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Crop-specific seasonal estimates of irrigation water demand in South Asia

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Abstract

Especially in the Himalayan headwaters of the main rivers in South Asia, shifts in runoff are expected as a result of a rapidly changing climate. In recent years, our insight in these shifts and their impact on water availability has increased. However, a similar detailed understanding of the seasonal pattern in water demand is surprisingly absent. This hampers a proper assessment of water stress and ways to cope and adapt. In this study, the seasonal pattern of irrigation water demand resulting from the typical practice of multiple-cropping in South Asia was accounted for by introducing double-cropping with monsoon-dependent planting dates in a hydrology and vegetation model. Crop yields were calibrated to the latest subnational statistics of India, Pakistan, Bangladesh and Nepal. The representation of seasonal land use and more accurate cropping periods lead to lower estimates of irrigation water demand compared to previous model-based studies, despite the net irrigated area being higher. Crop irrigation water demand differs sharply between seasons and regions; in Pakistan, winter (Rabi) and summer (Kharif) irrigation demands are almost equal, whereas in Bangladesh the Rabi demand is ~100 times higher. Moreover, the relative importance of irrigation supply vs. rain decreases sharply from west to east. Given the size and importance of South Asia, improved regional estimates of food production and its irrigation water demand will also affect global estimates. In models used for global water resources and food-security assessments, processes like multiple-cropping and monsoon-dependent planting dates should not be ignored.

1 Introduction

As global demand for food increases, water resources – one of the main resources for producing food – are becoming increasingly stressed. South Asia, home to ~25 % of the world population, is often identified as one of the future water-stress hotspots (Kummu et al., 2014; Wada et al., 2011). Excess food production in recent years has

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obscured this bleak future; increases in both agricultural productivity and cropland extension have made the region food self-sufficient in its staple crops in recent decades. But the resources that supported this increase – surface- and groundwater extracted for irrigation, land converted into cropland, increased use of nutrients and pesticides – are not unlimited. Groundwater levels are already falling rapidly in large parts of South Asia due to overexploitation (Rodell et al., 2009; Tiwari et al., 2009) and surface-water irrigation is reaching its limits (Biemans, 2012), costly river interlinking schemes aside (Bagla, 2014; Gupta and Deshpande, 2004). On top of this, higher temperatures and an expected higher variability in climate due to global warming further jeopardizes future food production in the region (Krishna Kumar et al., 2004; Mall et al., 2006; Moors et al., 2011).

In order to understand if, when and where water availability to sustain crop production becomes critical, a more thorough understanding of the potential mismatch between seasonal water availability and demand is required. In recent years, our insight in the seasonal pattern of water availability has increased due to a better understanding of fluctuations in monsoon onset (Goswami et al., 2010; Kajikawa et al., 2012; Ren and Hu, 2014), and the variation in the active-break cycle of the monsoon, which governs intra-seasonal droughts (Joseph and Sabin, 2008), both influenced by large-scale phenomena like El Nino (Joseph et al., 1994). Effort has also gone into quantifying the seasonal availability of snow and glacier melt runoff on the regional scale (Bookhagen and Burbank, 2010; Siderius et al., 2013a), with intra-annual shifts in runoff expected in the future due to climate change (Immerzeel et al., 2013; Lutz et al., 2014; Mathison et al., 2015; Rees and Collins, 2006). When it comes to estimating water demand, however, a similar detailed understanding of the seasonal pattern is surprisingly absent.

Two essential and well-known agricultural characteristics that distinguish South Asia from most other large food-producing regions in the world govern this water demand. First, South Asia's agriculture is characterized by a high degree of multi-cropping. A first crop during the monsoon season (Kharif) is often succeeded by a second

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crop during the dry season (Rabi) (Portmann et al., 2010). Planting dates for the Kharif crop are determined primarily by the onset of the monsoon rather than by an accumulation of degree days. High maximum temperatures form a constraint for crop production during the Rabi season, favouring planting as early as possible. Second, with rainfall highly concentrated during June till September and significant moisture deficits occurring during the other months of the year, crop production is to a very large extent supported by a combination of canal and groundwater irrigation, especially in the dry winter season (Rabi) (GoI, 2013).

Many models that are used for global to regional water resources assessments still lack representation of multi-cropping (e.g Arnold and Fohrer, 2005; Best et al., 2011; Rost et al., 2008; Liang et al., 1994). Typically, a single cropping period per year is simulated with a degree-day based or predefined single planting date (see e.g. Elliott et al., 2014; Kummu et al., 2014; Waha et al., 2012). Exceptions are the model by Wada et al. (2011) who apply multi-cropping in their estimation of water stress, but in a simplified aggregated form without distinguishing between different crops and the models of Alcamo et al. (2003) and Hanasaki et al. (2008) who apply multiple-cropping seasons using optimized planting dates. However, Hanasaki et al. (2008) note that their optimization mainly reacted to cold spells and was performed under rainfed conditions, which does not lead to optimal planting dates for the South Asia region. As a result, crop-specific seasonal estimates of irrigation water demand in South Asia are still lacking.

In this paper, we aim to provide such spatially explicit, crop-specific seasonal estimates of water demand and crop production, using a revised version of the LPJmL hydrology and vegetation model (Gerten et al., 2004; Rost et al., 2008; Bondeau et al., 2007), adjusted for the region. We distinguish two main South Asian cropping periods, Kharif and Rabi, and introduce zone-specific, monsoon-onset-determined planting dates for 12 major crop types, both rainfed and irrigated. We calibrate the improved model against the latest sub-national statistics on seasonal crop yields from four

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different countries – India, Pakistan, Nepal and Bangladesh – and explicitly evaluate the irrigation water demand and crop production for the two cropping seasons.

2 Methodology

2.1 LPJmL

We used the LPJmL global hydrology and vegetation model for bio- and agro-spheres (Bondeau et al., 2007; Sitch et al., 2003), but developed a version that contains more spatial and temporal detail for South Asia. The LPJmL model has been widely applied to study the effects of climate change on water availability and requirements for food production at a global scale (Gerten et al., 2011; Falkenmark et al., 2009) and the potential of rainfed water-management options for raising global crop yields (Rost et al., 2009). For South Asia, the model has been applied to study the adaptation potential of increased dam capacity and improved irrigation efficiency in light of climate change (Biemans et al., 2013).

LPJmL physically links the terrestrial hydrological cycle to the carbon cycle, making it a suitable tool for studying the relationship between water availability and crop production. The model includes algorithms to account for human influences on the hydrological cycle, e.g. irrigation extractions and supply (Rost et al., 2008). Production and water use for 12 different crops, both rainfed and irrigated are simulated. LPJmL is a grid-based model, run at a resolution of 0.5°, and at daily time step.

Net irrigation water demand (consumption) for irrigated crops is calculated daily in each grid cell as the minimum amount of additional water needed to fill the soil to field capacity and the amount needed to fulfil the atmospheric evaporative demand (Rost et al., 2008). Subsequently, the gross irrigation demand (withdrawal) accounts for application and conveyance losses, and is calculated by multiplying the net irrigation water demand with a country-specific efficiency factor (Rohwer et al., 2007), which is different for surface-water irrigation and groundwater irrigation (as in Biemans

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et al., 2013). Surface water is defined as the water available in local rivers, lakes and reservoirs and is calculated by a daily routing algorithm (Biemans et al., 2009). Irrigation water demand is assumed to be withdrawn from available surface water first. If surface water is unavailable, it is assumed to be withdrawn from groundwater (Rost et al., 2008).

Crop growth is simulated based on daily assimilation of carbon in 4 pools: leaves, stems, roots and harvestable storage organs. Carbon allocated to those pools depends on crop phenology and is adjusted in case of water stress on the plants. Crops are harvested when either maturity or the maximum number of growing days is reached (Bondeau et al., 2007; Fader et al., 2010).

To improve the understanding of spatial and temporal heterogeneity in irrigation water demand and crop production in South Asia, we made some adjustments to the version of LPJmL that is used for global studies. First of all, we introduced the simulation of two cropping cycles per year by developing two different land-use maps for Kharif and Rabi. Second, we applied zone-specific sowing dates related to monsoon patterns, and third, we accounted for regional differences in crop management by performing a calibration of crop yields at the subnational level. In the next three sections, those adjustments to LPJmL are explained in more detail.

In our experimental set-up, LPJmL is forced with daily precipitation, daily mean temperature, net longwave and downward shortwave radiation derived from the Watch Forcing Data applied to Era Interim data (WFDEI) (Weedon et al., 2014). Using this dataset, all LPJmL simulations were done for the period 1979–2009 after a 1000 year spin-up period to bring carbon and water pools into equilibrium. The calibration and all analysis presented in this paper uses the simulation results of the period 2003–2008 for comparison with available statistics. Kharif and Rabi irrigation water demand and crop production are estimated by performing two simulations using different land-use input and sowing-date input datasets. Those two runs are subsequently combined to attain the seasonal pattern for irrigation water demand and crop production.

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2.2 Development of land use maps for Kharif and Rabi seasons

To derive land-use input for two separate cropping seasons for South Asia, we used the MIRCA2000 database (MIRCA, version 1.1, Portmann et al., 2010) on a 5 min resolution. MIRCA is a global spatially explicit data set on irrigated and rainfed monthly crop areas for 26 crop classes around the year 2000. On an annual basis, MIRCA is consistent with other gridded datasets for total cropland extent (Ramankutty et al., 2008), total harvested area (Monfreda et al., 2008), and area equipped for irrigation (Siebert et al., 2007), but has more temporal detail. For India, MIRCA2000 includes sub-national (i.e. state-level) information on the start and end of cropping periods. The dataset explicitly includes multi-cropping.

Crop classes in MIRCA2000 were first aggregated to the crop classes available in the LPJmL model, which are fewer (12, irrigated and non-irrigated, plus one class with "other perennial crops", vs. 26 in MIRCA) but include the most important food crops for South Asia (see Fig. 2 for distinguished crops). The exact period of monsoon (Kharif) and dry season (Rabi) cropping differs according to region. In India, Kharif sowing is strongly related to the onset of the monsoon, whereas in large parts of Pakistan – where the monsoon is less pronounced – sowing can happen earlier or later because other factors like water availability for irrigation are more important. From the monthly MIRCA cropping calendars we decided to define the cropped area of the Kharif season as the area under cultivation per crop as in September and that of Rabi as the area per crop as in January. Perennial crops were only included in the Kharif land-use map.

Next, a few adjustments to the obtained data were made. First, MIRCA specifies three rotations of rice in northern India, two during summer and one during winter months. We merged the two summer rotations to the Kharif rice area and allocated one to the Rabi rice area, accepting a potential minor mismatch between datasets. Second, we corrected wheat and rice areas, both of which MIRCA equally divides over Rabi and Kharif. In reality, rice is mainly cropped during the Kharif season and wheat is only cropped during the Rabi (winter) season, when temperatures are lower and

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heat stress is avoided. We shifted all irrigated wheat to the Rabi season and made compensations where possible by shifting an equal amount of irrigated rice area to the Kharif season. Third, we shifted 45 % of area cropped with pulses from the Rabi to Kharif season to comply with the latest agricultural statistics (GoI, 2012). In this way, consistency with other datasets was largely maintained (i.e. total cultivated area, cultivated area per crop, area irrigated), while at the same time a better match with crop phenology and regional agricultural practices was achieved.

Finally, we updated the area irrigated to the latest statistics. MIRCA represents land use and irrigated area for the period 1998–2002. Over the past 10 years, irrigated area has further increased in India alone from 76 to 86 million ha (gross irrigated area), to 44 % of the total area. Statistics for India show (GoI, 2012) that the increase in irrigated area occurred for all crops. By shifting 10 % of rainfed area to irrigated area, while keeping the overall cropped area the same, we achieved an increase in gross irrigated area. We assumed that the all-India trend is mirrored in the neighbouring counties. Cropped area was then aggregated to 0.5° grids for both Kharif and Rabi, which formed the input into the LPJmL model. The resulting land use input is in good agreement with subnational statistics on cropping areas in Kharif and Rabi (see Supplement , Fig. S1–S6).

Figure 1 shows the cropping intensity in the study region according to this newly compiled dataset, as well as the delineation of the river basins for which we will present our results. Figure 2 shows the total cropped area during the Kharif and Rabi seasons for all major crops in South Asia (India, Pakistan, Nepal and Bangladesh) according to the input data compiled here and compared to the agricultural statistics (GOI, 2014; GoP, 2014).

2.3 Adjusted planting dates for Kharif and Rabi crops

Sowing dates for Kharif crops are closely related to the onset of the monsoon as farmers start (trans)planting rice or other crops when the first rains have arrived. Normal onset dates of the monsoon over South Asia are determined by the India

Meteorological Department, at 5–15-day interval (IMD, 2015) (Fig. 3). The onset of the monsoon starts in Kerala in southern India around the first of June (Julian day 152) and arrives in western Pakistan around mid-July (Julian day 197). For the model simulations in this study, sowing dates for Kharif crops were set to five days after the onset of the monsoon, because several days of rain are needed before a crop is (trans)planted (Fig. 3). Inter-annual variations in the onset of the monsoon were not taken into account in this study. The perennial crop sugarcane is assumed to be planted on this date as well.

In general, the Kharif season ends by the end of October and the sowing of Rabi crops starts early – till mid-November until early January, depending on local temperatures during winter and water availability in spring. As the exact date is difficult to determine, we set the first of November as the single sowing date for the Rabi crops over the whole study area. Because the Rabi crops are generally harvested by the end of March, the irrigation water demand in the warm pre-monsoon summer months of April and May can almost entirely be attributed to perennial crops. In the analysis of seasonal irrigation demand, we therefore distinguish three seasons: Kharif, from June until October; Rabi, from November until March; and a "summer" season from April to May.

2.4 Calibration of crop yields

Crop yields in LPJmL are calibrated by varying management intensity, which is represented by three parameters: maximum leaf-area index, maximum harvest index, and a parameter that scales leaf-level biomass production to plot level (Fader et al., 2010). The value of these management factors affects the estimated water demand, because a poorly developed crop with little leaf area will evaporate less and therefore demands less (irrigation) water and vice versa.

The calibration is performed for each crop individually, and management factors are usually determined at the country level in global applications of LPJmL. For this model version, we calibrated crop yields for Kharif and Rabi separately, as they are

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differentiated in the agricultural statistics. Moreover, we calibrated the management parameters at the sub-national level for India and Pakistan (state- and province-level respectively) and at the national level for Nepal and Bangladesh. By calibrating at the sub-national level, existing spatial heterogeneity in management and crop yields between regions could be better represented. We used 5 year average yield statistics, for 2003–2004 till 2007–2008, the most recent period for which consistent records are available from different national agricultural statistics (India: GoI, 2012; Pakistan: http://www.pbs.gov.pk/content/agriculture-statistics-pakistan-2010-11, last accessed 1 July 2014; Bangladesh for the years from 2003–2004 till 2005–2006 from http://203.112.218.66/WebTestApplication/userfiles/Image/Wing/Agriculture_Wing/Survey_AW/annual_agri_stat.pdf and for 2007–2008 in the 2011 yearbook (http://www.bbs.gov.bd/PageWebMenuContent.aspx?MenuKey=234); Nepal: (GoN, 2012). After calibration, simulated crop yields matched well with observed yields in most regions (Fig. 4). Kharif rice and Kharif maize crops show the highest variation between states and provinces. Overall, yields during the Kharif season are lower than yields during the Rabi season, when a higher percentage of the area cropped is irrigated, and temperatures are more favorable.

3 Results

3.1 Seasonality in agricultural water demand

Table 1 shows estimates of seasonal net (consumption) and gross (withdrawal from surface and groundwater) irrigation water demand between the four countries. India and Pakistan have the largest water demand, both in terms of consumption and withdrawal. While Pakistan's net irrigation demand is almost equally divided over the Kharif and Rabi seasons, India's demand is skewed towards the Rabi season; almost 3/4 of net irrigation demand in India occurs in this dry season (including summer). This difference between Kharif and Rabi is less pronounced for gross irrigation demand,

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i.e. water withdrawals, which include application and conveyance losses. In the Rabi season a much higher proportion of the irrigation water is supplied from groundwater (Table 1), which has a higher overall efficiency than surface-water irrigation from canals. Irrigation efficiency for canal water was estimated at 37.5 % in India, Bangladesh, Nepal and 30 % in Pakistan (Rohwer et al., 2007); efficiency of groundwater irrigation was estimated at 70 % for all countries (following Gupta and Deshpande, 2004).

The seasonal distribution of irrigation water demand is a result of rainfall patterns in the region. In Bangladesh and Nepal, monsoon rainfall is abundant for sustaining crop production during the Kharif season and irrigation is therefore concentrated in the dry Rabi season. Groundwater irrigation, modelled as the resultant of demand minus surface-water availability, provides most water resources during the Rabi season in all countries, especially in India. In Pakistan, the Indus provides annually approximately 120 BCM (billion cubic meters) of utilizable runoff, of which approximately 2/3 is used during the Kharif (Randhawa, 2002). Our estimate of mean annual groundwater withdrawal in Pakistan is at 60 BCM, of which 3/4 occurs during the Rabi season and summer. This is somewhat higher than previous estimates of groundwater withdrawal, which were in the range of at 47 to 55 BCM (Ahmed et al., 2007; Qureshi et al., 2003; Wada et al., 2010) but still lower than the estimated total potential of 68 BCM (Randhawa, 2002). For India, the exact distribution of surface-water and groundwater withdrawal between the Kharif and Rabi seasons is not well documented. Our model estimate of 217 BCM of groundwater withdrawal per year, mainly occurring during the Rabi season, is in agreement with earlier groundwater studies with estimates ranging from 190 (±37) BCM by Wada et al. (2010) to 212.5 BCM (GoI, 2006).

Overall, our estimates of national total net and gross irrigation water demand are in line with earlier studies and statistics, but at the lower end of the range for India. Accounting for monsoon dependent planting dates, and thereby a more effective use of rainfall during the main Kharif cropping season, reduced our estimate of total agricultural water demand compared to earlier regional studies, e.g. with the LPJmL model (Biemans et al., 2013). For Pakistan, our estimates are on the high

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side compared to other studies. Especially for the Rabi season, we estimate a high additional demand from cash crops like cotton. This demand has to be met largely by groundwater abstractions, because runoff from the Indus and its tributaries is low during these months.

Evaluating the mean annual cycle of irrigation water demand per crop reveals the reason behind seasonal differences in demand (Fig. 5). The single peak in net water demand for wheat during the Rabi season stands out, while rice peaks in both Rabi and Kharif seasons. The moderating effect of monsoon rainfall during the Kharif season is obvious, with net irrigation water demand during the Kharif season only accounting for about 30 % of the annual net irrigation water demand (Table 1). So while water-use efficiency improvements in rice receive much attention, paddy fields being the epitome of excessive water consumption, rice is actually not the most water-demanding crop in the region. Because rice is grown mainly during the Kharif season in most states, its water demand is lower than for wheat and sugarcane, which are grown during the dry Rabi season. Those crops therefore depend much more on groundwater availability (see also Table 1 and Fig. 6 for contribution of groundwater irrigation per cropping season). Additionally, sugarcane has an atypical demand in time, caused by its very long cultivation period of about 12 months; it requires large amounts of irrigation water in the hot dry months of March, April and May, a period when rainfall is scarce and most other fields are left fallow.

3.2 Seasonal patterns of water demand for different basins

As a result of varying climatological conditions and availability of spring and summer runoff from snow- and glacier-fed rivers, cropping patterns and thereby seasonal water demand pattern differ greatly between the major river basins (Figs. 6 and 7). The Indus basin shows a relatively stable irrigation water demand during the year, which is primarily fed by groundwater in winter and melt runoff in summer (Fig. 7). Downstream, monsoon rainfall contributes little to crop water needs. In the Ganges basin, a more seasonal pattern can be seen with demand for irrigation water being

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lower during the monsoon, when rainfall is sufficient over large parts of the basin, and no additional irrigation is needed. The same pattern can be seen to be even stronger in the Brahmaputra basin.

3.3 Food production in South Asia during the Kharif- and Rabi- cropping seasons

Figure 8 shows the total seasonal production of only the five most important food crops (wheat, rice, maize, tropical cereals and pulses), both for the region as a whole as for the individual basins. The total area irrigated to grow these food crops is smaller in Kharif than Rabi (35 Mha vs. 46 Mha total for the four counties), but total (rainfed plus irrigated) area used to grow these food crops is much larger in Kharif than Rabi (95 Mha vs. 57 Mha). While the percentage of area under irrigation, productivity per hectare and sources of water used greatly differ between the Kharif and Rabi seasons, total regional food-crop production is remarkably similar in the two seasons. A lower cropped area during the Rabi season is compensated for by higher yields. Of the total production of food crops in South Asia during the Kharif season, ~ 50 % is supported by irrigation (Fig. 8). In the Rabi season up to ~ 95 % of food-crop production is supported by irrigation. We also calculated the potential rainfed yield on those areas currently irrigated. Absence of irrigation would reduce the Kharif food-crop production with ~ 15 % (dark blue bar in Fig. 8), against a reduction of almost 60 % in Rabi. This stresses the importance of sufficient irrigation- water supply for achieving food security in this region.

A closer look into the seasonal food production in the different river basins shows clear differences. The Indus and the Ganges have a much higher annual production of food crops than the Brahmaputra.

Rabi is the most important season for the production of food crops in the Indus. The same is true for the Ganges, although the production levels between the seasons are closer to each other. The rainfed production is much larger in the Ganges than in the

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Indus. In the Brahmputra basin, the majority of food-crop production takes place during the Kharif season.

4 Discussion

The seasonal estimates presented here on food production and related irrigation water demand in South Asia form a new baseline estimate of South Asian seasonal-water demand and food-crop production, as they provide more spatial, temporal and crop-specific details than previous estimates.

Incorporating seasonal cropping patterns in more detail leads to improved estimation of the timing of water demand. We show that seasonal water demand is a factor of crop-specific seasonal consumption, availability of rainfall and different sources of water supply, i.e. groundwater or surface water, and the irrigation efficiencies connected to these sources. Despite these improvements, when modelling such large basins with complex hydrology and high diversity in agricultural and water-management practices, inevitably simplifications and local inaccuracies remain.

Our estimate of gross irrigation demand, the water withdrawal, is strongly influenced by the water use efficiency value used, which is determined by a variety of factors like local irrigation practices, scale of analysis and source of water use. We used the most commonly reported values for the region, similar to other model-based studies in order to be able to compare results. Inclusion of regional, more application- and water-source-specific water use efficiency values in models would improve the estimation of gross water demand. Such detail is also necessary to gain better insight into the adaptation potential of different measures like drip irrigation and alternate wetting and drying.

More attention to seasonal cropping patterns and their water demand opens the scope for further model improvement. Double-cropping was evaluated by combining two seasonal model runs, one for Kharif and one for Rabi. Use of residual soil moisture from one season to the other was not incorporated in this way, nor could

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the continued depletion of groundwater be accurately modelled. An integrated double-cropping routine, with proper calibrated crop-specific planting dates and yields, would provide such necessary analysis in a region where groundwater depletion is of serious concern.

Next, estimation of planting dates should be further improved, using detailed information on local agricultural practices and local water availability. Ample information is available in the irrigation domain but it will require a form of cooperation between experts at the local to national level and the water resources modelling community. Sharing of input data might reduce costs and time expenditure, will increase its uptake and improve overall quality of water resources assessments.

Finally, cropped area and sources of irrigation used are not constants or slowly evolving properties, but can be highly variable on inter-annual time scales in response to climate variability (Siderius et al., 2013b). These fluctuations were not assessed in the current study but are of high importance to individual farmers and the overall profitability of agriculture in regions with a variable climate. Combining an improved baseline of seasonal water demand with the inter-annual fluctuations in cropped area will lead to a more realistic assessment of both water demand and crop production, of high relevance in today's world with its volatile food commodity markets.

This paper highlights crop-specific periods of peak water demand that can form critical moments in agricultural production. Such better understanding of the size of water demand during critical moments, the crops that are responsible for this water demand, and its relative importance for food production is essential to guide sustainable development of climate adaptation measures. This analysis can support the selection of promising options to decrease irrigation water demand. When combined with information on the (un)availability of surface water and the resulting pressure on groundwater resources (Fig. 7), it improves our understanding on the causes of water shortages and groundwater depletion. Finally, insight in the yield gap between rainfed and irrigated agriculture in specific regions, and between regions, can help target investments to improve irrigation practices or to increase productivity of rainfed agriculture.

5 Conclusions

Introducing seasonal crop rotation with monsoon-dependent planting dates in a global vegetation-hydrological model leads to better seasonal estimates of irrigation water demand. Irrigation water demand between the two main cropping seasons differs sharply both in terms of source and magnitude; gross irrigation demand during the Rabi season is ~ 30 % lower than during the Kharif season, the traditional cropping season, when monsoon rainfall reduces the amount of supplemental irrigation water needed. Our estimate of total annual water demand is lower than that of previous studies (Biemans et al., 2013), despite the net irrigated area being higher. Overall, gross annual irrigation demand is estimated at 714 BCM; 247 BCM during the Kharif monsoon season, 361 BCM during Rabi and 106 BCM during the summer months of April and May.

Seasonal estimates of agricultural water demand better highlight crop-specific differences in peak water demand. Such increased temporal detail is needed for properly evaluating the impact of expected shifts in supply of water as a result of a rapidly changing climate, especially in the Himalayan headwaters of some of the main rivers in South Asia. With temperatures rising and total precipitation fairly constant, increased melt from glaciers combined with an early melt of the snow cover is expected to shift the peak in spring runoff to early in the season (Immerzeel et al., 2010; Lutz et al., 2014). Whether this shift will affect critical moments for irrigation or the ecosystem as a whole is to be assessed.

Our study has thereby more than regional relevance. Given the size and importance of South Asia, in terms of population and food production, improved regional estimates of production and its water demand will also affect global estimates. In models used

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for global water resources and food-security assessments, processes like multiple-cropping and monsoon-dependent planting dates should not be ignored.

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Table 1. Seasonal and total net and gross irrigation water demand estimates in billion cubic meters (BCM) and groundwater contribution to irrigation-water supply for individual countries and South Asia as a whole (India, Pakistan, Nepal and Bangladesh).

	Net irrigation demand (consumption)				Other estimat	Percentage groundwater irrigation					Gross irrigation demand (withdrawal)				Other estimates
	Kharif (M6–10)	Rabi (M11–3)	Summer (M4–5)	Total	Total	Kharif (M6–10)	Rabi (M11–3)	Summer (M4–5)	Total		Kharif (M6–10)	Rabi (M11–3)	Summer (M4–5)	Total	Total
Nepal	0.1	1.0	0.2	1.4		19%	62%	34%	54%		0.3	2.0	0.5	2.7	10 [e]
Pakistan	38	42	16	96	117 [d]	25%	68%	25%	44%		110	86	47	243	200.2[h], 162.7[b], 117–120[c], 187.8[g]
India	59	148	31	235	317 [d]	27%	79%	63%	64%		136	249	58	443	575.9[h], 54[f], 558.4[b], 710–715′
Bangladesh	0.1	11	0.3	12		10%	43%	2%	41%		0.2	24	0.8	25	3[e]
South Asia	97	202	48	346		26%	74%	50%	58%	247	361	106	714	985	

[a] GOI (2005). Water Data Complete Book, Central Water Commission, Ministry of Water Resources, Government of India.
[b] AQUASTAT (http://www.fao.org/nr/water/aquastat/main/index.stm).
[c] Rost et al. (2008).
[d] Siebert et al. (2010).
[e] AQUASTAT with reference to 2008 for Bangladesh and 2005 for Nepal. Approximately 79 % of the total water withdrawal comes from groundwater (Nepal) and 21 % (Bangladesh).
[f] Rosegrant and Cai (2002). 1995 estimate using a basin efficiency of 0.54.
[g] Water Resources Section, Ministry of Planning and Development in (Ahmed et al., 2007).
[h] Biemans et al. (2013).

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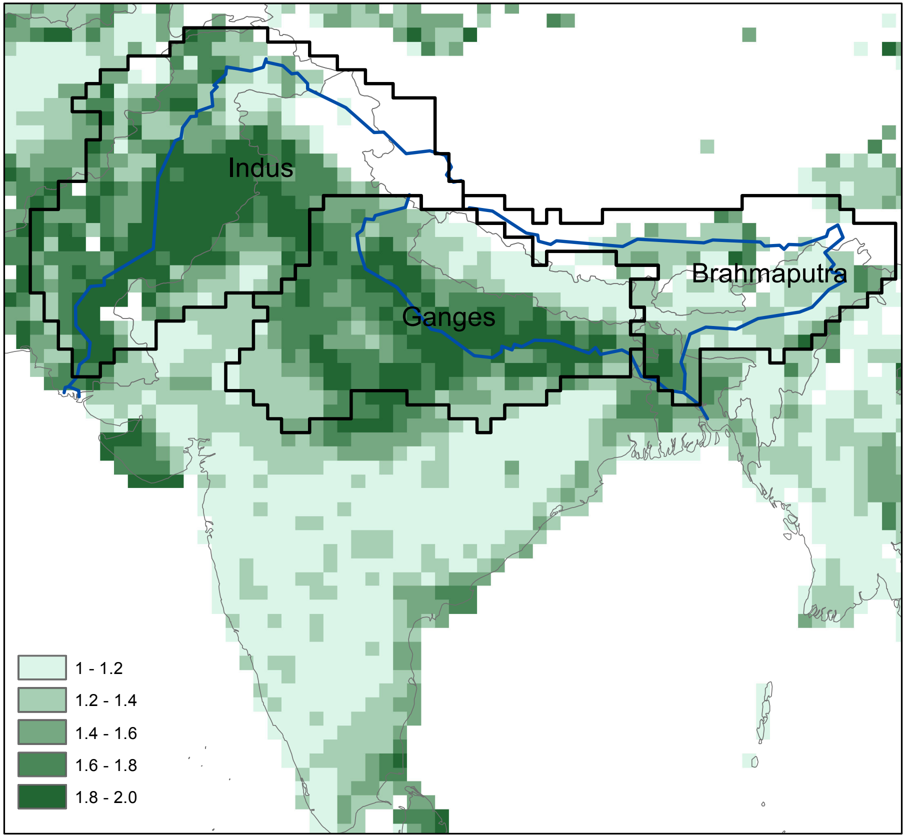

Figure 1. Cropping intensity in South Asia (derived from the land use datasets described in Sect. 2.2). Average cropping intensity is defined here as the total annual harvested area (Kharif and Rabi) divided by the maximum cropped area of the two cropping seasons. Study-basin delineations are indicated in black.

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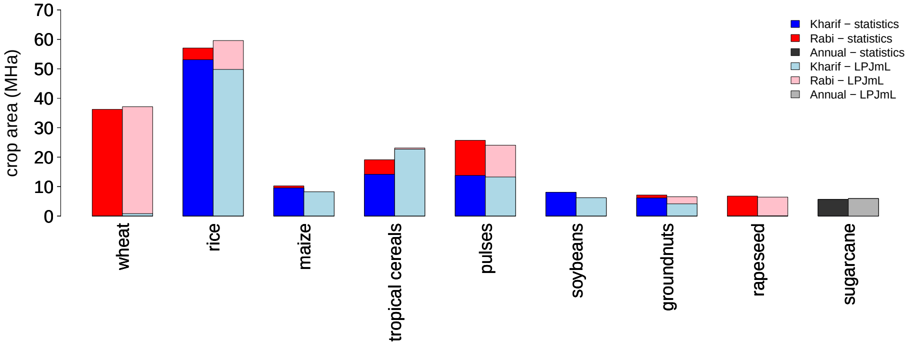

Figure 2. Total crop area in South Asia (India, Pakistan, Nepal and Bangladesh) for different crops in the two dominant growing seasons. National statistics (average of 2003–2008) vs. LPJmL input data derived from MIRCA as described in Sect. 2.2. For the spatial distribution of crops between states and provinces of India and Pakistan, Nepal and Bangladesh, see Supplement. Temperate and tropical roots and sunflower are not shown because they occupy relatively small areas; other perennial crops are not shown because there are no statistics available.

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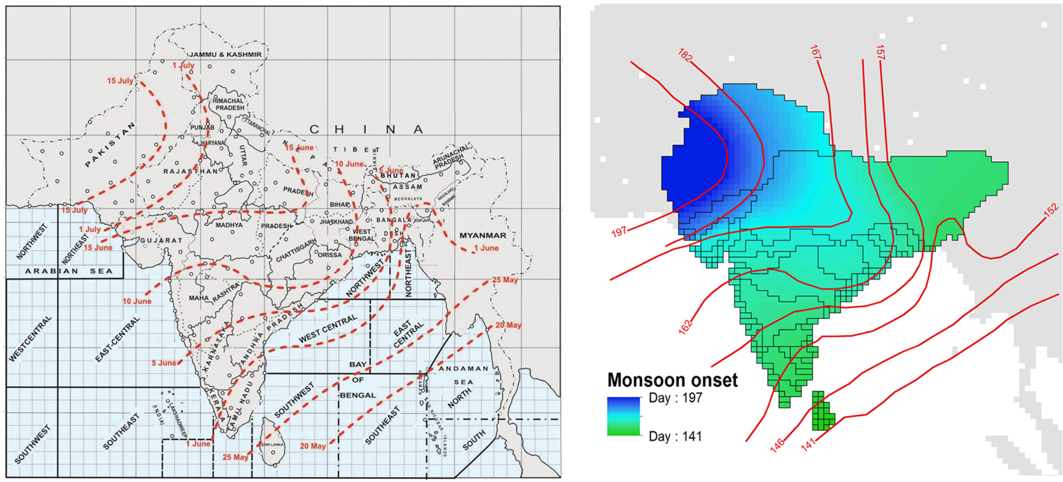

Figure 3. Normal dates for the onset of the Southwest Monsoon as presented by the Indian Meteorological Department (left) and interpolated over South Asia (right) derive input data for LPJmL, red numbers indicating Julian days, grey lines showing basin boundaries.

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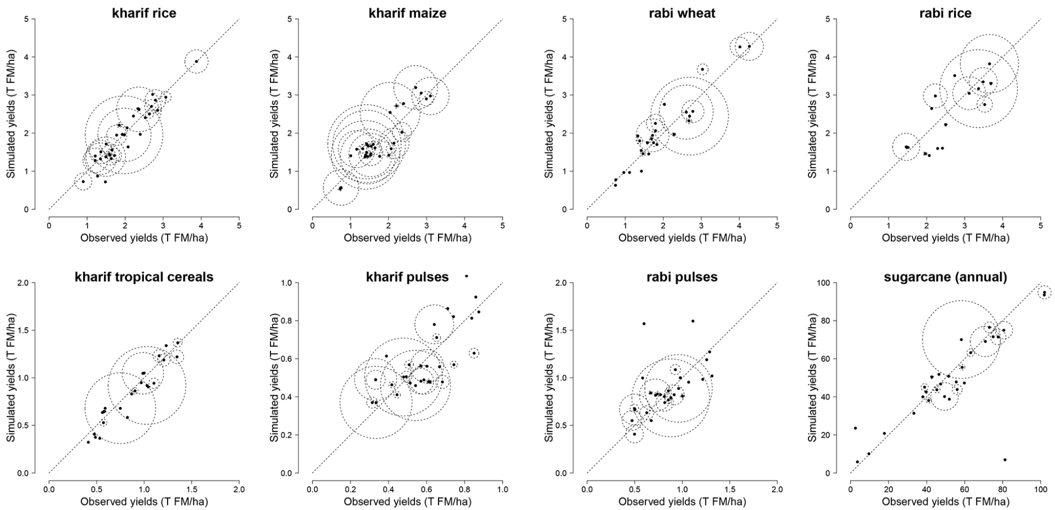

Figure 4. Observed vs. simulated (calibrated) crop yields for the most important crops in the different cropping seasons. Each dot represents one state (India), province (Pakistan) or country (Nepal, Bangladesh). Size of the circle represents the relative area under that crop (for areas, see Figs. S1–S6 in the Supplement).

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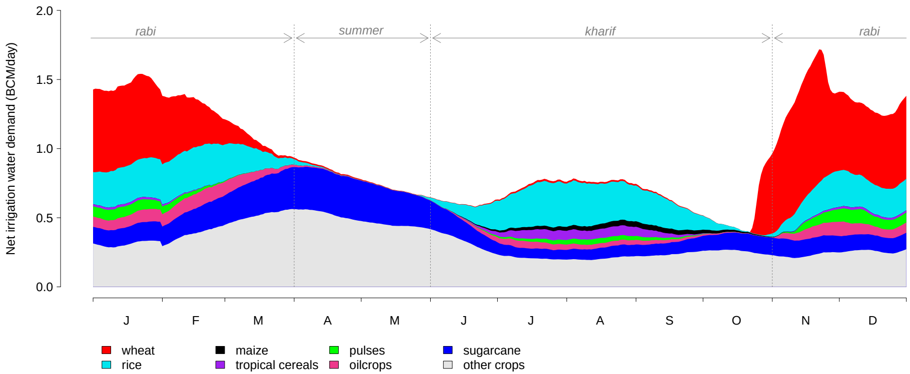

Figure 5. Mean annual cycle of net irrigation requirements for main agricultural crops in South Asia (30-day moving average).

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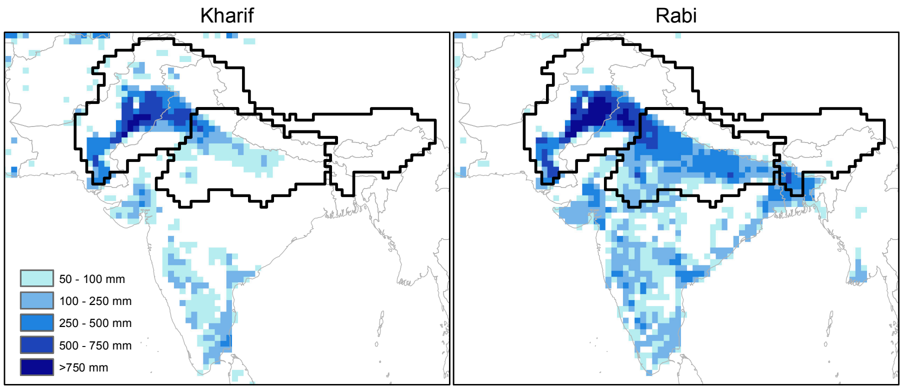

Figure 6. Gross irrigation water demand for Kharif (M6-10) and Rabi (M11-3) cropping seasons, with selected river basins (Indus, Ganges, Brahmaputra).

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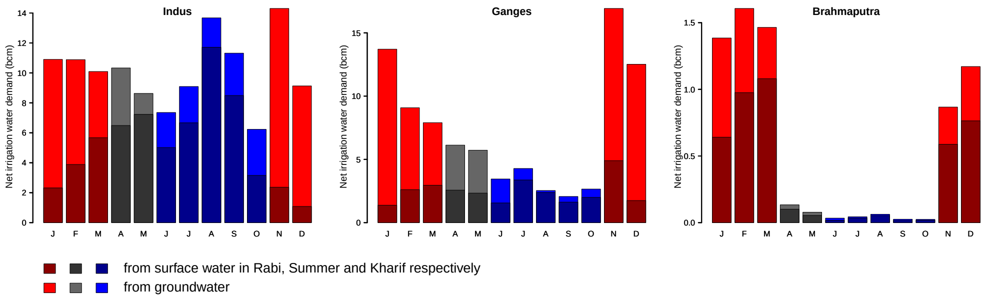

Figure 7. Monthly net irrigation water demand for three river basins. Colours indicate the different seasons (red – Kharif, grey – summer, blue – Rabi) and the dark areas the source for supplying the irrigation water (dark – surface water, light – groundwater).

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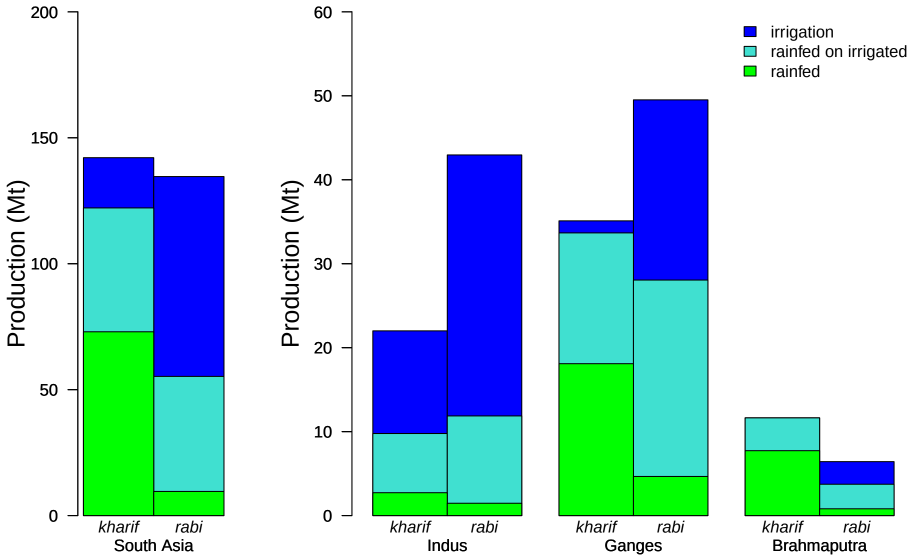

Figure 8. Seasonal irrigated (blue) and rainfed (green) production of food crops (sum of wheat, rice, maize, tropical cereals and pulses) in South Asia (Nepal, Pakistan, India and Bangladesh) and individual river basins. Light blue corresponds to potential rainfed production on irrigated land, i.e. dark blue corresponds to the increase in production due to irrigation.

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