INITIATIVE ON
Asian Mega-Deltas

Climate change impacts on hydrology, upstream water dependencies and crop production in the Asian Mega-Deltas

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Contents

Summary

This research brief explores the interplay between water and food systems in the Ganges-Brahmaputra-Meghna and Mekong River basins, highlighting regional dynamics and climate change impacts. To do so, a hydrology-vegetation model is used. Based on the climate change scenarios chosen in this study, in the Ganges-Brahmaputra- Meghna basin, future water inflows are projected to rise, while in the Mekong, large dam expansions are expected to decrease wet-season flooding and increase dry-season flows. Both basins have sufficient water availability to meet full irrigation demands, excluding other sectoral and ecological needs now and in the future. However, during the dry season, the simulated agricultural water withdrawal in the deltas suppose an important part of the water inflows, making clear that deltas' inflows during the dry season in both basins are highly sensitive to upstream irrigation abstractions, which are already substantial and projected to remain so by 2050. Upstream irrigation intensification puts at the risk the downstream deltas by increasing water scarcity and complicating water allocation for other sectors, including ecosystems.

Climate change impacts on food production varies significantly accordingly to the model set-up: in the Ganges-Brahmaputra-Meghna, where land use change is considered but with no variation of CO_2 concentration, yields are expected to decline due to heat stress on non-rice cereals; whereas in the Mekong, where land use change is considered constant but with variation of CO_2 concentration, the effect of CO_2 fertilization limited heat stress for rice, enhancing productivity.

Key adaptation challenges include improving groundwater management and promoting sustainable upstream cropping intensification in the Ganges-Brahmaputra- Meghna without deteriorating downstream water stress. In the Mekong, adaptations must address altered flooding patterns, including reduced riverine flooding and increased erratic flash floods, which could impact the Cambodian floodplains and Tonle Sap. Equitably distributing increased streamflow, to mitigate salinity intrusion in the delta while supporting upstream agricultural intensification, is also critical. This study underscores the need for integrated basin-scale water management to navigate these challenges sustainably.

Background and objectives

The hydrological regime of the Ganges-Brahmaputra-Meghna and Mekong River basins will be impacted by climate change. This will lead to changing precipitation patterns, increasing temperatures, accelerated glacier retreat, melting snowpacks and changing sediment regimes. In both river basins, agriculture is a large consumer of water and adapting agriculture to the changing hydrological system is a cornerstone of food security and sustainable development of the riparian countries. An increase in agricultural water demand might result in (over)abstraction of surface and groundwater resources and, up- and midstream developments may affect the amount and timing of water inflow downstream - likely increasing water scarcity and negatively impacting agricultural production in the deltas. At the same time, the changing precipitation patterns and increasing heat will directly affect crop growth and evaporation demands in the delta.

The CGIAR Initiative on Asian Mega-Deltas (AMD) and Wageningen University and Research (WUR) have collaborated together on making an integrated quantitative and spatially explicit analysis of those potential threats with a focus on Ganges-Brahmaputra-Meghna Delta and Mekong Delta. The main research questions are

"How will current and future water availability in the Ganges-Brahmaputra-Meghna and Mekong deltas be affected by climate and socioeconomic changes both in the Delta and upstream?"

And

"How will the complex interplay of climate change and socio-economic changes, both upstream and in the Delta, affect water availability, water use and crop production in the Ganges-Brahmaputra-Meghna and Mekong deltas?"

Answering these questions is a difficult task that requires an integrated modelling approach, accounting for many factors that influence the water-food system in the Deltas. In the next sections we describe the approach we use to improve our understanding of crop-water interactions in the Mekong and GBM basins. Subsequently, we present the estimates of current and future water availability and demand, rainfed and irrigated crop production and discuss key learnings.

We focused on two of the largest, most populated, but also most productive and intensively cultivated areas in Asia, the Ganges-Brahmaputra-Meghna and the Mekong River basin and their deltas (Figure 1). The societal importance of these large basins makes them pivotal case studies through which we explore the interaction of water and crop production under current and future conditions and how upstream and downstream dependencies are projected to change up to 2050.

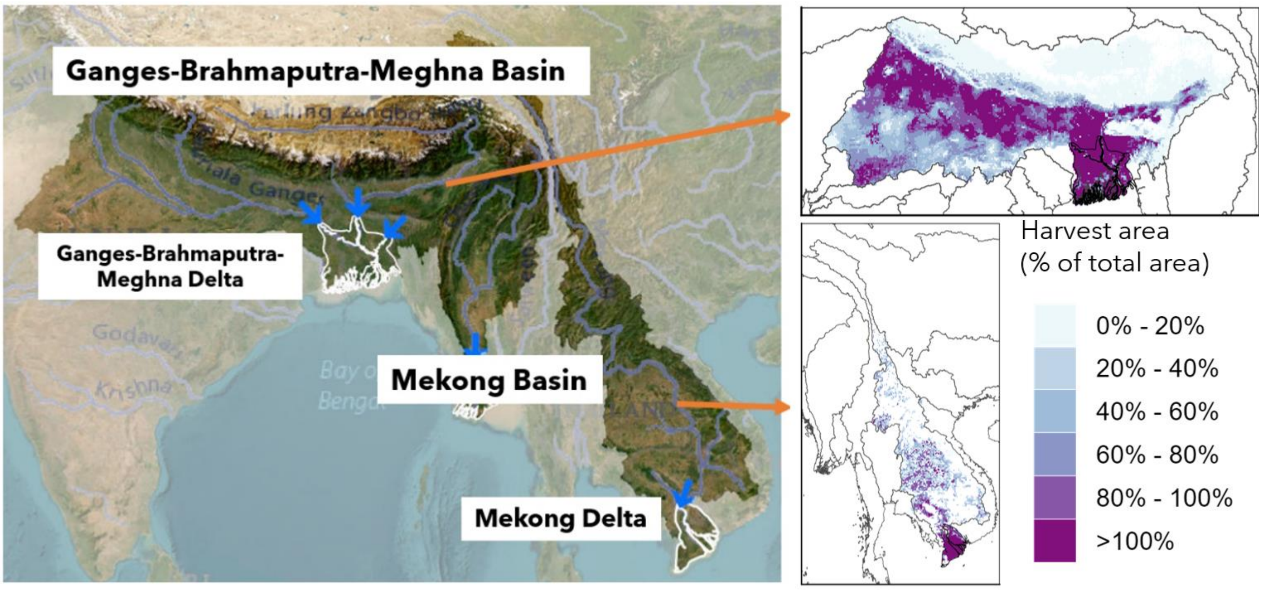

Figure 1. Study area, main water inlets (blue arrows) into the GBM and Mekong deltas and harvested area, defined as % of agricultural lands harvested over the total area.

Improved understanding of crop water interactions

Both the Mekong and the Ganges-Brahmaputra-Meghna deltas are complex agro-hydrological systems where different pressures act upon the interaction between water and food production at the same time. In order to understand these complex dynamics, we make use of an integrated agro-hydrological model that we feed with the most recent data and run at high resolution. With this model we evaluate the future water availability, water demand and crop production, and how they will be influenced by climate change.

We use the Lund Potsdam Jena managed Land (LPJmL) model, which is designed to simulate crop growth as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems. This makes the model a very suitable tool to study the interactions between water (availability and demand) and food production in the historical and different future situations. Below, a short description of the model set-up for both the Ganges-Brahmaputra-Meghna and Mekong basins and deltas is shown. More details on LPJmL model and the specific methodology used can be found in the Annex.

Downscaling LPJmL from global to regional scale

LPJmL is typically applied at the global scale, with a 30 min resolution (about 50x50km at the equator) (Biemans et al., in preparation; Gerten et al., 2011; Jägermeyr et al., 2017). However, to assess impacts of global change at regional water-food systems such as the Ganges-Brahmaputra-Meghna and Mekong River basins and their deltas, run the model with a higher level of detail is desired. Therefore, we implement LPJmL at a 5 min resolution (about 9x9km at the equator). The main improvements that were made are described below.

Hydrology: changing snow and glacier melt patterns

Both the Ganges-Brahmaputra-Meghna and the Mekong River basin have their origin in the High Mountains of Asia, which are also referred to as the 'Third Pole', because of the enormous amounts of ice and snow they store. The seasonal melting of this ice and snow contributes to the streamflow of all basins that originate from those mountains. With rising temperature, climate change will have profound impacts on the amount and timing of meltwater flows from the mountains (Khanal et al., 2021). But the relative importance of snowmelt and changes therein is not the same in all basins. For the upstream mountainous part of the Ganges-Brahmaputra-Meghna basins, we therefore applied a mountain hydrology model to better simulate the impacts of climate change on the meltwater flow regime (Biemans et al., 2019; Lutz et al., 2022). For the Mekong, we did not have the mountain hydrology model implementation available, although according to literature we consider that the relative importance of meltwater in the total streamflow is less (Lutz et al., 2014).

Hydrology: assessing impact of upstream dams and reservoirs on downstream hydrology

Both the Mekong and the Ganges-Brahmaputra-Meghna basins are heavily dammed with dam capacity increasing especially rapidly in the Mekong basin from 2000-2020 (Figure 2). The impact of dam and reservoir operation on the hydrology of these basins is therefore important to take into account in the simulations. LPJmL includes a simple dynamic reservoir operation module that estimates the impact of reservoir operation on streamflow and irrigation water supply (Biemans et al., 2011b). For the Ganges-Brahmaputra-Meghna basin, we include the construction year, the reservoir capacity and the purpose of the reservoirs as listed in the Global Reservoirs and Dams database (GRanD) (Lehner et al., 2011). For the

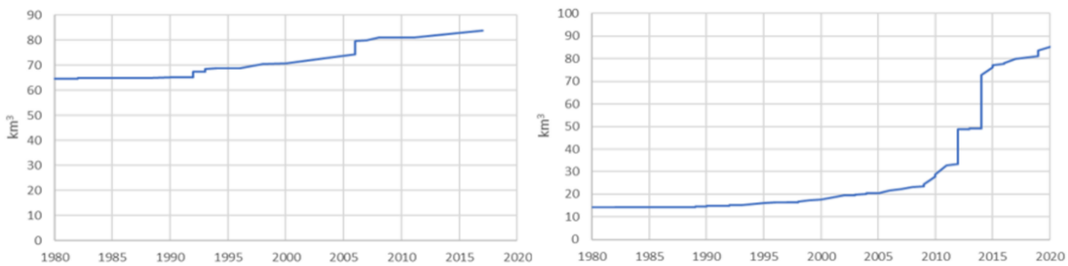

Figure 2. Cumulative reservoir capacity between 1980 and 2020 in the Ganges-Brahmaputra (left) and Mekong (right) river basins (year defined when dams enter in operation).

Mekong basin, we used an updated georeferenced database recently published (2024). Figure 2 shows the cumulative capacity of reservoirs as implemented in the model. Note that we used only the records of the dam databases that had records for year (enter in operation) and reservoir capacity.

Hydrology: impact of irrigation canals on water availability and water withdrawals[1]

The irrigation system of the Indo-Gangetic Plain is characterized by a dense network of irrigation canals that transport water from main rivers, sometimes hundreds of kilometres, to irrigated fields. The local irrigation water availability depends to a large extent on whether the irrigated fields are connected to a canal system. For the Ganges-Brahmaputra-Meghna, we implemented the water supply through irrigation canals by delineating irrigation command areas and connecting them to inlet location at main river stems (as described in Biemans et al., 2019).

For the Mekong, we used the canal network of OpenStreetMap and a map of Garmin to delineate the irrigation command area of the delta and connected it to the main river at the delta inlet. In this way, we simulate the distribution of fresh water from the Mekong River to all irrigated fields in the Mekong Delta.

It is important to note that the LPJmL model assumes that surface water is available for irrigation in a cell only when it is crossed by a river/canal section or when an artificial lake for irrigation is located in neighbouring upstream cells. If not, LPJmL assumes groundwater is used for irrigation. A detailed delineation of irrigation canals will therefore provide a more realistic distribution of water into the cells, although it can also overestimate surface water supply to some specific areas, since canals are not always operated as designed.

Agriculture: intensive agriculture with multi cropping

Both the Ganges-Brahmaputra-Meghna and the Mekong River basin have a very intensive agricultural system, where multiple crops per year are grown on the same fields. However, most global cropland databases do not explicitly account for multiple cropping or are not up to date.

For the Ganges-Brahmaputra-Meghna we developed a cropping map based on the crop distribution of MIRCA2000 (Portmann et al., 2010), but we corrected it using subnational agricultural statistics from more recent years (Biemans et al., 2019). The crop calendars were developed based on the same agricultural statistics and a relation to typical monsoon onset dates, which led to an improved representation of the seasonal pattern of irrigation water demand (Biemans et al., 2016).

For the Mekong River basin and its delta, we used the crop distribution from the recently published MAPSPAM2020 database (https://mapspam.info) (Lu et al., 2020; Yu et al., 2020). Shares of rice cultivated in different seasons as well as sowing dates for rice and all other crops are taken from the recently updated MIRCA-OS database (that is still under development and therefore not without errors) (Kebede et al., 2024).

Climate forcing

For the Ganges-Brahmaputra-Meghna we selected a representative climate model ensemble of 4 climate models that was bias-corrected and downscaled to be used as climate forcing to the LPJmL model (Lutz et al., 2016). In this project, we present the RCP4.5 combined with SSP1 projections. This is one of the stabilization scenarios, assuming a peak of CO_2 concentrations in 2040 and then declines. For the Mekong river basin and delta, a downscaled climate model ensemble was not available, and we used a widely used bias corrected climate forcing ensemble from ISIMIP3b with 5 climate models (Hempel et al., 2013; Lange, 2021). From the available forcing sets, we selected SSP3-7.0 which is a combination of SSP3 (regional rivalry) and RCP7.0. It assumes a doubling of CO_2 concentrations by the end of this century.

Assessing model outputs

We conducted a comprehensive evaluation using the LPJmL model to simulate water and food availability in the Ganges-Brahmaputra-Meghna and Mekong River basins. Specific attention has been paid to understand how upstream changes can impact the Deltas, as these are major food baskets in the region that are increasingly coming under pressure from climate change and upstream developments. The LPJmL model simulates water flows in the

[1] Also defined as water abstraction, is the freshwater taken from surface and groundwater sources, either permanently or temporarily. It includes water lost by lost due to conveyance and application.

rivers, food production and water withdrawal through the entire basin. In order to assess the impacts at delta level, we defined specific "inlet" points of the two Deltas within each basin, downstream of which we considered all watersheds to belong to the delta (Figure 1). Upstream regions were divided between Plains and Mountains, as described by Biemans et al., (Biemans et al., 2019) to describe better climate particularities. Specific results from a set of quantitative indicators related to climate, food production, water availability and water demand for the historical (1991-2010, also referred as 1995) and future (2036-2065, also referred as 2050) situation under different climate change scenarios can be found in the following sections.

Since the fine-tuning of the model (defining exact sowing dates and growing periods of different crops, calibration of management factors to simulate yields, estimating the uncertainty related to CO2 fertilization effect) is a continuous work-in-progress, especially for the Mekong River basin, the results shown below are a first estimate that will be improved when better input data becomes available. The analysis therefore focuses more on trends and relative changes between current and future situation at this moment than a presentation of absolute values.

In order to understand the effect of climate and water availability, but also land use change patterns on food production, an analysis of the future situation has been performed, with some particularities in the set-up of the model for each basin. While in case of Ganges-Brahmaputra-Meghna, land use change has been modelled considering the scenarios provided by the IMAGE[2] model (Doelman et al., 2018), this change has been neglected for the Mekong basin. Similar to this, the CO_2 concentration has been considered as constant for the Ganges-Brahmaputra-Meghna, while an increase considering RCP7.0 has been included in the Mekong delta. With this different model set-up, we aim to understand better the isolated effects of land use change (GBM basin) and CO_2 fertilization (Mekong basin).

Results

Historical climate and future trends

A temperature rise of 1.2-2.4°C is projected in both Ganges-Brahmaputra-Meghna and Mekong River basins likely affecting crop water demand. However, overall increase in accumulated rainfall, but with marked spatial differences, will likely improve water availability for downstream users.

Although climate is not an output of LPJmL model *per se*, but an input, the analysis of the historical and projected climate pattern (i.e. rainfall and temperature) is essential to understand its influence on the water and food system. According to the historical climate scenarios used by LPJmL 5 min model set-up, the Ganges-Brahmaputra-Meghna river basin is characterized by average monthly temperatures ranging from 15°C to 31°C, with monthly temperature higher in the Delta than in the Plains, although the latter is characterized by a warmer pre-monsoon season (Figure 3). During the Monsoon (mid-June to October), the average temperature remains constantly above 27°C. Opposite to this, the average monthly temperature in the Mountains remains below 0°C for at least 4.5-5 months per year, from mid-October to March. The rainfall pattern in the Ganges-Brahmaputra-Meghna River basin is mainly driven by the Monsoon, following a unimodal distribution with a clear dry season from November to April-May and a wet season, from May to September. Although rainfall is well distributed across the basin, the Delta is the area with the highest rates and longest duration of the rainy season.

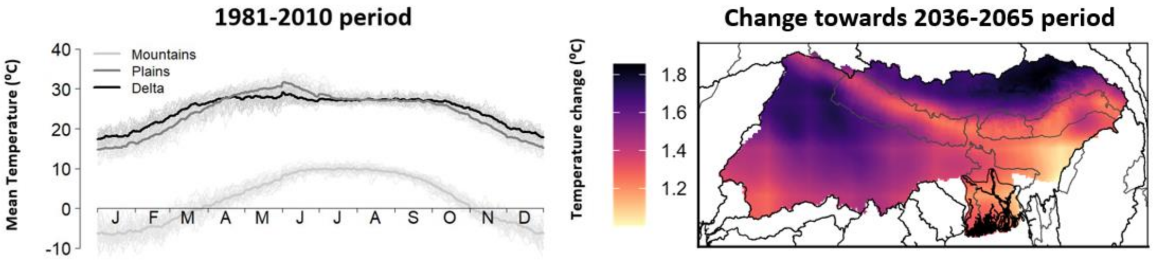

Figure 3. Mean annual cycles of temperature of the period 1981-2010 (left) and temperature change of the 2036-2065 period over 1981-2010 in the Ganges-Brahmaputra River basin (average values of the 4 RCMs used and for RCP 4.5).

According to the climate models used as input for LPJmL, in the Ganges-Brahmaputra-Meghna River basin, **an increase of the monthly temperatures between 1.2-1.8°C** is expected for the historical period in comparison with the future period (Figure 2). This temperature increase is especially pronounced in upstream regions, such as the Indo-Gangetic Plains of **India and the mountains region, which likely will affect snowmelt patterns.** Within the year, the climate models assessed predict **a higher temperature increase during the hotter summer months (March-May)**, putting further pressure on the time management in the cropping systems which will likely results in burning of straw residue to clear the field for the next season, thereby increasing air pollution while also increasing water demand.

Our model inputs predict an **increase of monthly rainfall both in the Delta and upstream areas for the future, especially during the monsoon**, with increments of almost 6% over the historical period (1981-2010) (Figure 4). This increase would affect water availability and flooding patterns by increasing water runoff from upstream regions – while increasing rainfall variability poses increased risks to water storage infrastructure.

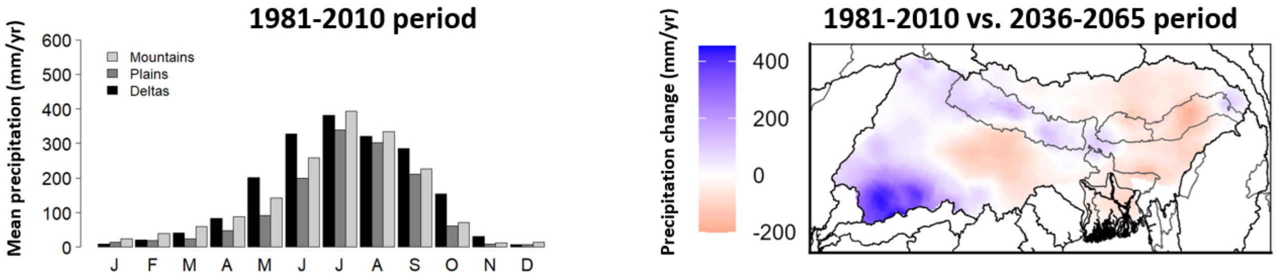

Figure 4. Accumulated annual rainfall (mm/year) for the period 1981-2010 (left) and rainfall change (mm/year) of the 2036-2065 period over 1981-2010 in the Brahmaputra-Meghna river basin (average values of the 4 RCMs used and for RCP 4.5).

The Mekong river basin follows a similar pattern to the one described for Ganges-Brahmaputra-Meghna river basin, both for the historical and projected climate although with some particularities (Figure 5 and Figure 6). Temperatures are more homogeneous, hovering between 27°C and 30°C year-round in the Delta, and between 20°C and 28°C in the Plains, with an **expected average increase of 1.4-2.4°C in the whole basin**. **Rainfall** is also **expected to increase for the Delta and Mountains, and precipitation to decrease for the mid-stream** regions of the Mekong basin by an average 50 to 100 mm per year by 2050.

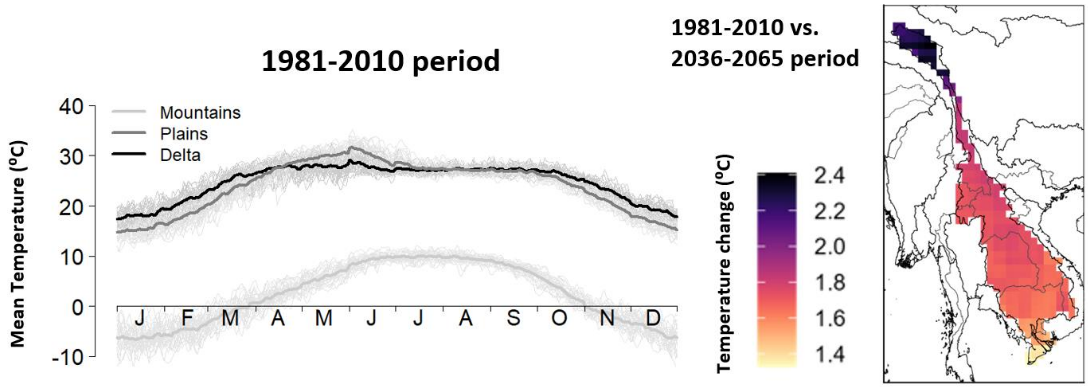

Figure 5. Mean annual cycles of temperature of the period 1981-2010 (left) and temperature change of the 2036-2065 period over 1981-2010 in the Mekong River basin (average values of the 4 GCMs used and for RCP 7.0).

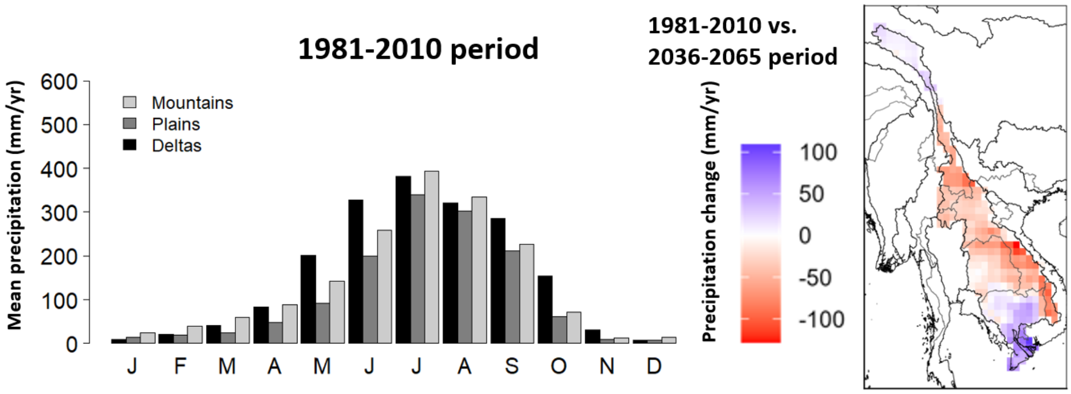

Figure 6. Accumulated annual rainfall (mm/year) for the period 1981-2010 (left) and rainfall change (mm/year) of the 2036-2065 period over 1981-2010 in the Brahmaputra-Meghna river basin (average values of the 4 GCMs used and for RCP 7.0). .

Historical and future water availability in the Deltas

Growing upstream water use impacts Delta's water inflows - up to 40% in the pre-monsoon season

In our modelling setup, the Ganges-Brahmaputra-Meghna delta has three inlet points, and the Mekong Delta has one inlet point for the (as it is shown in Figure 1). Through the comparison between the modelled historical and natural inflow (defined as the theoretical flow without any upstream water abstraction), we show that the water abstracted in the upstream plains of the Ganges-Brahmaputra-Meghna river basin produces a considerable reduction of the water inflow into the Delta of around 20% throughout most of the year (Figure 7). **The large impact is detected during the dry season, with monthly reductions of the actual inflow of 40-50% in comparison with the natural situation.** This period is characterised by a low water inflow into the Delta, due to a combination of water withdrawal from upstream users and low natural inflow. Opposite to this, the large upstream water abstraction during the monsoon period has only a minor effect on downstream users due to the large natural inflows. By 2050, an increase in upstream water withdrawal is also expected in the Ganges-Brahmaputra-Meghna basin. However, as shown in Figure 7, while the relative reduction in inflow will be higher, the increased rainfall in upstream areas is expected to lead to higher overall inflows. This will, in turn, enhance water availability for downstream users in the Delta. It is important to note that the reduction of inflow will have not only an impact in water availability for downstream users but also can affect water quality aspects (i.e. salinity).

In the Mekong River basin, upstream water abstraction reduces natural inflow into the Delta with an overall 10%, though **with large differences between the wet and dry seasons due to the impact of hydropower dam operations**. While during the dry seasons, the modelled actual flow is significantly higher than the natural one, it is the opposite during the monsoon season (Figure 7). In the future, the influence over the river dynamics is exacerbated due to the projected increase of the accumulated reservoir capacity in the upstream areas of the

Mekong river, with two potential consequences: during the dry season, more water can be available to meet water withdrawal for downstream users; during the wet season, the projected reduction of inflows into the Delta can have negative effects on the annual flooding around the Tonle Sap Lake and the Mekong River (Cambodia), vital for the region's ecology fisheries and replenishing of nutrients in the soil.

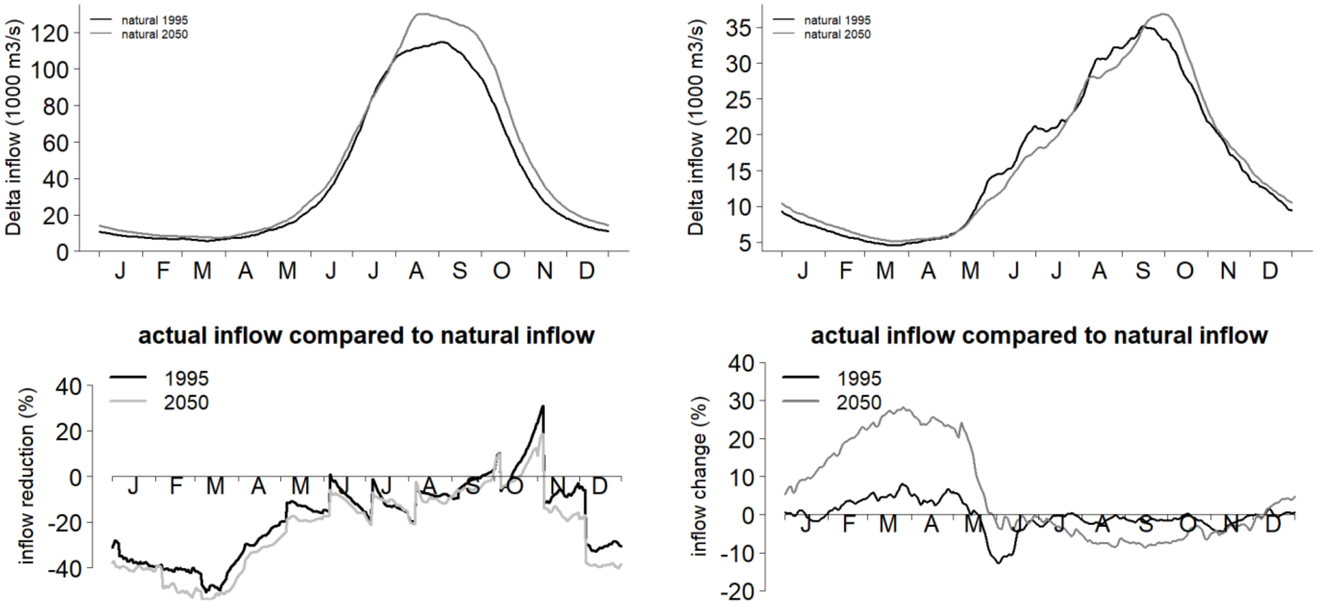

Figure 7. Simulations of actual and natural yearly water inflow into the delta's (m3/sec) (top) and inflow reduction (%) due to upstream developments (bottom) for the Ganges-Brahmaputra delta (left) and Mekong Delta (right) for the period 1981-2010 (1995) and 2035-2065 (2050) (modelled results from LPJmL).

Limited shifts in average monsoon onsets detected – interannual variability remains major challenge

Rice is a key crop both for the Ganges-Brahmaputra-Meghna and Mekong Deltas. Cultivation of rice requires a large amount of water during land preparation and sowing. Those practices are therefore linked with the beginning of the wet season (start of the monsoon), so any change in the monsoon onset can have large consequences in the planting dates for farmers with cascading negative impact on cropping system productivity. In order to understand whether potential changes in monsoon onset are expected in the future, an analysis of the interannual variability of inflow and rainfall in the Ganges-Brahmaputra-Meghna and Mekong Deltas for the historical and future situation has been performed. Our model predicts **no clear trend in shifting the beginning of the wet season (monsoon onset) for the period 2010-2070 has been detected for both basins**, neither for the inflow into the Delta or for the rainfall pattern (data only shown for Ganges-Brahmaputra-Meghna in Figure 8). From this analysis, it is also clear that in case of Ganges-Brahmaputra-Meghna, a clear growing trend of the expected peak discharge is projected. This increase of the peak discharge can be also detected for the Mekong delta (data not shown).

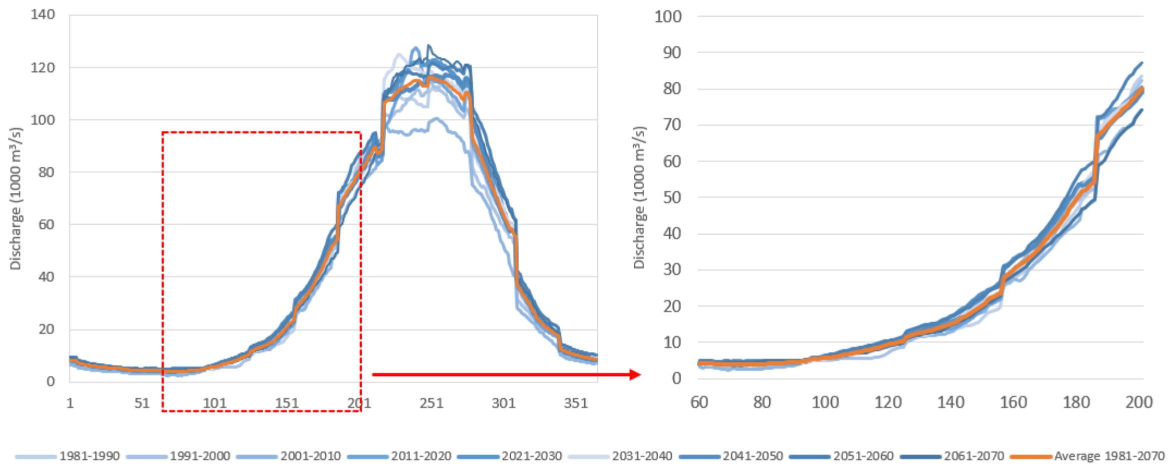

Figure 8. Interannual variability of modelled yearly water inflow (m3/sec) to the Ganges-Brahmaputra-Meghna delta for RCP 4.5 for the period 1981-2070. Average for the 4 climate models projection used, with average every 10 years in different colours (modelled results from LPJmL).

Current and future land use and crop production

The LPJmL model set-ups consider a total harvested area of 77.5 million ha and 17 million ha to crop production in the Ganges-Brahmaputra-Meghna and Mekong river basins respectively and constituting the largest land use type in each basin (Table 1). Lands managed under irrigation account for almost 52% and 42% of the total harvested area and are responsible for almost two third of the total food production in the entire basins. Both in the Ganges-Brahmaputra-Meghna and Mekong River basins, the Deltas play a major role as food baskets, producing roughly 13% and 29% of the total food production of each basin.

Table 1. Total area and production for the major crops in the Ganges Brahmaputra Meghna and Mekong river basins at country level for the period 1981-2010 and expected change on average yields from 1981-2010 to 2036-2065 period (modelled results from LPJmL).

	Country	Rainfed Area harvested (1000 ha)	Irrigated Area harvested (1000 ha)	Total Area harvested (1000 ha)	Change of harvested area 2050 (%)	Production (1000 tons)	Change of yield (%)
GBM river basin	*Upstream countries*						
	China	38	124	161	5.0%	166	0.1
	India	26,884	31,138	57,983	7.9%	125,819	-14.7
	Myanmar	3	1	4	-14.2%	7	-11
	Bangladesh	2,296	3,086	5,369	-14.4%	9,182	-7.1
	Nepal	2,302	1,539	3,865	-39.2%	7,413	-1.6
	Total (upstream countries)	**31,523**	**35,888**	**67,382**	**6.1%**	**142,587**	**-8.6**
	Delta	**5,667**	**4,708**	**10,375**	**4.8%**	**20,334**	**-6.8**
Mekong river basin	*Upstream countries*						
	Cambodia	2,325	641	2,966	-	8,720	19.5
	China	582	77	658	-	2,509	47
	Laos	865	400	1,265	-	7,144	0.5
	Myanmar	35	42	37	-	206	-0.7
	Thailand	4,634	1,946	6,580	-	27,630	1.2
	Vietnam	339	126	465	-	3,500	2.2
	Total (upstream countries)	**8,780**	**3,232**	**11,971**	**-**	**49,709**	**6.7**
	Delta	**749**	**4,258**	**5,007**	**-**	**50,355**	**10.8**

Note: for Mekong model set-up, i) land use change is considered constant; ii) yields are not calibrated against observed values.

Rice is by far the most common crop in both basins and their deltas, with around 27.6 million ha harvested in the GBM river basin (7.9 million in the Delta) and 12.7 million ha harvested in the Mekong River basin (4.7 million in the Delta). Temperate cereals and sugarcane are the second and third largest group for the Ganges-Brahmaputra-Meghna (tropical roots and sugarcane in the Delta), while tropical roots and maize are the second and third largest crops in the Mekong basin and its delta. As expected, yields modelled under irrigated systems are higher than those reported for rainfed, with an average 50-60% higher for crops managed under irrigated conditions.

The land use scenario used (IMAGE model) predicts an increase of the cropping area in the Ganges-Brahmaputra-Meghna, with special emphasis in irrigated lands, with expected increments of the total harvested area of 6.3% upstream and 4.8% in the delta. However, the projected yields in the GBM river basin are expected to decrease by 8.6% for the whole basin and 6.8% for the Delta, reducing total food production by -3% (Figure 9). The expected reduction on modelled yields in the Ganges-Brahmaputra-Meghna is probably due to the effects of temperature stress on crops, as well as the shorter crop growing season due to higher temperatures. It is important to note that the current model set-up does not consider any potential improvement on crops yields related with management factors or any other potential technological improvement, so modelled yield reduction is only related with the effects of climate and water.

The food production in the Mekong River basin, as opposed to the Ganges-Brahmaputra-Meghna, is projected to increase by 9%, due to a modelled increase of yields of 6.7% and 10.8% for the upstream areas and delta respectively. In this case, an increasing concentration of CO_2 has been considered (while area is constant), meaning that the fertilization effect of CO_2, increasing the rate of photosynthesis while limiting leaf transpiration, is larger than any potential decline due to temperature stress. This effect has been already assessed by Song et al., (2024), estimating that global rice production in the 2050s is expected to increase by 50.32 million tons (7.6%) due to the CO_2 fertilization effect compared with historical production. As we can see in the following section, this effect will have also important consequences in the crop water demand (water withdrawal).

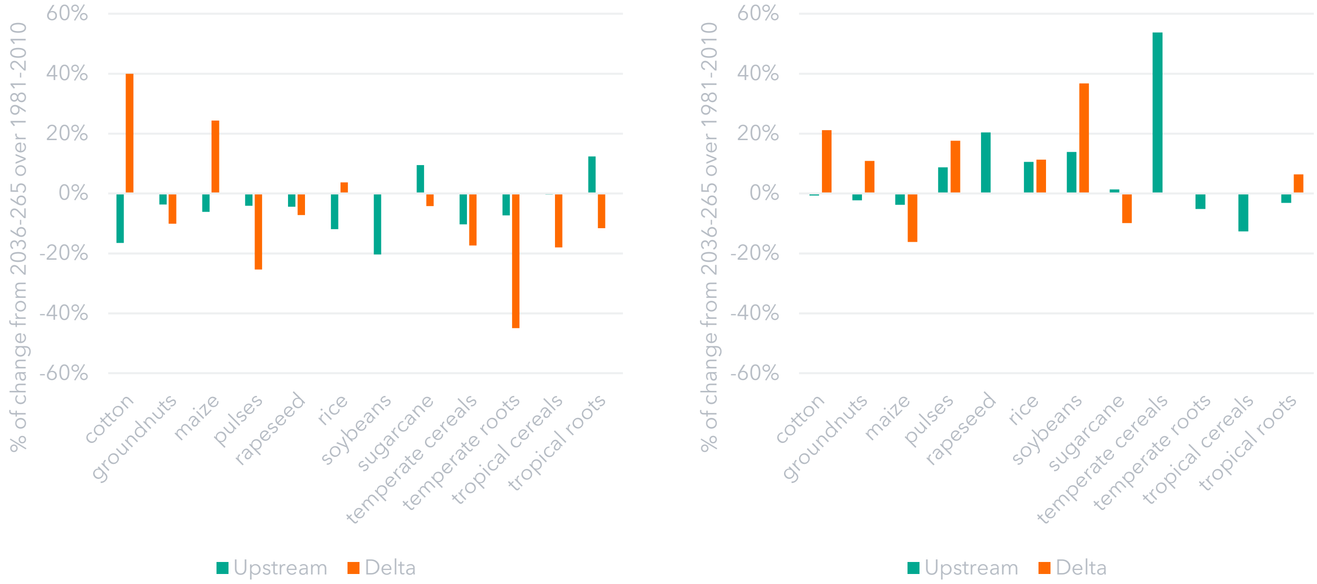

Figure 9. Change in food production (as % of change in the total dry matter) in the Ganges Brahmaputra Meghna (left) and Mekong (right) river basins and their deltas between 1981-2010 and 2036-2065 period (modelled results from LPJmL).

Current and future water demand

CO_2 fertilisation could substantially decrease total water demand by crops

LPJmL model simulates the water abstracted (withdrawal) and consumed by crops, as well as the source of water, either from rainfall or rivers and aquifers. Although rainfall is an important source of water used both by rainfed and irrigated crops, there are little actions farmers can take, other than those related to improve soil condition for water storage or some techniques related to rainwater harvesting. Blue water is therefore a key input for agriculture, allowing higher and more regular yields for irrigated crops. On the other hand, blue water resources are also demanded by other sectors, such as urban or industrial users, which in case of shortage, can enter in competition.

According to the model outputs, most of the water withdrawn[3] in the region is taking place in two specific moments of the year, from June to September and from November to March and coinciding with the two most relevant cropping seasons. In case of the Ganges-Brahmaputra-Meghna basin, the total water withdrawn from rivers and aquifers is estimated at 309 km^3/year (27.9 km^3/year in the Delta) for the period 1981-2010, with an expected reduction of almost 6% for the 2035-2065 period (1.3% in the Delta), due to a lower water demand during the initial months of the year (Figure 10).

In case of the Mekong basin, the total water withdrawal is estimated in 80.6 km^3/year (50.2 km^3/year in the Delta) for the period 1981-2010, but with an expected reduction of almost 24% for the 2035-2065 period (20% in the Delta). Considering that land use change has not been included in this model set-up, the reduction on the projected water withdrawal is only explained by the effect of CO_2 fertilisation. Higher CO_2 concentrations in the atmosphere would allow plants to reduce water losses per unit of carbon gain, increasing their water use efficiency (Swann et al., 2016). A similar result was reported by Elliott et al., (2014) through the comparison of six global crop models with and without the effect of CO_2 fertilisation, resulting in a projected decrease in global irrigation consumption on presently irrigated area from 8% to 15% by end of century.

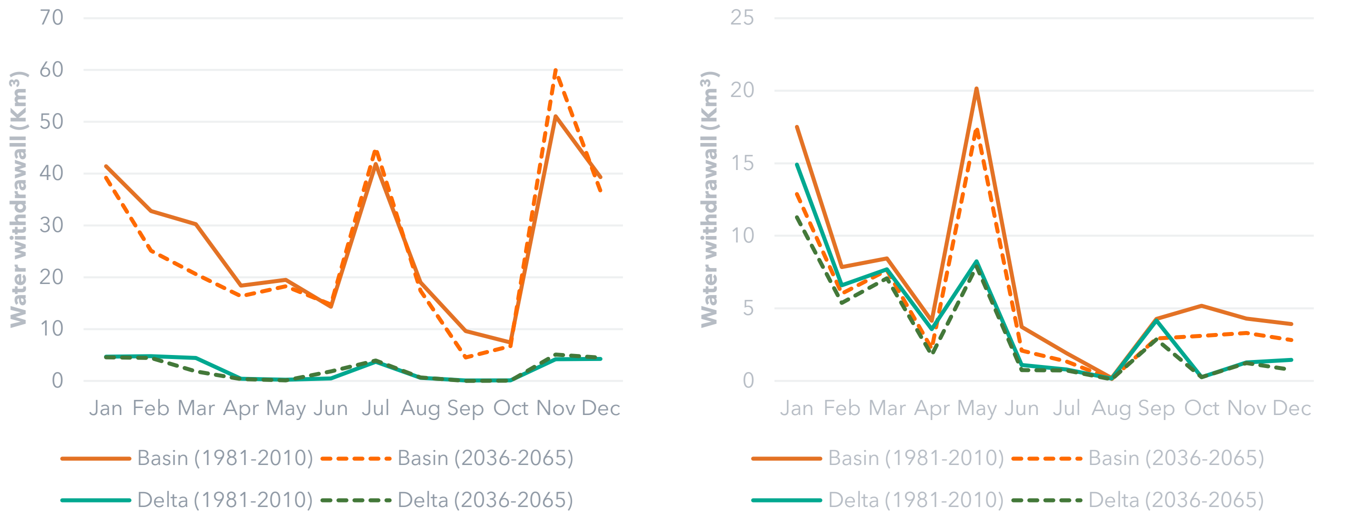

Figure 10. Water withdrawal in the Ganges Brahmaputra Meghna River basin and its delta (left) and Mekong river basin and its delta (right) for the periods 1981-2010 (solid lines) and 2036-2065 (dotted lines) (modelled results from LPJmL).

Expanding irrigation in the dry season most likely unsafe – wet season not affected

A water balance is the most suitable analysis to understand the relation between water availability and water demand, and therefore to determine if existing water resources can cope with the water requirements both in the historical situation and in the future. However, deltas are complex systems, where the interaction with the fluctuating sea level together with the difficulties to delineate the boundaries of the freshwater system, makes the estimation of water outflow difficult to assess. Nevertheless, a comparison between water inputs in the delta (inflow of rivers) and the water withdraw by crops on a monthly level can provide good insightful for water planning.

As it can be shown in Figure 11, the water inflow in the Deltas as modelled by LPJmL seems to be enough to cope with agricultural water demand during the whole year for both the Ganges-Brahmaputra-Meghna and Mekong deltas, thanks to the large inflows of water coming from upstream regions. In case of the Ganges-Brahmaputra-Meghna Delta, the annual water demand is around 2% of the total water inflow coming from upstream regions. In case of the Mekong, this value goes up to 10%.

However, once the monsoon retreats and the dry season starts (December to March), monthly water withdrawals can reach up to substantial fraction of the total water inflow in both deltas. This indicator, defined as the monthly upstream dependency ratio (similar to the monthly water stress defined by Pfister et at., (2014) can provide a better understanding of water scarcity that the annual figures.

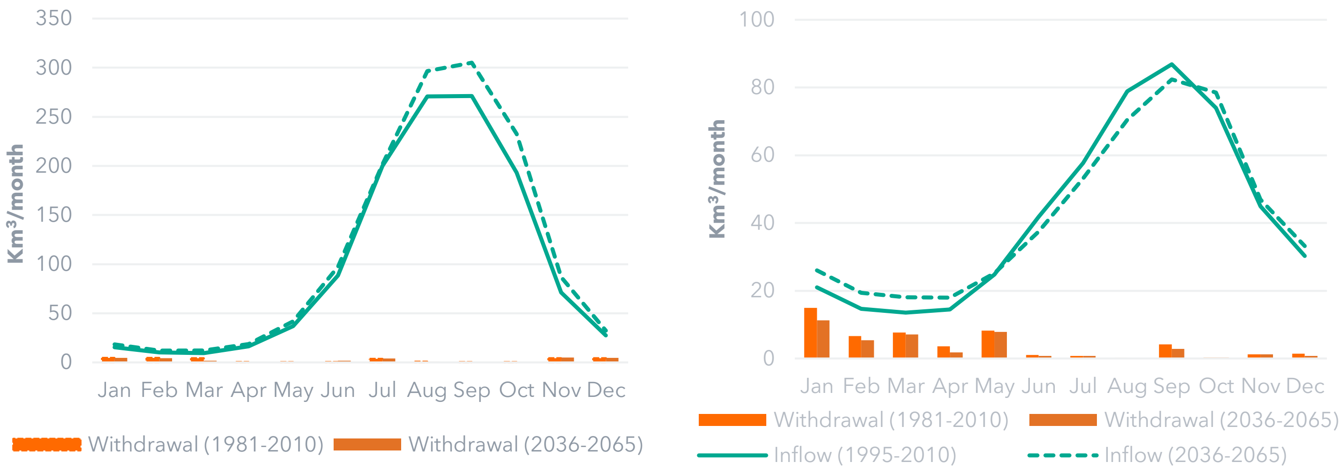

Figure 11. Water inflow and monthly water withdrawal for the Ganges-Brahmaputra-Meghna Delta (left) and Mekong Delta (right) for the period 1981-2010 and 2036-2065 (modelled results from LPJmL).

Thus, in the Ganges-Brahmaputra-Meghna delta (Figure 12), the upstream dependency ratios can go to almost 45% of the total monthly water inflow. Those values, already considered as a water stress condition, can be even higher if we consider the interannual variability associated to the river inflows during the dry season. This ratio can reach even 60-70% of the total inflow in case of dry years. When we look into the future situation, the water stress is expected to decrease, mainly because of a projected increase of the inflow. If we compare this situation with the natural inflow (theoretical inflow of the rivers without upstream water abstraction), we can see that the upstream dependency ratio decreases considerably during the dry season, with values ranging 20-25% and even lower for the future situation. Meaning that the water abstracted upstream from the Delta has a large influence in the water available during the dry season and increase the water stress situation of downstream users.

In case of the Mekong delta, a similar pattern is found, but with water withdrawal values reaching 70% of the total river inflow for several months of the year (January to May). The interannual variability make the situation even worst during dry years, with a modelled water withdrawal reaching almost 80-90% of the water inflow in the delta. This stress condition is expected to be reduced in the future due to the combined effect of an expected increase of water inflows and a reduction on the water withdrawal.

It is important to note that this analysis doesn't consider other water sources of the Delta, such as internal runoff or groundwater. Although this cannot be considered as a detailed water stress analysis, it already shows the high dependency of the Ganges-Brahmaputra-Meghna delta on upstream water resources and its vulnerability on future developments. The water stress conditions underpinned that several portions in the deltas can be subjected to increasing water shortages during the dry season.

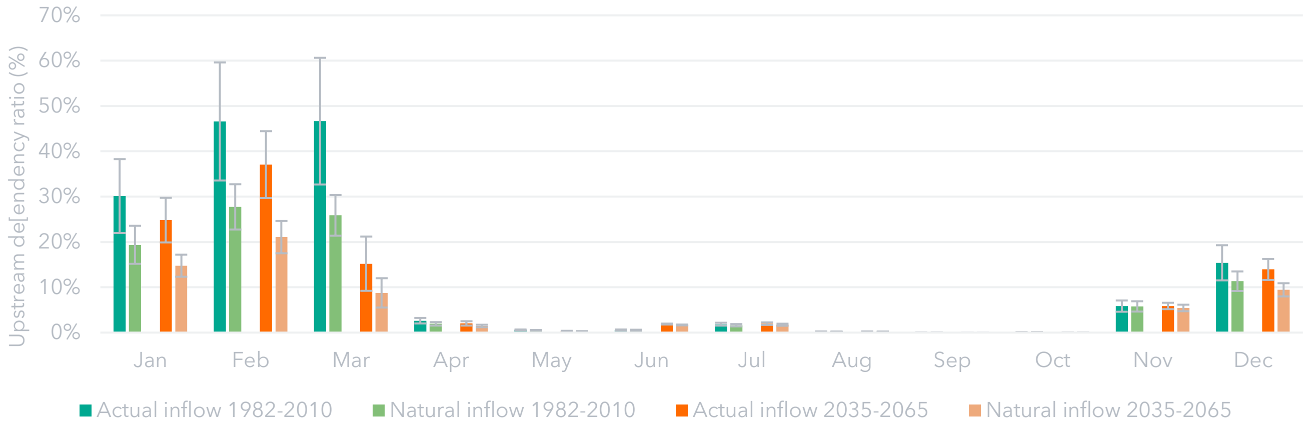

Figure 12. Monthly water upstream dependency ratio in the Ganges-Brahmaputra-Meghna delta, defined as the relation between water withdrawal and water inflow into the Delta from upstream regions for the period 1981-2010 and 2036-2065 under actual and natural flow. Modelled results from LPJmL). Error bar is defined as one standard deviation for the annual monthly river inflow.

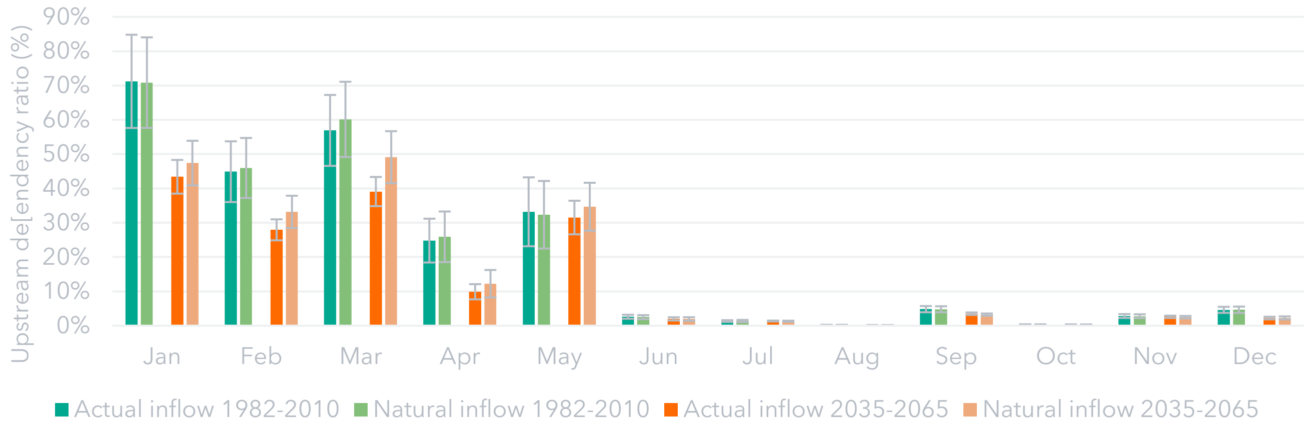

Figure 13. Monthly water upstream dependency ratio in the Mekong delta, defined as the relation between water withdrawal and water inflow into the Delta from upstream regions for the period 1981-2010 and 2036-2065 under actual and natural flow. Modelled results from LPJmL). Error bar is defined as one standard deviation for the annual monthly river inflow.

Key learnings

This section presents a summary of the findings of our study on the impact of upstream irrigation water abstraction and climate change on the water and food availability in the GBM and Mekong Deltas.

Climate and water availability

- According to the climate scenarios and climate models used as input for LPJmL:
    - An increase temperature is expected in both basins, especially **in pre-monsoon season, as average monthly temperature are set to increase 1.2-2.4°C**. The plains areas of India and the mountainous region are the ones most subjected to the temperature increase.
    - An increase in the monthly rainfall both in mountainous regions and deltas is also expected, likely affecting water availability for downstream users. Further information regarding (uncertainty in the) timing of the rainfall needs to be investigated.

- Water inflow at the two deltas is highly influenced by rainfall patterns, but also by upstream developments, although on a different manner:
    - In case of the Ganges-Brahmaputra-Meghna delta, the relation between the natural and actual inflow is particularly affected during the dry season, where upstream water abstraction can suppose a reduction of the natural inflow of almost 30-40%, both in the historical and future situation.
    - In case of the Mekong delta, the water inflow is clearly marked by the operation of hydropower dams and their effects intensified in the future; during the dry season, the projected actual inflow is higher than the natural, improving downstream water availability; during the Monsoon, a large reduction of actual inflow is projected, which could has an influence on the seasonal flooding of downstream floodplains of Cambodia.

- The analysis of the interannual variability did not reflect any clear trend in water availability (discharge or rainfall) that could have a significant effect on shifting the planting dates for farmers. However, the projections assessed report a continuous increase in water discharge, both in the total and peak discharge of the hydrograph, which fits well with the projected increase of rainfall over the upstream regions.

Food production and water use for agriculture

- As expected, modelled yields of irrigated crops are higher than rainfed. Irrigated crops produce almost two-thirds of the total food production in both basins, highlighting the importance of irrigation for food security in the region, but also globally, given the fact that both basins are the largest rice exporters.

- Water demand is distributed over the year, with two clear peaks in June-August (wet season) and December-February (dry season), both coinciding with the water demand for rice planting and cultivation. Water abstraction during dry seasons is generally higher than during the wet season largely to due higher evaporative demand during this time.

- Historical and future water availability in the deltas, if other water uses are not considered, appears to be sufficient to satisfy agricultural water demand for both the Ganges-Brahmaputra-Meghna and Mekong deltas, due to the large inflows of water coming from upstream regions. When the figures of historical and future water withdrawal reported by LPJmL are compared with the modelled water inflow at the inlet of the Deltas (also called as upstream dependency ratio), they represent less than 2.3% in case of the GBM and 10% in case of the Mekong.

- However, during the dry season, water withdrawal can reach 45-50% of the total water inflow in case of the Ganges-Brahmaputra-Meghna and 70% in case of Mekong. This can be exacerbated if we consider the interannual variability associated with the water inflows after the Monsoon retreats, causing occasionally or even recurrently water shortages and impacting competition amongst different water users including natural ecosystems.

The 5 min resolution LPJmL model set-up: improvements, potential limitations and next steps

The current LPJmL 5 min resolution provides clear advantaged with the global model-set-up, when regional analysis is performed. However, it is still not free from certain required updates and improvements.

- Modelled food production and water use by LPJmL is largely affected by the particularities of the model set-up as well as the inputs used, as it is depicted in Table 2. Thus:
    - LPJmL can model future food production and water withdrawal based on the land use change scenarios provided by the IMAGE model framework. The IMAGE scenarios aim to fulfil the demand for production, and this is mainly driven by continued population and per capita income (GDP) growth up to 2050. Global land use change scenarios should be carefully validated when they are used to subregional scales, especially in already populated areas such as the deltas, where expansion of agricultural lands is unlikely.
    - When assessing water demand for future periods, it is difficult to elucidate which is the factor affecting the future water demand the most. However, CO_2 fertilization can have a major effect on crop water demand (and production), likely increasing yields and reducing the irrigation needs even in case of temperature increase. Other factors include the reduction in growing periods that can negatively affect yield in the absence of varietal adaptation.

Table 2. Inputs and particularities of the model set-up for GBM and Mekong River basin.

Input	GBM	Mekong	Effect
Climate models	Regional RCP4.5 from CMIP5 and bias-corrected in HI-AWARE project	Global SSP3 7.0 from CMIP6 and bias-corrected in ISIMIP3b project	Higher temperatures in the future for the Mekong basin compared to GBM. The range of precipitation is higher in the GBM with more increase of precipitation. In Mekong there are large areas midstream with a decrease of precipitation
Agricultural area increase	Irrigated area increase, rainfed area decreases	Both irrigated and rainfed area are constant	Increase or decrease of areas results in increase or decrease of production. Irrigated fields have often higher yields and therefore an increase of irrigated area and decrease of rainfed area increases yields.
CO_2	CO_2 is kept constant at 2000 level	CO_2 is increasing following RCP7.0 projection	An increase of CO_2 results in CO_2 fertilization in the Mekong, which increase the yield.
Calibration	The yields in GBM are calibrated using subnational agricultural statistics	The yields in the Mekong are not (yet) calibrated	The production in the Mekong is overestimated because they are not calibrated yet, while the yields in the GBM are calibrated. Therefore, trends are more reliable to analyze than absolute yields.
Reservoirs	Dynamic Increase of reservoirs (GRanD database)	Dynamic increase of reservoirs (GDW database)	A large increase in reservoir capacity in recent decennia in the Mekong basin, affecting water availability in downstream areas

- The introduction of double, and event triple cropping system improve the accuracy of water demand by crops, not only in total water abstracted, but in the annual distribution. As it is show in Figure 14, the global model set-up, characterised by a single season, brings most of water withdrawal during the months of June-August, coinciding with the wet season (more water available). While the 5 min resolution model set-up distributes better water withdrawal over the year, with two clear peaks of water demand, one during the wet season (June-August) but the other during the dry season (November-March). Meaning that the 5 min model set-up not only reflect much accurate the reality in the region, characterised by a two/three crop seasons, but allow a better comparison of the monthly water stress.

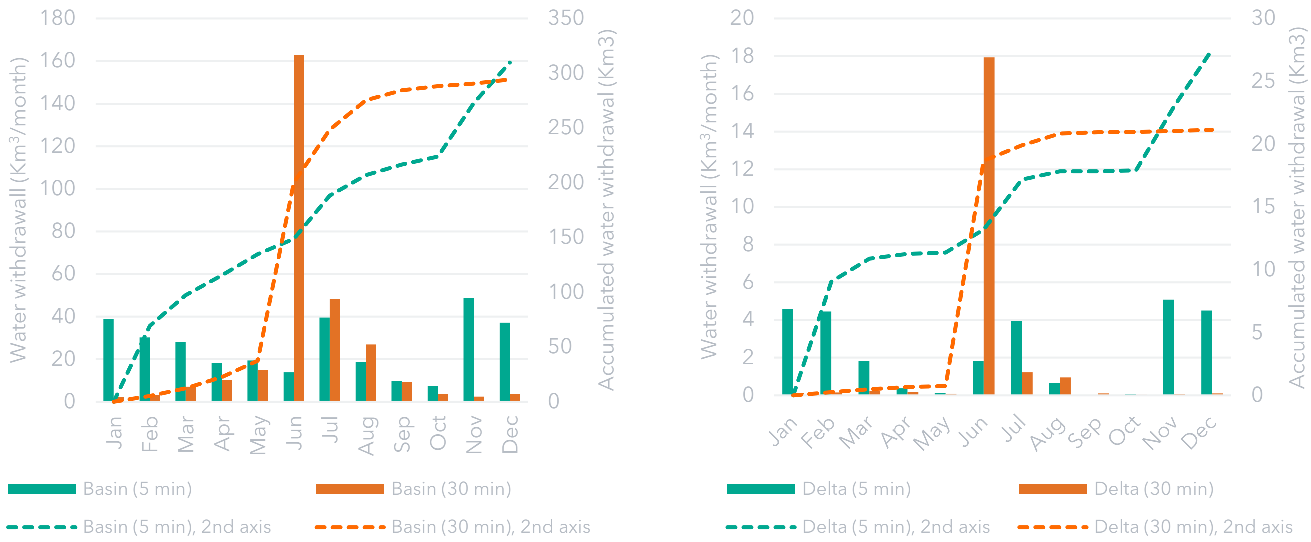

Figure 14. Monthly and accumulated water withdrawal for the 5 min resolution and 30 min resolution LPJmL model set-up, for the GBM basin (left) and its Delta (right) in the 1981-2010 period.

- It should be noted that urban expansion is not part of the LPJmL modelling set-up and is an important factor of change to be considered in assessing future agricultural production, especially in the Delta of the Ganges Brahmaputra Meghna Basin. The LPJmL model also does not account for other significant agricultural sectors, such as vegetable production, aquaculture, or livestock, despite their substantial contributions to food security and their significant impact on water demand in some geographies, nor does it account dietary changes, and therefore changing demand for crops.
- LPJmL consider surface water as the preliminary source, shifting to groundwater only when surface water is not sufficient to meet crop water demands, with the general assumptions that farmers have access to it. This can overestimate groundwater extraction in areas where infrastructure is not available, but provides an good overview of the trends in water use.
- To have a better understanding of the suitability of LPJmL results to the studied area, the current LPJmL outputs should be compared with observations and other similar studies. To do so, a comparison with other authors, such as Yu et al. (2010), is recommended.

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Annex I. The LPJmL Model set-up

For a assessment of the effects of climate change on a series of quantitative indicators related to water and food security in the Mekong river basin and Ganges-Brahmaputra-Meghna (GBM) basin, we have used a LPJmL model set-ups already implemented from previous exercises for the GBM basin (Biemans et al., 2023). For the Mekong basin a new version of the model set-up was developed. Both model set-up versions had a 5min resolution. In both cases, the core of LPJmL model is the same, however, some differences can be found. The general set-up of the model is described in the following section (The Model). Next, two sections with a short elaboration on the specific case studies can be found also found (Ganges-Brahmaputra-Meghna basin set-up and Mekong basin set-up).

The Model

To assess the effects of climate change on a series of quantitative indicators related to water and food security, we used the Lund Potsdam Jena managed Land model (LPJmL) (Schaphoff et al., 2018). LPJmL is designed to simulate vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems. This makes the model a very suitable tool to study the interactions between water (availability and demand) and food production in the actual and future situation. A comprehensive description of the core of LPJmL model, including equations and parameters, can be found in Schaphoff et al., (2018), and the changes made to tailor the model to South Asian hydrology and agriculture in Biemans et al., (2019). In the forthcoming sections, we provide a broad overview of the model's key features used for this study. It is important to note that the present study is mainly focused on the relations between water and food production, so the main features described are the ones related with the water balance, crop functions and land use. Additionally, we describe the features that have been added or updated for this particular study, even if the results were not explicitly reported, including: a groundwater module to simulate groundwater withdrawals and groundwater depletion rates; dynamic crop management factors to account for future increases in yield related to better technology (global model); and double cropping to simulate the complex pattern of water demand in an intensive agricultural system (South Asia model).

i. Performing the water balance assessment

The water balance is one of the key elements of LPJmL, as there are multiple interactions between available water and vegetation (natural and crops) which are: plant transpiration and carbon uptake (photosynthesis); regulation of plant growth and productivity according to soil water limitations; effects of vegetation (type, distribution, stage) on the soil water balance (evaporation, transpiration, infiltration, run-off or soil moisture); and the effects of human interventions through irrigation and water abstraction.

LPJmL performs a daily soil water balance at sub-grid scale, dividing the soil column into five hydrological active layers (0.2, 0.3, 0.5, 1, and 1 m thickness), where hydraulic soil properties are assigned to each layer (i.e. water holding capacity and hydraulic conductivity) from the Harmonized World Soil Database (Nachtergaele et al., 2023). Water enters in the system either by precipitation or irrigation and is diverted into surface runoff and infiltration in the soil. Subsequently, the infiltrated water percolates through the soil depending on the current soil water content of the first layer, or percolate to lower levels when soil water content of the above layer exceeds saturation. Percolation through the soil layers is calculated by the storage routine technique (Arnold et al., 1990), according to the hydraulic soil properties, and limited by the soil moisture of the lower layer.

Water evaporates from the soil as a combination of three components: 1. Evaporation from (bare)soils according to the available energy for the vaporization of water, and considering as evaporation-available soil water the volume of water above the wilting point of the upper layer and one-third of the second layer (first 20 cm of soil), so capillary rise is partially included; 2. Evaporation of intercepted rainfall from the canopy, limited either by potential evapotranspiration (Priestley and Taylor, 1972) or the amount of intercepted rainfall (Gerten et al., 2004); and 3. Plant transpiration through leaf stomata, according to functions of lesser of plant-available soil water supply and atmospheric evaporative demand, following Federer (1990).

Excess water over the saturation level percolates to the groundwater and eventually contributes to baseflow. LPJmL incorporates a river routine to simulate daily discharge of water in the river channels by i) calculating the total amount of runoff generated for each grid cell as the sum of surface runoff, subsurface runoff and baseflow, and ii) routing the total runoff downstream along a river network with a constant flow velocity of 1 m/s (Wijngaard et al., 2018). The impact of large reservoirs on streamflow and irrigation water supply is simulated by a simple generic reservoir operation scheme, in which different operating rules are implemented for irrigation reservoirs and reservoirs with other purposes such as hydropower production (Biemans et al., 2011a). The irrigated areas that can get water from irrigation reservoirs are assigned based on elevation and distance to the reservoir.

ii. Irrigation

When the water demand of irrigated crops is not met by the available water in the soil, irrigation takes place. The daily net irrigation water requirement is based on the soil water deficit. When root-available soil water goes below a specific threshold (tolerable soil water depletion to avoid water limitation of crops), irrigation is required. The net daily irrigation demand for each crop is determined by calculating the minimum of the water required to saturate the upper soil to field capacity and meet atmospheric demand. Up to this, gross irrigation demand (withdrawal demand) accounts for water lost during conveyance, distribution, and application of irrigation water, and depends on the irrigation technology used (surface, sprinkler, or drip) and soil properties (Jägermeyr et al., 2015). Water that is not consumed (evapotranspiration by crops or direct evaporation during conveyance, distribution, and application) will recharge groundwater or discharge as return flow to the river. Irrigation only takes place between the sowing and harvesting periods. In this study, we assume that all irrigated crops of the two project areas rely on flood irrigation and that the fractions under sprinkler or drip irrigation are negligible (AQUASTAT; FAO, 2016).

The primary source for irrigation is surface water. This is the water available in the river section and natural lakes of the cell where the irrigated crops are located, or a neighbouring upstream cell with higher water availability. If there is an artificial reservoir for irrigation supply accessible for the irrigated fields, water can also be withdrawn from these reservoirs. In cases where the irrigation demand exceeds the available surface water, groundwater available is withdrawn, potentially leading to overexploitation and depletion when groundwater withdrawal exceeds recharge (more details below).

iii. Management of dams and reservoirs

The operation of large reservoirs influences seasonal river discharge patterns and the water locally available for irrigation (Biemans et al., 2011a)(Biemans et al., 2011a). The reservoir is filled on a daily time step, with discharge from upstream locations and local precipitation. At the start of an operational year (defined as the first month when mean monthly inflow falls below the mean annual inflow), the reservoir's actual storage is compared to its maximum capacity. A target release is established based on the reservoir's primary purpose, with dams built primarily for irrigation releasing water proportionally to downstream gross irrigation demand. Reservoirs designed for other purposes (e.g., hydropower, flood control) are assumed to release a constant water volume throughout the year.

The actual release from a reservoir is simulated depending on its storage capacity and relative to its inflow. If the reservoir is used for irrigation, a portion of the outflow is diverted to irrigated lands downstream. Cells receive water from reservoirs if they are at a lower altitude than the reservoir-containing cell and are situated along the main river segment downstream or a maximum of five cells upstream. Therefore, a cell may receive water from multiple reservoirs. Since irrigation demands fluctuate daily, water released from reservoirs can be stored in the conveyance system for up to five days. If the total irrigation water demand cannot be met, all requesting fields receive the same fraction of their demand (Biemans et al., 2011a) and groundwater for irrigation comes into play.

iv. Groundwater extraction rate

Groundwater is a very important source of irrigation globally. In order to better estimate it, but also to define how sustainable it is used, we have introduced a simple groundwater module to estimate depletion rates. Water percolated through the lower layer is stored in each cell as daily groundwater recharge and contributing to base flow. A linear reservoir algorithm with an average residence time of 100 days controls the base flow of the grid cell as in Alcamo et al. (2003). However, this groundwater can also be extracted for irrigation if surface water is not enough to meet crop water demand of irrigated crops. We assume that groundwater withdrawals are used in the same location of extraction, so no conveyance losses are computed. When long term groundwater withdrawals exceed the recharge, groundwater tables drop too far to contribute to base flow, withdrawals are unsustainable and lead to depletion as in Wada et al., (2010).

v. Crop growth

LPJmL simulates the growth of a total of 12 different annual crop functional types (CFTs). CTFs are parameterized as one specific crop, but represent a broader group of similar crops (i.e. wheat as representative of temperate cereals). Rain fed and irrigated crop growth is simulated based on daily assimilation of carbon in four pools: leaves, stems, roots and harvestable storage organs. The amount of carbon allocated to those pools depends on crop phenology (accumulation of growing degree days) and is adjusted in case of water deficit for the plants. The latter is considered as the ratio between accumulated daily transpiration and accumulated daily water demand since planting. Crops are harvested when either maturity or the maximum number of growing days is reached (Bondeau et al., 2007). At harvest, storage organs are collected from the field and crop residues can be left on the field or removed, although in any case, a fraction of 10% of the aboveground biomass is assumed to remain on the field as stubbles.

vi. Land use

The LPJmL model simulates the dynamics of land use, and its interactions with vegetation and climate, by dividing grid cells into fractions of different crops and natural vegetation (defined as stands). The size of each stand is defined by the input data, through the prescription of fractions, which also has specific characteristics and management practices. In case of crop lands, a distinction between rainfed and irrigated cultivation is done, considering crops as monocultures within the stand, where only one irrigation system can be selected.

Ganges-Brahmaputra-Meghna basin set-up

For the GBM basin a downscaled 5min resolution model set-up previously developed by Biemans et al. (2019) was used. Table A.1 shows the main input for the model for the GBM basin. This version simulates a double-cropping system, distinguishing between monsoon-season crops (the kharif season) and winter-season crops (rabi season). Moreover, it includes a representation of canal systems, which can deliver water over hundreds of kilometres, in LPJmL to be able to simulate this important means of water supply. Initially, the key irrigation canal systems within the Indus, Ganges, and Brahmaputra River basins were identified and mapped. These canals were then linked to their respective command area inlet points along the main river. Water extraction for irrigation was modelled at these inlet points, with the flow directed to supply water to the irrigated fields located downstream within the command area.

The results in this project were based on existing output from the study of Biemans et al. (2019). This output includes a future outlook for the scenario RCP4.5 from the study of Lutz et al. (2016) The names of these models are BNU-ESM_r1i1p1, inmcm4_r1i1p1, CMCC-CMS_r1i1p1 and CSIRO-Mk3-6-0_r4i1p1. Crop yields have been calibrated at country level against subnational statistics in South Asia. The calibration is done by varying three coupled parameters that represent management intensity: maximum leaf area index, maximum harvest index and a parameter to scale leaf-level biomass production to grid level.

Table A.3 – input data for the LPJmL set-up of the GBM basin

Input data	**Source**
Land use	MIRCA2000 (Portmann et al., 2010b)
Cropping calendars	Biemans et al. 2016
Dams & reservoirs	Global Reservoirs and Dams database (Lehner et al., 2011a)
Irrigation canals	Biemans et al. 2019
Climate (temperature, precipitation and radiation)	Bias-corrected and downscaled RCP4.5 from CMIP5 (Lutz et al., 2016b)

However, the outputs of the existing GBM model set-up did not cover the whole delta and a large part of the western delta, which contains more than 50% of the agricultural production, was not considered. For example, when looking into the data of the existing model set-up, more than half of the harvested area of irrigated- and rainfed rice is located in this area (Figure A.1). Therefore, another LPJmL simulation including India was taken as a baseline, which had the same area and production for the eastern part of the delta, but also include the missing western area of the delta. But this simulation did not contain future projections, only historical. To include the missing area for the future, we assumed that the effect of climate change and socio-economic developments is the same in the whole delta, so the projection done for the eastern part of the Delta was also extrapolated to the missing western part. This means for example, that if towards the future the area with rice harvest increases in the eastern part with 5%over the baseline situation, that the same will happen in the western missing part. The same accounts for yield increase and water withdrawal.

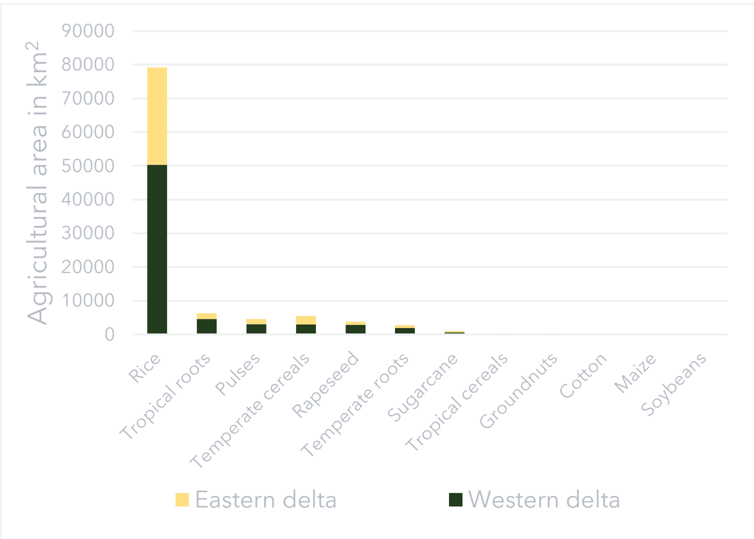

Figure A.15. Agricultural area division between the eastern and western part of the GBM delta in the period 1981-2010.

Mekong basin set-up

For the Mekong basin, a completely new downscaled 5min resolution model was developed in this project. The updated datasets that were used in this model are shown in Table A.2. The climate data that was used for the historic period is WFDE5 (Cucchi et al., 2020). For the future outlook the SSP370 scenario was used including five climate models GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL (Hempel et al., 2013; Lange. ,2021).

Table A.4 – Input data for the LPJmL set-up of the Mekong basin

Input data	Dataset
Land use	MAPSPAM2020 (IFPRI, 2024)
Cropping calendars	MIRCA-OS (Kebede et al., 2024)
Dams & reservoirs	Global Dam Watch (Lehner et al., 2024a)
Irrigation canals	Garmin and OpenStreetMap
Climate (temperature, precipitation and radiation)	WFDE5 (historical) and ISMIP3b SSP370 (future)

This developed model set-up version includes, similar to the GBM version, a detailed distribution of the irrigation canals for the delta. Spatial information about the location of these canals were taken from Garmin and OpenStreetMap. The canals were subsequently connected to the inlet points serving their respective command areas along the main river. At these inlet points, water was extracted for irrigation and directed to irrigated fields downstream within the command area.

To show the correct water withdrawal trend through the year, double cropping was also implemented in the model. For the Mekong basin, the most important crop with more than one sowing date per year is rice. Double cropping, and sometimes triple cropping, was included in this model version by creating three different land use input files. These were based on the cropping calendars of MIRCA-OS (Kebede et al., 2024) and spatially divided over the area with the crop fractions taken from MAPSPAM2020 (IFPRI, 2024). These cropping calendars included different growing periods for irrigated and rainfed rice. To get to the results, the model simulated the Mekong basin three times, with the three different land use input files.

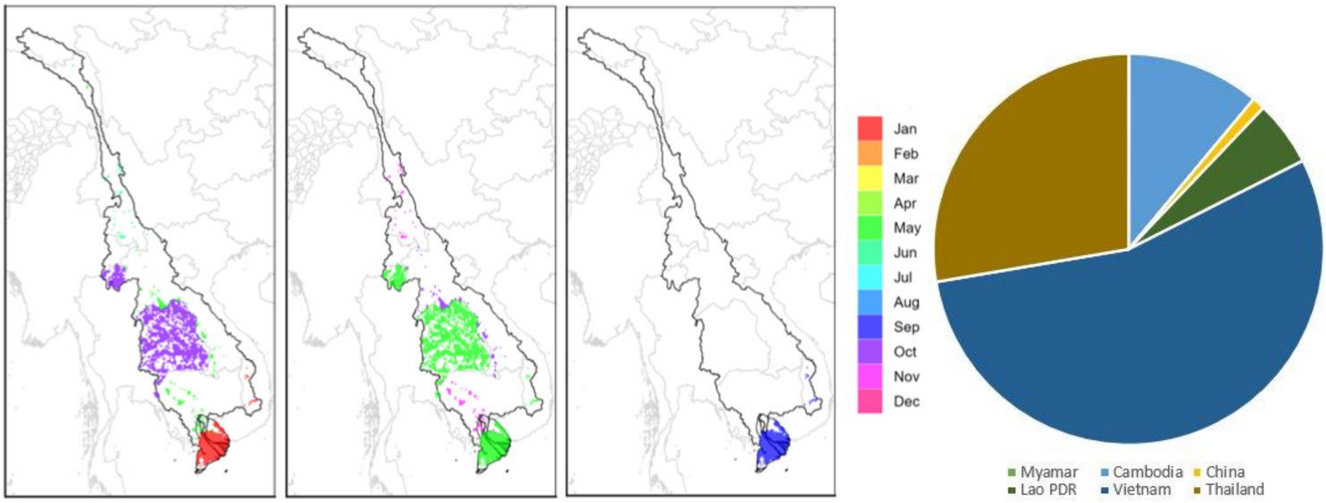

Figure A.2. Distribution of sowing months of rice in the countries in the Mekong basin according to MIRCA-OS and contribution to the total agricultural area of rice per country.

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