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A Site-sPecific Agricultural water Requirement and footprint Estimator (SPARE:WATER 1.0)

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Abstract. The agricultural water footprint addresses the quantification of water consumption in agriculture, whereby three types of water to grow crops are considered, namely green water (consumed rainfall), blue water (irrigation from surface or groundwater) and grey water (water needed to dilute pollutants). By considering site-specific properties when calculating the crop water footprint, this methodology can be used to support decision making in the agricultural sector on local to regional scale. We therefore developed the spatial decision support system SPARE:WATER that allows us to quantify green, blue and grey water footprints on regional scale. SPARE:WATER is programmed in VB.NET, with geographic information system functionality implemented by the MapWinGIS library. Water requirements and water footprints are assessed on a grid basis and can then be aggregated for spatial entities such as political boundaries, catchments or irrigation districts. We assume inefficient irrigation methods rather than optimal conditions to account for irrigation methods with efficiencies other than 100 %. Furthermore, grey water is defined as the water needed to leach out salt from the rooting zone in order to maintain soil quality, an important management task in irrigation agriculture. Apart from a thorough representation of the modelling concept, we provide a proof of concept where we assess the agricultural water footprint of Saudi Arabia. The entire water footprint is 17.0 $km^3\,yr^{-1}$ for 2008, with a blue water dominance of 86 %. Using SPARE:WATER we are able to delineate regional hot spots as well as crop types with large water footprints, e.g. sesame or dates. Results differ from previous studies of national-scale resolution, underlining the need for regional estimation of crop water footprints.

1 Introduction

According to the Food and Agriculture Organization (2012a), 70 % of withdrawn surface water and groundwater is used by irrigated agriculture. For the analysis of water utilisation in the agricultural sector at large scales, Hoekstra and Hung (2002) have developed the concept of the water footprint (WF), which is an indicator for direct and indirect gross water consumption of commodities. In our study, the water footprint is limited to the water consumption by growing crops. WF consists mainly of water necessary to meet the needs of crops represented by green (WFg) and blue (WFb) water, which are given by rain for the first type and groundwater or surface water for the second type, respectively. The total WF is formed by adding a third type of water necessary to dilute pollutants in the water to meet water quality standards, which is known as grey water (WFgr). The total WF is defined according to Hoekstra et al. (2011):

$$\mathrm{WF} = \mathrm{WFg} + \mathrm{WFb} + \mathrm{WFgr}, \tag{1}$$

where WF is given in water volume that is consumed and/or polluted per unit biomass (yield) or area. Using this approach, several WFs have been estimated. These studies offer insight into the WF of sectors, products or nations. A global perspective is given by Hoekstra and Mekonnen (2012), who estimate the water footprint of humanity to be 9087 $km^3\,yr^{-1}$, whereby agriculture contributes the largest fraction of 92 %. Further publications focus on nations (Chapagain et al., 2006; Hoekstra and Chapagain, 2007; Hoekstra and Hung, 2002; Chapagain and Hoekstra 2008) or

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commodities produced worldwide (Chapagain et al., 2006; Gerbens-Leenes et al., 2009). Others investigate the water footprint of a business (Ercin et al., 2011) or give deeper insight into the water footprint of single food products (Ercin et al., 2012). Mekonnen and Hoekstra (2010a, b) have assessed worldwide water footprints of a large number of crops and secondary agricultural products. The basis for all these water footprint analyses have been the FAO evapotranspiration guidelines by Allen et al. (1998) or the CropWat model (Smith, 1992), which is based upon the same guidelines. Those studies considered irrigation but did not specifically define and investigate irrigation practices such as furrow irrigation, sprinkler irrigation and drip irrigation.

However, the continued deterioration in the quality of irrigation water as well as different irrigation methods requires the consideration of local environmental conditions if the water footprint of irrigation agriculture is to be assessed. A closer look at the local WF of cotton crop, for example, highlights the need for such an approach. The area under cultivation for cotton production shows a large spatial variability in cultivation and management conditions all over the world. According to Chapagain et al. (2006), the water footprint (WF) of cotton varies between 5404 and 21 563 ($m^3\,t^{-1}$) for China and India, respectively. Hence, the influence of spatial variation on the water footprint is more visible at the local level, especially in the case of irrigation management. However, the regional approach to get an accurate estimate of the water footprint requires high spatial resolution input data to capture the local variations of soil, climate and especially management practices, which in turn requires high-resolution models.

The WF is derived by dividing the simulated water requirement by the crop yield. Often, authors derive information on crop yields from agriculture statistical data, which are provided by national departments or can be found in public available data sets such as FAOSTAT (FAO, 2012b). Alternatively, yields are predicted along with crop water requirements. The FAO model AquaCrop (Raes et al., 2009; Steduto et al., 2009) supports decision making and addresses questions such as deficit or supplementary irrigation as well as crop growth and yield response to water stress. Liu et al. (2007) have incorporated the EPIC model (Williams et al., 1984) into ESRI's ArcGIS to estimate global green and blue water from agriculture land, thereby capturing spatial variability. The Soil Water Assessment Tool (SWAT), another GIS-based model, was used by Schuol et al. (2008) to derive green and blue water estimates of the African continent. The water resource model H08model (Hanasaki et al., 2010) and the dynamic vegetation and water balance model LPJmL (Fader et al., 2010) have been applied to derive water consumption on a global scale. Most of these applications are limited to blue and green WF without taking into consideration the inherent significance of irrigation practice on the blue water footprint. Furthermore, the grey water footprint has not been considered, and thus local water quality is not represented, although agricultural production often reduces the quality of surface water and groundwater. Some studies have considered the impact of pesticides and fertilisers by the estimation of the grey water footprint (Dabrowski et al., 2009; Mekonnen and Hoekstra, 2010; Ene and Teodosiu, 2011). Liu et al. (2012) have calculated past and future phosphorus and nitrogen inputs into rivers and their effect on the grey WF. In accordance with Hoekstra et al. (2011), the grey WF in these studies refers to the fresh water needed to dilute concentrations of pollutants in order to meet water quality standards.

Irrigation with relatively poor water quality due to salinity in arid/semi-arid regions could contribute significantly to soil degradation. Along with low irrigation efficiency, the leaching of salts in irrigation agriculture increases the demand for water in order to get the maximum productivity of crops. Apart from geogenic background and weathering, the irrigation water itself is a major source of salts, which ultimately accumulate in the rooting zone. To maintain the soil quality it is necessary to leach out salts from the rooting zone by means of additional irrigation water. Currently, this quantity of water is not considered in WF estimations of irrigation agriculture, and an accounting approach for leaching water needs to be defined to enhance the calculation of the grey water footprint.

The required amount of leaching water to counteract salinisation can be quantified by empirical equations, steady-state assumptions or transient models. Recently, Letey et al. (2011) and Corwin et al. (2007) reviewed steady-state and transient models. In general, transient models (Corwin and Waggoner, 1991; Simunek and Suarez, 1993) are very complex, aiming at capturing physical and chemical processes, and thus require a large amount of input parameter. In contrast, empirical equations (Ayers and Westcot, 1994) such as the steady-state models WATSUIT (Rhoades and Merrill, 1976) and WPF (Letey et al., 1985) are less complicated and require only a small number of parameters. Visconti et al. (2012) have assessed leaching requirement under Spanish conditions and have stated that WATSUIT, empirical equations and SALTIRSOIL produce similar results, whereby the latter one considers the most processes. Recently, Hussain et al. (2010) have recommended the application of empirical equations for leaching management under arid conditions.

The aim of this study is to develop a spatial decision support system, SPARE:WATER, for the assessment of green, blue and grey water footprints in irrigation-dominated regions. Our goal is to provide a computer program, based on well-established irrigation guidelines, which can be used in areas with limited environmental information. For this, the calculation of the blue water footprint has been slightly modified in comparison to Hoekstra et al. (2011) by considering two important characteristics of irrigation agriculture, i.e. the irrigation efficiency and the irrigation method. Furthermore, the grey water footprint in our approach refers to

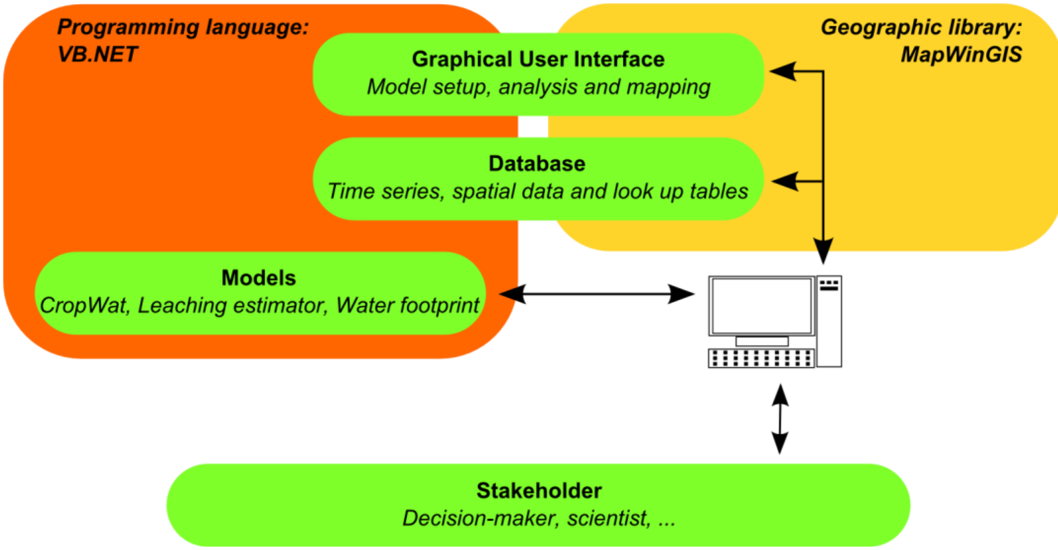

Fig. 1. Components of SPARE:WATER (green). Models are implemented with VB.Net. Graphical user interface (GUI) and database are programmed with VB.Net by using the spatial programming library MapWinGIS.

the amount of leaching water required to preserve soil quality for maximum crop production, in contrast to the original concept of grey water, which aims to dilute contaminants in surface water and groundwater to acceptable standards. The spatial WF data management and analysis are achieved by integrating all calculations in a geographic information system (GIS) environment. In the following, the software tool, its technical layout and structure are described. Furthermore, a proof of concept is presented by calculating the water footprint of the agricultural sector of Saudi Arabia.

2 Model and data

2.1 Model concept

The spatial decision support system SPARE:WATER (http://www.uni-giessen.de/cms/ilr-download) consists of four basic components: simulation models, a database, a graphical user interface (GUI) and relevant stakeholders (Fig. 1). The current version uses three models to assess the agricultural water footprint. Site-specific simulations of crop water, irrigation and leaching requirement are assessed in accordance with FAO irrigation guidelines (Allen et al., 1998; Ayers and Westcot, 1994) and in line with the water footprint manual (Hoekstra, 2011), in which the utilisation of CropWat (Smith, 1992) or EPIC (Williams et al., 1984) is recommended. The water footprints are estimated by aggregating simulation results with agricultural statistical data by the concept of Hoekstra et al. (2011). A database with site-specific information on climate, irrigation management and agricultural statistics is used to set up the simulation models. Modelling steps in SPARE:WATER are supported by a GUI for easy and straightforward utilisation by non-GIS-experts. The software is implemented in VB.NET and available for Microsoft Windows. The software utilises an open source spatial programming library called MapWinGIS Active X (http://mapwingis.codeplex.com/) for management of grid and shape files as well as the GIS-based GUI.

The SPARE:WATER tool allows the quantification of agricultural water footprints across a range of spatial scales, which is defined by the spatial resolution of required input data. For this, SPARE:WATER combines statistical site-specific data, i.e. crop yield and harvest area, with simulations of water requirements to derive the water footprint of a crop for any geographical location. The three consecutive steps involved in this calculation are illustrated in Fig. 2. Firstly, environmental data as well as data on irrigation management are used to simulate water requirements for each grid cell. The water requirements are aggregated with statistical crop yields to derive the crop water footprint (WF_{crop}) for each grid cell. In the second step, the WF_{crop} of a certain geographically delineated area is estimated, which is represented by the average value of gridded WF_{crop}. Such a geographically delineated area can be given by administrative units, catchment boundaries or agro-ecological zones. Finally, total crop production and WF_{crop} are aggregated to estimate the regional agricultural water footprint WF_{area}.

2.2 Regional agricultural water footprint (WF_{area})

The water footprint for a certain geographically delineated area can be expressed in the form suggested by Hoekstra et al. (2011):

$$WF_{area} = \sum WF_{crop} \cdot Prod \times 10^{-9}, \quad (2)$$

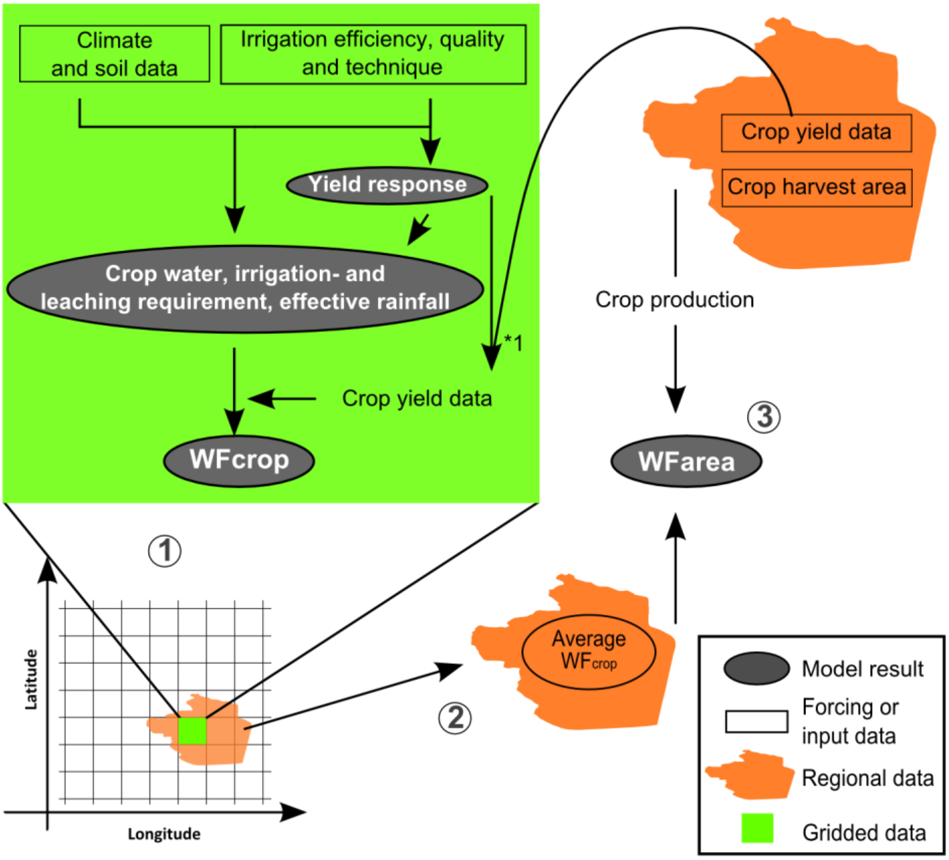

Fig. 2. SPARE:WATER uses gridded site-specific data (1) to assess the water requirement, the yield response factor and the water footprint of growing a crop (WF_{crop}). Results are averaged for each geographically delineated area (2) and aggregated with agricultural statistical information (3) to calculate the water footprint of an area (WF_{area}). Agricultural statistics include crop yields per hectare as well as total harvest area for each region in hectares ($*^{1}$ crop yield data are taken from regional statistics and adjusted on the grid scale to account for salinity influences).

with the water footprint of a geographically delineated area (WF_{area}) in [$km^3\ yr^{-1}$], crop water footprint (WF_{crop}) in [$m^3\ t^{-1}$] and crop production (Prod) in [$t\ yr^{-1}$]. WF_{area} can be further subdivided into irrigation from groundwater or surface water (blue water), rain water (green water) as well as leaching water from groundwater or surface water (grey water), and is abbreviated for each type of water with WFg_{area} (green), WFb_{area} (blue) and $WFgr_{area}$ (grey).

2.3 Crop-specific agricultural water footprint (WF_{crop})

The water footprint of growing a crop WF_{crop} is the sum of the green (WFg_{crop}) and blue (WFb_{crop}) water required by the specific plant for its growth, whereby the colours refer to the type of water source. In addition, grey ($WFgr_{crop}$) is needed to leach out salts from the rooting zone. Each component is derived by calculating the localised yield-specific water requirements. The calculation requires the simulation of the crop water requirement (CWR) [$m^3\ ha^{-1}$], the irrigation requirement (IRR) [$m^3\ ha^{-1}$] and the leaching requirement (LR) [$m^3\ ha^{-1}$] as well as effective rainfall (P_{eff}) [$m^3\ ha^{-1}$] per growing season:

$$WFg_{crop} = \frac{\max\left(P_{eff}, \mathrm{CWR} - P_{eff}\right)}{Y}, \tag{3}$$

$$WFb_{crop} = \frac{\mathrm{IRR}}{Y}, \tag{4}$$

$$WFgr_{crop} = \frac{\mathrm{LR}}{Y}, \tag{5}$$

with WFg_{crop}, WFb_{crop} and $WFgr_{crop}$ in [$m^3\ t^{-1}$] WFg_{crop} in [$m^3\ t^{-1}$] and the yield (Y) [$t\ ha^{-1}$] per growing season. WFg_{crop} thereby considers how much of the crop water required for crop growth can be matched by incoming precipitation. WFb_{crop} is derived from the amount of irrigation water which is applied to the field. The third type of water, defined as $WFgr_{crop}$, is calculated from the leaching requirement to wash out salts from the rooting zone. WFb_{crop} and $WFgr_{crop}$ come from groundwater or surface water resources.

2.4 Site-specific crop water (CWR) and irrigation requirement (IRR)

The calculation of the crop water requirement (CWR) basically depends on the potential evapotranspiration (PET). The SPARE:WATER model implements four methods to estimate PET depending on the geographical location and available climatic factors:

– Turc (Turc, 1961) and Priestley–Taylor (Priestley and Taylor, 1972): based on solar radiation, temperature and humidity.

– Hargreaves–Samani (Hargreaves and Samani, 1985): based on extraterrestrial radiation and temperature.

– Penman–Monteith (Allen et al., 1998): based on solar radiation, temperature, wind speed and humidity.

A dimensionless crop coefficient K_c is used to adjust PET to crop-specific properties as described by Allen et al. (1998). Accordingly, crop development is divided into four stages, i.e. initial season (L_ini), growth season (L_dev), mid-season (L_mid) and late season (L_end). Three dimensionless crop coefficients (K_c) are defined for L_ini, L_mid and L_end. For days between initial and mid-season as well as between mid-season and late season, K_c values are linearly interpolated. An adjusted crop coefficient $K_\mathrm{c\,adj}$ is used by Allen et al. (1998) for specific climatic conditions ($20\,\% < \mathrm{RHmin} < 80\,\%$; $1\,\mathrm{m\,s^{-1}} < u_2 < 6\,\mathrm{m\,s^{-1}}$; $0.1\,\mathrm{m} < h < 10\,\mathrm{m}$) in the mid-season and late season (Eq. 6). Under all other climatic conditions $K_\mathrm{c\,adj}$ equals K_c:

$$K_\mathrm{c\,adj} = K_\mathrm{c} + \left[0.04 \cdot (u_2 - 2) - 0.004 \cdot (\mathrm{RH_{min}} - 45) \cdot \left(\frac{h}{3}\right)^{0.3}\right] \quad (6)$$

with K_c, $K_\mathrm{c\ adj}[-]$, wind speed u_2 in 2 m height [$\mathrm{m\,s^{-1}}$], minimum relative humidity $\mathrm{RH_{min}}$ in [%] and crop height h in [m]. The CWR is calculated as (Allen et al., 1998)

$$\mathrm{CWR} = \mathrm{PET} \cdot K_\mathrm{c\,adj}, \quad (7)$$

with PET in [$\mathrm{m^3\,ha^{-1}}$]. The model accounts for the runoff losses (RO) as a constant ratio of 20 % of precipitation (P)($\mathrm{RO} = P \times 0.2$). Effective rainfall P_eff is calculated as follows (Allen et al., 1998):

$$P_\mathrm{eff} = P - \mathrm{RO}, \quad (8)$$

with P and RO given in [$\mathrm{m^3\,ha^{-1}}$]. The fixed runoff loss of 20 % is in agreement with the general water footprint accounting scheme. If higher temporal resolution data are available and a daily accounting of the water footprint is aimed for, more-sophisticated approaches are needed to more precisely estimate runoff losses, which are not included in the current version of SPARE:WATER 1.0.

When the available effective rainfall P_eff is not sufficient to meet the water requirement of crops, additional irrigation water is added. Irrigation requirement (IRR) from surface water and/or groundwater resources is estimated according to Allen et al. (1998):

$$\mathrm{IRR} = \max\left(\mathrm{CWR} - P_\mathrm{eff}, 0\right) \cdot \mathrm{IRR_{eff}}, \quad (9)$$

with $\mathrm{IRR_{eff}}$ in [%]. $\mathrm{IRR_{eff}}$ is defined for each cell of a grid map during model setup by the user. We note that the term irrigation efficiency has been intensively discussed (e.g. Jensen, 2007; Lankford, 2012) and that there is not a common definition available. The problem is to define which fraction of water contributes to irrigation efficiency (e.g. consumptive and non-consumptive water use, recovered and non-recovered return flow). Thus, users of SPARE:WATER are requested to carefully think about the irrigation use efficiency used in their respective study.

2.5 Site-specific leaching requirement (LR)

Irrigated agriculture in dry locations with high temperatures often faces the problem of increasing soil salinity due to evaporation of irrigation water. Leaching out the accumulated salts from the soil profile is a farming technique common to maintain quality of the soil at the beginning of the growing season. The required amount of water for leaching, the so-called leaching requirement (LR), is calculated by the total amount of IRR and a leaching fraction (LF) according to Ayers and Westcot (1976):

$$\mathrm{LR} = \frac{\mathrm{IRR}}{1 - \mathrm{LF}} - \mathrm{IRR}, \quad (10)$$

with dimensionless LF [−]. The leaching fraction (LF) represents the water volume that is lost beyond the root zone in relation to the amount of water irrigated, and is estimated in two slightly different ways, depending on the method used for irrigation. For sprinkler/pivot and drip irrigation the maximal tolerable salt concentration of a crop ($\mathrm{EC_{e0\,\%}}$) is used to estimate the leaching fraction (LF_p). Under surface irrigation an adjusted crop salt tolerance value ($\mathrm{EC_{e\,adj}}$) is applied to derive the leaching fraction (LF_s). The calculation of LF_p and LF_s is given by Al-Zeid et al. (1988) as follows:

$$\mathrm{LF}_p = \frac{\mathrm{EC}_w}{2 \cdot \mathrm{EC_{e0\,\%}}}, \quad (11)$$

$$\mathrm{LF}_s = \frac{\mathrm{EC}_w}{5 \cdot \mathrm{EC_{e\,adj}} - \mathrm{EC}_w}, \quad (12)$$

with EC_w, $\mathrm{EC_{e0\,\%}}$ and $\mathrm{EC_{e\,adj}}$ given in [$\mathrm{dS\ m^{-1}}$]. The adjusted crop salt tolerance ($\mathrm{EC_{e\,adj}}$) depends on the site-specific yield response factor.

2.6 Site-specific yield response (Y_ratio)

Irrigation with saline irrigation water decreases crop yields because high salt concentrations limit plant water uptake. Two thresholds $\mathrm{EC_{e100\,\%}}$(no limitation of crop growth) and

Table 1. Input data for SPARE:WATER.

Type	Description	Unit	Status	Format
Input parameters	Crop characteristics			
	Crop coefficient (Kc_{ini}, Kc_{mid}, Kc_{end})	[–]	Needed	Coefficient, look-up table
	Length of growing season (L_{ini}, L_{dev}, L_{mid}, L_{late})	[days]	Needed	Coefficient, look-up table
	Rooting depth (Zr_{max}, Zr_{ini})	[cm]	Needed	Coefficient, look-up table
	Crop height (H_{max})	[cm]	Needed	Coefficient, look-up table
	Crop-tolerable salt concentration in the soil extract ($ECe_{0\,\%}$, $ECe_{100\,\%}$)	[dS m^{-1}]	Needed	Coefficient, look-up table
	Sowing	[date]	Needed	Coefficient, look-up table
	Harvest	[date]	Needed	Coefficient, look-up table
Input data	Irrigation quality (salt concentration)	[dS m^{-1}]	Needed	Spatial, grid map
	Irrigation efficiency	[%]	Needed	Spatial, grid map
	Irrigation method	[–]	Needed	Spatial, grid map
	Yield target	[%]	Needed	Spatial, grid map
	Geographic units		Needed	Spatial, shape file
	Digital elevation model	[m]	Needed	Spatial, grid map
Forcing data	Climate			
	Precipitation (monthly)	[m^3 ha^{-1}]	Needed	Time series, grid map
	Radiation (monthly)	[MJ m^{-2}]	Optional	Time series, grid map
	Sunshine hours (monthly)	[h]	Optional	Time series, grid map
	Humidity (monthly)	[%]	Optional	Time series, grid map
	Wind speed (monthly)	[m s^{-1}]	Optional	Time series, grid map
	Temperature (monthly)	[°C]	Needed	Time series, grid map
	Agricultural statistics			
	Yield per crop (annual)	[t ha^{-1}]	Needed	Time series, table or grid
	Harvest area (annual)	[ha yr^{-1}]	Needed	Time series, table

$EC_{e0\,\%}$(full limitation of crop growth) define the relationship between crop yield and electric conductivity of the soil solution and thus the yield response (Y_{ratio}). A straightforward function is used to calculate Y_{ratio} according to Maas and Hoffman (1977):

$$Y_{ratio} = \frac{100\,\%}{ECe_{0\,\%} - ECe_{100\,\%}}, \quad (13)$$

with $EC_{e0\,\%}$ and yield loss per unit increase in salinity Y_{ratio} [% (dS m^{-1})$^{-1}$]. High salt concentrations in the soil solution require a large amount of leaching water to maximise crop yield. However, in order to decrease the water requirement of growing a crop, the trade-off between maximum crop yields on the one hand and low leaching requirements on the other hand should be taken into account. For this reason, the user can set a target yield value (Y_{target}) in SPARE:WATER, which leads to lower crop yields but less leaching water. Under such condition, the crop-tolerable salt concentration will differ from $EC_{e100\,\%}$, and needs to be adjusted to the new Y_{target}. To do this, SPARE:WATER calculates the associated adjusted crop salt tolerance value ($EC_{e\ adj}$) (Maas and Hoffman, 1977):

$$EC_{e\ adj} = \frac{100 + EC_{e100\,\%} \cdot Y_{ratio} - Y_{target}}{Y_{ratio}}, \quad (14)$$

with Y_{target} in [%]. All data and parameters required to calculate the site- and region-specific WFs according to Eqs. (2)–(14) need to be provided in a database.

2.7 Database

SPARE:WATER data requirement is grouped into input parameters, spatial input data and forcing data. The required data are presented in Table 1. Input parameters are coefficients, which define a specific crop according to the crop coefficient concept reported by Allen et al. (1998). A specific crop is characterised by the length of growing season, crop coefficients, maximum crop height and salt tolerance, as well as sowing and harvesting date. These data are stored in look-up tables. The spatial input data mainly consist of grid maps containing information on irrigation management (irrigation practice, efficiency and salt concentration of irrigation water) as well as target yields. Additional maps needed contain a digital elevation model and a shape file of political (e.g. county, province) or geographic boundaries (e.g. catchments) if predictions for certain spatial entities are requested. The forcing data of the model include gridded climate time series.

Once all data are available in the required format, data are read into SPARE:WATER through the GUI, and a project folder is generated when starting a new session. This folder is subdivided in the four sub-folders *Forcing data*, *Input data*, *Input parameter* and *Output files*, which are structured as follows:

- *Forcing data* contain climatic information stored in the form of grid maps (ASCII or ESRI grid format). The climatic data set includes monthly sums of precipitation and average temperatures, and in dependence on the selected PET calculation method, a number of further climatic variables such as radiation, sunshine hours, wind speed, and/or relative humidity. Moreover, this folder contains a table with specific information on crop production

- *Input data* include a map of geographical units represented as a shapefile and as a grid map. Further data on elevation and three maps with irrigation data are stored here. Irrigation data contain irrigation efficiency, irrigation technique and electrical conductivity of irrigation water (salinity).

- *Input parameter* covers a text file on crop-specific coefficients.

- *Output files* consist of 8 sub-folders for storing results. Results are stored in the form of grid maps (ASCII format). The following grid maps are stored during a session: PET, CWR, IRR, LR, P_{eff}, Y per crop and growing season as well as $\mathrm{WFg}_{\mathrm{crop}}$, $\mathrm{WFb}_{\mathrm{crop}}$ and $\mathrm{WFgr}_{\mathrm{crop}}$ per crop.

2.8 Graphical user interface (GUI)

The GUI of SPARE:WATER follows a two-tiered approach, which is represented through a setup window and an analysis window. In the setup window, $\mathrm{WF}_{\mathrm{crop}}$ is calculated under the current circumstances. The calculation consists of eight steps which are sequentially processed. Results are then shown in the analysis window. Here, site-specific WFs are aggregated for each geographical unit (e.g. administrative units or catchments). The system includes a descriptive statistics analysis routine containing median, average and standard deviation for each $\mathrm{WF}_{\mathrm{crop}}$ (separated into WFg, WFb and WFgr) and spatial entity. Furthermore, an overall crop water footprint balance is calculated for the entire region and alternative crop production scenarios can be defined and evaluated. Results can be exported in the form of text and comma-separated value (.txt, .csv) files or grid maps (ASCII or ESRI grid format).

3 Application of SPARE:WATER: crop production in Saudi Arabia

Saudi Arabia has 24.6 M inhabitants and is divided into 13 geographically delineated areas, i.e. provinces. The capital city, Riyadh, is in the centre of the country. The country covers an area of 215 M ha and is the largest country on the Arabian Peninsula. Total potential agriculture land covers 52.7 M ha from which 1.2 M ha are actually cultivated (Frenken, 2009). Rainfall is low with an average amount of 40 to 140 $\mathrm{mm\,yr^{-1}}$. Exceptions include the Asir Mountains (south-west, Asir) and Oman mountains (south-east, Eastern Province) with up to 500 $\mathrm{mm\,yr^{-1}}$ rainfall. The reference evaporation is high and varies from 2500 $\mathrm{mm\,yr^{-1}}$ (north-west, coast line) to 4500 $\mathrm{mm\,yr^{-1}}$ in the desert (Al-Rashed and Sherif, 2000).

3.1 Data

Crop parameters for the main crops cultivated in Saudi Arabia were derived from Al-Zeid et al. (1988). These data include crop coefficients and lengths of growing seasons as well as sowing and harvesting dates. The same source was used to obtain irrigation efficiencies of 55, 70 and 85 % for surface, sprinkler and drip methods, respectively. Data from Allen et al. (1998) were used to get heights and rooting depths of crops, whereas crop salt tolerance data were taken from Ayers and Westcot (1976). For this study, a baseline scenario is adopted with relatively good irrigation water quality of 1.2 $\mathrm{dS\,m^{-1}}$, inefficient irrigation technique of 55 % and a target yield of 100 % for the whole country.

The weather data for 1985–2005 were averaged to monthly means (or sums in the case of precipitation) for each of the available 30 climate stations (PME, 2010) throughout Saudi Arabia. The analyses of variance from year to year of climatic variables were conducted for testing their suitability to be used outside the observation period. The average annual standard deviations of minimum (0.8–1.5 °C) and maximum (0.8–1.9 °C) temperature, relative humidity (2.1–8.5 %) and wind speed (0.19–0.48 $\mathrm{m\,s^{-1}}$) indicate very low inter-annual and intra-annual variations (Appendix A1). We therefore conclude that the annual variation is low and that average data can be used to simulate water footprints in other time periods as well. The 30 climate stations were finally interpolated (ESRI®ArcGIS™ kriging tool; settings: ordinary kriging, spherical semivariogram) to grid maps with a resolution of 0.063°.

Agricultural statistics were taken from PME (2010). The data set included crop yield and harvest area for each province (Fig. 3). The total amount of crops produced in 2008 summed up to 9.73 M t, differentiating into 20 single crops and into additional four categories, namely other fodder crops, other vegetables, other cereals and other fruits, which represented the crops which are not allocated to a single crop category. The majority of these crops (> 68 %) were

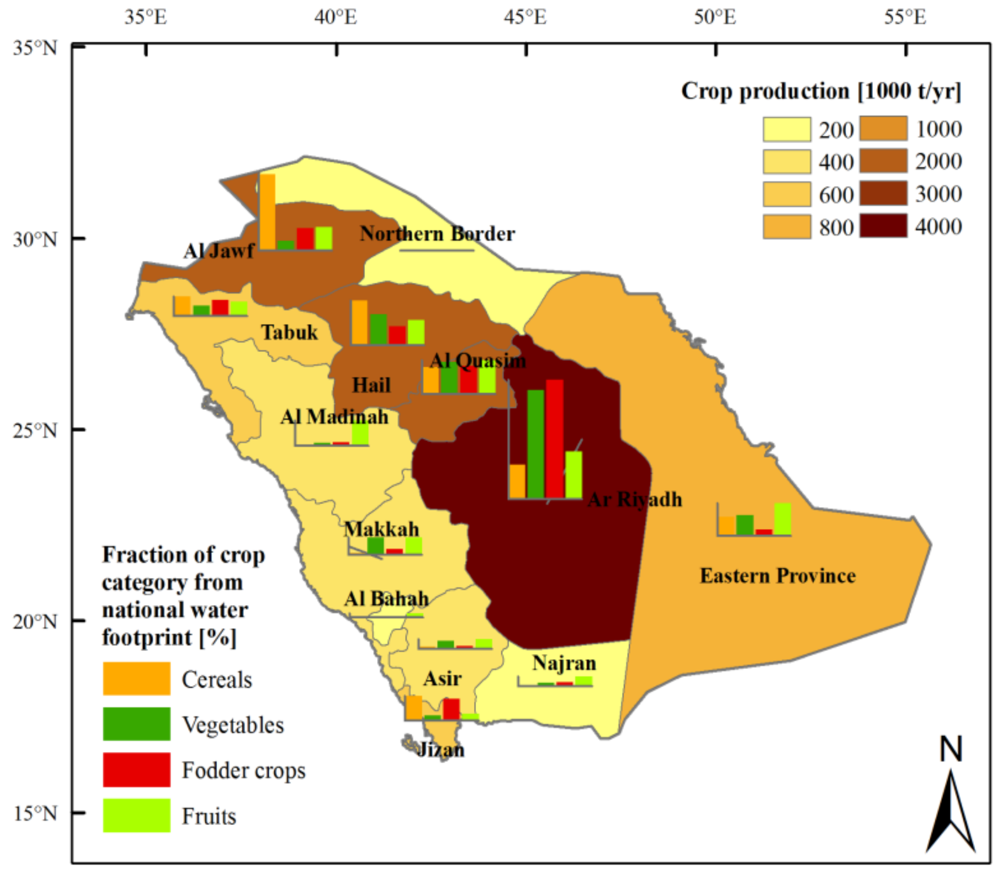

Fig. 3. Crop production in Saudi Arabia in 2008. Brown colours indicate the total amount of crop production in each province, and coloured bar charts indicate the fraction of crop categories in each province from the national sum of that category. Total production in 2008 of all crops is 9.73 M t.

produced in four provinces (Ar Riyadh with 33 %, Al Jawf 13 %, Al Quasim 11 % and Hail 11 %). Figure 3 depicts the fraction of the four agricultural commodity categories – cereals, vegetables, fodder crops and fruits – in each province from the national sum of that category. More than half of fodder crops (58 %) and 44 % of vegetables were cultivated in Ar Riyadh. A high amount of cereals were produced in Al Jawf and Hail. Fruits were mainly grown in Ar Riyadh (19 %), Al Quasim (12 %) and the Eastern Province (14 %). Cereals were dominated by wheat (86 %), vegetables by tomatoes and potatoes (36 %), fodder crops by alfalfa with 76 % and finally fruits by date palms (63 %).

3.2 Simulation of water requirements in Saudi Arabia

Figure 4 illustrates calculated water requirements CWR, IRR and LR in Saudi Arabia. For most crops, median CWR range from 250 mm to 1250 mm. Overall highest values are simulated for alfalfa and citrus trees, where maximum CWR exceeds 2000 mm. In the case of date palms, CWR varies from 839 to 1342 mm, which is two times lower than reported CWRs (2100–2892 mm) from Alamoud et al. (2012), who have carried out field experiments in Saudi Arabia to measure CWR of date palms. In another field experiment Alazba et al. (2003) quantified the CWR of barley and wheat to 930 mm and 898 mm, respectively, which is also substantially higher than our own estimates of 486 mm and 563 mm. The differences can be explained by the distinctions in crop coefficients. In our study, crop coefficients were taken from Al-Zeid (1988), where, for example, crop coefficients of date palms vary from 0.55 to 0.75. These values are lower than those quantified by Alamoud et al. (2012), which range from 0.8 to 0.99 for the same fruit.

Furthermore, the selection of the reference crop for the estimation of reference evapotranspiration plays a major role in estimating CWR. In this study, the FAO methodology has been applied, in which PET is based on grass reference evapotranspiration in contrast to Alamoud et al. (2012) and Alazba et al. (2003), where alfalfa is the reference crop. Abu Rizaiza and Al-Qsaimy (1996) have simulated CWR for a number of field crops and perennials for three sites in Saudi Arabia by using two PET methods (modified Penman, Blaney–Criddle). The authors have reported the following ranges for CWR: vegetables vary from 308 to 669 mm,

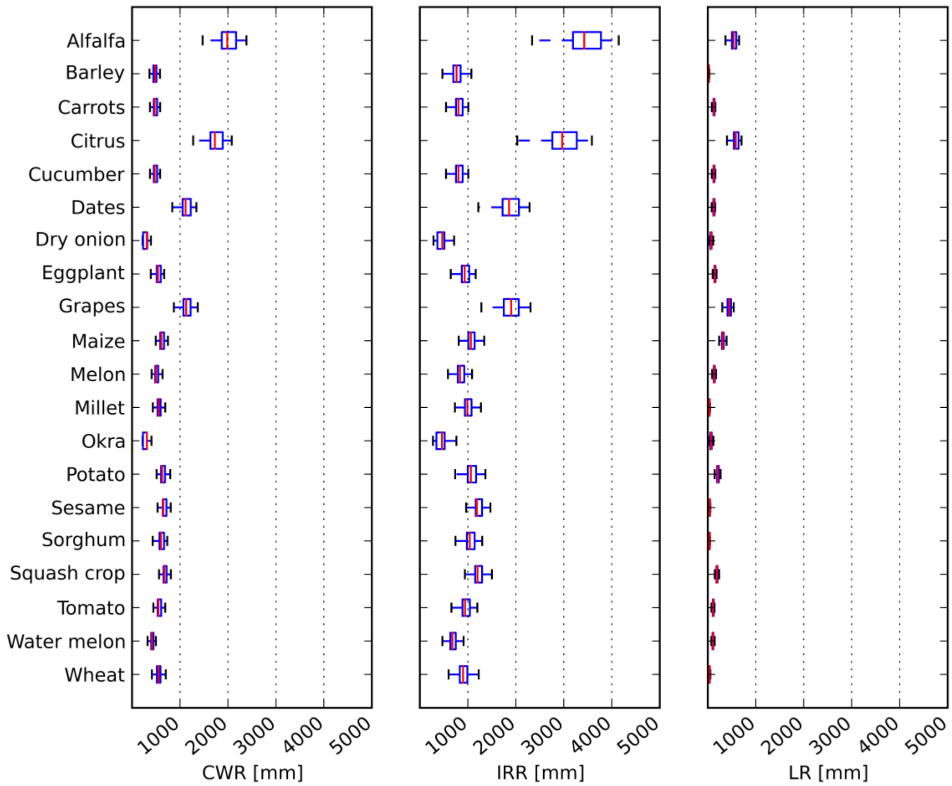

Fig. 4. Crop water (CWR), irrigation (IRR) and leaching (LR) requirement per growing season of 20 major crops grown in Saudi Arabia in 2008. Values have been calculated with long-term average climate data. Box plots indicate range of different values in Saudi Arabia, red lines depict medians, length of blue boxes shows interquartile ranges and length of whiskers indicates values which are less than 1.5× interquartile range. Extreme values are not shown.

fodder crops and cereals from 364 to 884 mm and perennials from 849 to 1976 mm. Our own estimates are in the same range of those reported by Abu Rizaiza and Al-Qsaimy (1996): vegetables (e.g. tomatoes, squash crop and potatoes with 568, 682 and 643 mm, respectively), cereals (e.g. barley and wheat with 486 and 563 mm, respectively), and perennials (e.g. dates, citrus and grapes with 1132, 1745 and 1139 mm, respectively). In accordance with this study, Al-Ghobari (2000) also highlights the use of the FAO-Penman equation, especially for southern Saudi Arabian conditions.

The irrigation requirement for most crops is close to 1000 mm (Fig. 4). Dry onions and okra have the lowest IRRs, while high IRRs are found for dates and grapes that exceed 2000 mm. Alfalfa and citrus trees have the highest IRR requirement and have an average requirement above 3000 mm. In the study from Abu Rizaiza and Al-Qsaimy (1996), reported IRR values are similar to our estimates for vegetables as well as for fodder crops and cereals. In the case of perennials IRRs range from 1202 to 4436 mm. While our estimates are in the same range with regard to average IRRs, the maximum values are slightly lower.

LRs are lower than 200 mm for most crops, with a distinctly higher LR for maize (312 mm, Fig. 4). All other cereals have the lowest LR, e.g. barley 25 mm and wheat 40 mm. In the case of vegetables, LR for tomatoes, squash crop and potatoes is calculated to 113, 190 and 212 mm, respectively. Large amounts of LRs are simulated for perennials such as dates, citrus and grapes with 128, 588 and 445 mm, respectively. A study by Corwin et al. (2007) in California (EC of irrigation water: 1.23 dS m^{-1}) quantified the LR with the same empirical approach from Ayers and Westcot (1994) for alfalfa and wheat to 283 mm and 31 mm, respectively. Our estimate of LR for wheat (40 mm) is similar, while that for alfalfa (546 mm) is nearly two times higher, which is caused by a larger amount of irrigation in SPARE:WATER with a difference of 1722 mm, while leaching fraction for wheat and alfalfa is almost identical in both studies.

In summary, alfalfa, citrus, dates and grapes have the highest water demand, resulting in large irrigation amounts to meet CWR. As a consequence, also LR is relatively high in comparison to other crops where LR plays a minor role for the total water requirement. Overall, grey water contributes 11 % to average total water requirements, whereby maize has the highest (22 %) and barley (3 %) the lowest fraction of grey water.

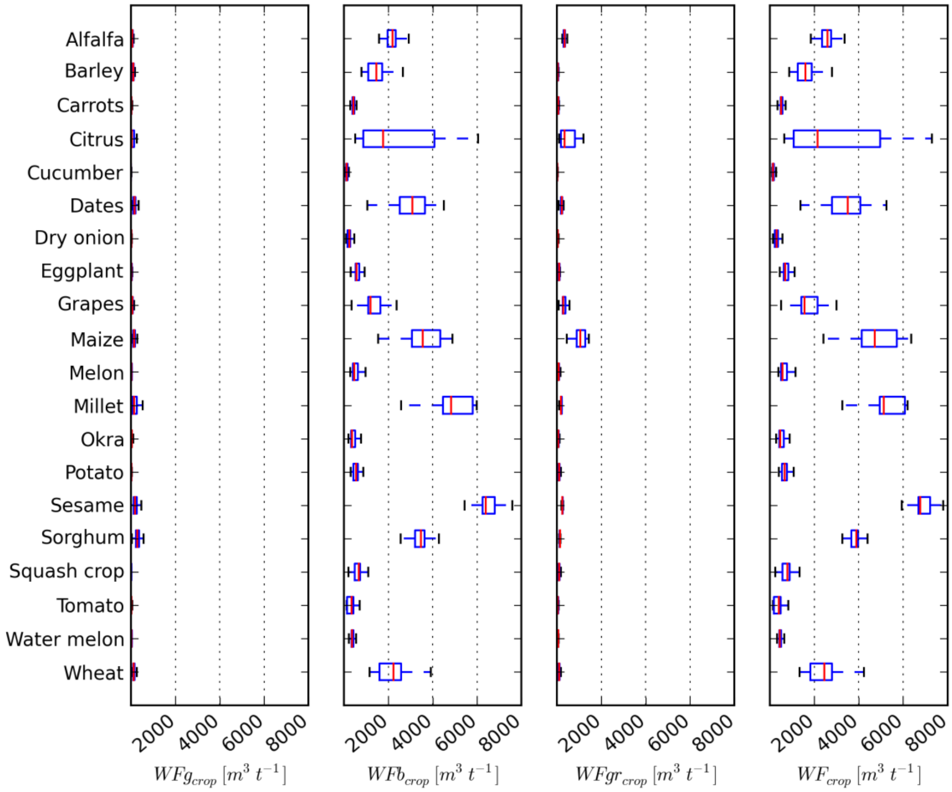

Fig. 5. Green (WFg_{crop}), blue (WFb_{crop}) and grey ($WFgr_{crop}$) water footprint of 20 major crops grown in Saudi Arabia. Values have been calculated with agricultural census data for yields in 2008 and long-term average climate data. Box plots indicate range of different values in Saudi Arabia, red lines depict medians, length of blue boxes shows interquartile ranges, length of whiskers indicates values which are less than 1.5 × interquartile range. Extreme values are not shown.

3.3 Crop water footprints (WF_{Crop}) in Saudi Arabia

WF_{crop} has been calculated for 20 of the most relevant crops in Saudi Arabia (Fig. 5). On a national scale, average WF_{crop} varies from 167 $m^3\ t^{-1}$ (cucumber) up to 7026 $m^3\ t^{-1}$ (sesame). Especially vegetables have a low WF_{crop}, with values smaller than 500 $m^3\ t^{-1}$, e.g. for water melon, okra, tomato, dry onion and cucumber, which is in agreement with other reports of WF_{crop} (Mekonnen and Hoekstra, 2010). In general, WFs decrease with higher crop yields, e.g. between 20 $t\ ha^{-1}$ and 55 $t\ h^{-1}$ for potatoes, tomatoes and cucumber in Saudi Arabia. Cereals range from 1701 $m^3\ t^{-1}$ (barley) to 7026 $m^3\ t^{-1}$ (sesame), whereby low values can also be observed for wheat, and medium ones for maize and millet. Fruit trees such as date palms and citrus have an average high WF_{crop} of 3439 and 5263 $m^3\ t^{-1}$.

The average contribution of green water to WF_{crop} is generally low in Saudi Arabia, with less than 300 $m^3\ t^{-1}$ (4 %) on average, reflecting the very low annual rainfall. The major proportion of water requirement in Saudi Arabian agriculture is taken from blue water resources, in this case almost entirely from fossil groundwater (Al-Rashed et al., 2000), thereby dominating the water footprint. Also grey water shows marginal importance for many crops, with around 11 % on average. However, leaching is an important management task, especially under environmental conditions in Saudi Arabia (Hussain et al., 2010). Without annual leaching, future crop yields would decline as a consequence of salt stress, especially in the case of salt-sensitive crops such as alfalfa, citrus, grapes and maize. These crops exceed average $WFgr_{crop}$ values of around 1000 $m^3\ t^{-1}$, even under low salt concentrations (1.2 $dS\ m^{-1}$). For this reason, $WFgr_{crop}$ plays a quantitative minor role but is essential in terms of qualitative aspects and sustainability of soil quality. The importance of such qualitative aspects in comparison to water quantity for decision making has also been reported by Dabrowski et al. (2009), who highlight the consideration of pesticides and fertiliser inputs in the frame of virtual water trade.

Average WF_{crop} for each crop in each province are depicted in Fig. 6. The majority of provinces have an average WF_{crop} lower than 3000 $m^3\ t^{-1}$, except Jizan (3472 $m^3\ t^{-1}$) and Northern Borders Province (6395 $m^3\ t^{-1}$). Lowest values are found for Tabuk, Hail, Al Jawf and the Eastern Province, where the average WF_{crop} is lower than 1500 $m^3\ t^{-1}$. No crops with a high WF_{crop} are produced in these particular provinces, whereas in Jizan and Northern Borders Province

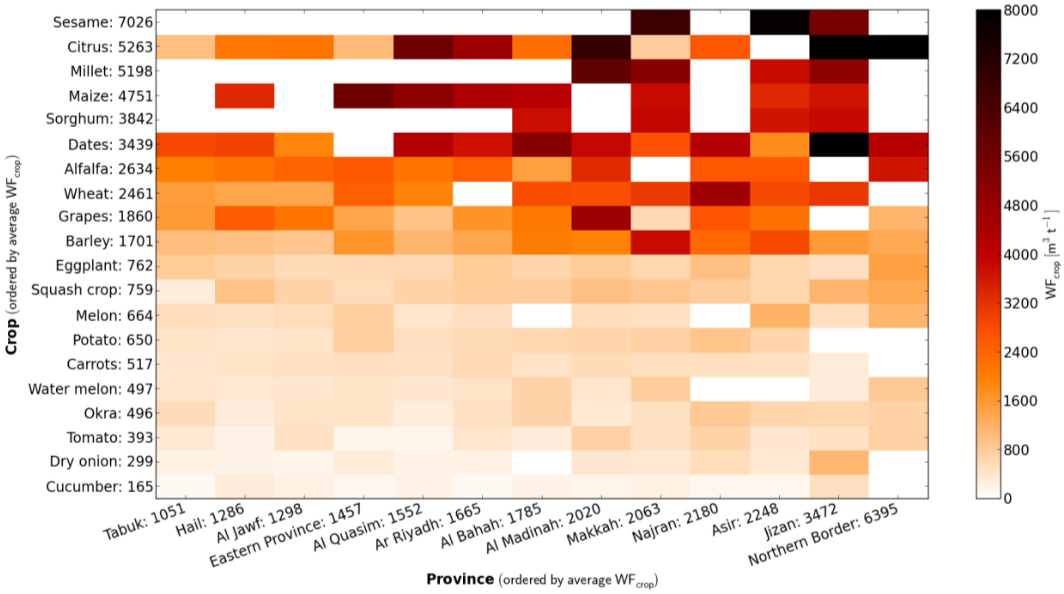

Fig. 6. WF_{crop} [$m^3\,t^{-1}$] of main crops and for each province in Saudi Arabia. Numbers along axis show the average WF_{crop} in each province or for each crop. White areas indicate no data values.

water intensive crops such as sesame, citrus or date palms are grown. The largest variation of the WF_{crop} can be observed for citrus, with very low values in Tabuk of around $1000\,m^3\,t^{-1}$ and very large values in the Northern Borders Province exceeding $8000\,m^3\,t^{-1}$. But not all crops with a large average WF_{crop} are produced in regions where the average WF_{crop} is large. For example, Asir, which has a large average WF_{crop} of $2248\,m^3\,t^{-1}$, requires a low amount of water to produce dates, with around $1600\,m^3\,t^{-1}$ – similar to the province Al Jawf, which has an overall very low average WF_{crop}. The low and high values for WF_{crop} for particular crops in different provinces are mainly attributable to variation in yields and only to a lesser extent to differences in irrigation water quality or climate. We compared results of this study (for details, see Appendix A2) with global estimates published by Mekonnen and Hoekstra (2010) in their Water Footprint of Nations ($WaterStat_{global}$) for all crops and obtained an $R^2 = 63\,\%$. While this correlation is satisfying for total WF_{crop}, large discrepancies occur for the blue water footprint ($R^2 = 15\,\%$), indicating that the proportion of blue and green water for crop growth is wrongly estimated if global-scale data are applied to Saudi Arabia. One should acknowledge the fact that arid climate conditions in Saudi Arabia differ from global averages, and for this reason only a national or sub-national assessment can give insight into Saudi Arabia's agricultural water footprint.

To further validate SPARE:WATER, results have been compared with data provided for Saudi Arabia in the work of Mekonnen and Hoekstra (2011). On a national scale, the alignment of our own estimates with the Water Footprint of Nations for Saudi Arabia ($WaterStat_{SA}$) is $R^2 = 71\,\%$

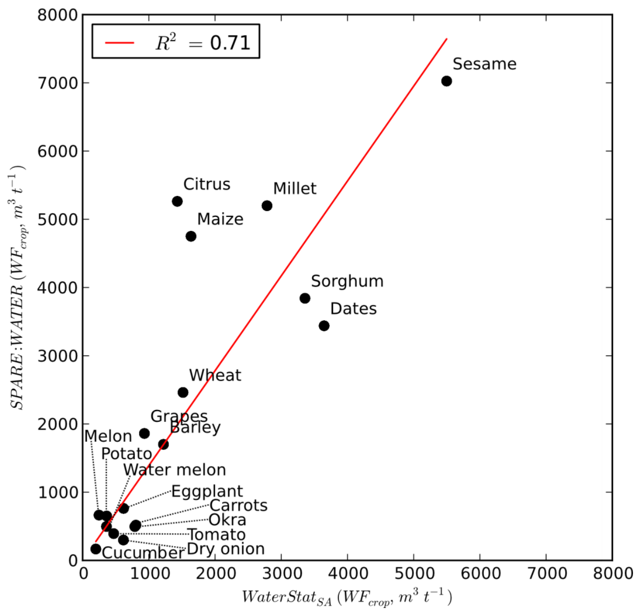

Fig. 7. Correlation of crop water footprint of Saudi Arabia estimated with SPARE:WATER and published data for Saudi Arabia from the study $WaterStat_{SA}$ (Mekonnen and Hoekstra, 2010).

(Fig. 7), and therefore higher than that for $WaterStat_{global}$. Obviously, the higher spatial resolution accounts better for the local climate conditions driving the WF_{crop}. Especially the blue WF_{crop} is in better agreement, with $R^2 = 79\,\%$. The remaining differences between $WaterStat_{SA}$ and our estimates can be lead back to non-optimal irrigation conditions with an efficiency of 55 %, which has been considered in

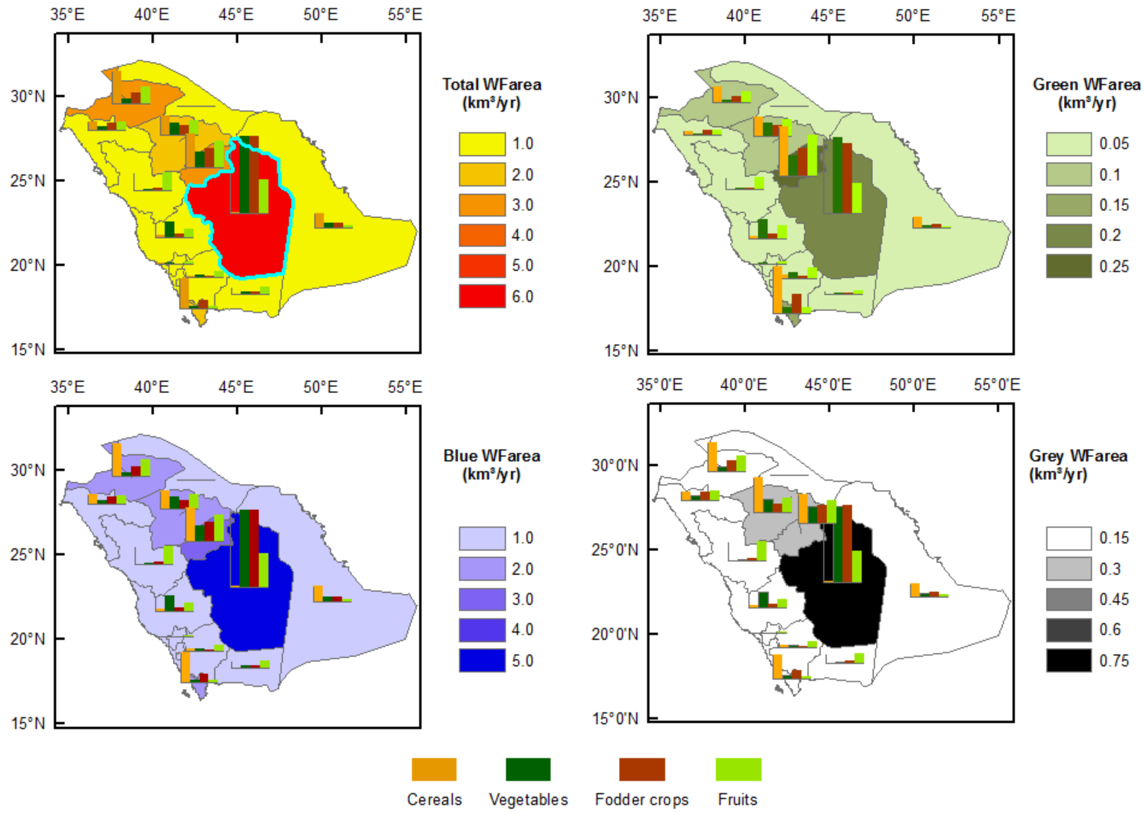

Fig. 8. WF_{area} of Saudi Arabia's crop production in 2008. The four maps show total, green, blue and grey water consumption. Coloured bar charts indicate the fraction of a crop category in a province from the national sum. Total values are $WFg_{area} = 0.773\,km^3\,yr^{-1}$, $WFb_{area} = 14.697\,km^3\,yr^{-1}$, $WFgr_{area} = 1.574\,km^3\,yr^{-1}$ and $WF_{area} = 17.043\,km^3\,yr^{-1}$.

this study, while Mekonnen and Hoekstra (2010) assumed no losses through inefficient irrigation methods. Green WF_{crop} correlates with an $R^2 = 63\,\%$. Contrary to green and blue water, grey WF_{crop} shows no similarity with $R^2 = 9\,\%$. This can be traced back to the different accounting methods. While in our study $WFgr_{crop}$ has been calculated from the amount of leaching requirement, Mekonnen and Hoekstra (2010) derived the $WFgr_{crop}$ from the amount of water needed to dilute pollutants to water quality standards. The associated green, blue and grey WF_{crop} from SPARE:WATER, $WaterStat_{SA}$ and $WaterStat_{global}$ can be found in Appendix A (A2).

In summary, large differences between water footprints of this study in comparison to global and other coarse-scale estimates highlight the importance of regional estimation of crop water footprints. The ratio between green and blue water in Saudi Arabia differs from that of global estimates, and water footprints in Saudi Arabia are dominated by the blue component, while global values are dominated by green water. Such differences emphasise the importance of using regional climate data as well as regional crop coefficients and considering agricultural management, leaching and irrigation techniques. In the case of Saudi Arabia, inefficient irrigation methods are used and large amounts of water are lost through percolation and evaporation.

Under the climatic conditions of Saudi Arabia, no return flow of irrigation water to rivers or groundwater exists. Thus, water pollution through fertilisers or pesticides usually considered in estimating the grey water footprint component need not be considered in Saudi Arabian agriculture. Maintaining soil quality is more important, e.g. through low salt concentrations, and thus should be taken into account when estimating crop water footprints.

3.4 Regional water footprint of Saudi Arabia

On a national scale, agricultural production consumed $17.0\,km^3\,yr^{-1}$ (WF_{area}) in 2008. Figure 8 illustrates this consumption distributed over all provinces in Saudi Arabia. A high percentage of 86 % is blue water, grey water contributes 9 % and a minor portion of 5 % is provided through green water. One has to acknowledge that blue water for irrigation agriculture in Saudi Arabia is almost entirely taken from fossil groundwater sources (Al-Rashed et al., 2000), and thus these numbers indicate an unsustainable water consumption of the agricultural sector in Saudi Arabia. Assuming that most of the grey water is also stemming from the same groundwater resource, it shows the dependence of agricultural production on this non-refreshable resource. Our results are in agreement with other work. Mekonnen and Hoekstra (2010) estimated a blue water footprint of 8.6 $km^3 yr^{-1}$ in Saudi Arabia, which equals 75 % of the average national water footprint in the period 1996–2005. This substantial lower value is a result of the differences in assumed irrigation efficiency. Mekonnen and Hoekstra (2010) used a fixed 100 % efficiency, whereas in this study irrigation efficiency has been adapted to the dominant irrigation method in Saudi Arabia (surface and sprinkler irrigation) with an associated field application efficiency of 55 % (Al-Zeid et al., 1988). Considering this lower efficiency, reported values of Mekonnen and Hoekstra (2010) would increase to 15.6 $km yr^{-1}$, only 6 % above our calculated WFb_{area}. Green and grey water footprints were estimated as 1.8 $km^3 yr^{-1}$ and 1.1 $km^3 yr^{-1}$ in that study, corresponding to our own estimates of 1.5 and 0.9 $km^3 yr^{-1}$, respectively. However, one has to consider that the $WFgr_{area}$ by Mekonnen and Hoekstra was calculated for the dilution of pollutants, whereas in our study leaching requirement has been estimated for desalinisation in irrigation agriculture. Results by Hussain et al. (2010) for blue water consumption amount to 14.5 $km^3 yr^{-1}$, also in the same range, but slightly lower than our WF_{area}. However, this value was estimated for 1996 and is assumed to be higher today. Frenken (2009) analysed blue water resources in Saudi Arabia and reported an increase of water consumption from 6.8 $km^3 yr^{-1}$ in 1980 to 21.0 $km^3 yr^{-1}$in 2006 ($>$ 1.2 M ha cultivated land). Their substantially larger estimate can be explained by the differences in calculation method. Frenken (2009) have estimated water withdrawal, which includes all water taken from surface water and groundwater resources for irrigation purpose. It includes also those amounts of water that are lost off-farm, while in our study only on-farm water use has been considered.

As SPARE:WATER allows refinement of the country scale WF assessment, WF has been broken down to the province level. A high percentage of 69 % (11.7 $km^3 yr^{-1}$) is consumed in four provinces, i.e. Ar Riyadh (30 %), Al Quasim (17 %), Al Jawf (12 %) and Hail (9 %). All remaining provinces contribute relatively minor proportions to the total water footprint, in total 31 % (5.3 $km^3 yr^{-1}$). A further division into crop categories (cereals, fodder crops, vegetables and fruits) within each province shows that more than 50 % of the WF_{area} in Ar Riyadh is attributable to fodder crop and vegetable production. Most water for cereal production is consumed in Al Quasim (23 %), Al Jawf (22 %) and Jizan (21 %), summing up to 66 %. Fruit production is dominant in Ar Riyadh and Al Quasim with together 41 %, and another 34 % in Al Jawf, Al Madinah and Hail.

One could hypothesise that the highest WF_{area} can be found in provinces with highest population, as production is located close to consumers. This would be reflected in the WF_{area} for Ar Riyadh and Al Quasim, where production of perishable vegetables and fruits is concentrated. However, this explanation would only fit to Riyadh, while other larger cities in Saudi Arabia are located closed to the Red Sea in provinces with a low WF_{area}. A more likely explanation is that the WF_{area} is correlated with the distance to major groundwater reservoirs, which are mainly located in the centre, the east and in the north of Saudi Arabia (Foster and Loucks, 2006). Irrigation in Saudi Arabia is sustained by fossil groundwater, and therefore the largest WF_{area} can be found in regions of good groundwater access.

4 Conclusions

Sustainability of irrigation agriculture is a complex issue in arid and semi-arid ecosystems, especially when considering the often inherent low irrigation efficiency in such regions. We have developed a spatial decision support system accounting for specific environmental conditions and existing irrigation practices. SPARE:WATER can be easily adapted to new environmental information and cultivation sites as well as irrigation practices. Furthermore, SPARE:WATER gives non-GIS-experts the possibility to make site-specific calculations on their own, reflecting the importance of a simple GUI, which has also been recommended by Renschler (2003).

In contrast to Mekonnen and Hoekstra (2010) non-optimal irrigation with inefficient surface irrigation techniques has been assumed. This assumption implies that the water footprints calculated with SPARE:WATER are related to all water applied to the field and not only to that water which directly contributes to crop growth. Compared to temperate regions or regions with a shallow ground water table, the water loss in semi-arid and arid agro-ecosystems by inefficient irrigation systems is evaporated to the atmosphere or percolated to deep soil layers, and for this reason is not available for future water use. This is especially the case for crop production in Saudi Arabia. Under other conditions percolation water may return to the same catchment where it has been withdrawn and then the part that returns does not contribute to the water footprint (Hoekstra et al., 2011), because the water is available for crop water uptake downstream. Such conditions have been considered by Chapagain and Hoekstra (2011) in rice production systems in China, where percolation makes up to 1025 $m^3 t^{-1}$ but is not included in the water footprint.

Grey water is added for furnishing a healthy soil for plant growth in this study, in contrast to Mekonnen and Hoekstra (2010), who defined grey water as the water needed to dilute pollutants. We conclude that only by accounting for inefficient irrigation techniques and leaching requirement, results can be used to improve water resource management in irrigation agriculture. Although grey water contributes only a minor fraction to the entire water footprint on a quantitative perspective, it is essential in terms of qualitative aspects and sustainability of soil quality.

SPARE:WATER estimates crop water footprint on the basis of simulated optimal crop water requirements and observed crop yields from statistics. This is in accordance with the current water footprint method (Hoekstra et al., 2011),

Table A1. Water footprint of major crops in Saudi Arabia calculated with SPARE:WATER and published data for Saudi Arabia and the global average from the study WaterStat – Water Footprint of Nations (Mekonnen and Hoekstra, 2010); $\text{WaterStat}_{\text{global}}$ refers to global averages, and $\text{WaterStat}_{\text{SA}}$ gives average values for Saudi Arabia.

	SPARE:WATER WF_{crop} [m^3t^{-1}]				$\text{WaterStat}_{\text{global}}$ WF_{crop} [$\text{m}^3\ \text{t}^{-1}$]				$\text{WaterStat}_{\text{SA}}$ WF_{crop} [$\text{m}^3\ \text{t}^{-1}$]			
Crop	Green	Blue	Grey	Total	Green	Blue	Grey	Total	Green	Blue	Grey	Total
Alfalfa	60	2223	351	2634								
Barley	108	1544	49	1701	1213	79	131	1423	194	800	227	1221
Carrots	23	427	67	517	106	28	61	195	70	556	179	805
Citrus	140	4281	842	5263	1145	62	35	1242	186	1162	82	1430
Cucumber	8	137	22	167	206	42	105	353	20	114	65	199
Dates	171	3059	209	3439	930	1250	98	2277	462	3042	143	3647
Dry onion	18	243	38	299	192	88	65	345	62	397	157	616
Eggplant	28	634	100	762	234	33	95	362	71	334	213	618
Grapes	72	1448	341	1861	425	97	87	608	113	754	66	933
Maize	154	3556	1041	4751	947	81	194	1222	367	1270		1637
Melon	28	549	87	664	147	25	63	235	54	151	42	247
Millet	167	4848	184	5199	4306	57	115	4478	527	2258		2785
Okra	35	398	63	496	1479	181	128	1788	93	305	390	788
Potato	24	524	103	651	191	33	63	287	14	265	84	363
Sesame	209	6568	249	7026	8460	509	403	9371	1750	3748		5498
Sorghum	292	3420	130	3842	2857	103	87	3048	1029	2329		3358
Squash crop	11	646	102	759	228	24	84	336				
Tomato	15	338	40	393	108	63	43	214	63	278	128	469
Water melon	26	407	64	497	147	25	63	235	88	225	47	360
Wheat	132	2233	97	2462	1277	342	207	1827	238	1093	185	1516

but has a methodological limitation. Crop yields in irrigation agriculture often show a strong response to the performance of the water supply system. Any shortage in water supply is likely to be reflected in crop yields of the real world. As SPARE:WATER only estimates crop water requirements without simulating water supply effects on yields, low observed yields can substantially increase the water footprint. For this reason, adequate crop yield data are absolutely essential for the estimation of correct water footprints.

In the case of the Saudi Arabian agricultural sector, the largest fraction of the water footprint is blue and relies on water taken from fossil groundwater aquifers. Water footprints for Saudi Arabia are somewhat higher in comparison to earlier published results, mainly because of considering non-optimal irrigation practices. Considering this lower efficiency, reported values of Mekonnen and Hoekstra (2010) would increase to 15.6 $\text{km}\,\text{yr}^{-1}$, only 6 % above our calculated WFb_{area}.

The spatial explicit SPARE:WATER approach facilitates new directions of calculating water footprints. So far, many water footprint applications focus on the long-term impact of agriculture on water resources and use monthly data to describe seasonal variability because daily data are often not at hand. However, daily data could become relevant if the impact of weather extremes (droughts, shift of precipitation patterns and intensity) on water resources utilisation are of interest. Furthermore, inter-annual variation of the water footprint and its change in response to climate change could become relevant in future water footprint application. We therefore suggest to further test SPARE:WATER and also investigate the uncertainties of agricultural water footprints associated with input data and model structure.

The current version of SPARE:WATER is focusing on irrigation agriculture that is primarily relying on blue water sources and where precipitation is very limited. If irrigation is used in a supplementary manner and if soil salinisation is caused by high groundwater tables and water logging rather than saline irrigation water, these additional processes need to be considered in SPARE:WATER. The same is true for climatic conditions where precipitation outside the vegetation period leads to wash out of salts from the root zone, such as winter rains in Mediterranean climates. Users should consider this and add relevant modules to SPARE:WATER. This is highly appreciated and supported by the open source code of the model.

Appendix A

Additional data

Figure A1 illustrates the climate variability in Saudi Arabia. Plots show 30 climate stations in Saudi Arabia with 21 yr

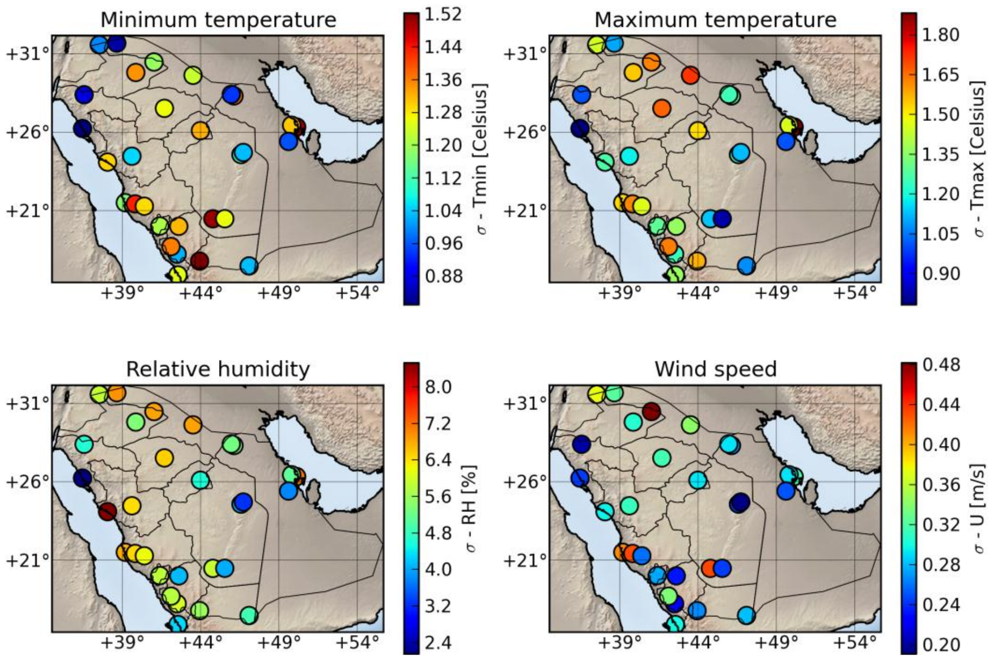

Fig. A1. Climate variability in Saudi Arabia. Plots show 30 climate stations in Saudi Arabia with 21 yr long time series (1985–2005). Data have been used to estimate the standard deviations of monthly means in comparison to long-term monthly means for each station and parameter. [source: figure and shaded relief have been created with Python Matplotlib and Basemap Toolkit; climate data from PME, 2010].

long time series. Data have been used to estimate the standard deviation of monthly means in comparison to long-term monthly means for each station and parameter.

Table A1 lists the water footprint of major crops in Saudi Arabia calculated with SPARE:WATER as well as those published by Mekonnen and Hoekstra (2010).

Supplementary material related to this article is available online at: http://www.geosci-model-dev.net/6/1043/2013/gmd-6-1043-2013-supplement.pdf.

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