

Dear Dr. Stamm,

*Thank you very much for the very constructive comments and suggestions. We have carefully considered all remarks. Specific replies to the different points are included below (in italic).*

*Best regards,*  
*Hester Biemans and co-authors*

**Editor Decision: Publish subject to minor revisions (Editor review)** (15 Feb 2016) by Dr.

Christian Stamm

Comments to the Author:

Dear Dr. Biemans

Thanks for the revised manuscript entitled "Crop-specific seasonal estimates of irrigation water demand in South Asia".

I appreciate the efforts you have put into addressing the points raised by the reviews, which includes running additional simulations for the model without multiple-cropping. In my view, your revision provides good responses to the critique. There are a few minor issues though that should be improved before I can accept the manuscript for publication. I list them below:

- Description and discussion of the single-cropping model run: in your response, you explain what you actually did ("LPJmL was run with the single cropping landuse input as in previous model studies by the authors (Biemans et al, 2013) and sowing date was determined based on climate as in Waha et al (2012)."). I cannot find this information in the revised version, though. This has been added in the method section.

*In the method section (description of the model which ends with the setup of the experiment) we added the lines above stating that we also perform a model run with single cropping and calculated sowing dates for comparison and show model improvement.*

Additionally, you neglect this result in the results section and you are rather brief on that aspect also in the discussion. There you only introduced a single sentence. I asked myself whether such a strikingly different pattern between the two model versions is not worth a bit more discussion. Should one not elaborate more on consequences for interpreting earlier results from models that neglected the multiple-cropping aspect? I have the impression Fig. 5 is a very strong result that you should make use of in a more pronounced manner. But this is an aspect that you as authors have to decide.

*In the results section we added a few lines describing that the results of a simulation with single cropping and calculated sowing dates based on climate are now also included in figure 5.*

*Also, in the discussion we added few more lines to discuss the importance of this improved representation of the timing of water demand for our understanding of current and future water stress.*

The notion of "Zaid season": it was proposed by the first reviewer to clarify that what you call the summer season is also called the Zaid season. You argue that this inclusion would cause confusion. However, my experience when reading the text was different. Actually, I could imagine that you

avoid confusion if you state in the text at one point that what you call summer season corresponds to the Zaid season. Please reconsider this aspect.

*In section 2.3 we have now added the remark that the pre-monsoon summer season is also called the Zaid season. Further we have gone through the text again to make sure that we everywhere clearly distinguish between the dry pre-monsoon summer and the monsoon summer (Kharif).*

- Reviewer 2 asked for some clarification regarding the calibration process and the meaning of the word "plot" in this context. You nicely explain this in your reply but did not include that in the manuscript. I also not sure what you mean by "plot" and suggest you include your explanation in the text.

*I have included the explanation that I provided in the reply to the reviewers in the text to give some better explanation on the calibration procedure.*

In addition to these comments, I add two issues from my side:

- Correct units for water fluxes: Please use coherent units for all water fluxes that express them as volume per time (see HESS guidelines: "Fluxes, such as precipitation, evaporation, infiltration, percolation, or runoff, are always expressed as a flux, expressed in L3 T-1 or L T-1 if the flux is per unit area. Even if fluxes are accumulated over a period of time, the period of integration needs to be reflected in the denominator (e.g. mm/year).")

*In the captions of figures 6,7,8, we have changed the units into fluxes (e.g. mm/yr)*

Please report water abstraction and the like as "BCM/yr" instead of "BCM" in the text.

*All occurrences of BCM in the text have been replaced by BCM/yr*

- Explain units in Fig. 4. I assume that "T FM/ha" stands for "tons of fresh matter per ha". Please explain in the caption.

*Explanation of unit T FM/ha was added in the caption (tons of fresh matter per hectare)*

- Fig. 5: Some of the different colours are hard to distinguish. Can you improve on that?

*I find it hard to tell which colours are difficult to distinguish, as I don't see this on my screen and print. Would it be an idea to discuss with the layout unit which colours could be changed, as this easy to do.*

- Fig. 6: You may consider replacing "M6 – 10" by "June to Oct" and "M11 – 3" by "Nov. to March"). This is probably more reader friendly for people who are not too much into the topic but may still wish to read your paper.

*Thank you for this suggestion. Caption of figure 6 was changed accordingly.*

Sincerely

Christian Stamm

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

3

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1     **Abstract**

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

## 1     1. Introduction

2     As global demand for food increases, water resources – one of the main resources for producing food –  
3     are becoming increasingly stressed. South Asia, home to ~25% of the world population, is often  
4     identified as one of the future water-stress hotspots (Kummu et al., 2014; Wada et al., 2011). Excess  
5     food production in recent years has obscured this bleak future; increases in both agricultural productivity  
6     and cropland extension have made the region food self-sufficient in its staple crops in recent decades.  
7     But the resources that supported this increase – surface- and ground- water extracted for irrigation, land  
8     converted into cropland, increased use of nutrients and pesticides – are not unlimited. Groundwater  
9     levels are already falling rapidly in large parts of South Asia due to overexploitation (Rodell et al., 2009;  
10    Tiwari et al., 2009) and surface-water irrigation is reaching its limits (Biemans, 2012), costly river  
11    interlinking schemes aside (Bagla, 2014; Gupta and Deshpande, 2004a). On top of this, higher  
12    temperatures and an expected higher variability in climate due to global warming further jeopardizes  
13    future food production in the region (Krishna Kumar et al., 2004; Mall et al., 2006; Moors et al., 2011).

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

25    Two essential and well-known agricultural characteristics that distinguish South Asia from most other  
26    large food-producing regions in the world govern this water demand. First, South Asia's agriculture is

1 characterized by a high degree of multiple-cropping. A first crop during the monsoon season (Kharif) is  
2 often succeeded by a second crop during the dry season (Rabi) (Portmann et al., 2010). Planting dates for  
3 the Kharif crop are determined primarily by the onset of the monsoon rather than by an accumulation of  
4 degree days. High maximum temperatures form a constraint for crop production during the Rabi season,  
5 favouring planting as early as possible. Second, with rainfall highly concentrated during June till  
6 September and significant moisture deficits occurring during the other months of the year, crop  
7 production is to a very large extent supported by a combination of canal and groundwater irrigation,  
8 especially in the dry winter season (Rabi) (Gol, 2013).

9 Many models that are used for global to regional water resources assessments still lack representation of  
10 multiple-cropping (e.g. (Arnold and Fohrer, 2005; Best et al., 2011; Gerten et al., 2004; Liang et al., 1994)).  
11 Typically, a single cropping period per year is simulated with a degree-day based or predefined single  
12 planting date (see e.g. (Elliott et al., 2014; Kummu et al., 2014)). Exceptions are the model by (Wada et al.,  
13 2011) who apply multiple-cropping in their estimation of water stress, but in a simplified aggregated  
14 form without distinguishing between different crops and the models of (Alcamo et al., 2003) and  
15 (Hanasaki et al., 2008) who apply multiple-cropping seasons using optimized planting dates. However,  
16 Hanasaki et al. (2008) note that their optimization mainly reacted to cold spells and was performed  
17 under rainfed conditions, which does not lead to optimal planting dates for the South Asia region. The  
18 study of Hoogeveen et al. (2015) accounts for multiple-cropping by incorporating national level FAO  
19 cropping calenders, but only present total mean annual irrigation demands for South-Asia (table 1).  
20 Siebert and Döll (2010) also take into account for multiple-cropping by using MIRCA land use data (as the  
21 present study, see section 2.2) and cropping calenders. They show results for global seasonal irrigation  
22 demands, but not for South Asia specifically. As a result, crop-specific seasonal estimates of irrigation  
23 water demand in South Asia are still lacking.

24 In this paper, we aim to provide such spatially explicit, crop-specific seasonal estimates of water demand  
25 and crop production, using a revised version of the LPJmL hydrology and vegetation model (Gerten et al.,  
26 2004), adjusted for the region. We distinguish two main South Asian cropping periods, Kharif and Rabi,  
27 and introduce zone-specific, monsoon-onset-determined planting dates for 12 major crop types, both

- 1 rained and irrigated. We calibrate the improved model against the latest sub-national statistics on
- 2 seasonal crop yields from four different countries –India, Pakistan, Nepal and Bangladesh– and explicitly
- 3 evaluate the irrigation water demand and crop production for the two cropping seasons.

1      **2. Methodology**

2      **2.1. LPJmL**

3      We used the LPJmL global hydrology and vegetation model for bio- and agro- spheres (Bondeau et al.,  
4      2007; Sitch et al., 2003), but developed a version that contains more spatial and temporal detail for  
5      South Asia. The LPJmL model has been widely applied to study the effects of climate change on water  
6      availability and requirements for food production at a global scale (Gerten et al., 2011); (Falkenmark et  
7      al., 2009) and the potential of rainfed water-management options for raising global crop yields (Rost et  
8      al., 2009). For South Asia, the model has been applied to study the adaptation potential of increased dam  
9      capacity and improved irrigation efficiency in light of climate change (Biemans et al., 2013). LPJmL  
10     physically links the terrestrial hydrological cycle to the carbon cycle, making it a suitable tool for studying  
11     the relationship between water availability and crop production. The model includes algorithms to  
12     account for human influences on the hydrological cycle, e.g. irrigation extractions and supply (Rost et al.,  
13     2008). Production and water use for 12 different crops, both rainfed and irrigated are simulated. LPJmL is  
14     a grid-based model, run at a resolution of 0.5 degrees, and at daily time step.

15     Net irrigation water demand (consumption) for irrigated crops is calculated daily in each grid cell as the  
16     minimum amount of additional water needed to fill the soil to field capacity and the amount needed to  
17     fulfil the atmospheric evaporative demand (Rost et al., 2008). Subsequently, the gross irrigation demand  
18     (withdrawal) accounts for application and conveyance losses, and is calculated by multiplying the net  
19     irrigation water demand with a country-specific efficiency factor (Rohwer et al., 2007), which is different  
20     for surface-water irrigation and groundwater irrigation (as in Biemans et al. (2013); [Rost et al. \(2008\)](#)).  
21     Irrigation efficiency for canal water is estimated at 37.5% in India, Bangladesh, Nepal and 30% in Pakistan  
22     (Rohwer et al., 2007); efficiency of groundwater irrigation is estimated at 70% for all countries (following  
23     Gupta and Deshpande, 2004b).

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

1 groundwater (Rost et al., 2008) .

2 Crop growth is simulated based on daily assimilation of carbon in 4 pools: leaves, stems, roots and

3 harvestable storage organs. Carbon allocated to those pools depends on crop phenology and is adjusted

4 in case of water stress on the plants. Crops are harvested when either maturity or the maximum number

5 of growing days is reached (Bondeau et al., 2007; Fader et al., 2010).

6 To improve the understanding of spatial and temporal heterogeneity in irrigation water demand and

7 crop production in South Asia, we made some adjustments to the version of LPJmL that is used for global

8 studies. First of all, we introduced the simulation of two cropping cycles per year by developing two

9 different land-use maps for Kharif and Rabi. Second, we applied zone-specific sowing dates related to

10 monsoon patterns, and third, we accounted for regional differences in crop management by performing

11 a calibration of crop yields at the subnational level. In the next three sections, those adjustments to

12 LPJmL are explained in more detail.

13 In our experimental set-up, LPJmL is forced with daily precipitation, daily mean temperature, net

14 longwave and downward shortwave radiation derived from the Watch Forcing Data applied to Era

15 Interim data (WFDEI) (Weedon et al., 2014). Using this dataset, all LPJmL simulations were done for the

16 period 1979-2009 after a 1,000 year spin-up period to bring carbon and water pools into equilibrium. The

17 calibration and all analysis presented in this paper uses the simulation results of the period 2003-2008

18 for comparison with available statistics. Kharif and Rabi irrigation water demand and crop production are

19 estimated by performing two simulations using different land-use input and sowing-date input datasets.

20 Those two runs are subsequently combined to attain the seasonal pattern for irrigation water demand

21 and crop production.

22 [For comparison and to show model improvements, LPJmL is also run with the single cropping landuse](#)

23 [input as in previous model studies \(Biemans et al, 2013\) for which sowing date are determined based on](#)

24 [climate as in Waha et al \(2012\).](#)

25

1        **2.2. Development of land use maps for Kharif and Rabi seasons**

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

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

20      Next, a few adjustments to the obtained data were made. First, MIRCA specifies three rotations of rice in  
21      northern India, two during summer and one during winter months. We merged the two summer  
22      rotations to the Kharif rice area and allocated one to the Rabi rice area, accepting a potential minor  
23      mismatch between datasets. Second, we corrected wheat and rice areas, both of which MIRCA equally  
24      divides over Rabi and Kharif. In reality, rice is mainly cropped during the Kharif season and wheat is only  
25      cropped during the Rabi (winter) season, when temperatures are lower and heat stress is avoided. We  
26      shifted all irrigated wheat to the Rabi season and made compensations where possible by shifting an

1 equal amount of irrigated rice area to the Kharif season. Third, we shifted 45% of area cropped with  
2 pulses from the Rabi to Kharif season to comply with the latest agricultural statistics (Gol, 2012). In this  
3 way, consistency with other datasets was largely maintained (i.e. total cultivated area, cultivated area  
4 per crop, area irrigated), while at the same time a better match with crop phenology and regional  
5 agricultural practices was achieved.

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

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

20

### 21 **2.3. Adjusted planting dates for Kharif and Rabi crops**

22 Sowing dates for Kharif crops are closely related to the onset of the monsoon as farmers start  
23 (trans)planting rice or other crops when the first rains have arrived. Normal onset dates of the monsoon  
24 over South Asia are determined by the India Meteorological Department, at 5 to 15 day interval (IMD,  
25 2015)(figure 3). The onset of the monsoon starts in Kerala in southern India around the first of June  
26 (Julian day 152) and arrives in western Pakistan around mid-July (Julian day 197). For the model

1 simulations in this study, sowing dates for Kharif crops were set to five days after the onset of the  
2 monsoon, because several days of rain are needed before a crop is (trans)planted (figure 3). Inter-annual  
3 variations in the onset of the monsoon were not taken into account in this study. The perennial crop  
4 sugarcane is assumed to be planted on this date as well.

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

14

#### 15 2.4. Calibration of crop yields

16 Crop yields in LPJmL are calibrated by varying management intensity, which is represented by three  
17 coupled parameters: maximum leaf-area index, maximum harvest index, and a parameter that scales  
18 leaf-level biomass production to plot level (Fader et al., 2010). The three parameters are related to crop  
19 density, crop varieties and the occurrence of poor soils, pests and diseases respectively (for a detailed  
20 description of the calibration procedure, see Fader et al., 2010). “Plot level” in this context means the  
21 total area of the crop within the gridcell; a plot shares the same climate, soil and landuse. “Scale” means  
22 that a yield reduction has been applied to translate from biomass production of individual plants to plot  
23 level. Fader et al (2010) explain this as follows: “The assumption is that intensively managed crop stands  
24 ( $LA_{max} = 7$ ) have little or no areas with reduced productivity due e.g. to poor soil conditions or pests  
25 and diseases ( $\alpha - a = 1.0$ ), while such areas are more common in extensively managed crop stands  
26 ( $LA_{max} = 1; \alpha - a = 0.4$ )” (for a detailed description of the calibration procedure, see Fader et al., 2010).

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1 The value of these management factors affects the estimated water demand, because a poorly  
2 developed crop with little leaf area will evaporate less and therefore demands less (irrigation) water and  
3 vice versa.

4 The calibration is performed for each crop individually, and management factors are usually determined  
5 at the country level in global applications of LPJmL. For this model version, we calibrated crop yields for  
6 Kharif and Rabi separately, as they are differentiated in the agricultural statistics. Moreover, we  
7 calibrated the management parameters at the sub-national level for India and Pakistan (state- and  
8 province- level respectively) and at the national level for Nepal and Bangladesh. By calibrating at the sub-  
9 national level, existing spatial heterogeneity in management and crop yields between regions could be  
10 better represented. We used 5-year average yield statistics, for 2003-04 till 2007-08, the most recent  
11 period for which consistent records are available from different national agricultural statistics (India: GoI,  
12 2012; Pakistan: <http://www.pbs.gov.pk/content/agricultural-statistics-pakistan-2010-11>, last visited 1-7-  
13 2014; Bangladesh for the years from 2003-04 till 2005-06 from  
14 <http://www.moa.gov.bd/statistics/statistics.htm#3> and for 2007-08 in the 2011 yearbook  
15 (<http://www.bbs.gov.bd/PageWebMenuContent.aspx?MenuKey=234> ; Nepal:(GoN, 2012). After  
16 calibration, the model is able to simulate the heterogeneity of (mean annual) yields between states and  
17 regions (illustrated in fig 4). Kharif rice and Kharif maize crops show the highest variation between states  
18 and provinces. Overall, yields during the Kharif season are lower than yields during the Rabi season,  
19 when a higher percentage of the area cropped is irrigated, and temperatures are more favorable.  
20 Interannual variations in crop yields are shown and discussed by Siderius et al (2016).

21

### 22 **3. Results**

#### 23 **3.1. Seasonality in agricultural water demand**

24 Table 1 shows estimates of seasonal net (consumption) and gross (withdrawal from surface and  
25 groundwater) irrigation water demand between the four countries. India and Pakistan have the largest

1 water demand, both in terms of consumption and withdrawal. While Pakistan's net irrigation demand is  
2 almost equally divided over the Kharif and Rabi seasons, India's demand is skewed towards the Rabi  
3 season; almost ¾ of net irrigation demand in India occurs in this dry season (including [pre-monsoon](#)  
4 summer). This difference between Kharif and Rabi is less pronounced for gross irrigation demand, i.e.  
5 water withdrawals, which include application and conveyance losses. In the Rabi season a much higher  
6 proportion of the irrigation water is supplied from groundwater (table 1), which has a higher overall  
7 efficiency than surface-water irrigation from canals.

8 The seasonal distribution of irrigation water demand is a result of rainfall patterns in the region. In  
9 Bangladesh and Nepal, monsoon rainfall is abundant for sustaining crop production during the Kharif  
10 season and irrigation is therefore concentrated in the dry Rabi season. Groundwater irrigation, modelled  
11 as the resultant of demand minus surface-water availability, provides most water resources during the  
12 Rabi season in all countries, especially in India. In Pakistan, the Indus provides annually approximately  
13 120 BCM/yr of utilizable runoff, of which approximately 2/3 is used during the Kharif (Randhawa, 2002).  
14 Our estimate of mean annual groundwater withdrawal in Pakistan is at 60 BCM/yr, of which ¾ occurs  
15 during the Rabi season and [pre-monsoon](#) summer. This is somewhat higher than previous estimates of  
16 groundwater withdrawal, which were in the range of at 47 BCM/yr to 55 BCM/yr (Ahmed et al., 2007;  
17 Qureshi et al., 2003; Wada et al., 2010) but still lower than the estimated total potential of 68 BCM/yr  
18 (Randhawa, 2002). For India, the exact distribution of surface-water and groundwater withdrawal  
19 between the Kharif and Rabi seasons is not well documented. Our model estimate of 217 BCM/yr of  
20 groundwater withdrawal [per year](#), mainly occurring during the Rabi season, is in agreement with earlier  
21 groundwater studies with estimates ranging from 190 ( $\pm 37$ ) BCM/yr by (Wada et al., 2010) to 212.5  
22 BCM/yr (Gol, 2006).

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

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

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

17 [The mean annual cycle of irrigation demand as calculated with single cropping and sowing dates](#)  
18 [determined based on climate \(before model improvement\) are also shown in figure 5.](#)

19

### 20 **3.2. Seasonal patterns of water demand for different basins**

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

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

3

4 **3.3. Food production in South Asia during the Kharif- and Rabi- cropping seasons**

5 Figure 8 shows the total seasonal production of only the five most important food crops (wheat, rice,  
6 maize, tropical cereals and pulses), both for the region as a whole as for the individual basins. The total  
7 area irrigated to grow these food crops is smaller in Kharif than Rabi (35 Mha vs 46 Mha total for the four  
8 countries), but total (rainfed plus irrigated) area used to grow these food crops is much larger in Kharif  
9 than Rabi (95 Mha vs 57 Mha). While the percentage of area under irrigation, productivity per hectare  
10 and sources of water used greatly differ between the Kharif and Rabi seasons, total regional food-crop  
11 production is remarkably similar in the two seasons. A lower cropped area during the Rabi season is  
12 compensated for by higher yields. Of the total production of food crops in South Asia during the Kharif  
13 season, ~50% is supported by irrigation (figure 8). In the Rabi season up to ~95% of food-crop production  
14 is supported by irrigation. These estimates agree with the recent study of Smilovic et al. (2015) who  
15 focus on rice (kharif and rabi) and wheat (rabi) production in India only. They show that during kharif  
16 68% of rice production is produced on irrigated lands, which is only 56% of the rice area sown. During  
17 rabi this percentage is much higher: 96% of the rice was irrigated (on 89% of the sown area) and 97% of  
18 the wheat production was irrigated (on 93% of the sown area) (Smilovic et al., 2015).

19 We also calculated the potential rainfed yield on those areas currently irrigated. Absence of irrigation  
20 would reduce the Kharif food-crop production with ~15% (dark blue bar in figure 8), against a reduction  
21 of almost 60% in Rabi. This stresses the importance of sufficient irrigation- water supply for achieving  
22 food security in this region.

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

25 Rabi is the most important season for the production of food crops in the Indus. The same is true for the

1 Ganges, although the production levels between the seasons are closer to each other. The rainfed  
2 production is much larger in the Ganges than in the Indus. In the Brahmaputra basin, the majority of food-  
3 crop production takes place during the Kharif season.

4

#### 5 **4. Discussion**

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

9 Incorporating seasonal cropping patterns in more detail leads to improved estimation of the timing of  
10 water demand. Figure 5 shows that the simulated timing of water demand is very different compared to  
11 a simulation with old settings – thus single cropping season and calculated sowing dates. [This difference](#)

[shows the importance of including multiple cropping in the simulation of irrigation water demand.](#)

[Especially in this region with a very strong seasonal variability in both water availability and demand, an](#)

[improved understanding of the \(changes in\) timing of both water availability and demand is essential to](#)

[understand current and future water stressed regions. Therefore, the effect of multiple cropping on](#)

[patterns of irrigation water demand should not be neglected.](#) We show that seasonal water demand is a

17 factor of crop-specific seasonal consumption, availability of rainfall and different sources of water supply,  
18 i.e. groundwater or surface water, and the irrigation efficiencies connected to these sources. –Despite  
19 these improvements, when modelling such large basins with complex hydrology and high diversity in  
20 agricultural and water-management practices, inevitably simplifications and local inaccuracies remain.

21 Our estimate of the net irrigation requirement (consumption) is influenced by the performed calibration  
22 and resulting management factors. Generally, regions with high management factors will show higher  
23 yields and higher transpiration, but lower soil evaporation. The effect of the calibration on our estimate  
24 of net irrigation requirements was tested by making two model runs: one with all management  
25 parameters set to the lowest possible value and one with all management parameters set to the highest

1 possible values. This resulted in a net irrigation requirement for South Asia between 307 and 389 km<sup>3</sup>, a  
2 variation of about 10% compared to the here reported mean annual value of 346 km<sup>3</sup>.

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

10 More attention to seasonal cropping patterns and their water demand opens the scope for further  
11 model improvement. Double-cropping was evaluated by combining two seasonal model runs, one for  
12 Kharif and one for Rabi. Use of residual soil moisture from one season to the other was not incorporated  
13 in this way, nor could the continued depletion of groundwater be accurately modelled. An integrated  
14 double-cropping routine, with proper calibrated crop-specific planting dates and yields, would provide  
15 such necessary analysis in a region where groundwater depletion is of serious concern.

16 Next, estimation of planting dates should be further improved, using detailed information on local  
17 agricultural practices and local water availability. Further, the sowing dates were kept constant during  
18 the whole simulation period and was based on average data of monsoon onset, although actual onsets  
19 vary year by year. In reality a farmer might decide year to year to sow earlier or later which introduces  
20 an uncertainty in our calculations. Ample information is available in the irrigation domain but it will  
21 require a form of cooperation between experts at the local to national level and the water resources  
22 modelling community. Sharing of input data might reduce costs and time expenditure, will increase its  
23 uptake and improve overall quality of water resources assessments.

24 Finally, cropped area and sources of irrigation used are not constants or slowly evolving properties, but  
25 can be highly variable on inter-annual time scales in response to climate variability (Siderius et al.,  
26 2013b). These fluctuations were not assessed in the current study but are of high importance to

1 individual farmers and the overall profitability of agriculture in regions with a variable climate.  
2 Combining an improved baseline of seasonal water demand with the inter-annual fluctuations in cropped  
3 area will lead to a more realistic assessment of both water demand and crop production, of high  
4 relevance in today's world with its volatile food commodity markets.  
  
5 This paper highlights crop-specific periods of peak water demand that can form critical moments in  
6 agricultural production. Such better understanding of the size of water demand during critical moments,  
7 the crops that are responsible for this water demand, and its relative importance for food production is  
8 essential to guide sustainable development of climate adaptation measures. This analysis can support  
9 the selection of promising options to decrease irrigation water demand. When combined with  
10 information on the (un)availability of surface water and the resulting pressure on groundwater resources  
11 (figure 7), it improves our understanding on the causes of water shortages and groundwater depletion.  
12 Finally, insight in the yield gap between rainfed and irrigated agriculture in specific regions, and between  
13 regions, can help target investments to improve irrigation practices or to increase productivity of rainfed  
14 agriculture.

15

## 16 **5. Conclusions**

17 Introducing seasonal crop rotation with monsoon-dependent planting dates in a global vegetation-  
18 hydrological model leads to better seasonal estimates of irrigation water demand. Irrigation water  
19 demand between the two main cropping seasons differs sharply both in terms of source and magnitude;  
20 gross irrigation demand during the Rabi season is ~30% higher than during the Kharif season, the  
21 traditional cropping season, when monsoon rainfall reduces the amount of supplemental irrigation water  
22 needed. Our estimate of total annual water demand is lower than that of previous studies (Biemans et al,  
23 2013), despite the net irrigated area being higher. Overall, gross annual irrigation demand is estimated  
24 at 714 BCM/yr; 247 BCM/yr during the Kharif monsoon season, 361 BCM/yr during Rabi and 106 BCM/yr  
25 during the dry summer months of April and May.

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

8 Our study has thereby more than regional relevance. Given the size and importance of South Asia, in  
9 terms of population and food production, improved regional estimates of production and its water  
10 demand will also affect global estimates. In models used for global water resources and food-security  
11 assessments, processes like multiple-cropping and monsoon-dependent planting dates should not be  
12 ignored.

13

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23

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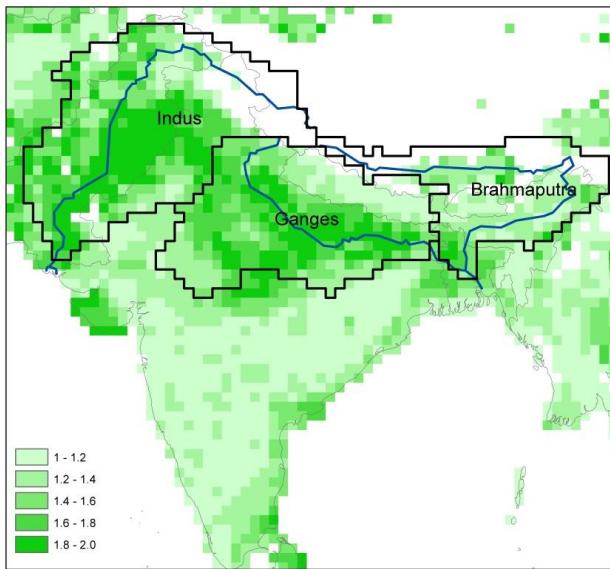
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46

1 **Table 1.** Seasonal and total net and gross irrigation water demand estimates (BCM/yr) and groundwater contribution to irrigation-  
 2 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				Other estimat	gross irrigation demand (withdrawal)				Other estimates	
	Kharif	Rabi	Summer	Total		Total	Kharif	Rabi	Summer		Total	Kharif	Rabi	Summer	Total	
	(M6- 10)	(M 11-3)	(M4-5)		(M6- 10)	(M 11-3)	(M4-5)		(M6- 10)	(M 11-3)	(M4-5)					
Nepal	0.1	1.0	0.2	1.4	4.4 <sup>d</sup>		19%	62%	34%	54%	20% <sup>e</sup>	0.3	2.0	0.5	2.7	10 <sup>f</sup>
Pakistan	38	42	16	96	91 <sup>d</sup>		25%	68%	25%	44%	33% <sup>g</sup>	110	86	47	243	200.2 <sup>h</sup> , 162.7 <sup>i</sup> , 17–120 <sup>j</sup> , 187.8 <sup>k</sup>
India	59	148	31	235	317 <sup>d</sup>		27%	79%	63%	64%	64% <sup>l</sup>	136	249	58	443	575.9 <sup>h</sup> , 541 <sup>i</sup> , 558.4 <sup>j</sup> , 710–715 <sup>k</sup>
Bangladesh	0.1	11	0.3	12	24 <sup>d</sup>		10%	43%	2%	4%	76% <sup>l</sup>	0.2	24	0.8	25	31 <sup>f</sup>
South Asia	97	202	48	346	480 <sup>l</sup> , 532 <sup>l</sup>		26%	74%	50%	58%		247	361	106	714	985 <sup>l</sup> , 910 <sup>l</sup>

3  
 4 a GOI (2005). Water Data Complete Book, Central Water Commission, Ministry of Water Resources,  
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 6 b AQUASTAT (<http://www.fao.org/nr/water/aquastat/main/index.stm>).  
 7 c Rost et al. (2008).  
 8 d Siebert et al. (2010)  
 9 e AQUASTAT with reference to 2008 for Bangladesh and 2005 for Nepal. Approximately 79 percent of the  
 10 total water withdrawal comes from groundwater (Nepal) and 21 percent (Bangladesh)  
 11 f Rosegrant and Cai (2002). 1995 estimate using a basin efficiency of 0.54.  
 12 g Water Resources Section, Ministry of Planning and Development in (Ahmed et al., 2007)  
 13 h Biemans et al. (2013)  
 14 i Siebert and Döll (2010)  
 15 j Hoogeveen et al. (2015)  
 16



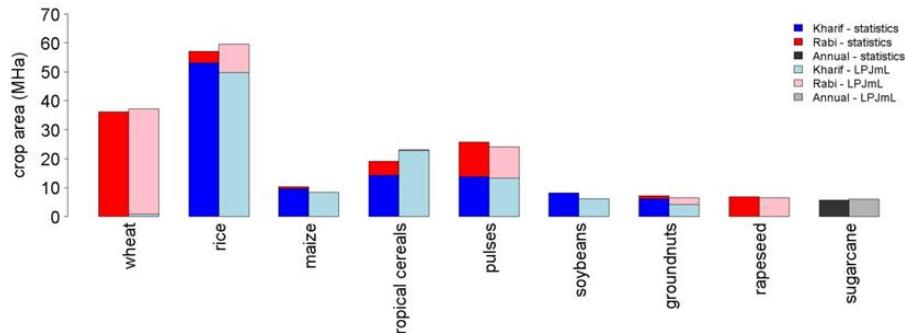
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2 *Figure 1. Cropping intensity in South Asia (land use datasets derived for this study based on MIRCA2000. Average*  
3 *cropping intensity is defined here as the total annual harvested area (Kharif and Rabi) divided by the maximum*  
4 *cropped area of the two cropping seasons. Study-basin delineations are indicated in black.*

5

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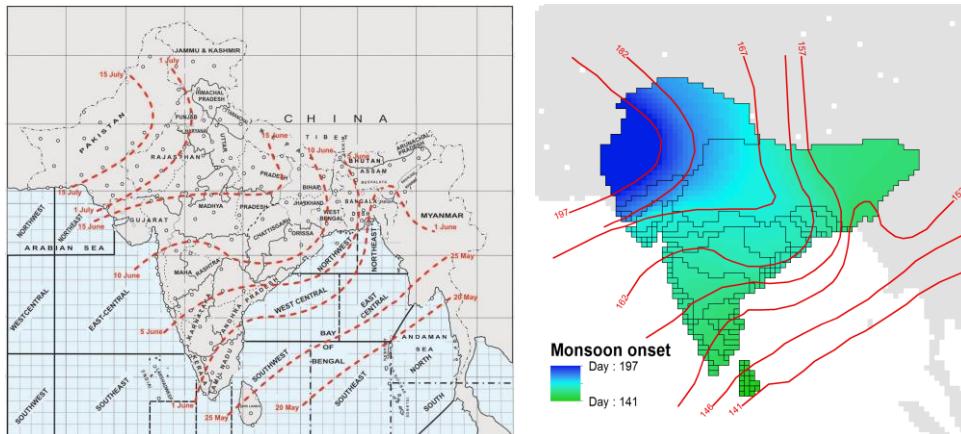
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2 *Figure 2. Total crop area in South Asia (India, Pakistan, Nepal and Bangladesh) for different crops in the two*  
3 *dominant growing seasons. National statistics (average of 2003-2008) versus LPJmL input data derived from MIRCA*  
4 *as described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

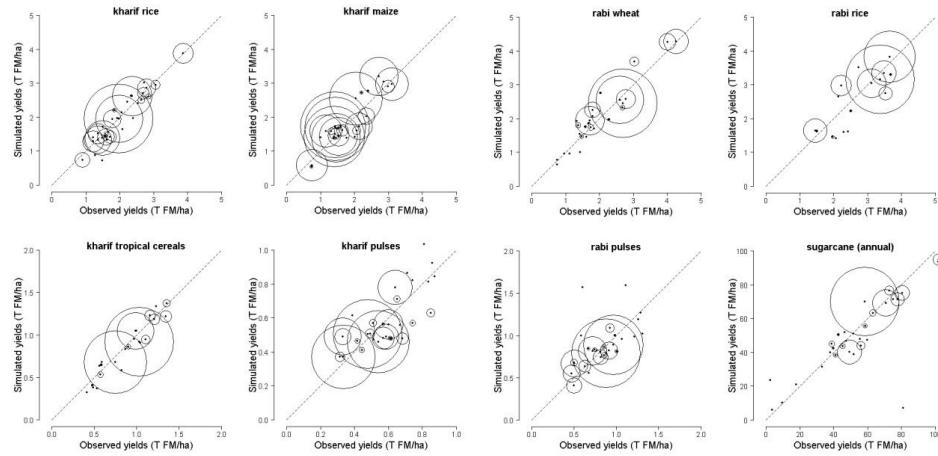
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11 *Figure 3. Normal dates for the onset of the Southwest Monsoon as presented by the Indian Meteorological*  
12 *Department (left) and interpolated over South Asia (right) derive input data for LPJmL, red numbers indicating Julian*  
13 *days, grey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

1



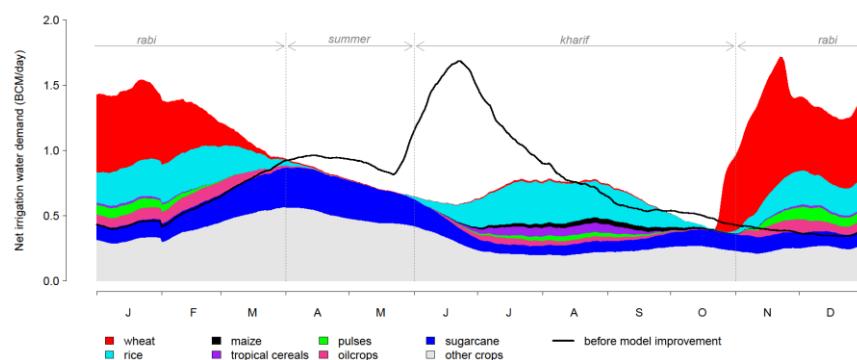
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3 *Figure 4. Observed vs simulated (calibrated) crop yields for the most important crops in the different cropping*  
4 *seasons in tons of fresh matter per hectare (T FM/ha)s. Each dot represents one state (India), province (Pakistan) or*  
5 *country (Nepal, Bangladesh). Size of the circle represents the relative area under that crop (for areas, see figures S1-*  
6 *S6 in the Annex).*

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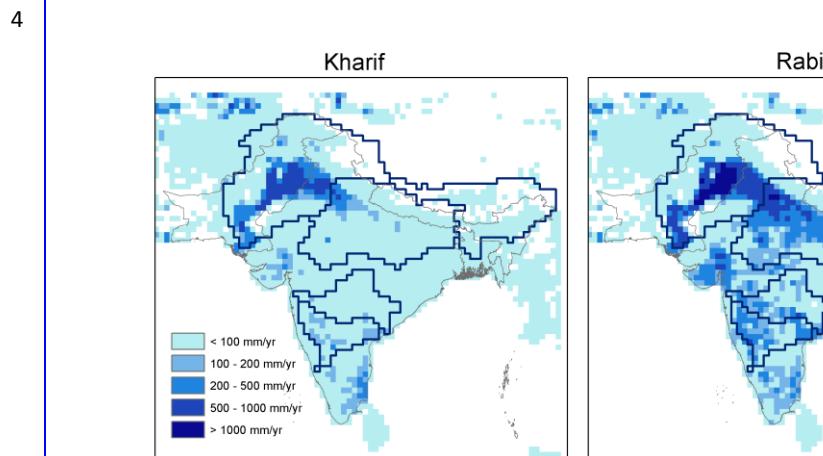
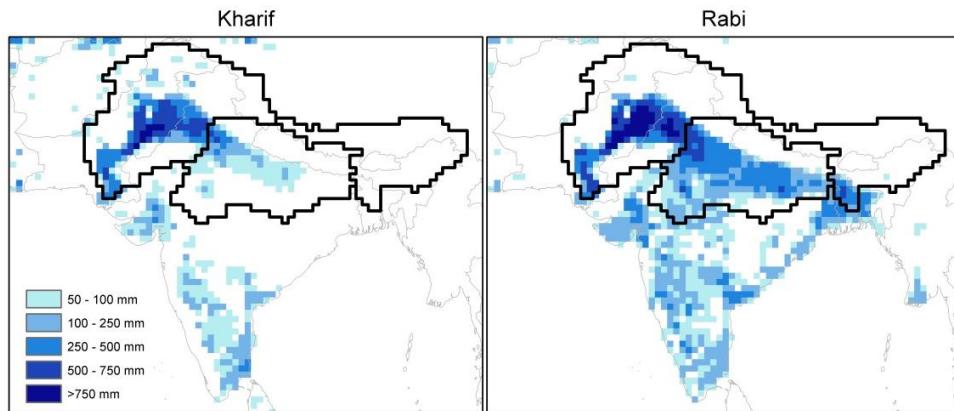
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1 Fig 5. Mean annual cycle of net irrigation requirements for main agricultural crops in South Asia [in BCM/day](#) (30-day  
2 moving average). For comparison, the mean annual cycle of net irrigation requirements before model improvements  
3 (with single cropping season and climate driven sowing dates determination) is added in black.



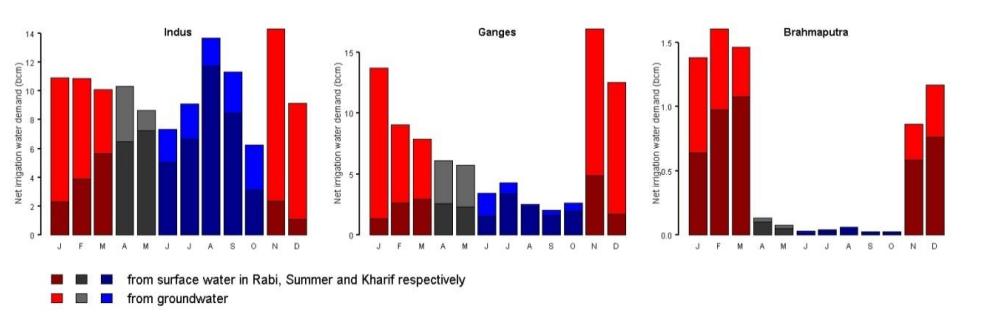
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6 Fig 6. Gross irrigation water demand for Kharif ([M6-10](#) June to October) and Rabi ([M11-3](#) November to March)  
7 cropping seasons, with selected river basins (Indus, Ganges, Brahmaputra).

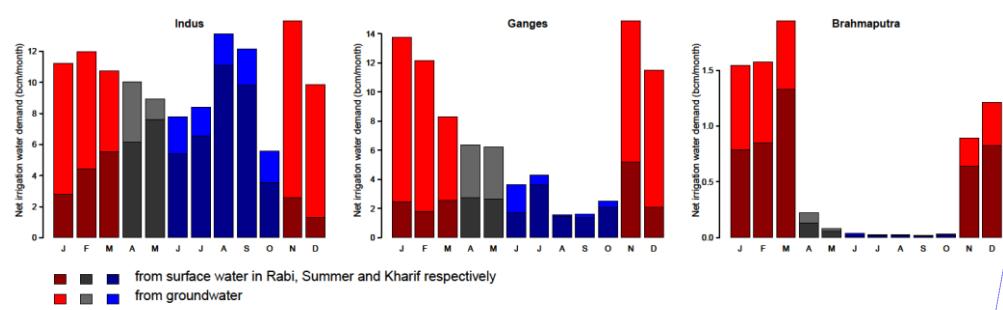
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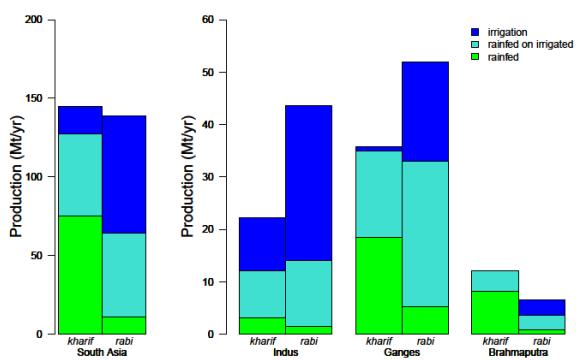
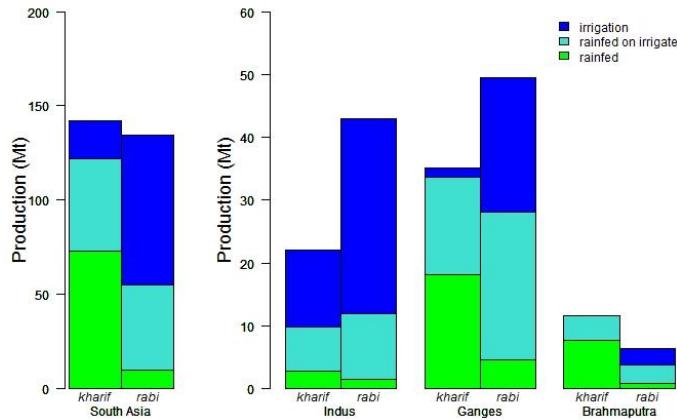
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7 *Figure 7. Monthly net irrigation water demand for three river basins. Colours indicate the different seasons (red – Kharif, grey – summer, blue – Rabi) and the dark areas the source for supplying the irrigation water (dark – surface water, light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



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Figure 8. Mean annual 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.