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Modelling historical and current irrigation water demand on the continental scale: Europe

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Abstract. Water abstractions for irrigation purposes are higher than for any other pan-European water use sector and have a large influence on river runoff regimes. This modelling experiment assesses historic and current irrigation water demands for different crops in five arc minute spatial resolution for pan-Europe. Two different modelling frameworks have been applied in this study. First, soft-coupling the dynamic vegetation model LPJmL with the land use model LandSHIFT leads to overestimations of national irrigation water demands, which are rather high in the southern Mediterranean countries. This can be explained by unlimited water supply in the model structure and illegal or not gauged water abstractions in the reported data sets. The second modelling framework is WaterGAP3, which has an integrated conceptual crop specific irrigation module. Irrigation water requirements as modelled with WaterGAP3 feature a more realistic representation of pan-European water withdrawals. However, in colder humid regions, irrigation water demands are often underestimated. Additionally, a national database on crop-specific irrigated area and water withdrawal for all 42 countries within pan-Europe has been set up and integrated in both model frameworks.

1 Introduction

Large scale irrigation modelling has made significant progress during the last years (Siebert and Döll, 2008), which has been fuelled by the availability of new data sets (e.g. Portmann et al., 2008; Thenkabail et al., 2008).

The overall aim of this modelling experiment was to assess historic irrigation water demand for different crops in five arc minute resolution for pan-Europe. Two different modelling frameworks have been applied to analyze their suitability for simulating time series of crop specific irrigation requirements. The first framework refers to soft-coupling a dynamical vegetation model with a land use model, whereas the second framework relies on conceptual modelling of crop evapotranspiration. Both frameworks produce gridded data sets of net and gross irrigation requirements with high spatial and temporal resolution. This offers new opportunities for hydrological modellers, as integrating information about water abstractions is crucial for the realistic representation of most European river basins.

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2 Data and methods

2.1 Data

Climate forcing data used in this study has been compiled and regionalised by the Climate Research Unit (CRU) of the University of East Anglia, Norwich, UK (versions TS 1.2 and TS 2.1, Mitchell and Jones, 2005). CRU data covers the time period from 1901 to 2002 in 10′ and 0.5° resolution and monthly time steps, providing nine climatic parameters, e.g. precipitation, air temperature, cloud cover.

The land use data is based on the Corine 2000 data base (EEA, 2007) for the EU-25 countries. Land use data for the remaining pan-European countries (for spatial extent see Fig. 2) is taken from Heistermann (2006), who provides a crop specific version of the GLCC land use map (USGS, 2006). Both, Corine and GLCC have been harmonized to eighteen classes and aggregated to 5′ ($\sim 6\times 9$ km) spatial resolution.

Most large scale irrigation modelling approaches, such as Thomas (2008) for China, employ the global 5′ map “Area Equipped for Irrigation” (AEI, Siebert et al., 2007) to spatially allocate irrigated area in their models. However, in many regions not all of the entire AEI is actually irrigated.

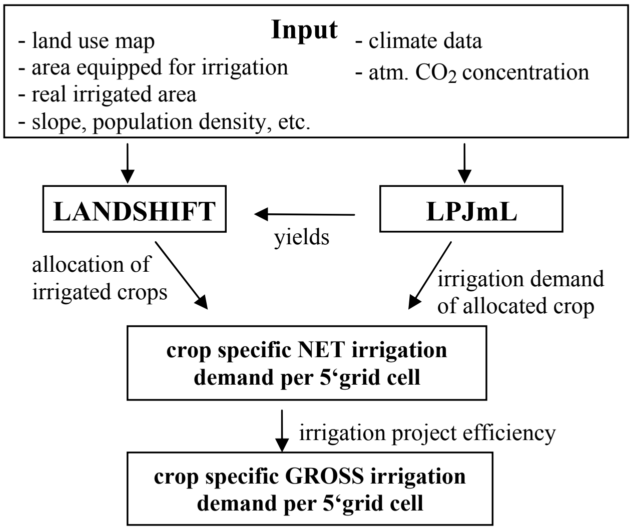

Fig. 1. Model framework concept LPJmL/LandSHIFT.

Therefore, we have carried out an extensive literature and data research to assess the real irrigated area (RIA) for each country, including national RIA data for each of the thirteen crops modelled. As reporting years vary within pan-Europe due to inconsistent national reporting periods, years 1997 to 2003 are used representative for the year 2000. For example, countries in Eastern Europe have experienced a massive reduction in irrigated area between 1990 and 2005 (GTZ, 2005). Furthermore, also in highly industrialised countries RIA can vary within very few years, depending on climate, economical demands, water use reporting procedures and policies. For example, Knox et al. (1997) state that irrigation water use in England and Wales increased from 35 to 135 mil m^3 between 1987 and 1990.

In order to evaluate the performance of the models we have set up a data base with national values of crop specific irrigation water use for the year 2000 based on national reports, statistics (e.g. AQUASTAT), and literature reviews. However, these data sources contain many potential sources of uncertainty, as for example year and procedure of reporting, assumed project efficiency, greenhouses, illegal water abstractions, etc. Furthermore, reported water uses are often estimated and not gauged by the local authorities. Collecting the required data has not been possible for every crop in each country.

2.2 Methods

Both modelling frameworks calculate crop specific monthly net irrigation requirements (NIR) (Fig. 1), based on climate, spatial extent of RIA and crop type, as is described in detail in sections below. Crop specific monthly gross irrigation requirements (GIR) are computed for each $5'$ cell by taking into account national irrigation project efficiencies EF_{proj} (Rohwer et al., 2006; Kulkarni et al., 2006):

$$\mathrm{GIR} = \frac{\mathrm{NIR}}{\mathrm{EF_{proj}}} \tag{1}$$

Irrigation efficiency reflects the state of irrigation technology within each country. Hereby, irrigation field efficiency and irrigation project efficiency have to be differentiated. Irrigation project efficiency is more applicable compared to 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.

All calculations in this study are carried out for the time period 1901–2002 in monthly time steps on a $5'\times5'$ grid. However, the quality of the input data declines with age, especially before 1960, where fewer climate stations and less information about RIA and irrigation efficiency are available. Therefore, this modelling experiment focusses on results for the last 42 years, i.e. 1960–2002. Time series of national RIAs have been constructed from scaling year 2000 with relative changes in AEI (Freydank and Siebert, 2008), as it is assumed that the change in AEI can be used as an indicator for the change in RIA.

Monthly GIR and NIR in $5'$ resolution are then exported to the global hydrology and water use model WaterGAP, where accumulated anthropogenic water requirements from the different sectors (livestock, electricity production, manufactures and domestic) are considered as abstractions from the naturally available water in each grid cell to give a holistic approach for the calculation of total European water use (Alcamo et al., 2003).

2.2.1 LPJmL/LandSHIFT

The concept of this approach relies on soft-coupling a global land use model, LandSHIFT (Schaldach and Koch, 2009), with a global dynamical vegetation model, LPJmL (Bondeau et al., 2007), within a MySQL environment to calculate crop specific monthly net irrigation requirements (NIR) in $5'$+resolution (Fig. 1).

LandSHIFT (Land Simulation to Harmonize and Integrate Freshwater availability and the Terrestrial environment) is a spatially explicit dynamic model to simulate land-use change on the continental and global scale. It has been applied and validated in assessments of land-use change (LUC) in Africa (Weiß et al., 2009), grazing management in the Jordan River region (Koch et al., 2008), and LUC associated with increased use of biofuels in Brazil (Lapola et al., 2010). The model, fully described by Schaldach and Koch (2009) couples two modules to represent human and environment components of the global land-use system and their linkages. The LUC-module computes changing land-use patterns caused by competing human activities such as settlement, crop cultivation and livestock grazing. This is done by regionalizing country-level input for agricultural production (crops and livestock) and human population development to a 5′ grid. Information about potential crop yields under rain-fed and irrigated conditions as well as biomass productivity of grasslands is provided by the productivity module based on simulation runs conducted with the LPJmL model.

The LPJmL model, a more comprehensive version of the LPJ-DGVM (Sitch et al., 2003), is a biogeochemical process model that simulates global vegetation dynamics and associated carbon and water fluxes on 0.5° grid cells. Agricultural land use productivity is simulated through the consideration of 13 crop functional types (CFTs), either rain-fed or irrigated, representing the world's most important annual field crops: temperate cereals, rice, maize, tropical cereals, pulses, temperate roots, tropical roots, sunflower, soybean, groundnuts, rapeseed, sugar-cane and pasture. Moreover, LPJmL's crop module simulates sowing dates, crop phenology, growth and carbon allocation at a daily time step (except sowing dates). All four processes respond to climatological variables such as precipitation, temperature and radiation. Living carbon storage is divided in three compartments: roots, leaves, reserves and storage organs, the latter representing the plant's biomass fraction that is harvested. Soil water storage is considered in two layers up to 1.5 m deep (0.5 m upper and 1.0 lower). Water content is updated daily, taking into account snowmelt, percolation, rainfall, evapotranspiration, runoff and interception (Sitch et al., 2003; Gerten et al., 2004). Evaluation of LPJmL's performance for simulation of yields, phenology and carbon fluxes is fully presented in Bondeau et al. (2007).

Potential irrigation water requirements for each crop have been determined from the soil water deficit below optimal growth of that CFT, i.e. additional soil water required to avoid plant water stress. Water stress (ω) is calculated as the ratio between plant canopy water supply (E_{sup}) and atmospheric demand for transpiration (E_{demand}):

$$\omega = \frac{E_{\text{sup}}}{E_{\text{demand}}} \tag{2}$$

$$E_{\text{sup}} = E_{\max} \cdot \text{wr} \tag{3}$$

$$E_{\text{demand}} = E_{\text{pot}} \cdot \alpha_m \left[1 - \exp\left(\frac{-g_{\text{pot}}\phi}{g_m} \right) \right] \tag{4}$$

Where $E_{\max}$ is the crop dependent maximum transpiration rate (5 mm/d for maize); wr is plant root weighted soil moisture (fraction of roots in the upper soil layer at the current time step); E_{pot} is equilibrium evapotranspiration based on Prescott equation and dependent on latitude, temperature and sunshine hours; α_m and g_m are empirical constants (= 1.4 and 5.0, respectively); $g_{\text{pot}}\Phi$ is non-water stressed potential canopy conductance (see Monteith, 1995, and Sitch et al., 2003). The plant is considered under water stress when ω is below 0.7.

The model has been run for the period 1901–2002, preceded by a 1000-year spin-up phase in order to bring carbon pools into equilibrium. Annual atmospheric CO_2 concentration has been taken from Keeling and Whorf (2005) and Sitch et al. (2003). The crop specific water demands as calculated with LPJmL have been downscaled from 0.5 to 5′ to be concordant with the LandSHIFT resolution. The model version applied in this study does not consider double cropping, nor agricultural vegetation that falls into a plant functional type (PFT) class, such as olive trees and grapevines, which account for 24% of the pan-European RIA. These area are not considered.

2.2.2 WaterGAP3

The second modelling framework applied in this study is WaterGAP3. WaterGAP3 is a global hydrology and water use model (Alcamo et al., 2003), which calculates water fluxes and anthropogenic water abstractions on a 5′ grid. River runoff is calibrated and validated against 1600 stations of observed river flow. The irrigation module plays a dominant role within the WaterGAP3 framework, as irrigation globally causes 70% of all anthropogenic water abstractions (UNEP, 2007) and can severely alter natural runoff regimes. For this model study, the irrigation module has been further developed to account for 18 different crop types. The model concept (Allen et al., 1998) applied here relies on calculating net irrigation requirements (NIR) as a product of crop coefficient K_C and evapotranspiration ET_{PT} according to Priestley-Taylor (Priestley and Taylor, 1972):

$$\text{NIR} = K_C \cdot \text{ET}_{\text{PT}} \tag{5}$$

K_C values feature a crop specific distinctive distribution curve throughout the growing period and are closely related to LAI development (Liu and Kang, 2007), as they mimic plant development. For example, the barley K_C increases between day 1 and 120 from 0.3 to 1.2, and then decreases until day 150 to 0.25. As K_C curves vary within different climatic regions of the world, different K_C values for arid and humid grid cells have been incorporated in the model. All K_C curves applied in this study are based on field observations (Allen et al., 1998). The growing period of each crop has been scaled to 150 days, which allows for two cropping periods within one year.

3 Results and discussion

The country scale comparison of the new RIA database with the AEI database reveals large differences. According to the RIA database, 167.000 km^2 have been irrigated in the year 2000 within pan-Europe, whereas AEI indicates an area of 270.000 km^2 (see Table 1). In addition, the RIA crop distribution differs significantly from the spatial join of AEI and CORINE/GLCC. For example, RIA statistics claim that 31% of the total European irrigated area is cropped with temperate

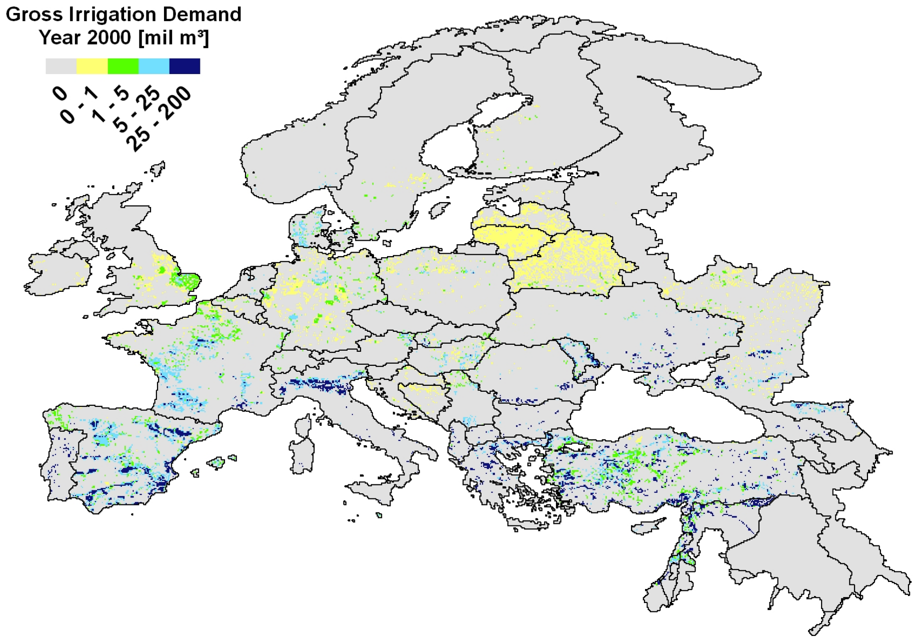

Fig. 2. Gross irrigation water requirements for the year 2000, as modelled with LPJml.

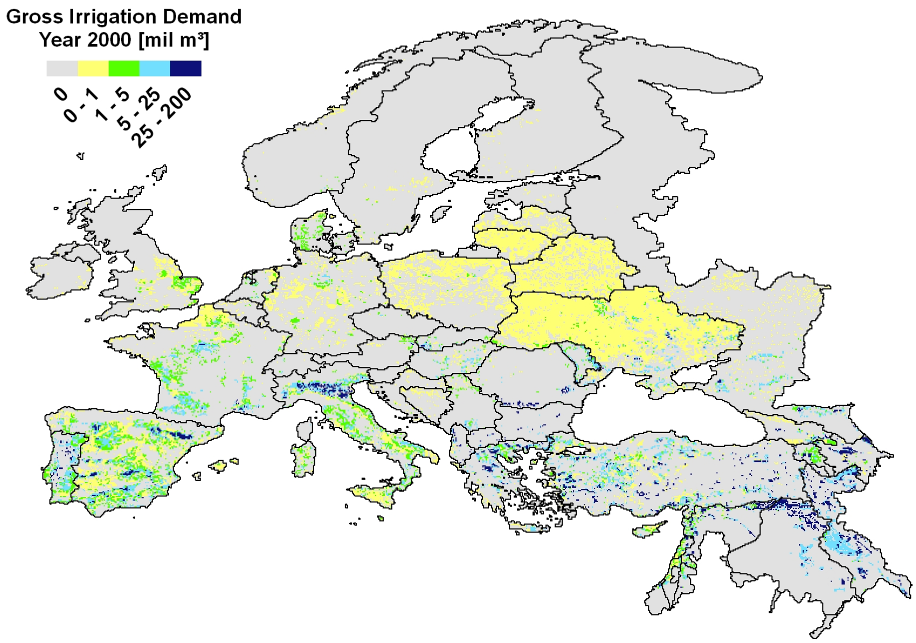

Fig. 3. Gross irrigation water requirements for the year 2000, as modelled with WaterGAP3.

cereals, while AEI indicates 55%. This shows that the RIA concept is more reliable, not only in terms of irrigated area but also in terms of crop composition. Irrigation modelling with the AEI concept would lead to highly overestimated irrigation water requirements and inadequate cropping patterns.

Pan-European gross irrigation water requirements (GIR) for the year 2000, as calculated with LPJmL (see Table 1 and Fig. 2) show a deviation of 66 km^3 or 60% compared to reported irrigation water uses. This is mainly caused by large overestimations in the southern Mediterranean countries of Turkey and Spain, which alone account for 50 km^3 or 45% of the total deviation. Generally, due to unlimited water supply and missing economical constraints in the irrigation model framework, gross irrigation water requirements are overestimated in 29 out of 40 countries (Table 1). However, an underestimation of irrigation water requirements would have been

Table 1. Country based RIA (Real Irrigated Area), AEI (Area Equipped for Irrigation), E_{proj} (irrigation project efficiency), GIR_R (reported Gross Irrigation Requirements), GIR_{WG} (modelled Gross Irrigation Requirements from WaterGAP3), GIR_{LPJ} (modelled Gross Irrigation Requirements from LPJmL). Please note that Azerbaijan, Iran, Iraq, Jordan, Russia, and Syria are not included in this table, as they are not fully embedded within the pan-European borders.

Country	RIA [km^2]	AEI [km^2]	E_{proj} [–]	GIR_R [mil m^3]	GIR_{WG} [mil m^3]	GIR_{LPJ} [mil m^3]
Albania	1800	3400	0.55	1060	1133	1422
Austria	400	970	0.62	100	210	440
Armenia	1870	2860	0.42	1500	1884	2266
Belgium	100	350	0.71	10	13	46
Bosnia-Herzegovina	30	46	0.42	missing	37	49
Bulgaria	540	5450	0.45	1185	740	843
Belarus	1150	1150	0.71	200	354	236
Croatia	30	58	0.71	20	19	30
Cyprus	380	560	0.76	166	177	132
Czech Republic	170	506	0.61	60	66	116
Denmark	2040	4760	0.71	465	381	1344
Estonia	6	13.6	0.40	8	9	2
Finland	200	1040	0.62	40	16	60
France	16 520	29 060	0.54	4872	7388	14 673
Georgia	1970	3000	0.38	2040	1799	1451
Germany	2670	4970	0.62	163	585	1817
Greece	11 610	15 450	0.57	7600	9081	11 924
Hungary	1000	2920	0.61	1010	666	980
Ireland	10	10	0.40	0.2	1	8
Israel	1770	1830	0.75	898	450	952
Italy	26 980	38 920	0.49	20 000	13 393	12 235
Lebanon	1170	1170	0.51	780	736	964
Latvia	8.3	11.5	0.71	40	1.4	2.6
Lithuania	44	44	0.62	8.1	8.6	23
Luxembourg	2.4	2.7	0.71	missing	0.9	1.4
Macedonia	270	1280	0.40	1369	382	512
Malta	23	23	0.40	19	16	51
Moldova	2560	3070	0.38	760	1943	4260
Netherlands	1140	4760	0.51	260	250	133
Norway	400	1340	0.42	73	44	118
Poland	740	1340	0.41	110	212	401
Portugal	5820	7920	0.39	6551	5566	3910
Romania	4230	21 500	0.55	4200	3328	4916
Serbia-Montenegro	570	1650	0.42	760	575	831
Slovakia	1110	2250	0.62	321	589	734
Slovenia	28	156	0.57	6.6	6.3	28
Spain	34 080	35 750	0.53	20 535	21 151	40 337
Sweden	490	1880	0.71	94	63	226
Switzerland	150	400	0.71	50	29	33
Turkey	30 980	41 860	0.38	31 500	31 721	62 029
Ukraine	10 000	23 960	0.61	2400	4613	6363
United Kingdom	1710	2290	0.62	280	548	892
SUM	166.772	269.981		111.514	110.147	177.741

expected, as multi-annual crops, such as olives and grapes, which cover 24% of the pan-European RIA, are not yet being considered by LPJmL. The national statistics to which the modelled GIR are compared to, include irrigation water use by these crops. This is the case in Italy and Portugal, where 43% and 65%, respectively, of the RIA are cropped with fruits, olives and fodder. Thus, LPJmL does not calculate crop water fluxes in these grid cells and underestimates GIR by 40% (see Table 1).

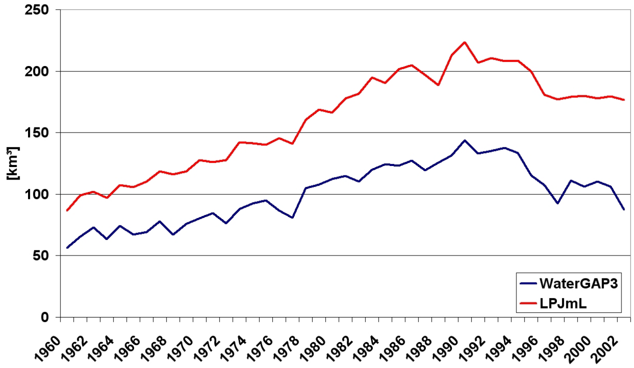

Fig. 4. Modelled gross irrigation water requirements for the period 1960–2002, aggregated from 42 European countries (see Table 1 for list of countries).

Pan-European GIR for the year 2000, as calculated with WaterGAP (see Table 1 and Fig. 3) show a deviation of 1 km^3 or 1% compared to reported irrigation water uses. However, GIR in the colder northern countries, such as Sweden, Finland, Norway and Latvia are constantly underestimated by this conceptual modelling approach, which points out the disadvantages of applying constant growing periods and non-regionalised K_C curves.

A visual comparison of GIR from both modelling frameworks (Figs. 2 and 3) shows higher values for most grid cells by LPJmL, as well as a larger spatial extent by WaterGAP3. The first point can also be observed in Table 1 and is caused by the overestimation of GIR for some pan-European regions. The second point is very well illustrated by Ukrainian GIRs, where large differences between Figs. 2 and 3 are apparent. 62% of the Ukrainian RIA is cropped with fodder, which is not included in the LPJmL/LandSHIFT version applied in this study. Moreover, 71% of the Ukrainian grid cells are used for irrigation, whereas only 1.6% of the Ukrainian land area is being irrigated. This discrepancy can be explained by extremely small field sizes in irrigated fodder production. The average Ukrainian field size is 1.3 km^2 per grid cell, while other countries, such as Italy or Lebanon, feature mean field sizes of more than 11 km^2 per grid cell.

Figure 4 shows the temporal development of GIR between 1960 and 2002. As the dynamics of both modelling frameworks are similar for most years, the large climatic influence on the simulation of GIR becomes evident. Exceptions, as for example in 1988 and 2002, point to the structural differences between a simple conceptual irrigation model and a plant growth model.

In general, many potential sources of uncertainty, as for example year and procedure of reporting, assumed project efficiency, greenhouses, illegal water abstractions, etc., exist and need to be analyzed for each country separately. Additionally, reported water uses are often estimated by the local authorities and not gauged.

4 Conclusions

This modelling experiment shows that we are able to depict historical and current European irrigation water requirements with two different modelling frameworks.

The more complex LPJmL model, which has the advantage of additionally simulating yields and nutrient fluxes, overestimates GIR in most countries. This general overestimation of water demand pinpoints two drawbacks of the model framework. First, irrigation limitations need to be introduced, as in the version of LPJmL used in this study crops are currently being irrigated as soon as soil water content drops below an optimum growth threshold, and thus, never endure water stress (Bondeau et al., 2007). Secondly, irrigation management strategies with regard to operating costs need to be implemented. In the current model version, crops are watered frequently to receive optimal yields, whereas in reality, a local farmer would balance out irrigation costs and marginal yield losses. Additionally, hard-coupling the irrigation model framework with a hydrological model would lead to more realistic results, as feedback loops between water availability and withdrawals could be reproduced (Gerten et al., 2009). However, to allocate water withdrawals within a hydrological model, information about the source of water (groundwater, surface water, or re-used waste water) would be required.

The conceptual WaterGAP3 modelling framework generally shows a good level of agreement between modelled and reported GIR for most pan-European countries. However, in colder northern countries, GIR often is underestimated. Thus, as different K_C curves can be found for cold regions (Allen et al., 1998), they should also be included in the model. They could, for example, be linked to the Köppen climate classification (Kottek et al., 2006). This might yield more realistic GIR results. Furthermore, the growing periods, which have been scaled to 150 days for each crop, should be set to their natural values and regionalised as well. Growing periods in the high latitudes vary from those in the warmer Mediterranean regions and could explain the underestimation of GIRs.

In order to assess the impact of climate change on irrigation water requirements for Europe, both model concepts offer essential prerequisites as future climate projections, irrigation efficiency changes, and crop yield assumptions are ready available and can easily be applied to calculate scenarios.

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