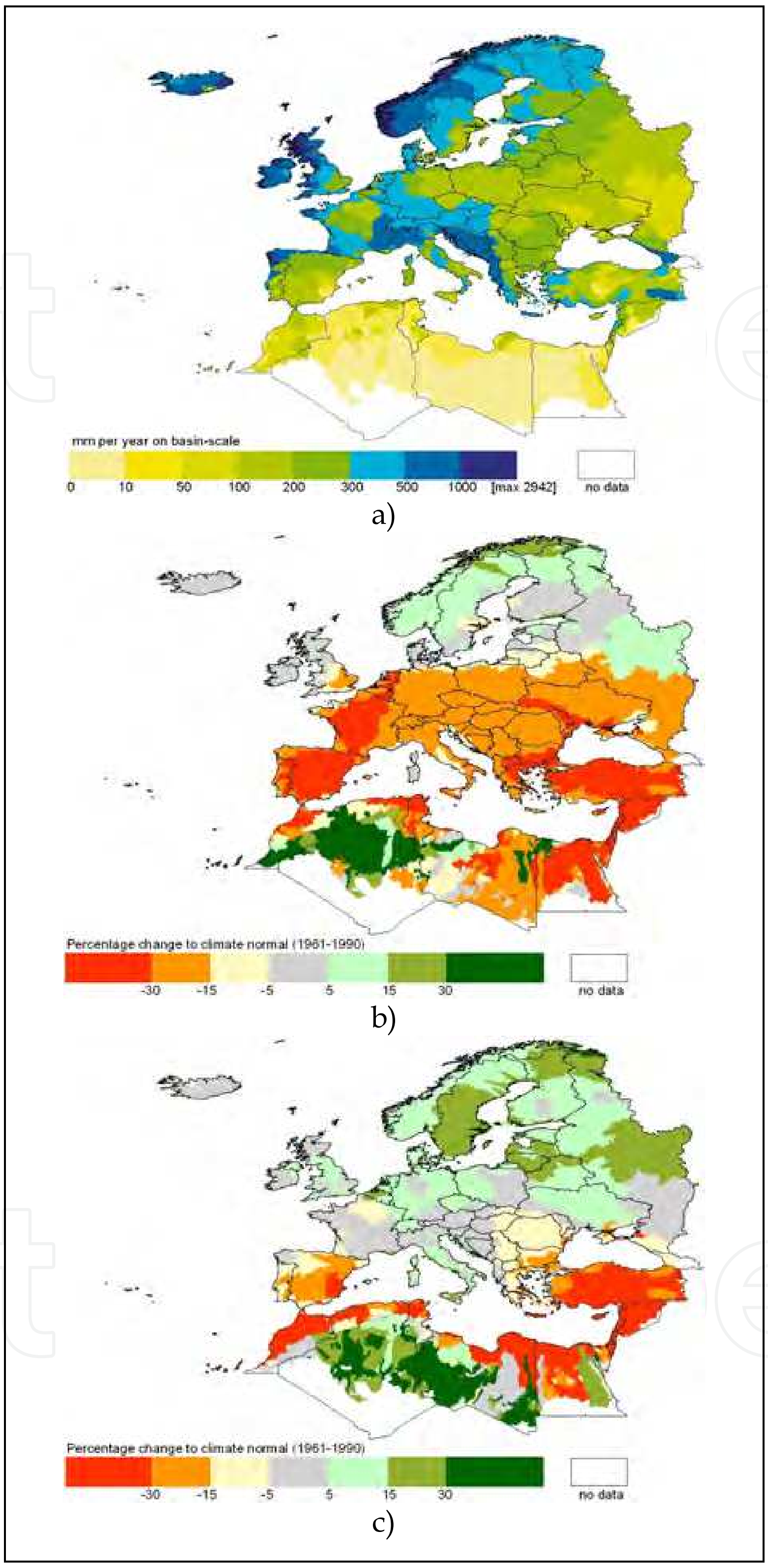


Fig. 7. a) Mean annual water availability for the baseline on river basin level for pan-Europe as modeled with WaterGAP3 with water uses; Relative change of mean annual water availability for the 2050s: b) scenario IPCM4/Economy First; c) scenario MIMR/Sustainability Eventually.

Figure 7b depicts the relative changes in water availability under the "pessimistic" IPCM4/Economy First scenario combination. High decreases of more than 30% can be observed in large parts of Spain, France, Turkey, and Israel, which is concordant with the findings of the irrigation induced summer water stress analysis (see Figure 6b). This leads to the conclusion, which is also supported by the data analysis that large parts of these decreases can be ascribed to irrigation water uses. Decreases of 15% to 30% are occurring in Central und Eastern Europe, whereas large parts of Northern Europe feature increases of 5% to 30%. The patchy patterns in Northern Africa can be explained with generally low water availabilities in the region, leading to large positive and negative changes in local water availabilities.

Figure 7c depicts the relative changes in water availability under the "optimistic" MIMR/Sustainability Eventually scenario combination. Here, decreases larger than 15% only occur in Western Asia, Northern Africa, and Spain. Also, in contrast to the pessimistic scenario described above, Central and Eastern Europe, except for Hungary, feature stable to increasing trends in water availability.

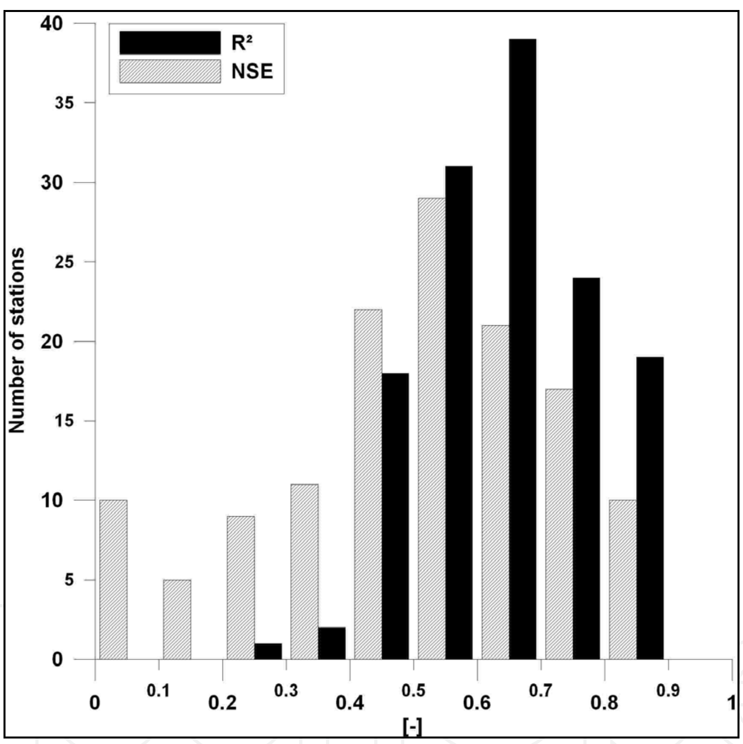


Fig. 8. Evaluation of the WaterGAP3 model performance: comparison of modelled and observed river runoff for 134 gauging stations in pan-Europe (R^2: coefficient of determination; NSE: Nash-Sutcliffe efficiency).

In order to analyze the performance of the hydrological module of the WaterGAP3 model, and thus the plausibility of the results of this study, we have compared observed to modelled river runoff at all river gauging stations available at Global Runoff Data Center (GRDC, 2004). Totally, runoff data from 152 stations have been available for the pan-European extent and the temporal domain of this study, whereas 18 stations have been deleted due to unrealistic data assumptions and trend tests. The goodness of fit between observed and modelled data has been evaluated by calculating the coefficient of determination R^2 and the Nash-Sutcliffe efficiency NSE (Krause et al., 2005) for each station. A histogram of the distribution of R^2 and NSE is given in Figure 8. Generally, an average R^2 of 0.64 with minimum and maximum values of 0.25 and 0.87 have been calculated. The NSE parameter, which is more sensitive to deviations in peak flows, features an average value of 0.5, whereas minimum and maximum values span a range of 0.01 to 0.86. The sensitivity of NSE is apparent when analyzing Figure 8. 35 stations, which is about 25% of the total station number, have a NSE smaller than 0.4, whereas only 3 stations (2%) feature a R^2 smaller than 0.4. This leads to the conclusion that at these 35 stations the magnitude of peak flows could not be very well represented by WaterGAP3, which is also supported by the visual analysis of the hydrographs. To display the differences in both evaluation criteria we have selected two out of the 134 hydrographs; one where the difference is large (Figure 9a) and one with small differences (Figure 9b). Figure 9a features a hydrograph of the Italian Adige River at the gauging station Trento which has a river basin size of 10049 km². The overestimation of peak flows, for example in summer 1967, as well as the underestimation of base flows, e.g. in winter 1969, leads to a poor NSE criterion of 0.14. However, as timing of peak and base flow is generally well represented by WaterGAP3, and overall volume errors balance out, the R^2 criterion shows a high value of 0.71. The opposite case where both, magnitude and timing of base and peak flows, are synchronic is given in Figure 9b. Here, modelled and observed runoff of the Duero River at the Spanish gauging station Villachica is displayed (basin size: 40513 km²). The high agreement of both data sets is reflected in the high model performance of 0.86 for both criteria, R^2 and NSE.

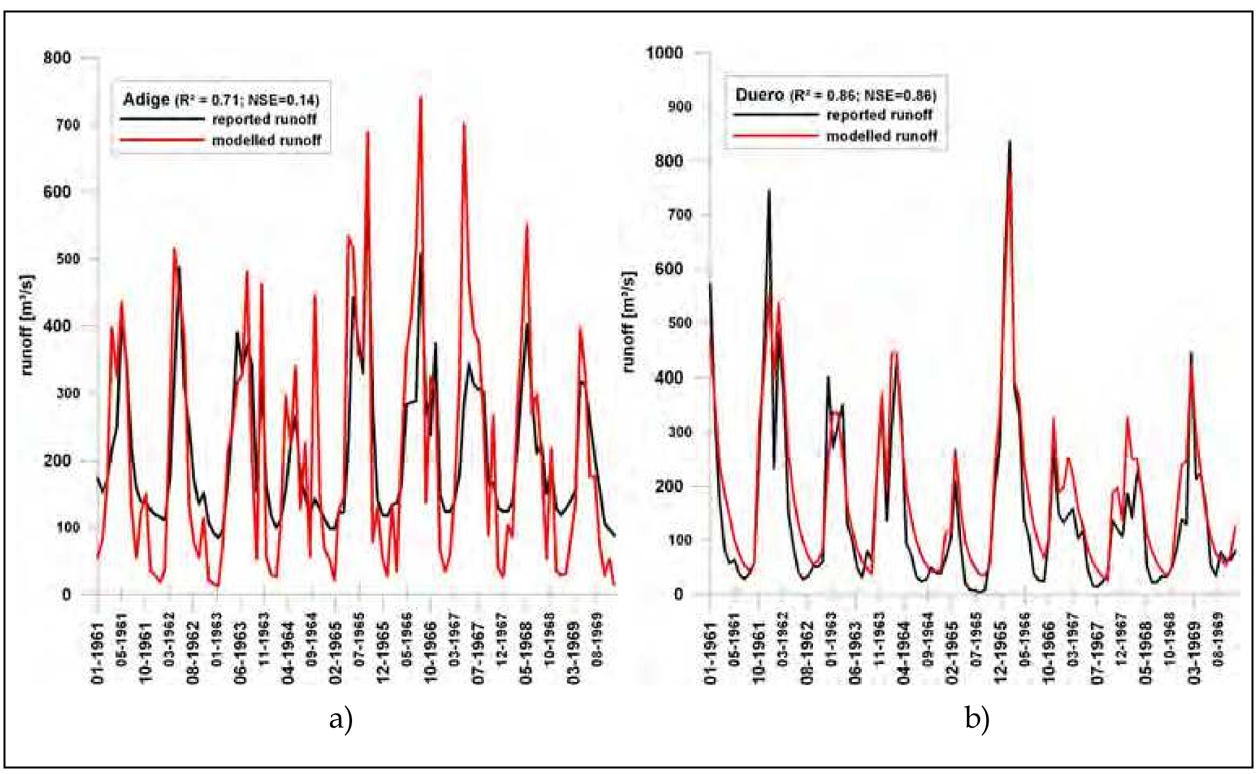


Fig. 9. Observed and modelled river runoff for 1961 to 1970: a) Adige River at station Trento (basin size 10049 km²); b) Duero River at station Villachica (basin size 40513 km²).

An analysis of the performance of the irrigation module in WaterGAP3 has been carried out in Aus der Beek et al. (2010, 2011).

3. Conclusions

Within this study the pan-European irrigation requirements as well as their impact on water resources has been analyzed and quantified by applying the continental hydrology and water use model WaterGAP3. Three regional hot spots of excessive irrigation water use have been identified which are all located in the vicinity of the Mediterranean Sea: Southern Europe, Western Asia, and Northern Africa. For the baseline period 1961 to 1990 about 84% of all pan-European irrigation water withdrawals occur in these three regions. Here, in opposition to the other regions, irrigation is also the dominant water use sector, except for Denmark and parts of the Ukraine. In Western and Eastern Europe water use for electricity generation is the largest sector, whereas it is domestic water use in the United Kingdom, and water use for manufacturing industries in Scandinavia. High unsustainable irrigation water withdrawals, especially in the often semi-arid and water scarce Mediterranean rim countries, lead to summer water stress, as mostly irrigation occurs in the dry and hot summer months. The water-stressed Mediterranean river basins can be separated into two classes: a) generally water scarce basins due to unfavourable climatic conditions, where already small water withdrawals drastically increase water stress (i.e. in Northern Africa and parts of Western Asia); b) overexploitation of water resources in semi-arid to humid regions, where sustainable irrigation applications would be possible (i.e. in large parts of Southern Europe). These model results have successfully been verified by comparing them to observed data, which has proven the plausibility of the methods applied in this study. Thus, it could be considered methodologically sound to transfer the WaterGAP3 model algorithms to calculate future scenarios of irrigation water use and their hydrological impacts. Here, the differentiation between climate change and socio-economic effects on irrigation water use has shown that model drivers such as land use change, due to changes in food demand, feature the largest impact on irrigation and thus hydrological quantities. Especially, as adaptive measures, such as shifts in crop sowing dates due to the elongated vegetation period, are already integrated in this study set-up and have shown to save 15% water for irrigation purposes. Thus, climate change impacts alone have nearly no impacts on future irrigation water requirements in this study. On the other hand, socio-economic impacts span a wide range of potential consequences for future irrigation water use of +2% to +48% for the 2050s. In combination with the smaller, often even slightly negative changes of climate change impacts, this range changes to -7% to +45%. According to the model results the dominance of the irrigation water use sector is also decreasing, as the electricity generation water use sector is gaining shares in the 2050s. In terms of future changes in summer water stress induced by irrigation water use, large differences between the best and worst case scenario can be observed. Here, especially river basins in Western and Southern Europe as well as in Northern Africa are affected, as a multifold of these basins stands at the crossroads of suffering (additional) water stress. Even more apparent differences between both scenarios are the changes in mean annual water availability. Here, Western and Eastern Europe show the most significant range, as water availability can drop by 15% to 30% in the worst case scenario, or can increase up to 15% in the best case scenario.

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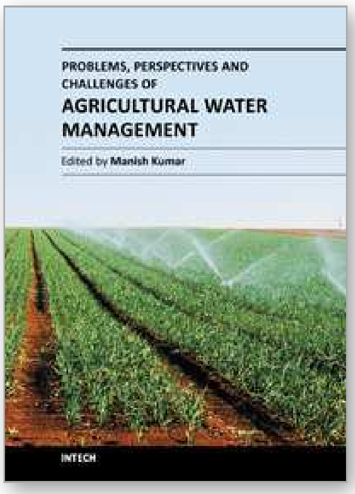

Problems, Perspectives and Challenges of Agricultural Water Management
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Food security emerged as an issue in the first decade of the 21st Century, questioning the sustainability of the human race, which is inevitably related directly to the agricultural water management that has multifaceted dimensions and requires interdisciplinary expertise in order to be dealt with. The purpose of this book is to bring together and integrate the subject matter that deals with the equity, profitability and irrigation water pricing; modelling, monitoring and assessment techniques; sustainable irrigation development and management, and strategies for irrigation water supply and conservation in a single text. The book is divided into four sections and is intended to be a comprehensive reference for students, professionals and researchers working on various aspects of agricultural water management. The book seeks its impact from the diverse nature of content revealing situations from different continents (Australia, USA, Asia, Europe and Africa). Various case studies have been discussed in the chapters to present a general scenario of the problem, perspective and challenges of irrigation water use.