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# The regional hydrological impact of farm-scale water saving measures in the eastern Gangetic plains

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## Important disclaimer

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# Executive summary

Agricultural development from Pakistan to Bangladesh in the Indo-Gangetic Plains, particularly the rise of dry season irrigated agriculture, has led to concerns over falling groundwater tables and the implied unsustainable use of groundwater. The Eastern Gangetic Plains (comprising approximately the Indian states of Uttar Pradesh, Bihar and West Bengal, plus northwest Bangladesh) has thus far seen less development of dry season irrigation, apart from some areas of northwest Bangladesh. However, increased population and increasing demands for food in the region are likely to see increased intensification of agriculture and more use of irrigation. The obvious concern is that the experience elsewhere in the region will be repeated.

One potential remedy for combatting the unsustainable use of groundwater is to use conservation agriculture techniques, which promote water saving. But does this really save water at the regional scale? We combined literature review and desktop studies in a scoping study to examine this question.

We review knowledge and knowledge gaps in the impact of conservation agriculture and farm-scale water saving measures on regional hydrology. There is a large body of literature showing the benefits of conservation agriculture in building up the soil and making crop water use more effective. However, more effective water use at the crop scale does not necessarily translate into water savings at the regional scale. Indeed, more effective use at the farm scale may reduce the cost of irrigation and lead to greater use.

At the farm scale, field case studies in the Eastern Gangetic Plains show that more efficient application of water can result in less water applied, and farm profitability can be improved particularly through the intensification of cropping. From a farmer's point of view this is more sustainable than a traditional system. Crop water use modelling also indicates that farm profitability can be improved, but more efficient water application does not necessarily reduce crop evapotranspiration. Indeed, increased productivity of a well-managed conservation agriculture system might lead to greater crop transpiration; in the case of Boro rice, a conservation agriculture system with no puddling might require greater water application than a traditional Boro system. Again, this leads to questioning of the extent to which water saving measures at the farm scale lead to water saving at the regional scale.

In a desk study of the regional water balance in several districts of the Eastern Gangetic Plains, we show that there is a large excess of rain over potential evapotranspiration in the northeastern parts of the region, and the actual evapotranspiration is likely to be close to the potential. Conversely, there is a large deficit of rain to satisfy the evapotranspiration demand in the southwestern parts. This suggests that incentive to save water at the farm scale is likely to be limited in the northeast, but significant in the southwestern parts. Furthermore, the impact of any water saving on the regional hydrology is likely to be more limited in the northeast and greater in the southwest.

Groundwater use and temporal trends in groundwater levels vary across the region. There is considerable use of groundwater in northwestern Bangladesh, and use may have reached a potential maximum. There may be opportunity to use more groundwater in the Terai region of Nepal. However, there are several confounding factors in the interpretation of groundwater trends, including the lack of reliable estimates of groundwater use. We discuss examples of large-scale estimates of evapotranspiration using remote sensing techniques, and show that they could help resolve some of the uncertainties in regional water balances and the interpretation of groundwater trends.

A comprehensive understanding of the EGP's groundwater resources and their future sustainability linking farm scale activities with the regional or basin scale modelling is needed to underpin sustainable use.

# 1 Introduction

The Indo-Gangetic Plain (IGP) hosting over 750 million people encompasses more than 250 Mha[1] across Bangladesh, India, Pakistan and southern Nepal, including over 100 Mha of agricultural land (Fendorf and Benner, 2016). The Lower Gangetic Plain, forming the eastern part of the IGP and known as the Eastern Gangetic Plain (EGP) (Figure 1), is one of the most important agricultural eco-regions in the world (Timsina and Connor, 2001).

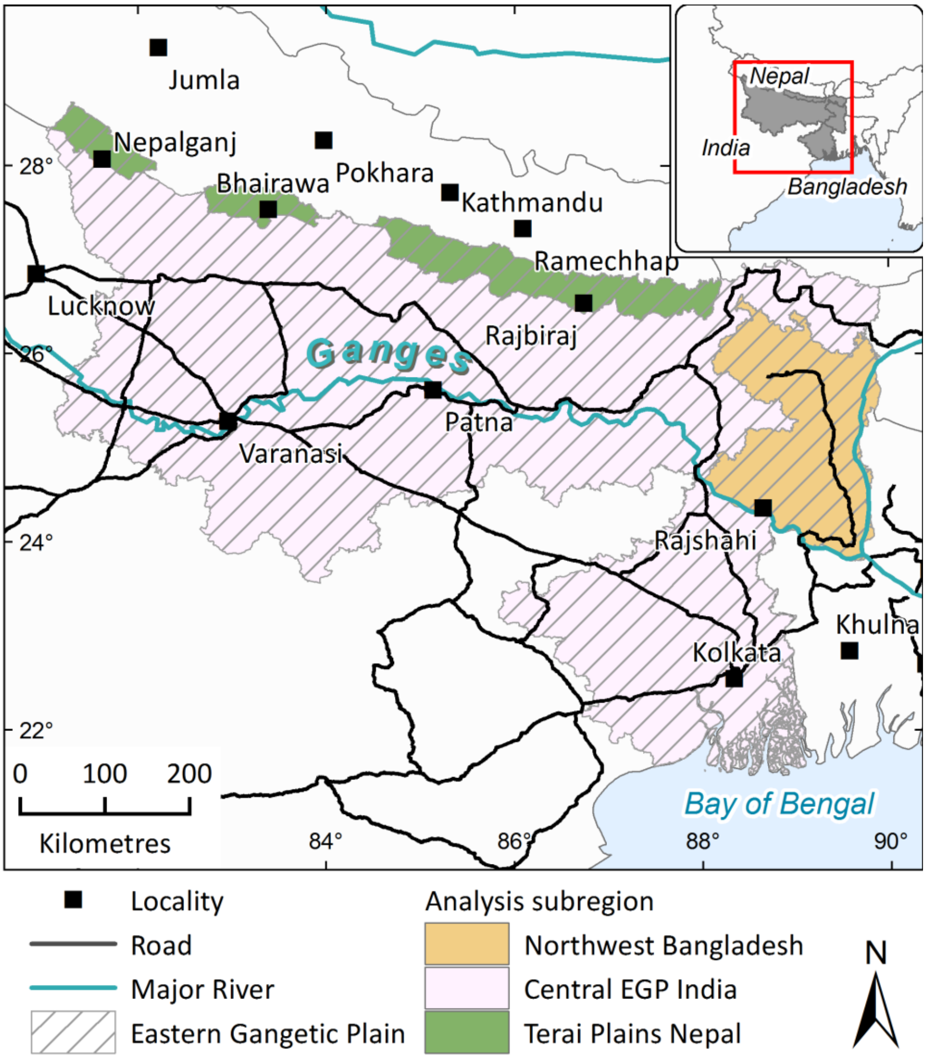


Figure 1. Map showing the Eastern Gangetic Plain (EGP).

The region plays an important role in providing livelihood to millions of people (Timsina and Connor, 2001; Humphreys and Gaydon, 2015a; Subash et al., 2015) from its dominant rice–wheat cropping

[1] This number was given in the Nature Geoscience paper (Fendorf and Benner, 2016). Wikipedia also gives 250 Mha, but this may not be right. The area of the Indus basin is 1.17 M $km^2$, and the Ganges basin is 1.73 M $km^2$. Combined they are 2.9 M $km^2$ or 290 Mha. After subtracting the mountainous areas in the north, and the plateau portions of the southern Ganges basin, then the plains adds up to maybe 1.5 M $km^2$ or 150 Mha.

system. The rice–wheat cropping system occupies approximately 13.5 Mha of land extending across the IGP and covering 2.2 Mha in Pakistan, 10.5 Mha in India, 0.8 Mha in Bangladesh and 0.5 Mha in Nepal. Rice production will need to increase further with the growth of population. For example, Bangladesh will need 39 million tons of rice by 2030 (Amarasinghe et al., 2014) and 44.6 million tons by 2050 (Kabir et al., 2015) against its current production of 34 million tons (BBS, 2018). Boro rice is produced in dry season (October–March) under irrigated conditions. It alone contributes more than half (55 %) of total rice production (Rahman and Parvin, 2009; Mainuddin et al., 2019a) and contributes enormously in food security of the country (Mainuddin and Kirby, 2015).

There are many challenges to implement necessary interventions to increase food production in the EGP. The major challenges include a shrinking net cropped area, decreasing availability of irrigation water and increasing pressure on soil fertility (Cassman, 1999; The Montpellier Panel, 2013; Stevenson et al., 2013; Kabir et al., 2015). The challenges in agriculture are likely to further increase when considering protection of the natural resources (e.g., forests, crop lands, water) for future generations (Cassman and Wood, 2005; Hobbs et al., 2008).

Agricultural development from Pakistan to Bangladesh in the Indo-Gangetic Plains, particularly the rise of dry season irrigated agriculture, has led to concerns over falling groundwater tables and the implied unsustainable use of groundwater, and hence concern about the availability of water for irrigation in the future. The concerns are great in the Pakistan and India Punjab, and in parts of northwest Bangladesh, particularly the Barind Tract. The Eastern Gangetic Plains of India and Nepal has thus far seen less development of dry season irrigation and falling groundwater tables are generally not yet of concern. Whereas northwest Bangladesh and, to a lesser extent, West Bengal have extensive groundwater irrigation of a dry season rice crop[2], Bihar and Uttar Pradesh have relatively little dry season rice but much wheat (Figure 2). However, increased population and increasing demands for food in the region are likely to see intensification of agriculture and more use of irrigation. The obvious concern is that the experience elsewhere in the region of falling and possibly unsustainable groundwater use will be repeated in the Eastern Gangetic Plains of India and Nepal.

At the same time, it is not clear as to what extent the falling groundwater tables in northwest Bangladesh indicate unsustainable use. Peña-Arancibia et al. (2020) observed that the large increase in crop intensity and in particular the cultivation of Boro rice has not been accompanied by a similar large increase in the actual evapotranspiration. There are some increases in actual evapotranspiration in some districts, but overall the increase is not of the same order as the increase in pumping of groundwater. This observation probably results from the fact that the irrigated rice replaced the previous vegetation in a wet landscape with mostly shallow water tables, circumstances in which the actual evapotranspiration of the previous vegetation was probably close to potential evapotranspiration. Changing to irrigated Boro rice would not much increase actual evapotranspiration. With this observation, the explanation for falling groundwater tables might be at least partly due to other factors such as the observed declining rainfall, or changing landscape infiltration properties with extensive puddling for rice. Furthermore, Rushton et al. (2020) have recently shown that falling groundwater tables in the region do not necessarily indicate unsustainable

[2] Rice grown during the dry season (November to May) is called Boro in Bangladesh and West Bengal, and Summer Rice in Bihar and Uttar Pradesh. Rice grown in the early part of the wet season (May to September) is called Aus in Bangladesh and West Bengal, and Autumn Rice in Bihar and Uttar Pradesh. Rice grown in the later part of the wet season (July to November) is called Aman in Bangladesh and West Bengal, and Winter Rice in Bihar and Uttar Pradesh. The months indicated are approximate only and vary considerably across the region.

water use. Pumping of groundwater might lower the groundwater table to a new equilibrium position in which the pumping can be maintained sustainably. Rushton et al. (2020) show that irrigating a dry season rice crop leads to a great deal of infiltration into the underlying aquifers, which helps maintain the recharge of the aquifer at the new lower water table.

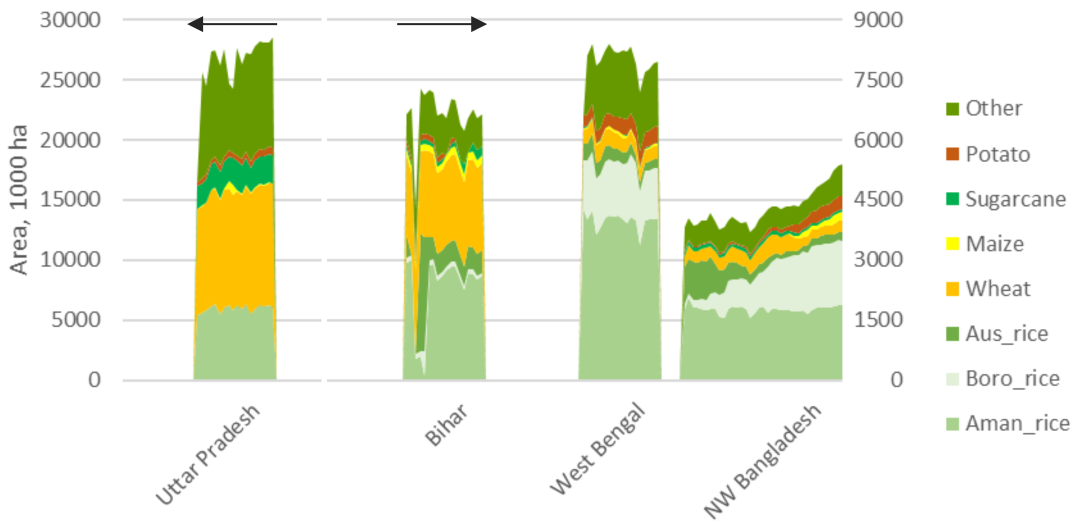


Figure 2. Areas of main crops in the Eastern Gangetic Plains, from 1996-97 to 2013-14 in Uttar Pradesh, Bihar and West Bengal, and from 1979-80 to 2015-16 in northwest Bangladesh. Uttar Pradesh areas are given by the left hand vertical axis, whereas the other three regions are given by the right hand axis. Sources: Indian states from https://data.gov.in/catalog/district-wise-season-wise-crop-production-statistics; Bangladesh compiled in previous CSIRO projects from various sources, and published in a summary form by Peña-Arancibia et al. (2020). The original data are for the districts in each of the four regions plotted, here aggregated to the region. The Bangladesh data have been "cleaned" to remove errors in formatting and actual values. The Indian data have not been cleaned other than to remove a few obvious gross errors; Bihar has some obvious missing data in the first few years.

One potential remedy for combatting the unsustainable use of groundwater is to use conservation agriculture techniques and other farm-scale water saving measures. But does this really save water at the regional scale? Ahmad et al. (2007a, 2007b) and Perry et al. (2017) give evidence that it may not.

With the above in mind, there are significant gaps in our knowledge of the water balance in the Eastern Gangetic Plains, and the likely consequences of changes to the regional hydrology that might result from changes such as increases in use, the implementation of farm-scale water saving measures, and climate change. The Eastern Gangetic Plains is taken in this study to include northwest Bangladesh, the Indian states of Bihar, Uttar Pradesh and West Bengal, and the Terai region of Nepal.

The aim in this report is to review the state of knowledge of farm water saving measures and their relation to the regional hydrology, particularly groundwater. We do this through a literature review (section 2), and through a review of relevant aspects of recent studies that we have conducted from farm (section 3, case studies, and section 4, APSIM modelling) to regional level water balance (section 5), from groundwater modelling (section 6) to remote sensing estimation of evapotranspiration (section 7). We particularly focus on the gaps in knowledge noted above. We conclude the report with recommendations to address the gaps in knowledge.

# 2 A review of conservation agriculture and agricultural water-saving measures and their impact on regional hydrology outcomes, with particular reference to the Eastern Gangetic Plains

## 2.1 Background

### 2.1.1 Water use in agriculture

Agriculture in many parts of the world, including South Asia, is likely to face great challenges in coming decades in increasing food production for the growing population. Global demand of food, energy and water by human has been forecasted to increase by 50 %, 50 % and 30 %, respectively in 2030 compared to their usages in 2012 (Parry, 2012). The sustainability of agricultural productivity is threatened in many regions of the world by environmental and socio-economic factors, such as (i) depletion and/or degradation of natural resources (e.g., water, soil, forests), (ii) low input-use efficiency (e.g., water, energy, fertilizers, pesticides, labour), (iii) environmental pollution (e.g., soil, water, air), (iv) changing climate, and (v) increasing scarcity of farm labour (Hira, 2009; Humphreys et al., 2010; Ladha et al., 2007; Yadvinder-Singh et al., 2005). Water is the most crucial factor for agricultural productivity and irrigated agriculture is the dominant global user of freshwater, accounting for about 70 % of consumptive use. Without further improvements in water productivity from its current level or major shifts in production patterns, the amount of water consumed by crop agriculture has been predicted to increase by 30 % by 2030 (Parry, 2012) and by 70 % – 90 % by 2050 (Gleick and Heberger, 2014). However, the growing competition for water by various sectors will affect farmers' ability to produce food. So, making food production sustainable, while conserving diminishing water supplies, will be a great challenge in the future (Leemans and De Groot, 2003), specifically in the densely-populated regions like the EGP.

The EGP is regarded a global priority for sustainably increasing food production. A tropical monsoon climate, with a hot, humid and rainy summer and a dry winter dominates the Ganges basin (Sanderson and Ahmed, 1979). Across most of the region, annual rainfall is more than 1500 mm, and areas near the hills in the East and North-East receives more than 4000 mm rainfall. However, most of the rainfall occurs during the monsoon period (June–September) and only a small amount occurring in dry winter season (November–February) (Hoque and Burgess, 2012), which is the main cropping season in the region. Because of inadequate surface water in the main cropping season, groundwater plays a vital role in sustaining agricultural productivity in many irrigated areas in the world, including the Eastern Gangetic Plain, EGP. Groundwater abstracted from the alluvial aquifer system comprises approximately a quarter of the world's total groundwater abstraction (Wada et al., 2010; Siebert et al., 2007) and supports the agricultural productivity of South Asia (Shah, 2009). The Indo Gangetic Plain has perhaps one of the most important water systems on the planet that accounts for 25 % of global groundwater abstraction (Fendorf and Benner, 2016). India has therefore become the world's largest user of groundwater (Aeschbach-Hertig and Gleeson, 2012) and groundwater provides 60 % of the total agricultural water use, accounting more than 50 % of the total irrigated area (Shah et al., 2003). In Bangladesh, the dry season agriculture was developed on irrigation where irrigation facility has been expanded to 85 % of the 6.93 Mha potential irrigated areas (FAO, 2016) and groundwater accounts for 79 % of the total irrigated area (BADC, 2016; Mainuddin et al., 2014, 2019a). Over the past 50 years, groundwater abstraction on the Indian subcontinent increased from about 10–20 $km^3$/year to approximately 260 $km^3$/year (Shah et al., 2003; Giordano, 2009).

Irrigated rice is the dominant crop in the EGP that is mostly cultivated under continuously flooded condition. Due to high input water requirement of this conventional puddled transplanted rice, irrigated agriculture is exerting increasing pressure on the region's finite freshwater resources (Li et al., 2011). This problem is especially acute in developing countries (e.g., Bangladesh), where groundwater extraction is mostly unregulated, un-priced and even subsidized (Fishman et al., 2015). Consequently, groundwater resources in many parts of the world are being depleted because of unsustainable extraction levels that exceed natural recharge rates (Wada et al., 2010, Famiglietti, 2014, Aeschbach-Hertig and Gleeson, 2012). In many South Asian regions, the level of aquifer exploitation has reached its maximum potential or has already exceeded it (Ahmad et al., 2002). Bangladesh is an example for this reality where the demand for groundwater consumption from dry season irrigation already has exceeded the natural recharge in some locations (Amarasinghe et al., 2014). The falling groundwater levels due to large extraction in some areas raises concerns about sustainability of the resource, most significantly in the Barind area in the North-West part of the country (Ahmad et al., 2014; Ali et al., 2012; Shahid and Hazarika, 2010; Kirby et al., 2015). Further increase in groundwater use may cause lowering of the groundwater level below which extraction may no longer be economically viable and may cause many-fold harms to the environment, including saltwater intrusion (Ahmad et al., 2002), degrading of water quality due to arsenic contamination and drying up of soil moisture for perennial trees. An imminent threat to the food security of Bangladesh is conceivable as declining groundwater levels in shallow aquifers in most areas in the North-Western region of the country have already rendered many low-cost pumping technologies (e.g., suction mode irrigation pumps) inoperable during the dry season (Mojid et al., 2019). This is because this region is considered as the food bowl of the country. While groundwater irrigation will remain crucial to sustain agricultural growth to meet Bangladesh's future food requirements, the scope for expansion in irrigated area as in the past decades remains very limited. The decreasing water availability both in terms of quantity and quality suggests that the unchecked expansion of dry season Boro rice cultivation may not be a long-term option for Bangladesh (Qureshi et al., 2015). Much of the additional food production must come from the intensification of land and water systems (FAO, 2003; Khan et al., 2006). Reducing agricultural water consumption may be a feasible and potential approach to relieving groundwater depletion (Hu et al., 2016).

### 2.1.2 Water losses in agriculture

Water requirement of rice crop comprises the water required for land preparation, natural losses from the field (e.g., surface evaporation, percolation) and consumptive use by plant (Zawawi et al., 2010). Puddling followed by (hand-) transplanting of rice seedlings and consecutive flooding of the fields with irrigation applications is the traditional method of rice cultivation in the Indo-Gangetic Plains. This method is widely practiced in the EGP and South-East Asia. Depending on soil texture, about 100–250 mm water is required for puddling only (Yadav et al., 2011a, b). Puddling provides several advantages in rice culture, such as weed control, easy transplantation and reduced percolation loss of water in the field. Water requirement of rice varies based on climate, soil, crop and adopted water management practices. Varying ranges of water requirement (775–3000 mm) has been reported in scientific literature (Zawawi et al., 2010; Lu et al., 2000; Tyagi et al., 2000; Mainuddin et al., 2015). Irrigation application to rice in South-East Asia greatly exceeds that needed to meet evapotranspiration requirement because of the practice of keeping the fields ponded for prolonged periods, together with the mostly permeable nature of the soils, leading to large amounts of deep percolation (Ahmad et al., 2014).

Water is lost from farmers' fields as transpiration via the plants, evaporation from the soil or from water lying on the soil surface, percolation beyond the crop root zone, seepage and surface runoff in times of over irrigation and excessive rains. Thus, the water used in irrigation goes to one or more of the three classes (Perry et al., 2017): (i) consumptive use that comprises beneficial consumption (e.g., crop transpiration, evaporation from crop lands) and non-beneficial consumption (e.g., evaporation from free water surfaces and non-crop lands, transpiration by weeds), (ii) non-consumptive use that comprises recoverable flows (e.g., returning to a river or aquifer for potential reuse) and non-recoverable flows (e.g., flowing to saline/polluted aquifer or sea or other economically unviable sink), and (iii) change in storage. At the field level, water that reaches an irrigated permeable soil by rainfall or irrigation splits into two main fractions – consumed, and non-consumed. Each fraction has two sub-fractions based on interaction between the method of irrigation application and the prevailing soil conditions (Burt et al., 1997; Foster et al., 2000; 2002). The first (consumed) fraction comprises beneficial transpiration consumed by the cultivated crop, and non-beneficial evaporation from the wet soil as conceptualized in Figure 3 (Mojid and Mainuddin, 2021). The second (non-consumed) fraction includes recoverable percolation to a freshwater aquifer, and non-recoverable percolation to a saline aquifer.

In rice fields with established plough pans, horizontal movement of surface water into bunds (raised boundaries around the field edges) and then vertical movement of that water through the bunds often provide the largest loss of water from the fields (Walker and Rushton, 1984; Tuong et al., 1994; Walker, 1999; Huang et al., 2003; Janssen and Lennartz, 2009). Generally, a substantial amount of applied water is lost from bypass flow through cracks during puddling (Cabangon and Tuong, 2000), by deep percolation from root zone, seepage through bunds (Janssen and Lennartz, 2007, 2008) and evapotranspiration (Hardjoamidjojo, 1992; Sharma and De Datta, 1992; Humphreys et al., 1992). Li et al. (2017) reported 32.5 % to 37.6 % of total input water as loss through percolation from the transplanted rice fields in the Taihu Lake Basin of East China. Maniruzzaman et al. (2019) and Mainuddin et al. (2020a) reported 2.80 mm/day to 3.80 mm/day of percolation losses from Boro rice fields in the northwest region of Bangladesh. Water percolated below the root zone cannot be recovered by crops and seepage is lateral flow through bunds and/or subsurface from one field to another. Both the percolated and seepage water is considered to be a primary loss for farmers. However, the real water losses to the hydrological system are those from evaporation and flows to sinks (Figure 3), such as saline aquifers, seas and contaminated water sources (Seckler et al., 2003; Mojid and Mainuddin, 2021). Although water may serve a valuable function in the sink but is not available for other uses outside the sink. So, water-saving occurs only when flows to the sinks are reduced.

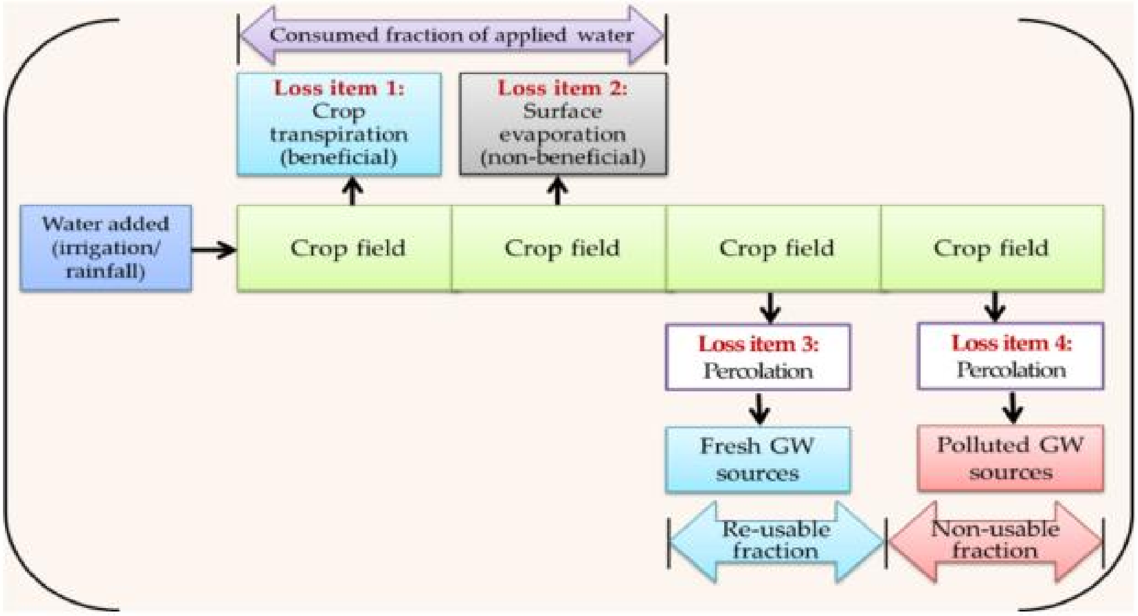


Figure 3. Destination of water added to crop fields (Source: Mojid and Mainuddin, 2021)

### 2.1.3 Water scarcity and resource-conserving technologies

Water scarcity is continuously increasing and currently affecting about a billion people around the globe (Mekonnen and Hoekstra, 2016). The lack of additional sources of fresh water for agricultural use is a key restrictive factor to maintain growth in food production for the ever-growing population. On the other hand, traditional agriculture, which is mostly mechanized and tillage-based, is considered to be accountable for more water consumption (Wolff and Stein, 1998) than the emerging conservation agriculture. The traditional transplanted rice cultivation still involves continuous flood irrigation, with a water depth of 5–10 cm. This irrigation system is associated with excessive losses of water as well as nutrients (Liu et al., 2014; Tan at al., 2015). It is presumed that water availability for agricultural use will further decrease under climate change scenarios (NATCOM, 2004; Mojid, 2020). Therefore, growing more rice with less water is considered one of the major challenges in agriculture of the 21st century. Many investigators (e.g., Fishman et al., 2015; Heydari, 2014; Lamaddalena et al., 2005; Perry et al., 2009; Wang et al., 2015) opine that it might be necessary to shift the current agriculture so that it can substantially improve water use efficiency and water productivity without affecting food security. Now pressure is increasing on irrigators and irrigation managers to increase water use efficiency and to achieve water-savings by conserving water that is otherwise lost through non-beneficial sink, such as evaporation or seepage to saline aquifers of sea (Khan, 2007; Gonćalves et al., 2007; Han et al., 2011; Pereira et al., 2007). Therefore, alternative strategies that can ensure sustainable use of the limited water resources are of absolute necessity. Currently one common policy prescription for conserving irrigation water is to promote water-saving irrigation technologies (Peterson and Ding, 2005).

Water, energy and food securities are very closely interlinked; an integrated approach is required for their management (Gain et al., 2015). However, until recently, these issues were only considered in isolation (Bazilian et al., 2011). But, now it has become paramount to develop technologies with the potential to reduce energy, labour and water use, and environmental pollution, and also that improve soil physical, chemical and biological properties while maintaining or more often boosting yields (Carrijo et al., 2017). Conversion of conventional agriculture to conservation agriculture is of particular interest in this regard (Giller et al., 2009; Hobbs et al., 2008; Jat et al., 2012). Consequently, increasing crop productivity with scarce water resources is now drawing more attention to Resource-Conservation Technologies such as zero/minimum tillage, laser land leveling and furrow bed planting in South Asia (Masih and Giordano, 2014) and elsewhere. Delayed rice transplanting, changing to shorter duration rice varieties and changing from continuous flooding to alternate wetting and drying (AWD) water management for rice are considered the most promising technologies for water-saving (Humphreys et al., 2010). So, water-saving technologies that can reduce water loss from diversion canals and irrigation fields with potential to increase water use efficiency (Zhang et al., 2012) are now spreading rapidly to sustain agricultural production. Rice-wheat system is the most important cropping system in the Eastern Gangetic Plain, and a wide range of water-saving technologies has been developed that reduce irrigation input to rice and/or wheat. The use of water-saving technologies is also thought necessary to check groundwater depletion in order to protect access of smallholders to groundwater (Kaur and Vatta, 2015). Water-saving irrigation, as one approach to mediate water conflicts between humans and nature, has already been popularized in some arid regions (Christen et al., 2007; Ibragimov et al., 2007; Scanlon et al., 2010).

## 2.2 Conservation agriculture

### 2.2.1 Principles and importance

Conservation agriculture (CA) has been developed as a response to concerns of sustainability of agriculture globally (Harrington and Erenstein, 2005; Hobbs, 2007, FAO, 2007; FAO, 2012). It is based on the principles of rebuilding the soil, optimizing crop production inputs, sustaining or enhancing food production and optimizing profits (Dumanski et al., 2006; Jat et al., 2014; Islam et al., 2019). CA comprises application of three interlinked principles: (i) no or minimum mechanical soil disturbance through conservation tillage (e.g., reduced, minimum or zero-tillage), (ii) biomass mulch soil cover, and (iii) crop diversification as well as a few complementary good agricultural practices of integrated crop and production management (Kassam et al., 2019). In the no-tillage system, a crop is planted directly into a seedbed, which has not been tilled since its first preparation in a previous crop season. Conservation tillage leaves at least 30 % of the soil surface covered with crop residue after planting to reduce soil erosion by water (CTIC, 2004).

The application of resource-conserving technologies can reduce field-scale irrigation and fertilizer application; increase crop diversification; improve resource use efficiency; reduce labour shortages, energy use (fossil fuels and electricity), greenhouse gas emissions, soil erosion and degradation of natural resource base; and increase yields and farm incomes (Erenstein et al., 2008; Jat et al., 2009; Nangia et al., 2010; Mujeeb-ur-Rehman et al., 2011; ADMIT, 2012; Pandey et al., 2012; Saharawat et al., 2012; Bhan and Behera, 2014; Masih and Giordano, 2014). Zero-tillage cropping system provides higher yields at a lower production cost, while being an environmentally friendly practice that saves water and soil (Gupta et al., 2002; Hobbs et al., 1997; Hobbs and Gupta, 2003). However, the prime interest for farmers' adoption of this practice is monetary gain and labour savings (Erenstein et al., 2008). Nevertheless, achieving water-saving by conserving water is being increasingly felt. The currently practiced irrigated rice–wheat system in some parts of the Ganges basin has become unsustainable due to over-exploitation of groundwater. Labour and water scarcity are driving farmers in the region to change from puddling and manual transplanting of rice to mechanized dry seeding (Humphreys and Gaydon, 2015b). Curtailing water demand through the adoption of water-conserving practices is thought to ease water stress (Qureshi et al., 2015). Other technologies such as laser leveling can generate more substantial water-savings and have recently been taken up by some farmers (Jat et al., 2009) in Pakistan and North-West India. Experimental evidence in the North-Eastern part of India suggests that conservation agriculture-based management has some immediate benefits (Bhushan et al., 2007; Hobbs, 2007; Parihar et al., 2017) as well as some long-term benefits (Gathala et al., 2011; Parihar et al., 2016). Rice-maize system with CA-based management practices enhances the system productivity (Gathala et al., 2015), sustains soil health and environmental quality (Singh et al., 2016), and saves irrigation water and labour costs (Parihar et al., 2017). Conservation agriculture and crop diversification or intensification is now regarded as the major components of the emerging farming systems for ensuring food security in South Asia (Jat et al., 2014; Islam et al., 2019).

Conservation agriculture has been practiced for the last three decades and the principles of conservation agriculture are now increasingly being recognized as essential for sustainable agriculture. Various resource-conservation technologies are being continuously developed and gaining acceptance in many parts of the world as an alternative to both conventional agriculture and organic agriculture, especially for rice cultivation (PARC-RWC, 2003; Mujeeb-ur-Rehman et al., 2011). The spread of zero-tillage wheat in the rice-wheat system is taking place in the IGP where rice-wheat cropping systems dominate (Bhan and Behera, 2014). A CA -based sustainable intensification program was initiated in 2014–15 in two districts each of Nepal, Bangladesh and Bihar and West Bengal in India (Sinha et al., 2019). In 2008/09, there were about 106 Mha of arable and permanent crops grown on these lands without tillage in CA systems, corresponding to a global annual rate of increase of 5.3 Mha since 1990 (Kassam et al., 2009). In 2015/16, the adoption of CA was reported by 78 countries, an increase in adoption by 42 more countries since 2008/09; the cropland under CA increased to about 180 Mha that correspond to about 12.5 % of the total global cropland.

### 2.2.2 Impacts on soil and water use

#### Impacts on soil properties

The effects of conservation agriculture on soil properties vary depending on the type of chosen system, type of soil, climatic conditions, cropping history, etc. (Mahboubi et al., 1993; Halvorson et al., 2002). Accordingly, available literature on soil properties and crop performance under zero-tillage systems is inconsistent and sometime contradictory also. Zero-tillage systems maintain high surface soil coverage with biomass mulch and result in change in soil properties; the change is significant in the upper few centimeters (Anikwe and Ubochi, 2007). Soils under zero-tillage with residue retention become more stable and less susceptible to structural deterioration, while soils under conventional tillage are more prone to erosion (Verhulst et al., 2010). Therefore, soil physical properties are generally more favorable with zero-tillage than with conventional tillage systems (Lal, 1997).

Organic carbon: The amounts of organic matter, residue retention and fertilization matter are higher in soil under zero-tillage/minimum tillage compared to the conventional tillage practice (Alvarez, 2005; Dalal et al., 2011; Somasundaram et al., 2017). Over time, soil organic carbon increases under no-tillage compared to conventional tillage system and under crop residue retention than under residue burning (Roper et al., 2013). Sinha et al. (2019) obtained higher organic carbon at 0–15 and 15–30 cm profile in Inceptisols and Entisols in the Eastern Gangetic Alluvial Plains under zero-tillage than conventional tillage. Singh et al. (2014) reported significant increase in soil organic carbon to a depth of 0.10, 0.15 and 0.25 m in sandy loam, loam and clay loam soil, respectively under zero-tillage compared to conventional tillage. This vertical distribution of organic carbon in different-textured soils indicates its build up to deeper depths with increase in fineness of soil texture. Zero-tillage also generally reduces soil pH compared to conventional tillage systems (Somasundaram et al., 2017).

Various organic materials along with crop rotation under conservation agriculture improve soil organic matter and preserve continuity of soil pores. Soil organic matter improves soil physical properties such as soil aggregation, which alter other soil properties; the well-aggregated soils with continuous pores enhance leaching through the soils and accelerate soil acidification (Sinha et al., 2019).

Bulk density: Cropping systems under conservation agriculture provide more crop residue than conventional agriculture and reduce bulk density of the field soils. However, in short-term, clear effect of the crop management systems on bulk density is not clearly evident. Verhulst et al. (2010) reported varying effects of the different tillage systems practiced for 10 years on soil bulk density. As the crop residues increase on the soil surface, the bulk density also increases; this effect is more distinct in 0–3 cm soil layer than in 3–10 cm soil layers (Blanco-Canqui and Lal, 2007). Although zero-tillage reduces plough pan formed under conventional tillage, Singh et al. (2014) observed a significant increase in bulk density in 0–5 cm soil profile in sandy loam and 0–10 cm soil profile in both loam and clay loam soils. Horne et al. (1992), however, observed contrasting results, reporting a lower bulk density under zero-tillage than under conventional tillage at a depth of 3–7 cm. They observed no difference in bulk density in the lower soil layers under the two tillage systems.

Porosity: More stable aggregates in the upper surface of soil with increased crop residue are associated with zero-tillage soils than tilled soils. This consequently results in reduced soil bulk density and high total and effective porosities within the top 5 cm soil profile under zero-tillage (Shaver et al., 2002; Busari et al., 2015). The increase in total porosity is associated with significant changes in pore-size distribution in the macropore class. In general, micro- and meso-porosity is reported to be higher in zero-tillage compared to the conventional tillage. In comparison with conventional ploughing, minimum tillage improved the soil pore system by increasing the storage pores (0.5–50 mm) and the amount of elongated transmission pores (50–500 mm) (Pagliai et al., 2004). The irregular and elongated pores (>1000 µm in diameter and length) are greater in number in conventional tillage compared to zero-tillage at a depth of 0–20 cm due to annual mixing and homogenization of the soil particles during tillage operations. Zero-tillage provides a greater proportion of macropores that are oriented in the horizontal direction within 5–15 cm profile than the conventional tillage (VandenBygaart et al., 1999). In absence of regular annual tillage, soil biopores (>500 µm) that are created by roots and fauna (e.g., earthworms) are maintained in the plough player. These pores are mostly round-shaped and more frequent under zero-tillage systems after a few years (VandenBygaart et al., 1999). This can be attributed to the maintenance of root and earthworm channels under zero-tillage over the years, while these are destroyed annually under conventional tillage. The zero-tillage can also result in the loss of total pore space within the plough layer when bulk density increases. The adoption of controlled traffic when converting to zero-tillage is important in limiting the possible loss of pore space (Verhulst et al., 2010). The extent of increase in porosity thus depends on building up of organic matter at the plough layer and macro faunal activity. A reduction in tillage is expected to result in a progressive increase in total porosity with time, eventually approaching a new steady state soil aggregate. However, the initial changes may be too small to be distinguished from natural variation.

Infiltration: Many soil properties, such as bulk density, porosity, sorptivity and aggregation control the infiltration characteristics of soils. In addition to these, many other factors such as soil texture and structure, top and subsoil thickness, flooded water depth, water and soil temperature and salinity, depth of groundwater table and other topographical conditions influence infiltration in rice fields (Wickham and Singh, 1978). Site latitude (related to evaporation potential), landscape slope and cropping system intensity interact to affect physical properties of surface soil that are also important to capturing water and infiltration (Shaver et al., 2002). The infiltration, retention and flow of water depend on the quantity and size of soil pores as well as on their interconnectivity and shapes (VandenBygaart et al., 1999). The hydraulic conductivity of deeper soil layers greatly influence the long-term infiltration rate. The surface soil (top 2.5 cm) is the initial soil-water interface and therefore its physical properties are the most important controlling factors of infiltration. As described in the previous sections, conservation tillage provides more favourable soil properties for infiltration than conventional tillage systems. Accordingly, infiltration is more under zero-tillage and crop residue retention and less under crop residue burning and cultivation (Roper et al., 2013). Infiltration of water is higher under long-term (e.g., 8–10 years) conservation tillage compared to conventional tillage (Bissett and O'Leary, 1996). Time-to-pond, final infiltration rate and total infiltration are significantly larger under zero-tillage with residue retention than with conventional tillage (McGarry et al., 2000; Shaver et al., 2002; Sayre and Hobbs, 2004). Abundance of continuous soil pores from the soil surface to deeper layer under zero-tillage as against a high-density surface crust that occurs under conventional tillage is the prime factor behind increased infiltration under zero-tillage.

Hydraulic conductivity: Zero-tillage significantly improves saturated and unsaturated hydraulic conductivity of soils owing to either continuity of pores (Benjamin, 1993) or flow of water through very few large pores (Allmaras et al., 1977). The increased number of biopores under conservation tillage generates larger macropore conductivity and consequently results in higher hydraulic conductivity under zero-tillage with residue retention compared to conventional tillage (Verhulst et al., 2010). Singh et al. (2014) reported significantly increased saturated hydraulic conductivity only to a depth of 10 cm under zero-tillage over conventional tillage. However, the results on hydraulic conductivity of different studies are not consistent.

### Impacts on water use

Water-holding capacity of a soil increases with increase in organic matter in the soil (Verhulst et al., 2010). The conservation agriculture being an organic matter enhancing practice has therefore potential to augment water holding capacity of soils. By reducing bulk density and increasing porosity and aggregation in the surface soil, conservation agriculture can increase the potential for rapid capture of rainfall. This consequently reduces the potential for water runoff and evaporation and ultimately leaves more water in the soil. Conservation agriculture thus makes more water available for plant use and increases system precipitation use efficiency (Shaver et al., 2002). The higher soil-water content under zero-tillage than under conventional tillage indicates reduced evaporation loss of water during the preceding period (De Vita et al., 2007). These investigators reported finding 20 % greater soil-water content under zero-tillage than under conventional tillage across the crop growing season.

Limited experimental results and farmers experience indicate that considerable saving in water and nutrients can be achieved with zero-till planting. Kahlown et al. (2006) reported that the use of resource-conserving technologies, such as zero-tillage, laser leveling and bed and furrow planting, can reduce irrigation water applications between 23 % and 45 % while increasing crop yield. Farooq et al. (2007) reported that the farmers who adopted zero-tillage practice in Pakistan’s Punjab could reduce irrigation applications by 5 % – 15 % and obtained similar yields compared to the conventional agricultural practices. Contrasting results are also reported in literature. A review of various studies (e.g., Gupta and Seth, 2007; Jat et al., 2009; Humphreys et al., 2010; ADMIT, 2012) suggests that, compared to conventional practices, laser land leveling in India, Pakistan and China can reduce irrigation water application by 25 % and increase wheat yield by 30 %. Direct-seeded rice has multiple benefits over transplanted puddled rice through savings in labour (40 % – 45 %), water (30 % – 40 %), fuel/energy (60 % – 70 %) and reductions in greenhouse gas emissions (Mohammad et al., 2018). However, the use of direct dry seeding of rice on flat and raised beds while results in considerable water-savings, generally, has negative impacts on yield (Bouman et al., 2007a; Choudhury et al., 2007; Humphreys et al., 2010). Under the farmers' usual practice comprising puddled transplanted rice, alternate wetting and drying water management for rice, rice straw removal and tillage for wheat, irrigation input has been reported 390 mm more than that under conservation agriculture in the Eastern Indo-Gangetic Plain (Jat et al., 2019). This, consequently, increased crop-water productivity from 11.3 to 11.7 kg/ha/mm. These investigators also found 10.6 % to 21.8 % lower total water-use (irrigation+effective rainfall) of rice-maize system under permanent bed and zero-tillage, respectively compared to conventional tillage. In their observation, the system-water productivity increased by 27.1 % – 57.4 % and 39.4 % – 68.3 % under conservation agriculture-based permanent bed and zero-tillage, respectively compared to conventional tillage. It is thus evident that conservation agriculture-based management (zero-tillage and permanent bed with partial residue retention) in rice-maize production system provides a potential option for producing more crops with less water. This can help meeting the future food requirements and increasing farm income on a sustainable basis to support resource-poor farmers of the Eastern Indo-Gangetic Plain (Dutta et al., 2020). However, as Humphreys and Gaydon (2015b) reported that the changing conventional agriculture to conservation agriculture can only reduce evapotranspiration of the highest yielding system by 4 % (55 mm) and of other current practices by even less than this. The perceptible way to achieve a substantial reduction in evapotranspiration is by growing short-duration rice varieties in both the farmers' usual practice and conservation agriculture systems. However, with the currently available short-duration varieties, this can be achieved at the cost of both rice and system yields (Humphreys and Gaydon, 2015b).

## 2.3 Agricultural water-saving

### 2.3.1 Apparent and actual water-saving

Any effort toward improving irrigation efficiency is considered worthwhile to save a substantial amount of good quality water (Babajimopoulos et al., 2007). However, the term 'water-saving' has different meanings to different people at different temporal and spatial scales (Dong et al., 2001). At the farm level, water-saving most often refers to a reduction in irrigation water applied to crops (Tuong and Bhuiyan, 1999). For a farmer, water-saving means using less irrigation water to grow a crop, likely with the same or higher yield. Seckler et al. (2003), however, reported that the most commonly used concepts of the efficiency of water consumption underestimate the actual efficiency of the hydrological system by a large amount. Many researchers have studied how efficiency of water consumption and water productivity respond to agricultural water-saving at the field scale (Gowing et al., 2009; Igbadun et al., 2008; Karam et al., 2007; Rao et al., 2016; Zhou, 2009). Studies in Asia show very large savings in irrigation water when moving from continuously ponded rice culture to saturated soil culture, alternate wetting and drying with shallow irrigations and furrow-irrigated beds (Humphreys et al., 2005). However, it is difficult to quantify the actual fraction of total water supply that can eventually be used efficiently at a regional scale. Difficulties also arise in estimating the productions that can be obtained due to the complex water exchange and spatial differences of crop type and growth conditions (Seckler et al., 2003).

Saving irrigation water does not necessarily mean that total water use (rain water, soil water and irrigation) is reduced at the field scale (Humphreys et al., 2005). An individual farmer considers the combined outflow of water by evapotranspiration, seepage and percolation as water use by the rice field and these components of the outflow are actual water losses for him/her. However, water-saving by one user may be a loss to another. This happens at a larger spatial scale when seepage and percolation from one field enter the groundwater or streams and drains, from where other farmers may reuse the water to irrigate other fields. For example, a gain at the upstream may be offset by a loss in fisheries at the downstream, or the gain may put more agrochemicals into the environment (Molden and De Fraiture, 2010). Whether or not reduced water application translates into real water-savings and reduces water use depends on several factors. The major factors include: (i) how a specific resource-conserving technology changes different components of the water balance in a given setting, (ii) what farmers do with water saved through reduced irrigation application, and (iii) the hydrologic interactions across scales between the field and farm, and between the irrigation system and entire river basin (Masih and Giordano, 2014). The fundamental cause of confusion about water-savings and increasing water productivity lies in two valid but different viewpoints on water scarcity. The farmers try to derive maximum returns from their resources. This in turn means consuming as much as possible of the scarce water available to them. While society, on the other hand, wants scarce water to be released from agriculture to other sectors of the economy. These two objectives are contrasting, and therefore appropriate terminology to describe real water-saving remains a central issue of debate over time (Perry et al., 2017).

All the water used for any purpose ends up at any or combination of consumptive use, non-consumptive use, non-recoverable flow and change in storage (Perry et al., 2017). These terms for accounting water allow a more clear definition of the issues and options that are being faced in irrigated agriculture over the past decades. Any statement of certain percent water-saving through a resource-conserving technology usually refers to a narrow local perspective of water application to the field. In does not account for return flows from the irrigated field that may recharge the underlying aquifers or contribute to downstream river flows. In some cases, such return flows may be non-recoverable outflows to saline/polluted groundwater, while in other cases the return flows are recoverable where they end up in rivers or useable groundwater source (Perry et al., 2017). The real water-saving occurs only when water losses that cannot be recaptured are reduced or eliminated. If the underlying aquifer is saline, or outflow of water goes directly to sea, then water-savings are real. But only a complete set of water accounts can reveal whether real water-savings are achieved so that water can be released to other users with no negative effects. Saving water in cropping systems actually means reducing non-beneficial losses of water, which cannot be economically recaptured elsewhere in the hydrological system. These non-beneficial losses include evaporation from the soil and applied irrigation water, and deep percolation into water sources that are too contaminated for reuse (e.g., saline groundwater, sea water) or into locations from which it is too difficult or expensive to recapture (e.g., aquifers with low transmissivity) (Humphreys et al., 2005).

Irrigation water-savings are likely due to reduced percolation beyond root zone, with little effect on evapotranspiration. But, the field scale reduction in irrigation application does not always translate into real water-savings or reductions in water use at the farm, cropping system and catchment scales, especially in areas where percolation from the root zone can be reused as groundwater irrigation (Masih and Giordano, 2014). More than 90 % of the major rice-wheat areas in North-West India are irrigated by using groundwater. The excess irrigation water application percolates to the groundwater reserve from where it is pumped by the same or other farmers for reuse (Keller and Keller, 1995; Keller et al., 1996; Seckler, 1996; Ahmad et al., 2002; Tuong et al., 2005). Also in large areas of the Indo-Gangetic plains, northern China and elsewhere, the development of wide-scale surface irrigation has formed a major new source of recharge to groundwater (Giordano, 2009). The seepage from one field is generally considered a gain for the adjacent fields, such that the system experiences no net loss (Huang et al., 2003). Therefore, percolation and seepage can no longer be considered as lost or wasted water from the soil-groundwater system (Ahmad et al., 2014) for water resources management. Reducing percolation will not actually save water nor reduce the rate of groundwater decline (Perry et al., 2017). Reducing non-beneficial evaporation losses is a true water-saving. Optimal planting time of rice to avoid the period of highest evaporative demand and changing to non-ponded rice culture can save significant amounts of water (Humphreys et al., 2005). The most potential technologies for reducing evapotranspiration are delayed rice transplanting and use of short-duration rice varieties. In areas where groundwater is not suitable for irrigation due to highly salinity, reducing percolation provides real water-savings in addition to other benefits like reduced waterlogging and secondary salinization. However, the recapture of water often comes at a cost in terms of energy for pumping, purchase of irrigation water and labour, construction of drainage systems and greenhouse gas emissions associated with the production or use of energy (Humphreys et al., 2005).

The scale-effects of water use are important for understanding and planning for water-savings and water productivity (Molden, 1997). The magnitude of any water-saving can vary considerably depending on the spatial and temporal scales of interest (Seckler, 1996; Loeve et al., 2002). At the basin scale, the main interest is reducing the total amount of water being exhausted by irrigated agriculture while maintaining or increasing the production and transfer of water to other higher-valued uses. Factors such as recycling of water and interaction of non-agricultural water uses with agricultural water uses play a major role in water-saving (Bouman et al., 2002). At the basin scale, it is often argued that only water saved by reducing evaporation and flows to sinks is a real saving. On the other hand, water-saving practices at the field scale, with the objective of reducing supplies to fields, do not necessarily lead to transferable savings at the basin scale. Some researchers (e.g., Shah, 2014) argue that micro-irrigation often delivers the same total volume of water in more frequent but smaller quantities, thus reducing percolation. This curtails return flows that can be used further downstream. Although there remain complexities, the ultimate objectives of water-saving are clear that are to cease unsustainable over-exploitation of surface and groundwater resources and increase the amount of water available for non-agricultural purposes (e.g., urban, industrial, fisheries, environmental, recreational).

In water accounting and efficiency analysis, the basin approach (Seckler, 1992, 1996; Frederiksen and Perry, 1995; Keller et al., 1996) provides importance of evaluating return flows, measuring both basin and field efficiencies and distinguishing between consumptive and non-consumptive savings. In brief, the basin approach suggests that many basins in the world are now approaching closed status, where all of the water that flows into them is used. The approach argues that all water in such basins is ultimately used beneficially or productively, even if there are small-scale or field inefficiencies; all of the usable drainage water (seepage and percolation) is also beneficially used. Seckler (1996) called the water efficiency measures that only reduce drainage water as ‘dry’ water-savings” and defined as reductions in non-consumptive water against “wet” savings, which are reductions in consumptive water use. Thus, the basin approach discounts the need to pay attention to individual water uses. Instead, it focuses on determining how much of the water that enters a basin is ultimately being recovered and used, as a measure of the overall basin efficiency (Frederiksen and Perry, 1995).

### 2.3.2 Water-saving measures

Gleick et al. (2011) argues that appropriate water-accounting procedures must be in place (both farm and basin) in order to identify the opportunities for water-savings. Then specific water conservation and efficiency practices based on a combined use of economic, technical, social and political tools need to be adopted to reduce pressures on scarce water supplies (Berbel et al., 2015). The range of measures for reducing net water usage regionally includes water-saving irrigation, groundwater regulation, shifts to rain-fed agriculture, artificial recharge to groundwater, rainwater preservation, imports of virtual water in the form of goods produced elsewhere and indirect approaches like energy pricing and regulation (Aeschbach-Hertig and Gleeson, 2012). At the farm level, water inputs can be reduced by minimizing the relatively large and unproductive losses from seepage, percolation and evaporation. A common policy prescription, which is most often promoted for conserving irrigation water, is the adoption of water-saving irrigation technologies that reduce evaporation and runoff losses (e.g., Johnson et al., 2001) and the extent or duration of free water or surface soil saturation.

Based on such concepts, various water-saving irrigation strategies have been developed in different rice-growing regions to maintain acceptable rice yields (Bouman et al., 2007a; Geerts and Raes, 2009). For example, a combination of a shallow water depth with wetting and drying (Liang et al., 2015; Mao, 2001), alternate wetting and drying (Bouman and Tuong, 2001; Loeve et al., 2002; Tan et al., 2013; Ye et al., 2013), semi-drying (Prathapar and Qureshi, 1999), aerobic rice cultivation (Bouman et al., 2007a; Kato and Okami, 2011), partial root zone drying (El-Sadek, 2014), moistening, non-flooded mulching (Zhang et al., 2008) cultivations, conveyance loss reduction through canal lining and piping, matching water-saving investments with higher value cropping systems, removing salinity constraints from farm to regional levels through efficient leaching of soils and promoting sustainable multiple use of water (Khan, 2007) are popular techniques that have been adopted around the world. Saturated soil culture and alternate wetting and drying (AWD) can drastically reduce in-field water losses (Zaman and Gangarani Th., 2014). AWD involves allowing the soil to dry out for a few days after the disappearance of ponded water before the crop is irrigated again (Feng et al., 2007). Multiple-shallow irrigation is a type of the AWD irrigation method that irrigates rice fields multiple times at shallow depths (e.g., 1–3 cm), depending on soil conditions and weather predictions. In aerobic rice cropping, high-yielding rice is grown in non-puddled aerobic soil with supplementary irrigation just like upland crops. In this system, rice is grown in well-drained, non-puddled and non-saturated soils without ponded water (Bouman et al., 2007a). Other water-saving techniques and improved irrigation technology such as raised beds with furrow irrigation, laser land leveling, drip and sprinkler irrigation, mulching, conservation tillage, deficit irrigation (Zaman and Gangarani Th., 2014), improved crop varieties and improved weed control have been proved to be effective to achieve substantial water-saving (Hu et al., 2016).

AWD is already being practiced by many farmers in the North-West Indo-Gangetic Plain and it is reported that a water-saving of 15 % – 40 % of the applied water has been achieved with AWD in puddled transplanted rice compared to continuous flooding, with no or minor decline in crop yield (Choudhury et al., 2007; Hira et al., 2002; Humphreys et al., 2008a; Jalota et al., 2009; Sudhir-Yadav et al., 2011; Maniruzzaman et al., 2019). Through the adoption of water-saving irrigation technologies, rice field can shift away from being continuously anaerobic to being partly or even completely aerobic. The cultivation method with multiple shallow depth irrigation can efficiently use rainfall and reduce the losses due to reduced percolation and surface runoff while stabilizing rice yields (Li et al., 2017). Some other water-saving technologies like piped water transmission and pressurized micro-irrigation instead of flood irrigation can also be potential means of promoting sustainable groundwater use (Shah, 2014). It is however emphasized that since most of the water-savings results from reduced percolation rates, adoption of such approach will reduce groundwater recharge (Li et al., 2017). The real water-savings, which result in more water being available for other users and/or for replenishing depleted aquifer storage, can only be achieved through any combination of: (i) reducing non-beneficial evaporation through reduced application of irrigation water, (ii) eliminating sources of non-beneficial evapotranspiration, and (iii) switching to cultivation of less water-consuming crops (Foster et al., 2000; 2002).

### 2.3.3 Impact on soil

Tillage operations in the fields at water-saturated conditions (e.g., puddling) destroys soil aggregates, thereby producing smaller soil particles that fill pore space and seal cracks and macropores as they settle (Moormann and van Breeman, 1978; Sharma and De Datta, 1986); they also form plough pan generally at a depth of 20 to 25 cm (Dittmar et al., 2007). The plough pan acts as a barrier to water flow. The difference in hydraulic conductivity between the plough pan and the subsoil causes for the development of an unsaturated zone beneath the pan, even while the field surface remains flooded (Takagi, 1960; Zaslavsky, 1964; Wopereis et al., 1994; Chen and Liu, 2002). The hydraulic conductivity of the puddled layer decreases with the increase in puddling intensity; for example, Kukal and Aggarwal (2002) reported hydraulic conductivity of 0.064 cm/h with medium-puddling and 0.009 cm/h with high-puddling. Tuong et al. (1994) in the Philippines and Chen and Liu (2002) in Taiwan determined that the puddled soil in their respective fields had an order of magnitude lower hydraulic conductivity than the non-puddled soil (0.15 versus 2.3 cm/d and 0.05 versus 1.5 cm/d, respectively), even though the bulk density (Tuong et al., 1994; Chen and Liu, 2002) and porosity (Chen and Liu, 2002) of the two soils varied by less than a factor of 2. In case of rice cultivation under flood irrigation, farmers plough the rice fields each year, destroying cracks and reducing hydraulic conductivity of the shallow soil, but leave the bunds unploughed to keep boundaries of their land distinct (Neumann et al., 2009). Consequently, bund flow was the dominant water loss for rice field since the hydraulic conductivity of the soil beneath the bunds is greater than that in the ploughed and planted region of the rice field. Soils in the rice fields usually crack (Tournebize et al., 2006) under drying and wetting cycles, leading to the formation of preferential flow paths (Janssen and Lennartz, 2007, 2008, 2009). In the Eastern Gangetic rice soils, abundant earthworm casts are a common feature that are known to cause preferential flow path for water. The higher field-observed hydraulic conductivity than the intrinsic matrix permeability suggests that cracks and macropores in the planted field, not the intrinsic matrix permeability, control field-scale infiltration rates (Neumann et al., 2009). Several studies (e.g., Wopereis et al., 1992; Tuong et al., 1994; Chen and Liu, 2002) have shown that excavating through the plough pan significantly increases water loss from the field.

### 2.3.4 Impact on water use

AWD effect: Alternate wetting and drying, AWD, is a recognized technology for the tropics and subtropics, with practical guidelines for its application using a simple, low-cost ‘field water-tube’ (Bouman et al., 2007b); the tube is known as ‘panipipe’ in local language in Bangladesh and India. It is widely practiced in irrigation in the water-scarce regions of China (Li and Barker, 2004). It also the recommended practice in many other countries or regions, including the IGP of India and Bangladesh (e.g., Sandhu et al., 1980; Sattar et al., 2009), the Philippines and Vietnam. Under AWD, the percolation rate remains high initially when the ponding water depth is high but decreases with the progress of infiltration and decrease in ponding water depth. So, water-saving is primarily due to less percolation beyond the root zone compared to continuous flooding; the reduction in evapotranspiration plays only a minimal role (Li et al., 2011). Average water-savings under saturated soil conditions with no standing water are reported to be 23 % (±14 %) with yield reductions of only 6 % (± 6 %) (Bouman and Tuong, 2000). AWD has been reported to reduce water inputs by 23 % (Bouman and Tuong, 2001) compared to continuously flooded rice systems. There are large number of reports from small plot studies in the IGP showing large irrigation water-savings (15 % – 40 % of the applied water or up to 840 mm) with AWD in puddled transplanted rice in comparison with continuous flooding and with no or only small effects on yield (e.g., Choudhary, 1997; Hira et al., 2002; Humphreys et al., 2008b; Sandhu et al., 1980; Sharma, 1989, 1999; Zhang et al., 2009). Tan et al. (2015) reported that AWD irrigation during the 2007 and 2008 growing seasons produced a decrease in percolation by 27.8 % and 19.0 % and in nitrogen leaching by 5.0 % – 11.2 % and 3.0 % – 23.5 %, respectively compared to continuous flood irrigation. Using a modelling approach in lowland rice in the Liuyuankou Irrigation System in Henan, China, Feng et al. (2005) found that AWD gave yields similar to those of continuous flooding but saved 30 % – 60 % of irrigation water by reducing percolation by 50 % – 80 % and had little effect on evapotranspiration. AWD also has the potential of reducing greenhouse gas emissions, especially methane (Wassmann et al., 2010; Li et al., 2006). Other benefits of AWD are the reduction of arsenic accumulation in the grain (Das et al., 2016; Linquist et al., 2014), reduction of methyl mercury concentration in soil (Rothenberg et al., 2016) and reduction of energy/fuel consumption in cases where irrigation is supplied by pumping (Nalley et al., 2015; Kürschner et al., 2010).

Bund effect: Rice field develops an unsaturated zone beneath standing water during the irrigation season and that recharge is focused through the bunds/field boundaries (Neumann et al., 2009). The soil beneath the bunds of rice fields is not ploughed and puddled each year like the planted portion of the fields. Consequently, the hydraulic conductivity of the soil beneath the bunds remains higher than the rest of the fields. If the plough pan does not extend through the bunds, which is usually the case, the applied irrigation water can move through the bunds and recharge the underlying aquifer. Results of investigations in Bangladesh and elsewhere has demonstrated that a notable fraction of applied water to rice fields is not used by the rice plants but instead is lost by percolation through the boundaries of the fields (Walker and Rushton, 1984; Tuong et al., 1994; Huang et al., 2003; Janssen and Lennartz, 2009; Patil et al., 2011; Patil and Das, 2013). This type of lateral seepage flow field (first horizontal and afterwards vertical below the bunds) is termed a downward flow-type (Liu et al., 2004). On the other hand, if an old and irregularly shaped rice field is converted to a homogenous/regular rotational irrigation rice field to enhance irrigation efficiency, the plough pan may exist beneath the bunds of the new rice field. In such case, irrigated water can only move horizontally through the bund and lateral seepage may be used by the adjacent fields. This type of lateral seepage flow field is termed a horizontal flow-type. In case of terraced rice fields, the lateral seepage moves through the bunds and acts as a subsurface return flow severing the downstream irrigation need. It is noted that the lateral water flux is much lower than vertical water flux in agricultural fields (Chen et al., 1994; Zhu et al., 2012).

In a flat rice field with plough pan beneath the bunds, Huang et al. (2003) observed infiltration rate below the bunds (0.40 cm/d) that was close to the average infiltration rate of a flooded rice field. These investigators reported the percolation rate under the bunds without plough pan as double (0.85 cm/d) the average infiltration rate of flooded rice field. The simulated infiltration flux of Huang et al. (2003) beneath the bund (1.47 cm/d) after 85 days of rice cultivation exceeded that into the planted area (0.54 cm/d) by a factor of 2.72. The final infiltration beneath the bund (1.24 cm/d) also exceeded the final infiltration through the plough pan (0.68 cm/d) by a factor of 1.82. Liu et al. (2004) also reported higher simulated infiltration rate through the bunds than through the planted area of the rice fields. Simulation results of Liu et al. (2004) reveals that the lateral seepage rates of silty clay, silty loam and sandy loam below the bunds are 0.12, 0.70 and 1.50 cm/day, respectively. The lateral seepage rate of sandy loam is 1.50 cm/day, which is 3.28 times the groundwater recharge rate of sandy loam (0.457 cm/day) through the planted portion of the rice field. The lateral seepage rate of subsurface return flow of silty loam is 5.13 times the percolation rate of silty loam through the planted rice field. The seasonal model of Neumann et al. (2009) demonstrates that half of the water lost from the surface of the rice field flows through the bund, a fourth of the water is lost to evapotranspiration, an eighth is lost to preferential flow through the subsoil and a final eighth infiltrates through the soil matrix. These investigators suggest that puddling the soil underneath the bunds and rebuilding the bunds each year will significantly reduce the amount of irrigation water applied to rice fields, especially in smaller fields where perimeter to area ration is greater than in larger fields. They estimate that 41 $km^3$ of water is unnecessarily lost down the bunds each year in Bangladesh. They found that, on average, bund sealing reduces seasonal water use by 52 ± 17 % and reduces arsenic loading to field soils by 15 ± 4 %; greater savings in both water use and arsenic loading can be achieved in fields with larger perimeter-to area ratio (i.e., smaller fields). Large perimeter-to area ratios can result in > 90 % of applied irrigation water lost down the bunds and small perimeter-to-area ratios can result in almost no loss of applied irrigation water down the bunds (Neumann et al., 2014).

Puddling effect: Farmers typically puddle field soils before transplanting rice seedlings. Puddling alters field soils to stratified layers with a top puddled layer, muddy layer, plough pan and underlying subsoil layer (Liu et al., 2001; Tournebize et al., 2006). After puddling, the finer fraction of the soils in suspension creates a semi-permeable layer at the top of the puddled layer and reduces percolation rate (Kukal and Aggarwal, 2002). After long period of cultivation, a 5- to 10- cm layer of plough pan is formed usually at 20–30 cm below the ground surface. The plough pan complicates infiltration by making it a variable saturated flow problem (Liu et al., 2005). The puddling of soils before rice transplantation eliminates large pores and reduces the hydraulic conductivity of soils with consequent reduction in percolation losses of water (Sharma and De Datta, 1985; Humphreys et al., 1992). The hydraulic properties of plough pan dominantly control the water regime of puddled rice fields (Wopereis et al., 1994; Tuong et al., 1994; Chen and Liu, 2002), often forming an unsaturated zone below the plough pan (Takagi, 1960; Wopereis et al., 1992; Tournebize et al., 2006). The unsaturated soil-water regimes are also developed in rice fields due to alternate wetting and drying conditions (Tournebize et al., 2006). The extent of percolation reduction depends on puddling intensity (Aggarwal et al., 1995), puddling depth (Sharma and Bhagat, 1993), time after puddling, soil type (Singh and Wichkam, 1977) and ponding water depth (Tabbal et al., 1992). The effect of puddling on percolation rate ranges from very small to reductions from 30 mm/day to 13 mm/day on flooded sandy loam soils and from 17 mm/day to 3 mm/day on flooded clay soils (Wickham and Singh, 1977; Sharma and De Datta, 1985; Humphreys et al., 1992, 1996; Kukal and Aggarwal, 2002). Percolation losses from rice field are reported as 1–5 mm/day from clay loam soil and 5–10 mm/day from sandy soil (Bouman et al., 1994; Guerra et al., 1998; FAO, 1989; Hardjoamidjojo, 1992). The percolation rate is high during the early growth period of the crop but decreases with the passage of time by 35 % – 45 % in puddled soils.

Re-bound effect: Rebound effect is a relatively less-known proposition that an increase in efficiency of use of a resource tends to increase the rate of its consumption (Berbel et al., 2015). This important proposition draws on an old debate in economics, known as Jevon's Paradox, which claims that energy-saving technologies end up achieving the opposite of what they were intended to do. The rebound effect has been well-studied in the energy literature (Greening et al., 2000). Irrigation modernization, which is understood as the enhancement of efficiency, flexibility and reliability through the transformation of water delivery and application systems, may have consequences in terms of the amount of water used and consumed. The European Commission (2012) has identified the rebound effect as a potential problem in water resource management and it has consequently received considerable attention in the academic sphere.

The potential of water-saving technologies to actually save water is less certain than might appear at the first glance. A common assumption in the promotion of such technologies is that reducing water inputs per unit of output is equivalent to reducing water use. This assumption may not be true for two reasons. First, whether reduced inputs translate into actual water-savings depends on what would have happened to the saved water. The excess irrigation water applications often percolate to the groundwater aquifer from where they are recycled through pumping by the same or other farmers and therefore not lost or wasted (Keller and Keller, 1995). Second, economic theory tells that the new technologies may induce farmers to use more of the now more productive resource, thereby increasing overall water use (Caswell and Zilberman, 1986). Qureshi et al. (2011) point to the problem of ignoring return flows and the danger of focusing on local efficiency. Loch and Adamson (2015) further proceed to identify the rebound effect whereby when water deliveries to the farm are more valuable, the demand for water actually increases. Whether the increased value of the input is offset by decreased need depends on the particular circumstances. For example, Peterson and Ding (2005) showed that new technologies in the central United States reduced use, while Ahmad et al. (2007a) and Kemper (2004) showed that overall water use increased with the introduction of water-saving technologies in Pakistan and Yemen.

To investigate a potential rebound effect in irrigation, it is important to distinguish between water extraction and water consumption since only a part of the extracted water is consumed in irrigated agriculture as illustrated in Figure 3. Consequently, efficiency improvements do not always reduce overall water use. By definition, more efficient systems increase the share of gross irrigation that becomes net irrigation. Efficiency improvements actually reduce the effective cost of net irrigation, and producers optimally respond to this cost change by increasing net irrigation (Whittlesey, 2003; Huffaker and Whittlesey, 1995). The water-savings resulting from water-saving irrigation have not remained in the river or other storage to recharge the groundwater for ecologic use. In fact, they have instead been reused towards the expansion of irrigation croplands, resulting in even more water consumption. Pfeifer and Lin (2013) analyzed panel data for over 20,000 groundwater-irrigated fields in western Kansas from 1996 to 2005 and concluded that the shift to more efficient dropped-nozzle irrigation technology increased the amount of groundwater use. So, the water-saving technologies have little impact on reducing the groundwater overdraft at the basin scale. The medium and large farmers tended to use the field-scale irrigation savings to increase their cropped area. Therefore, without regulations and policies to regulate the use of saved water, adoption of resource-conserving technologies can result in overall increase in water use with implications for the long-term sustainability of irrigated agriculture in the basin (Masih and Giordano, 2014). The field level water-savings by resource-conserving technologies cannot be linearly extrapolated to farm, cropping system and catchment scales. The prime message is that, in a conjunctive surface and groundwater use environment, water-savings on farm that leads to more productive enterprises will tend to be reused somehow and may even stimulate greater total water use in the basin (Masih and Giordano, 2014).

## 2.4 Regional hydrology outcomes

Irrigation water is a less understood component of hydrological cycle in a region with intensive agricultural irrigation due to the lack of appropriate monitoring facilities (Hu et al., 2016). In areas with highly connected hydrologic systems, separate management of surface and groundwater causes conflict in water resource allocation between various sectors, such as irrigation, households, industry and fisheries. The separate management may also exert stress on groundwater-dependent ecosystems (Winter et al., 1998; Fullagar et al., 2006). Consequently, water managers have long been suffering from inappropriate differentiation of the natural inter-connection between surface and groundwater resources (Giordano, 2009).

Groundwater is in the EGP is a renewable resource because of its linkage to the recharge mechanisms of the annual hydrologic cycle. Water extracted from the aquifers can follow a number of pathways in the hydrologic cycle; however, in many regions, such as the North Africa, recharge occurs in geological time spans and hence the resource is not considered renewable in human use terms. Most of the pathways that do not end up to groundwater aquifers have relatively short travel times and relatively small storage capacities (Alley et al., 2002; Oki and Kanae, 2006). Recharge to the aquifers in the Indo-Gangetic Basin occurs through several major mechanisms, such as rain-fed recharge and leakage from rivers and canals. Other mechanisms can also be important in some areas, such as irrigation return flow and recharge induced by groundwater abstraction (Bonsor et al., 2017). The distribution of water by irrigation canals and its application at the field level involves potentially high rates of seepage and percolation, respectively. Xu et al. (2010) reported that canal seepage and percolation account for 48 % and 44 %, respectively of the annual groundwater recharge for the Hetao Irrigation District in China. In groundwater resource balances, such irrigation return flows mostly constitute a substantial component of recharge. Consequently, rainfall and the irrigated crop fields are recognized the two basic sources for replenishing groundwater aquifers. Among all the irrigated crop fields, rice fields are the major source for groundwater recharge because of high percolation from the irrigated rice fields (Fujihara et al., 2013; Li et al., 2014). Thus, groundwater recharge is considered an outcome of irrigated rice agriculture (Mitsuno et al., 1982; Matsuno et al., 2006; Iwasaki et al., 2013).

The major factors that influence groundwater recharge from rice fields include top and subsoil thickness, soil structure, hydraulic conductivity of plough pan layer, ponding water depth, soil puddling intensity and irrigation management practices (Chen and Liu, 2002; Kukal and Aggarwal, 2002; Lin et al., 2014). Groundwater abstraction lowers the water table in aquifers and induces groundwater recharge by either capturing surface water from rivers (Bredehoeft, 2002) and other surface water sources or by increasing available aquifer storage during the dry season thereby enhancing recharge during the subsequent wet/monsoon season (MPO, 1987). Model study of Rahman and Roehrig (2006) reveals that most rivers in Bangladesh are in direct hydraulic contact with the aquifer systems, contributing to the aquifer recharge during March to November and receiving water from the aquifers during December to February. Thus the rivers have a considerable positive influence on groundwater recharge during the wet season. The regional groundwater flow modelling in the Bengal Basin (Michael and Voss, 2009) also supports this proposition. These behaviours of river–aquifer systems have led some researchers to investigate the possibility of deliberately lowering groundwater levels in the dry season so as to increase recharge during the monsoon. The expected outcome of such intervention is to help control flooding during monsoon and to increase water reserve available for irrigation during dry season. These ideas were first put forward in the 1970s within an idea called the Ganges Water Machine (Revelle and Lakshminarayana, 1975) and have recently been revisited by some investigators (e.g., Khan et al., 2014). MacDonald et al. (2016) assembled and analyzed a large dataset of thousands of in-situ measurements from across the region. In combination with other existing databases, they assessed groundwater levels, how much of that groundwater was within the top 200 m of the aquifer and groundwater contamination. The researchers found that, despite extensive abstraction, groundwater levels across 70 % of the region are stable or rising.

Percolation from rice fields is important to the economy, environment and water resources conservation in irrigated rice-dominated South Asian countries like Taiwan (Liu et al., 2004), Bangladesh and India. Flooded rice fields resemble as an artificial wet land and serve as a major source of groundwater recharge (Tzia, 1993; Kiriyama and Ichikawa, 2004). Groundwater recharge below the ponded rice fields is therefore a significant contributor to rising groundwater levels (Beecher et al., 2002). In northern Taiwan, for example, the terraced rice fields have the most efficient groundwater recharge, with 21.2 % to 23.4 % of irrigation water recharging to groundwater (Liu et al., 2004). In the Tarim River basin of western China, where agriculture consumes over 90 % of available water resources, the water exchange flux between the unsaturated vadose zone and groundwater reservoir is influenced strongly by irrigation. Using HYDRUS-1D model Patle et al. (2017) estimated that the groundwater recharge potentials of rice fields are 69.2 cm for sandy loam and 37.2 cm for clay loam soil during one crop-growing season starting from 1 July to 30 October of 2008 (total 123 days) in the Karnal district of Haryana of India, revealing significant contribution of the irrigated rice fields to groundwater recharge. It is noted that such recharge can often become a cause of soil and water salinization when the underground aquifer contains saline groundwater and depth of groundwater table is relatively low. In Bangladesh, groundwater recharge mostly depends on infiltration from rainfall and only small portion (0.04 %) of total recharge is occurred though river water (MPO, 1987). The average infiltration rate is reported to be 1–2 mm/day to 7.5 mm/day in different parts of Bangladesh (Sir MacDonald and Partners, 1983). Approximately 11 % of the total rainfall recharges the groundwater aquifer and the rest are lost due to evaporation and drainage to the nearby water bodies (Jahan et al., 2010a). The groundwater-irrigated agriculture in Bangladesh has dramatically altered aquifer recharge behaviour and groundwater flow patterns, reducing the residence time of water in the shallow aquifer by more than a factor of two (Harvey et al., 2006). From a study in Bangladesh, these investigators reported that rice fields contribute roughly half of the water that recharges the arsenic-contaminated aquifer every year.

As an efficient approach to alleviating water scarcity, agricultural water-saving has significant impact on groundwater dynamics (Ibragimov et al., 2007; Cha´vez et al., 2009; Huo et al., 2012; Zhang et al., 2014). The adoption of water-saving technologies at the farm level can change the water cycle and crop-water use, and hydrology at regional scale (Liu et al., 2016; Yang et al., 2005). The recharge from irrigation field can be significantly modified by changes in irrigation management practices (Foster et al., 2000; 2002). Most of the water-savings under resource-conserving technologies are obtained by reduced percolation rates, which are presumed to reduce groundwater recharge with eventual decreased opportunities for groundwater irrigation. Lining canals, removing bunds, reducing water diversion and leveling farmland also reduce groundwater recharge and thus lower groundwater tables (Pereira et al., 2007). Recently, mulched-drip irrigation system has been widely applied in the Tarim River basin in China that has greatly altered the water exchange flux and thus the regional groundwater dynamics (Zhang et al., 2014). The exchange flux at the groundwater table is predominantly downward during drip irrigation period. However, after the application of water-saving irrigation technologies, the downward exchange flux is greatly reduced during irrigation periods (Zhang et al., 2014). As discussed before, water saved at the farm level does not always mean water-saving when considering the whole irrigation system. Water lost from individual fields by seepage and percolation enters the surface flow system through streams, drains and subsurface system through groundwater, especially shallow groundwater. Where the surface and subsurface water systems have potential to be utilized downstream, field-level water-savings upstream do not lead to water-savings at the system level. Therefore, the water-saving measures with high irrigation efficiency at large scales can lead to significant decline in groundwater levels (Tabbal et al., 2002) and exert negative impacts on hydrology and ecology. The major negative impacts are degradation of soil quality and deforestation by deterioration of vegetation, which are particularly apparent when declining groundwater levels occur in arid regions (Chen et al., 2016).

Groundwater depletion has been recognized as a global problem that threatens the sustainability of water supplies (Mays, 2013) except where the depleted aquifers are completely replenished during the wet period of each hydrologic cycle. The groundwater table has declined substantially in many parts of the Eastern Gangetic Plain over the last decade, threatening the sustainable use of water for irrigation and drinking water supplies (Jahan et al., 2010a, 2010b; Shamsudduha et al., 2012; Shahid, 2008; Shahid and Behrawan, 2008). Frequent water shortages in this region have had an economic, social and environmental impact (Takara and Ikebuchi, 1997; Sajjan et al., 2002; Dey et al., 2011). Although MacDonald and colleagues reported that less than one-third of the Indo-Gangetic Basin has experienced declining groundwater levels over the past decade, the areas of decline are critically situated near high-population centers, where the impacts are potentially alarming. With decades of large-scale withdrawal and low recharge, the large urban areas (e.g., Dhaka city) already have deep water tables, which continue to drop with time (Fendorf and Benner, 2016), indicating groundwater overdraft. Groundwater overdraft occurs when the rate of groundwater extraction plus natural discharge from the aquifers exceeds the total recharge to the aquifers during an extended period of time. However, MacDonald and colleagues recounted that the most widespread threat across the entirety of the Indo-Gangetic Basin is not the diminished groundwater quantity, but degraded water quality resulting from high arsenic and salt contents. In Bangladesh, emphasis has been given recently on increasing dry season Boro rice production in the southern zone to reduce stress on groundwater use in the North-West region (MOA and FAO, 2013). This approach is also promoted partly to offset increasing production and energy subsidy costs in the existing Boro areas in the North-West region that predominantly relies on groundwater irrigation. However, the viability of this approach remains in question given the southern region’s soil and water salinity constraints along with the problems with coordinated water governance and concerns over the anticipated long-term effects of climate change (Bell et al., 2015; Bernier et al., 2016; Qureshi et al., 2015; Mainuddin et al., 2019b).

The national-scale dynamics of groundwater recharge in Bangladesh provide three fundamental possibilities regarding the relationship between groundwater recharge and abstraction. These possibilities are: (i) that the rates of groundwater recharge can change substantially in response to abstraction, (ii) that potential recharge can greatly exceed actual groundwater recharge, and (iii) that the magnitude of the difference between potential and actual recharge provides a measure of possible increase in groundwater recharge, which may be realized through more groundwater abstraction (Shamsudduha et al., 2011). These investigators reported growing evidence that increased pumping in areas with shallow water tables and permeable soils induces groundwater recharge by creating significant vertical head gradients. In many cases, water harvesting captures wet season flood waters that would have had little or no human or environmental benefit and might even have caused flooding. So, capturing it by drawing down the water tables in the dry season, may have a positive effect on overall water availability (Giordano, 2009), especially in dry season. Groundwater recharge has increased substantially in the North-Central, North-Western and parts of the South-Western Bangladesh following the widespread adoption of groundwater-fed irrigation for dry-season Boro rice cultivation in the 1980s. The net recharge in many parts of Bangladesh has been reported to increase by 5 to15 mm/year between 1985 and 2007 in response to increased groundwater abstraction for irrigation and urban water supplies, with the greatest increase in the areas where the density of groundwater-fed irrigation is the highest (Shamsudduha et al., 2011). During the dry season, mean seasonal groundwater recharge has increased and almost doubled over the last 29 years as a result of increased abstraction for irrigation. The investigators reported anomalous reductions (−0.5 to −1 mm/year between 1985 and 2007) in groundwater recharge in areas of low groundwater abstraction for irrigation.

## 2.5 Gaps in current knowledge

### 2.5.1 Uncertainty in water-saving

Conservation agriculture has been reported to primarily exert positive effects on the environment, such as increasing yield, saving fossil fuel and water, and reducing emissions of greenhouse gas. However, these environmental impacts are yet to be verified and valued more rigorously (Akhtar, 2006; Erenstein and Laxmi, 2008; Hobbs and Govaerts, 2009; Pathak, 2009; Sarwar and Goheer, 2007). While the impacts of resource-conservation technologies on crop yields are easy to measure and explain, impacts on water-savings are not yet well understood beyond the field scale because of the complex pathways for the movement of water (Masih and Giordano, 2014). Puddling is usually done to reduce percolation loss of water from rice fields where water flooded in the fields. Puddling causes structural changes in the top soil layer (0–20) leading to the formation of a plough pan of reduced hydraulic conductivity, which reduces percolation loss. Some investigators (e.g., Garg et al., 2009) however claim that soil cracking and presence of preferential flow paths in the puddle fields defeat this purpose. Water-saving technologies can be successful in improving field-scale irrigation efficiency (Gupta et al., 2002; Humphreys et al., 2005), resulting in savings in water application. But, the question remains whether the on-farm water-saving practices make any real water-savings that can be transferred to other agricultural and non-agricultural uses (Loeve et al., 2002). Saving water can be vague since reducing seepage, percolation and runoff losses from fields may not necessarily save water unless it can be recaptured at some other temporal or spatial scale. Whether or not improved irrigation efficiency translates to real water-savings actually depends on the hydrologic interactions between the field and farm, and between the irrigation system and the entire river basin. The field-scale water-savings do not necessarily translate into reductions in overall water use for two reasons. First, some of the water saved would have percolated into the groundwater table from where it would later be reused by farmers through pumping. Second, the increased crop-water productivity for medium and large-scale farms under resource-conservation technologies can make water use more profitable and hence increase water demand. If a farmer is able to increase the irrigated area while reducing percolation to a usable aquifer or return flows to downstream users, the overall impact is an increase in local water consumption and less water available for other users or at other times in the year (Perry et al., 2017).

Many resource-conservation technologies appear to save substantial amounts of water through reducing irrigation water requirement at field-scale. However, the effects of these technologies on real water-savings and overall levels of water use at larger scales (Masih and Giordano, 2014) are poorly understood at the farmers' field-scale and have hardly been considered at the higher spatial scales, since the components of the water balance have not been well quantified yet (Humphreys et al., 2005). Very few studies have so far determined the effects of alternative crop technologies on evapotranspiration and drainage/percolation and whether the drainage losses at the farmers' field scale are losses at the higher spatial or temporal scales and thus the real water-savings. It is possible that the real water-savings are much lower than what might be assumed when field-level calculations are extrapolated to larger scales because of water recycling and conjunctive use of surface and groundwater in many, particularly rice-based, cropping systems (Ahmad et al., 2002; Humphreys et al., 2005; Tuong et al., 2005). From the broader perspective of irrigation management and policy within the context of water resources as a whole, the concept of classical irrigation efficiency for an entire river basin is erroneous and misleading. The discrepancy arises since the water losses with respect to which the classical irrigation efficiency is calculated are not necessarily real water losses to the system as a whole. Many of the reported water losses are only losses on paper since they are captured and recycled elsewhere in the system (Seckler et al., 2003). While the destination of lost water is not correctly known, it is not possible to be clear as to the extent of water-savings (Perry et al., 2017). It is still not clear how water-saving irrigation alters the overall water balance dynamics and, in the long term, how it affects the evolution of human–water systems. There is also concern about whether sustainable development can be maintained by the application of water-saving irrigation and what additional steps we should take to implement better water management in the future (Zhang et al., 2014).

### 2.5.2 Uncertain causes of groundwater decline

Over-exploitation of groundwater, increased Boro rice cultivation, depletion of river water levels, reduction in wetland areas, decline in annual and dry season rainfall, lack of water conservation through artificial replenishing methods and low recharge potentiality of the soils are considered the key barriers to sustainable groundwater use for irrigation in the Indo-Gangetic Basin. These factors have resulted in the groundwater level declining in some areas of the region.

In areas with groundwater pumping for irrigation, reducing irrigation application is considered by some authors to be effective in reducing the rate of groundwater depletion (Kendy et al., 2004; Yang et al., 2006; Kumar and Gupta, 2010). Contrasting results are also reported: for example, in field experiments for maize, sunflower and watermelon crops, Ren et al. (2016) demonstrated that the shallow groundwater declined due to reduced irrigation application, while Xu et al. (2010) came to the similar conclusion in Hetao irrigation district in China. This raises question of how far irrigation return flow contributes to groundwater recharge. The relation between groundwater depth and groundwater recharge in the North-West Bangladesh reveals continuous increasing depth of groundwater with little response to groundwater recharge from irrigated rice field during dry season (Mustafa et al., 2016). The increased crop-water productivity for medium and large-scale farms under resource-conservation technologies can make water use more profitable and hence increase water demand and groundwater depletion through expansion in cropped area. However, there is still a lack of regional-scale study to evaluate the impact of agricultural water-saving on groundwater dynamics and evaporation (Yeh and Famiglietti, 2009; Feng et al., 2005), which must be reduced to prevent groundwater depletion (Humphreys and Gaydon, 2015b). Fishman et al. (2015), therefore, note that technology adoption and demand side management is not the only policy instrument for stabilizing groundwater tables. Whether conversion of conventional agriculture to conservation agriculture would help solving the problem of groundwater depletion is yet poorly understood. So, merely taking into consideration the magnitude of groundwater depletion is not a proper way of identifying problems related to sustainability issues of groundwater use (Dey et al., 2017). In addition to demand side management, supply side management through artificial recharge or alternative from surface sources may also need to be considered in certain situations (Dillon, 2005; Sharda et al., 2006). A combination of three factors: demand management, recharge enhancement and alternative supplies needs to be investigated for its feasibility to sustain or prolong groundwater resources and maximize the value of their utilization (Dillon et al., 2012).

### 2.5.3 Inadequate understanding of scale-effects

While it is important to ensure efficient use of water supplies by improved transmission and irrigation methods, this may cause reduced recharge to aquifers and hence lower availability of water to farmers relying on groundwater for agriculture. This problem requires a systems approach to determine the water balance at different scales as deep percolation losses from one administrative or hydrological unit may be reused in another unit (Rushton, 1999; Seckler, 1996). Also, the water lost through deep percolation from one hydrological unit may undergo geochemical changes before it becomes available as groundwater in another hydrological unit. This necessitates consideration of water-quality implications in the reuse of water in groundwater-dominant systems (Khan et al., 2002a). Adoption of a system approach is needed to identify proper water-saving options so that they can account for all surface water and groundwater use, losses, and interactions at the catchment, irrigation field and farm levels (Khan, 2007). A system approach is presumed to remove the technical, economic and institutional barriers to achieve real water-savings.

The basin approach (a system approach) of water accounting, as described before, entails that in closed basins there are no significant water-savings or new water to be gained through efficiency improvement , since all losses are presumed to be re-captured and re-used somewhere else downstream. The implication of resource-conserving technologies for many water-stressed regions is that there is no potential to reduce water stress or increase resilience through improved water use efficiency. The basin concept although useful to clarify some issues in the scale and scope of water use efficiency, has three fundamental flaws (Frederiksen and Allen, 2011). The major flaws are: (i) the basin approach excludes or discounts a major component of inefficient water use (the unproductive consumptive use), (ii) the basin approach does not adequately assess the broader measure of water productivity since it only values new water, and (iii) the basin approach fails to account for many non-water co-benefits of efficiency, including improved water quality, greater reliability, decreased energy demands and associated greenhouse gases and reduced or delayed infrastructure investments. The evaluation of the impact of water-saving technologies at the field and farm scales on the availability of water at larger scales is very complex. It requires the use of approaches that can integrate the plausible effects over space and time (Khan et al., 2002a, b; Khan et al., 2003). Several investigators (e.g., Bizhanimanzar et al., 2019, 2020; Diaz et al., 2020) proposed 3-dimensional surface-groundwater interaction models in this regard, but some of the problems still remain unexplored. The regional configuration of the water resources system and the way it is managed strongly determine the possibilities for reallocation and thus the overall effectiveness of water-savings (van der Krogt and Verhaeghe, 2002). The water-savings at the field level must be translated into water availability for other purposes at a larger scale. Then, according to these investigators, the alternative use of the saved water can determine its value.

### 2.5.4 Complex transient recharge and groundwater use

Groundwater recharge occurs through a variety of processes and water sources under varying levels of complexity. Operation of inefficient irrigation systems, which allow surface supplies of water to seep into the groundwater table, is perhaps one of the best methods for recharge. This is already playing a major role in recharging the aquifers in parts of India, Pakistan, Bangladesh and elsewhere (Giordano, 2009). So, common perception for more efficient irrigation systems to prevent such losses must therefore be viewed with caution.

Quantification of recharge under irrigated agriculture is one of the most important but difficult tasks. It is the least understood component in groundwater investigations because of its large variability in space and time, and the difficulty of its direct measurement. The main factors that control groundwater recharge under irrigated agriculture are soil type, irrigation management, water table depth, land cover or plant-water uptake, conditions of soil surface, and chemistry of soil, irrigation water and groundwater (Riasat et al., 2014). An accurate quantification of groundwater recharge under irrigated systems is also crucial because of its potential impacts on soil profile salinity, groundwater levels and groundwater quality. Although various studies have been carried out to examine groundwater flow and recharge from rice fields (Elhassan et al., 2001; Chen and Liu, 2002; Chen et al., 2002; Anan et al., 2007), the effects of land use conditions, in particular rice fields and crop-rotated areas, on groundwater recharge and groundwater level remain unclear (Iwasaki et al., 2014). Groundwater recharge, both from the rainfall and surface water bodies, occurs under transient condition as a response to groundwater withdrawal (Shamsudduha et al., 2011). It is not straight forward, even on a field scale, to determine the difference between groundwater removal (through tubewell, capillary rise, subsurface flow, etc.) and recharge to the aquifer. To comprehend these complex transient recharge and groundwater use processes, a complete understanding of soil-water fluxes in the unsaturated zone is essential (e.g. Hendrickx and Walker, 1997) but still lacking. Better management of groundwater resources is only possible if all the fluxes going into and out of a groundwater system can be accurately determined (Riasat et al., 2014). Reducing the current uncertainty in groundwater recharge under irrigated agriculture is to be addressed a pre-requisite for effective, efficient and sustainable groundwater resource management, especially in dry areas where groundwater usage is often the key to economic development.

### 2.5.5 Weakness in policy

The concept of water management in agriculture has changed over the years. In the past, agricultural water management concentrated attention mainly on irrigation options and water withdrawals from rivers and aquifers. Now, water management considers options across a spectrum of water management in agriculture, including rainfed and irrigation, and integrating fisheries and livestock. It devotes more attention to managing rainwater, evapotranspiration and water reuse, and views land-use decisions as water-use decisions (Molden and De Fraiture, 2010). It also incorporates the interconnectedness of water users through the hydrologic cycle. Expanding agricultural land to increase production was the primary thinking previously that has changed now to intensify agriculture by increasing water and land productivity to limit additional water use and expansion onto new lands. Environmental water use was viewed as wasted water in the past, but current view considers proper economic valuation of the environmental aspects of water use in tradeoffs and decisions for water use. In light of such current perceptions of water management, the key to achieving real and substantial water-savings lies in the technical, economic and institutional assessment of water-saving options in the context of a whole system (Khan, 2007). This is because even when technologies reduce water applications per unit of crop output, they may not reduce actual water use unless institutional arrangements are in place to limit demand of water, which is a big challenging under-taking in any region (Ahmad et al., 2007b; Masih and Giordano, 2014). For example, technologies to increase water productivity may actually increase overall water use (the rebound effect) if there is no institutional arrangement to limit individual user’s abilities to further utilize the saved water, which is now more productive to use (Giordano, 2009). Despite such counter-intuitive evidence, promoting water-saving technologies is still a popular policy instrument of groundwater governance in many countries, such as China, India, Bangladesh, Mexico, Spain and the USA. Most governments allocate substantial budgets to subsidize the adoption of micro-irrigation, mainly inspired by the widely-held belief that it can save groundwater (Shah, 2014). However, lack of attention, no strict legislation and ineffective institution to manage groundwater are common in developing and underdeveloped countries (Mechlem, 2016). The problems of groundwater management can become even more complex when aquifers are shared between two or more independent states (Giordano, 2009).

Shallow alluvial groundwater resources, such as in the Eastern Indo-Gangetic Plains, play a vital role in sustaining global agricultural activities through cropland irrigation. When farmers massively adopt water-saving technologies, groundwater recharge through percolation becomes less, leading to decline in groundwater tables. However, the declining groundwater table, in some cases, can increase the percolation rates by increasing hydraulic gradient or storage space in the aquifer; this offsets the gains in water-saving by the water-saving irrigation technologies. The recharge of shallow aquifers is therefore an important mechanism that needs to be well-understood for effective management of the aquifer (Duvert et al., 2015). The classical irrigation efficiency continues decreasing as the scale of the system extends because of increasing water losses. But, in terms of net efficiency, the opposite is the true: as the scale increases the efficiency generally increases because of increased water recycling (Seckler et al., 2003). The exception to this proposition occurs when water recycling is not feasible in the system level. For example, under saline ground-water conditions, improvement in classical irrigation efficiency by reducing percolation to recharge the underlying aquifer will contribute to real water-savings, sustainable crop intensification and increase food production (Masih and Giordano, 2014). The early groundwater regulation often erroneously suggested that the safe yield of a groundwater basin is the rate of natural groundwater recharge (Alley and Leake, 2004). This water budget myth completely ignores the fact that groundwater extraction can often lead to increased recharge and/or decreased discharge from the aquifer (Bredehoeft, 2002; Devlin and Sophocleous, 2005; Zhou, 2009). Consequently, many water managers have long been suffering from inappropriate differentiation of the natural interconnection between surface and groundwater, and the creation of separate surface and groundwater governance, policy and bureaucracies (Giordano, 2009). The term 'irrigation efficiency' can be a source of major miscommunication and misunderstanding at the policy level in both the agriculture and water sectors (Perry, 2007). The groundwater systems have to be understood as complex systems that react dynamically to the perturbation introduced by extraction. A more rigorous and consistent concept for accounting the soil-water zone in irrigated agriculture is crucially necessary (Foster et al., 2009; Hoekstra, 2019; Zhu et al., 2019). Such concept enables assessment of the impacts of change and interventions to be prioritized (Foster et al., 2000; 2002). The actual relation between the field-level hydrology and system level hydrology is still not well-understood. But, such relation is critically important to predict the large-scale and long-term effects of the introduction of water-saving irrigation technologies at the field level (Tabbal et al., 2002). A water balance is generally regarded as fundamental to the understanding of water availability in a region and hence to the development of sustainable policies and plans for water management (Molden and Sakthivadivel, 1999).

While the problems of groundwater are clearly intuitive, the solutions are not. Many of the problems of water-resources management are often due to the implementation of false, erroneous or misapplied concepts of efficiency in water-resources policy and management (Seckler et al., 2003). Effective governance is considered a prerequisite for a sound water resource management (Bhattacharjee et al., 2019) although it is lacking in many countries. Attempts to ban tubewells in some countries to reduce groundwater extraction have largely failed. Undertaking a similar policy in the Indo-Gangetic Basin would be unrealistic in the foreseeable future because of their political structures and systems. In India, several states already have elaborate legislation to control groundwater overdraft, but their enforcement has so far completely failed (Narayana and Scott, 2004; Phansalkar and Kher, 2003; Shah, 2009). However, other policy approaches relating to the cost of pumping (e.g., electrification of irrigation wells, introduction of solar irrigation pumps) are having a bit more success (Mukherji et al., 2020). The lack of robust information on aquifer reserves, their withdrawal patterns, changes in quality and consequences of use for irrigation are poorly understood in Bangladesh (Qureshi et al., 2015), which has risked the sustainable use of groundwater, especially in agricultural purpose. In the North-West Bangladesh, the crucial element is to estimate optimum amount of groundwater extraction for sustaining rechargeable groundwater aquifers in order to keep the groundwater level and irrigation cost stable (Salem et al., 2017). Direct management of groundwater through the introduction of groundwater use rights and limitations on groundwater access by enforcing permit systems is probably not a viable solution for Bangladesh due to large number of users and ineffective institutional arrangements to ensure implementation of laws and regulations. Therefore, a well thought-out, rational, patient and persistent strategy would be needed to address the issue of groundwater management. Efficient irrigation management practices, such as low water-demanding high value crops, volumetric water charging system, wet and dry irrigation system, etc. have been often thought to reduce excessive withdrawal of groundwater (Dey et al., 2017). Some of the potential drivers of success necessarily may include heavy engagement of users, refinements in water pricing structures, substantial investments in modern water and agricultural technology, provisions to encourage farmers' transition into less water-demanding crops, and the development of the enabling policies and decision-support systems. Water management options in terms of in situ rainwater conservation, deficit irrigation and modifying rice–wheat areas are other possible interventions to be adopted for managing groundwater (Ambast et al., 2006). Policy research, however, must address which options might be the best for future groundwater governance in Bangladesh (Qureshi et al., 2015). In Nepal, although the policy visions and frameworks for water resource management have aimed at sustainably managing water resources, there is a lack of their effective implementation (Regmi and Shrestha, 2018). Developing new policy visions are not synchronously linked to the new and evolving issues like climate change. Consequently, the water related policies are currently underperforming. The lack of functioning of local institutions has increased vulnerability of the communities.

The favorable hydrological conditions (e.g., rainfall, flood) of the IGP indicate possibility of artificial recharge to aquifer to manage declining groundwater. The artificial recharge of aquifers through natural drains, abandoned canals and topographical depressions is a technically feasible and economically viable option (Ambast et al., 2006). Rainwater harvesting and potentially active recharge may also be used to replenish groundwater levels and help curbing the continued declining levels. Limiting evaporative loss within the agricultural sector where groundwater depletion is a concern may also serve preserving sustainable groundwater levels (Fendorf and Benner, 2016). For many areas in Bangladesh, if groundwater-irrigated areas are not further increased, the rate of decline in groundwater levels may likely reduce and groundwater levels may even attain a new equilibrium at a lower level. This proposition means that current pumping rates can be maintained, subject to the assumption that the lower groundwater levels will be acceptable on environmental, economic and social grounds (Kirby et al., 2015). The post-monsoon groundwater levels are largely influenced by yearly rainfall variability. Thus, groundwater use in some areas may not be as unsustainable as considered. According to Kirby et al. (2015), policies to reduce groundwater use in such areas may not be as necessary or urgent as thought. However, all these potentials are propositions and there is no single solution for groundwater management, since climatic, hydrologic, political, social and economic conditions vary radically between different affected regions. It will be crucial to choose regionally-adapted strategies from a range of options and strengthen regulation, policy and management for water, energy and agriculture (Giordano, 2009; Theesfeld, 2010; Sophocleous, 2000). So, identification of appropriate, adaptable and sustainable long-term strategies for each region and finding ways to transfer knowledge and measures between regions are the important topics for future research (Aeschbach-Hertig and Gleeson, 2012).

# 3 Field case studies: improving water use for dry season agriculture in the Eastern Gangetic Plains

The Eastern Gangetic Plains (EGP) is one of the most densely populated, poverty-stricken belts in South Asia. Poor access to irrigation water in the dry season, limited investment capacity, and limited access to agricultural knowledge flows, combined with entrenched social structures of class and caste, have for decades impeded the sustainable intensification of agriculture. In spite of chronic food insecurity amongst a majority of rural households, large areas of land remain fallow during the dry months (Schmidt, Sugden & Scobie 2014).

The EGP is a region undergoing considerable environmental and economic stress, impacted by climate change, weak formal and informal institutions, rising costs of agricultural production and severe social inequalities. Technical, social and economic constraints limit effective use of irrigation, with low agricultural productivity, which impacts food security and resilience.

There is significant focus on diversification and intensification to improve food, energy and water security. However, there are often trade-offs and interactions in resource consumption (e.g. water and energy) and productivity as a result of intensifying and diversifying farming systems. Impacts at the field level may be different at the landscape level. Furthermore, institutions also need to adapt to better support diversified systems, for example in terms of access to information, different inputs, resources and market options (ACIAR, Diversification for sustainable food systems in South Asia. ACIAR SDIP Workshop. 10th – 11th December 2018).

Sustainable production intensification (SPI) is widely recognised a key element for improving livelihoods of marginal and tenant farmers. Increasing or improving water use at farm scale is a very tangible action that can drive sustainable intensification. In some cases, this may mean using more water than has previously been used but with significant potential increases to production (either yield or quality). However, this additional water must be used in an efficient manner, and monitoring and data collection will help in determining success or failure.

Methods to integrate knowledge from field scale projects, into local and regional scale initiatives need to be further developed. Assessing the impact of out scaling of farming systems and expanded agricultural practices on sustainable water resources is key.

In this Section, we describe irrigation and cropping systems commonly practiced across the Eastern Gangetic Plains drawing on case study examples from the previous ACIAR funded project 'Improving water use for dry season agriculture by marginal and tenant farmers in the Eastern Gangetic Plains (DSI4MTF, LWR 2012 79)' in Bihar and West Bengal (India), and Saptari (Nepal). This project sought to improve the understanding of the impact of farm scale water saving measures on the regional sustainability of water management. Linking field-based community and farmer led irrigation water management learning to larger (district/catchment) programs is important. This includes assessment of field scale irrigation scenarios on catchment/district level water management and sustainability using water balance models to better understand resource use efficiency.

The DSI4MTF project showed how irrigation by collective farming groups could improve agricultural productivity, increase incomes and provide food security to marginal communities, which comprise 60-80 % of farmers in the EGP (Schmidt et al. 2019). The project interventions saw cropping intensities increase from 120 % to (in some cases) over 200 %. Efficient irrigation practices and production improvements were demonstrated, and community-based water resource monitoring and irrigation performance assessments were implemented. Upskilling of farmers in vegetable production, water management, irrigation systems, and pumping efficiency occurred.

The Section aims to explain the nature of smallholder farms and describes some of the water use efficiency and crop production practices that have been implemented at a farm level. However, as indicated above, there is a disconnect between farm scale attempts to improve water use efficiency and basin scale modelling. This Section explains the utility of farm scale data to farmer decision making and introduces some policy and institutional aspects for sustainable water use. The importance of data collection, modelling and decision making at both the farm and catchment level is highlighted.

## 3.1 Study Sites

The DSI4MTF project operated in the districts of Madhubani and Cooch Behar in India and in Saptari District in Nepal shown below in Figure 4. Case studies presented in this section are from data collected from these sites between 2014 – 2019.

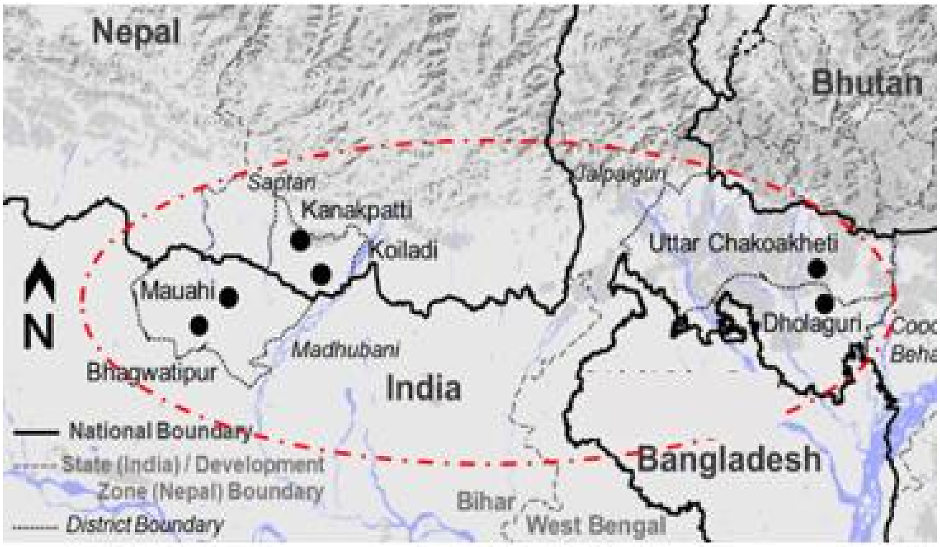


Figure 4: Location of study region in the DSI4MTF project

### 3.1.1 Saptari District

Saptari District lies in the Nepal Terai and is generally flat terrain with an altitude variation between 60m and 610m. The climate is sub-tropical to tropical with average temperatures varying from 16$^{o}$C in winter to 29$^{o}$C in the summer, with an annual rainfall of between 1,600 mm and 2,100mm.

The main aquifer underlying the district is variable along a north-south transect with relatively higher water tables to the south and lower water tables to the north towards the foothills of the Himalayas.

Despite the high precipitation and high-water tables, drought is a common challenge as much of the precipitation falls within the monsoon period from June to September with the rest of the year generally dry.

The cropping pattern generally falls into two seasons, Kharif (May to October) and Rabi (November to April). Apart from these two main seasons, a small number of farmers grow vegetables and other summer crops, between the main seasons, by either changing the planting/harvesting dates of the main crops and/or foregoing a season of the main crops. Constructed ponds are used for fish production or household use and not for irrigation. Irrigation is predominantly from shallow tube wells, with some water being extracted from surface water streams.

The project selected Two villages in Saptari District. At Koiladi Village two demonstration sites were established with a total area of 1.9ha. At Kanakpatti Village three demonstration sites were established with a total area of 2.3ha.

### 3.1.2 West Bengal

The study sites of West Bengal encompass both the pure Terai sites of Dholaguri (Cooch Behar district) to the south and the hill areas of Uttar Chakoakheti (Alipurduar district) to the north.

These two villages, though different in topographical, cultural and social characteristics are agriculturally similar with Kharif paddy as the dominant crop grown. Due to the cultural agricultural background, Dholaguri has a more robust crop production system than Uttar Chakoakheti where the residents still consider forest product harvesting a major activity outside the monsoon growing seasons.

At Dholaguri Village, three demonstration sites were established with a total area of 3.4ha. The site is characterised with Eutric Haplic Gleysols with sandy clay loam texture. The average temperatures across the region range between 12$^{o}$C – 22$^{o}$C in winter and 27$^{o}$C - 33$^{o}$C in summer. The average annual rainfall is 5,300mm, mainly from the South-West monsoon. Dholaguri village is rich in both surface and subsurface water resources. There is one perennial river, the Ghargharia, with over 20 ponds, which are seasonal and used mainly for fish production with only minor supplementary irrigation in drought years. There is a high density of shallow tube wells used for both domestic and irrigation purposes. The depth to groundwater varies between 1.5 to 4.5 m.

At Uttar Chakoakheti Village four demonstration sites were established with a total area of 7.2ha. The Uttar Chakoakheti study site is dominated by Haplic Gleysol soil with sandy clay loam soil texture and high infiltration capacity. The district is characterized by a warm and humid climate with summer temperatures ranging from 25-37$^{o}$C and winter temperature averaging between 6-18$^{o}$C. Six ponds were located in the project area, however due to the high infiltration capacity of the sandy soil material, no substantial storage is retained for summer irrigation. Depth to groundwater typically varies between 0.5 – 3.0m after monsoon rains and 4-6m at the end of the dry summer season.

### 3.1.3 Madhubani District

Madhubani District has an average annual rainfall of approximately 1,200mm, winter temperatures of 9-22$^{o}$C and summer temperatures of 27-36$^{o}$C. Madhubani, geologically lies along the alluvial plains of the north Terai, characterized by low-lying waterlogged areas, classified as an Entisol.

Two villages were selected in Madhubani. At Bhagwatipur village, four demonstration sites were established with a total area of 5.5ha. At Mauahi Village one demonstration site was established with a total area of 2.2ha. Bhagwatipur site is composed of Haplic Vertisols with higher clay contents (around 33 %). The soils are generally neutral with soil pH of around 6.6 and soils within 90cm of ground surface are generally of clay loam structure.

Across the greater Bhagwatipur village 16 permanent and 9 temporary ponds were identified with size ranging from 200 – 17,000 $m^2$. Most ponds are used for fishery and domestic use, although a few are used for supplementary irrigation, especially during land preparation and minimal dry season vegetable cropping. Depth to groundwater range between 2-3m below ground level in September and 4-5m below ground level in July. Four demonstration sites were established with a total area of 5.5ha.

Soils in the Mauahi Village area are classified as Haplic Vertisols, with high clay contents above 30 %. Seventeen temporary ponds and twenty-four permanent ponds ranging in sizes from 200$m^2$ to 15,000$m^2$ were identified. Monsoonal rain and recharge fill the ponds with gradual decline in water depth due to seepage and evaporation loss with occasional sharp drop in the water levels during an irrigation-pumping event. The groundwater level varies significantly across Mauahi Village both temporally and spatially. Greatest depth to groundwater is 6m recorded during pre-monsoon pumping for paddy field seedbed and field preparations. One demonstration site was established with a total area of 2.2ha.

## 3.2 Cropping systems

The cropping systems in the Eastern Gangetic Plains are both determined and dominated by the relative strength or weakness of the annual monsoon season. Highest temperatures are generally observed in the period between May and June. While average annual rainfall varies across the region, most of the rainfall is concentrated in June to September. There is also very high year to year variability in rainfall (Kirby et al. 2013).The monsoon or Kharif season is generally rice paddy growing season with much of the rural landscape covered by bunded paddy fields. Once the paddy has been harvested there is a two - six-week period where farmers decide on planting a Rabi season crop. The majority of the low land farmers will opt for a wheat or a legume crop. This is dependent on the recession of the monsoon, but also on the risk appetite and cash availability of the farmers. The lentil or legume crops are considered locally to not require irrigation (modelling may suggest otherwise) but wheat crops are grown with one or two irrigations at key growth stages. High value vegetable crops, potato, maize or jute can be grown depending on local conditions and farmer preference, but generally require irrigation for profitable yields.

The summer season sees much of the landscape of the EGP left fallow with a very low percentage of cropped area. The exception to this is in the North West Region of Bangladesh where extensive Boro rice production dominates requiring extensive groundwater irrigation (Kirby et al. 2013).

Poor socio-economic conditions and limited irrigation infrastructure resulted in low crop diversification in the EGP. This has resulted in poor nutrition and food insecurity from local extremes of weather.

The DSI4MTF project introduced irrigation infrastructure including shallow tubewells, pumps and irrigation systems, giving opportunity for dry season agriculture and a range of new crops (Table 1 and

Table 2). Technical support and training on irrigation, agronomical practices, pest and disease control, as well as access to better seed and inputs was critical to this transition.

Table 1: cropping systems at project sites after intervention

| | SAPTARI | | | | | | | | | | | | WEST BENGAL | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S-16 | Kh-16 | R-16, 17 | S-17 | Kh-17 | R-17, 18 | S-16 | Kh-16 | R-16, 17 | S-17 | Kh-17 | R-17, 18 | S-16 | Kh-16 | R-16, 17 | S-17 | Kh-17 | R-17, 18 |
| Rice | | ■ | | | ■ | | | ■ | | | ■ | | | ■ | | | ■ | |
| Wheat | | | | | | ■ | | | ■ | | | ■ | | | ■ | | | ■ |
| Legume | | ■ | | | | | ■ | | | ■ | | | | | | | | |
| Vegetables | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | ■ | | | ■ | | | ■ |
| Oilseed | | | ■ | | | ■ | | | | | | | | | ■ | | | ■ |
| Maize | ■ | | | | | | | | | | | | ■ | | | | | |
| Green Manure | | | | ■ | | | | | | | | | | | | | | |
| Jute | | | | | | | | | | | | | ■ | | | ■ | | |

1. Where S is summer, R is Rabi, Kh is Kharif.
2. Vegetable crops indicated in Table 2
3. 16, 17, 18 indicate the years 2016, 2017, 2018

Table 2: New crops introduced through project interventions

| Location | Rabi Crops Introduced | Summer Crops Introduced |
|---|---|---|
| Madhubani | Peas, potato, radish, cauliflower, spinach, and lentil, | Chilli, cowpea, cucumber, brinjal, gourd, ladyfinger and moong bean. |
| Saptari | Cabbage, cauliflower, garlic, onion, brinjal, tomato, potato, radish, coriander and lentil. | Chilli, cucumber, bitter gourd, ladyfinger, pumpkin, zucchini, cowpea, and moong bean. |
| West Bengal | Rapeseed(mustard), wheat, maize, potato, tomato, cabbage, lentil, garlic | Jute, brinjal, gourd, cucumber, beans |

Introduction of dry season irrigated production systems during DSI4MTF resulted in substantial diversification and realised a variable but generally positive economic return. Case Study 1 illustrates the economics of these irrigated cropping systems. There has been expansion into neighbouring farms and the regional hydrological impact of these practices is an important consideration.

### 3.2.1 Case Study 1: Economics of irrigated cropping systems.

The introduction of dry season irrigated vegetables has shown potential to improve financial return, food security and nutrition. Profitability is not the only driver for these communities. Improved nutrition, family tradition and self-empowerment are key benefits from diversified farming practices. Crop choice is often about cultural preferences, experience, risk aversion, market limitations, local consumption needs, as well as labour and input cost requirements.

## Crop Intensity and Diversification

With the introduction of irrigation and following the establishment of the farmer collectives cropping intensity increased markedly. Cropping intensity in Nepal and India sites, prior to the project, ranged between 100 % and 120 % and increased following introduction of a range of dry season crops through collectives to more than 200 % across Madhubani sites, between 136 % and 229 % in Saptari sites, and between 136 % and 205 % in West Bengal sites.

Notwithstanding crop intensification and diversification, production areas and volumes were small, limiting market access and bargaining power. In many cases production by groups was diverted first for home consumption, benefiting household nutrition. There was significant movement between crops and across seasons in response to changing farming and market conditions. Farmers selected crops in consultation with project staff and adapted to several challenges, including, pest and disease incursions, access to water, high irrigation costs, labour availability, low market prices, poor market access and poor yields due to early monsoon rainfall.

## Crop Yield

Crop yield was highly variable, impacted by many factors, including timing of planting and harvest, weather conditions, timing of irrigation, pest and diseases and fertilizer management. Table 3 provides typical yields of selected crops. Rice and wheat yields were in line with the national India average yield of 2.5 t/ha (rice) and 3.0 t/ha (wheat) and Nepal 3.3t/ha (rice) and 2.5t/ha (wheat). Vegetable yields were highly variable depending on the management skills and degree of input use. In many cases, farmer continued to operate with a subsistence mindset, and there is potential to increase yields further with improved agronomy, production systems and inputs.

Table 3: Typical yields of various crops at each intervention site (T/ha)

| CROP | MADHUBANI | SAPTARI | WEST BENGAL |
|---|---|---|---|
| Rice | 2.0 – 4.0 | 3.0 – 4.0 | |
| Wheat | 2.5 – 3.5 | 2.2 – 2.6 | 1.8 – 3.5 |
| Lentil | 0.6 – 0.8 | | |
| Mungbean | 0.3 – 0.4 | | |
| Cowpea | 2.3 – 3.0 | | |
| Bittergourd | 1.5 – 3.5 | 2.0 – 2.5 | |
| Tomato | | 9.0 – 11.0 | |
| Okra | 3.0 – 6.0 | 2.5 – 2.9 | |
| Maize | | 2.2 – 2.7 | |
| Zucchini | | 7.0 – 9.0 | |
| Jute | | | |
| Mustard | | 0.7 – 0.9 | 0.6 – 1.1 |

## Market prices and production costs

Profitability is impacted by market price and production costs. Local knowledge of product marketing, volatile prices, poor market price information and low prices paid by vendors for small volumes negatively impacted profitability.

Input costs which include agri-inputs (seed, fertiliser, pesticide), labour, and machinery (primarily land preparation and irrigation equipment) vary between sites and seasons. For example, at Madhubani sites, agri-inputs represented 39 % of input costs, labour 33 % and machinery 28 %. This varied between seasons. For rice production in Kharif season labour was the most significant cost.

In Saptari and West Bengal the proportion of costs attributable to labour were high in both summer, under labour intensive vegetable production, and in Kharif season, under rice production. For dry season vegetable crops, agri-inputs become an important cost component. Machinery was generally the lowest contributor to cost of production owing to low level of mechanisation.

## Profit Margin

Notwithstanding variable yields and fluctuating market prices, good profit margins could be achieved. Table 4 shows seasonal income, expenditure and gross margin (INR/ha or NPR/ha) for combined sites in Madhubani, Saptari and West Bengal. Profit margin (gross margin as percentage (%) of income), is also shown. Profit margins typically ranged between 20 % and 60 %. There was large variability, between sites and seasons, driven by the complex mix of crops, yield, seasonal productivity and market price.

For example, profit margin ranged between 8 % and 41 % in Madhubani. In Saptari, profit margin ranged between 30 % and 59 %, and was highest in Rabi season and lowest in Kharif season. There was also a reduction in gross margin per hectare in summer season between 2016 and 2017.

In West Bengal, the negative profit margin in summer 2016 was due to large loss in summer paddy in Dholaguri, whereas in Uttar Chakoakheti, where only jute was grown, there were significant profits of 43-54 %. In subsequent summer seasons, only jute was grown in Dholaguri, which was highly profitable due to its stable return over the last few years. Rabi 2017-18 was profitable in both villages however in Rabi 2016-17 farmers faced a loss due to poor farm gate price of potato in both villages and low price of wheat and mustard in Uttar Chakoakheti.

### Table 4: Income, expenditure and gross margin (INR/ha or NPR/ha)

| Saptari | | | | |
|---|---|---|---|---|
| Seasons | Income (NPR/ha) | Expenditure (NPR/ha) | Margin (NPR/ha) | % |
| 1.1 Summer 16 | 140,507 | 82,922 | 57,585 | 41% |
| 1.2 Kharif 16 | 101,914 | 67,259 | 34,655 | 34% |
| 1.3 Rabi 16/17 | 130,929 | 53,563 | 77,366 | 59% |
| 2.1 Summer 17 | 74,689 | 49,691 | 24,998 | 33% |
| 2.2 Kharif 17 | 83,364 | 58,120 | 25,244 | 30% |
| 2.3 Rabi 17/18 | 122,949 | 49,931 | 73,018 | 59% |
| Madhubani | | | | |
| Season | Income (Rs/ha) | Expenditure (Rs/ha) | Margin (Rs/ha) | % |
| 1.1 - Summer 16 | 13,206 | 12,201 | 1,006 | 8% |
| 1.2 - Khariff 16 | 45,798 | 34,830 | 10,968 | 24% |
| 1.3 - Rabi 16-17 | 43,823 | 25,712 | 18,111 | 41% |
| 2.1 - Summer 17 | 14,525 | 10,983 | 3,542 | 24% |
| 2.2 - Khariff 17 | 46,820 | 35,818 | 11,002 | 23% |
| 2.3 - Rabi 17-18 | 40,369 | 27,028 | 13,341 | 33% |
| West Bengal | | | | |
| Season | Income (Rs/ha) | Expenditure (Rs/ha) | Margin (Rs/ha) | % |
| 1.1 - Summer 16 | 100,243 | -101,399 | -1,156 | -1% |
| 1.3 - Rabi 16-17 | 50,776 | -70,539 | -19,764 | -39% |
| 2.1 - Summer 17 | 82,157 | -45,304 | 36,853 | 45% |
| 2.2 - Khariff 17 | 52,752 | -32,299 | 20,453 | 39% |
| 2.3 - Rabi 17-18 | 92,582 | -58,361 | 34,221 | 37% |
| 3.1 - Summer 18 | 83,387 | -37,634 | 45,754 | 55% |
| 3.2 - Khariff 18 | 50,067 | -35,325 | 14,742 | 29% |

Currently the main cropping pattern includes one or two crops per year. While there is potential for a three-crop system, given adequate groundwater resources, broader issues need to be considered.

Water access/availability is not the only limiting factor. Consideration must be given to a range of other factors including soil sustainability, pest and disease management, cash flow, labour constraints. The impact on available groundwater resources of large-scale adoption of a three-crop system is also necessary.

Case Study 2 illustrates the use of the APSIM model to optimise a triple crop system for Dholaguri, including the limitations of and opportunities for these modelling approaches. The use of APSIM will be explored in more detail in section 5.

### 3.2.2 Case Study 2: Optimising a triple cropping system for Dhaloguri

The development of irrigation infrastructure potentially makes triple cropping possible in the EGP. However, it is not known if triple cropping is logistically possible (regarding sowing and harvest dates) and what compromises in the yield of individual crops will need to be accepted to make triple cropping possible. A modelling excise has been undertaken to identify the optimal sowing dates for each of the crop and asses the yield compromises required to fit the three crops into an annual sequence.

#### Methods

Modelling was undertaken using APSIM. Daily weather data was sourced from the NASA POWER database and was corrected using locally available weather observations. Soil parameters were developed based on local observations. The cropping systems investigated was a rice-potato-sweet corn crop rotation. Crop management other than sowing dates (fertiliser, irrigation) was set based on the expected management for this system.

#### Results and interpretation

This work firstly modelled the optimum the sowing dates for the three individual crops. Sowing rice between 1-June and 1-July resulted in the best yields (Figure 5). Delaying sowing beyond 1 July lead to a decrease in yield.

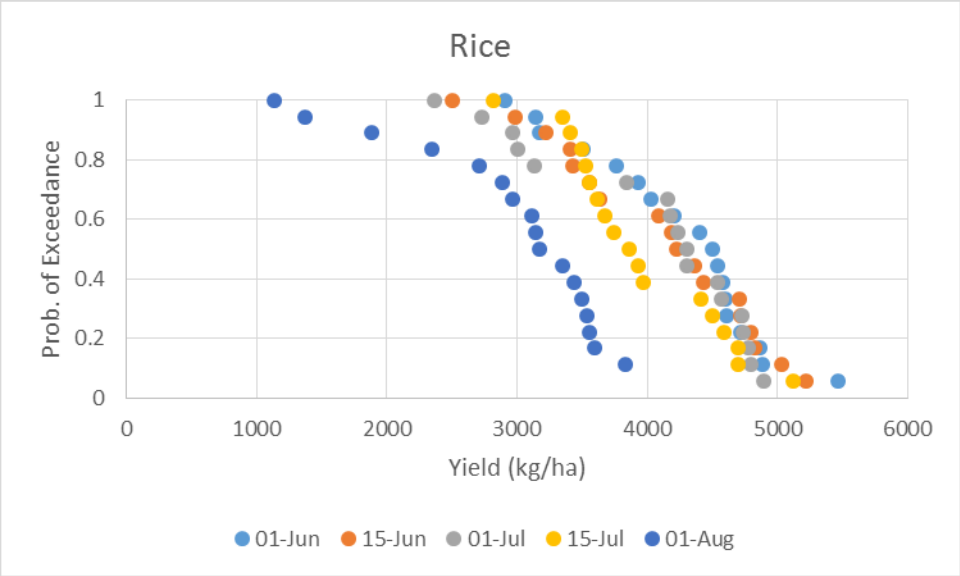


Figure 5: Probability of exceedance of rice yield across five sowing dates between 1 June and 1 August

Potato yields were increased by delaying the sowing date from 1-Ocotober to 15-November (Figure 6). There was no benefit from delaying sowing beyond 15-November.

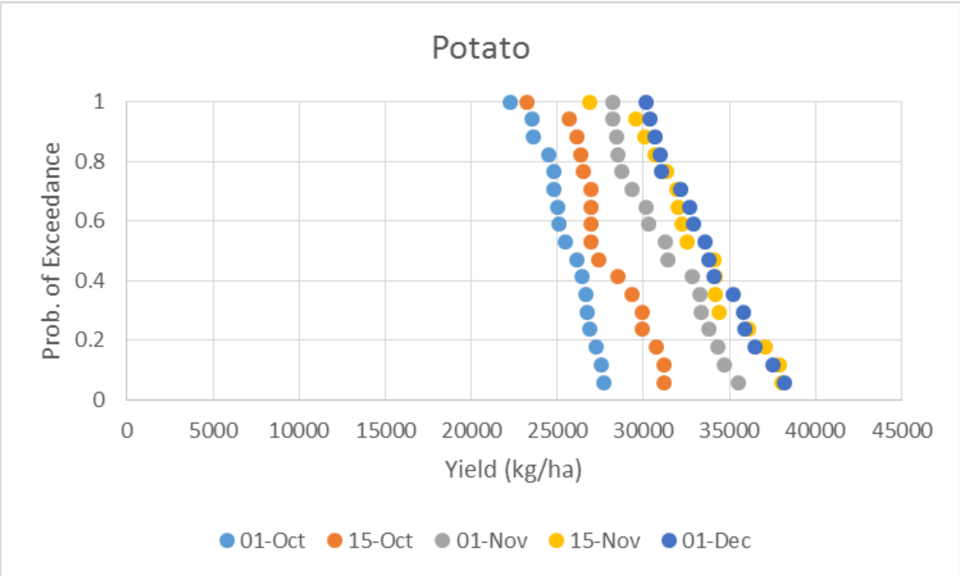


Figure 6: Probability of exceedance of potato yield across fives sowing dates between 1 October and 1 December

Sweet corn yields were increased by delaying the sowing date from 1-February to 1-April (Figure 7). The biggest increase in average yield occurred as sowing dates were delayed from 1-March to 15-March.

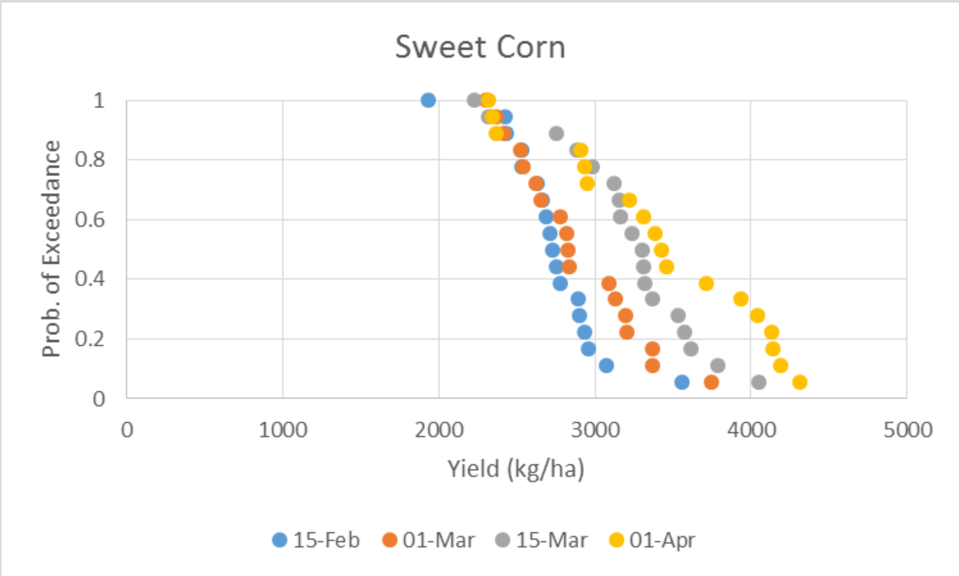


Figure 7: Probability of exceedance of sweet corn yield across four sowing dates between 15 February and 1 April

The optimal sowing dates and the resulting average harvest dates and yields of each crop are provided in Table 5. This table shows that is will not be possible to achieve the optimal sowing dates for each crop in a triple cropped system. Sweet corn sowing dates will have to be earlier to ensure there is enough time to facilitate the groundwork and sowing of the rice crop. This in turn will likely mean that the optimal sowing time for potatoes will also be compromised.

Table 5: Optimal sowing dates and resulting average harvest for rice, potato and sweet corn

| CROP | OPTIMAL SOWING DATE | AVERAGE YIELD (KG/HA) | AVERAGE HARVEST DATE |
|---|---|---|---|
| Rice | 15-June | 4,080 | 14-October |
| Potato | 15-November | 33,640 | 14-March |
| Sweet corn | 1-April | 3,390 | 28-June |

## Logistics and yield compromises in a triple cropping system

To identify how much sowing dates for each crop in a triple cropping system will need to deviate from the optimal sowing dates for each crop and what impact on yield will be from this compromise, a rice-potato-sweet corn triple cropping system was represented in APSIM. In this system it was assumed that rice must be sown between 15 June and 1 July and the simulation was then optimised to identify the possible sowing windows for potato and sweet corn. This simulation also considered the time required for ground/seedbed preparation for each crop (5 days between rice and potato, 5 days between potato and sweet corn and 25 days between sweet corn and rice). This optimisation aimed to ensure that all three crops were grown every year.

It was possible to optimise the sowing dates of each crop within the triple cropping system so that all three crops could be sown in every year. The sowing windows that facilitate this are 15-June to 1-July for rice, 25-October to 10-November for potato, and 1-March to 15-March for sweet corn (see Table 6). With these sowing windows a yield compromise of 2,660 kg/ha and 550 kg/ha could be expected for the potato and sweet corn crops under the triple cropping system. Figure 8 shows the average exceedance probability of the triple cropped optimised scenario.

Table 6: Sowing windows that facilitate successful triple cropping and the average change in yield

| CROP | SOWING WINDOW | AVERAGE SOWING DATE | AVERAGE HARVEST DATE | AVERAGE YIELD (KG/HA) | AVERAGE YIELD DEVIATION (KG/HA) |
|---|---|---|---|---|---|
| Rice | 15-June to 1-July | 25-June | 26-October | 4120 | +40 |
| Potato | 25-October to 10-November | 30-October | 26-February | 30980 | -2660 |
| Sweet corn | 1-March to 15-March | 2-March | 31-May | 2840 | -550 |

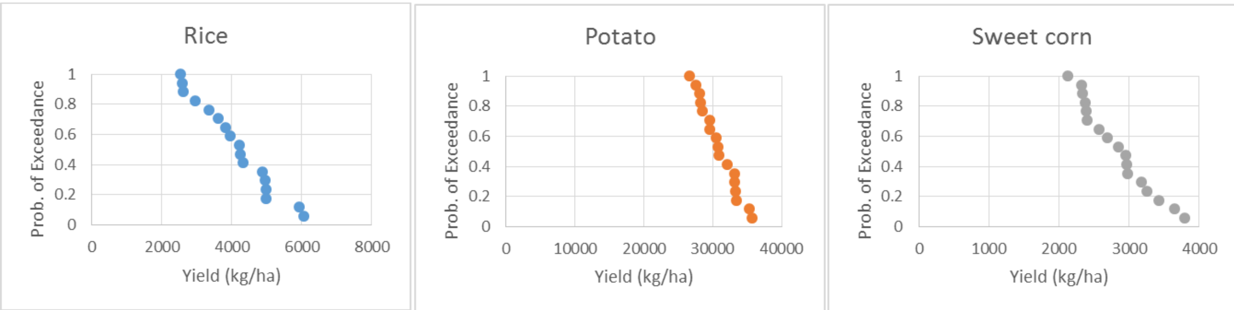


Figure 8: Probability of exceedance for rice, potato and sweet corn yield when grown in an optimised triple cropping system

### Limitations and future opportunities

This modelling is limited by a lack of parameters for locally adapted cultivars in the model. The cropping systems options are also limited by the crop types available in the model. Finally, there has been no on ground validation of the model's ability to represent crop growth and yield in this environment. Consequently, outputs presented here need to be treated as indicative only. We will explore these issues more in Section 5 on APSIM.

## 3.3 Crop Water Requirement

Crop water requirements vary depending both on the crop type and stage, and on the atmospheric drivers of evapotranspiration at any given site. To accurately calculate crop water requirement, significant effort and expense is required. However, to get a reasonable estimate of the crop water requirement a range of modelling techniques can be used. The base and industry standard method for calculating crop water requirement is the Food and Agriculture Organisation Paper 56 which details the Penman Monteith method for calculating crop water use (Allen et al. 1998). This method has been digitised into ready available software (Aquacrop) for calculating crop water use and for modelling yield and impact of various irrigation schedules (Steduto et al. 2009).

A study undertaken by Okwany (2016) assessed the crop water use and production of a series of common crops in the Eastern Gangetic Plains, including DSI4MTF sites. Modelling was based on optimal on-farm cultural management and no limiting crop production factors. The crop associated production (biomass production and yield) with related irrigation water requirements and harvest indices are shown in Table 7, Table 8 and Table 9 for Koiladi village, Saptari (Nepal), Dholaguri village (West Bengal) and Bhagwatipur Village (Bihar) based on generalized cropping pattern and optimal management around a rice crop. It is noted that for all crops, except rice paddy, irrigation is critical for production, contributing the major portion of evapotranspiration crop water demand.

Table 7: Modelled evapotranspiration for main season crops grown in Saptari using Aquacrop

| CROP | PLANTING | HARVEST | CYCLE | RAIN, MM | ETO, MM | GD, C.DAY | IRRI, MM | BIOMASS, TON/HA | YIELD, T/HA |
|---|---|---|---|---|---|---|---|---|---|
| Onion | 02/14/15 | 04/30/15 | 113 | 247 | 802 | 1767 | 642 | 12.782 | 6.39 |
| Monsoon Paddy | 06/29/15 | 10/30/15 | 98 | 803 | 596 | 1821 | 14 | 12.324 | 6.16 |
| Brinjal I | 08/30/15 | 11/14/15 | 63 | 287 | 369 | 1128 | 215 | 8.169 | 6.94 |
| Tomato I | 10/07/15 | 03/23/16 | 106 | 55 | 474 | 1390 | 536 | 12.224 | 7.70 |
| Potato | 12/16/15 | 03/30/16 | 105 | 54 | 601 | 2066 | 772 | 15.613 | 11.71 |
| Wheat | 12/16/15 | 04/15/16 | 116 | 59 | 631 | 2402 | 768 | 13.797 | 6.62 |

Table 8: Modelled evapotranspiration for main season crops grown in West Bengal using Aquacrop

| CROP | PLANTING | HARVEST | CYCLE | RAIN, MM | ETO, *MM* | GD, C.DAY | IRRI, MM | BIOMASS, TON/HA | YIELD, T/HA |
|---|---|---|---|---|---|---|---|---|---|
| Kharif paddy | 07/15/16 | 11/10/16 | 96 | 1719 | 482 | 1906 | 0 | 14.52 | 6.24 |
| Cucumber | 06/29/16 | 10/15/16 | 63 | 1607 | 328 | 1225 | 1 | 8.44 | 7.17 |
| Cow pea | 02/28/16 | 06/20/16 | 93 | 707 | 673 | 1473 | 313 | 12.26 | 6.13 |
| Cucumber II | 02/28/16 | 06/20/16 | 63 | 242 | 490 | 982 | 293 | 8.44 | 7.17 |
| Mustard | 11/25/16 | 03/05/16 | 83 | 21 | 406 | 703 | 421 | 11.07 | 5.54 |
| Potato | 11/25/16 | 03/20/16 | 70 | 17 | 364 | 1283 | 450 | 10.40 | 7.80 |
| Maize | 11/30/16 | 04/30/16 | 136 | 138 | 781 | 1702 | 812 | 29.88 | 14.35 |
| Wheat | 11/25/16 | 03/30/16 | 121 | 71 | 666 | 2407 | 672 | 14.76 | 7.08 |
| Boro paddy | 01/30/16 | 05/20/16 | 83 | 176 | 577 | 1086 | 459 | 11.92 | 5.96 |
| Lentil | 11/26/16 | 04/10/16 | 120 | 128 | 786 | 1426 | 593 | 15.09 | 6.79 |
| Tomato | 11/02/16 | 02/20/16 | 152 | 92 | 806 | 1935 | 751 | 18.60 | 11.72 |
| Brinjal | 11/02/16 | 02/20/16 | 63 | 20 | 323 | 655 | 344 | 8.17 | 6.94 |
| Chilli | 11/02/16 | 02/20/16 | 193 | 423 | 1120 | 2204 | 796 | 22.47 | 19.10 |
| Cabbage | 11/02/16 | 02/20/16 | 158 | 125 | 880 | 1653 | 739 | 18.91 | 16.07 |
| Cauliflower | 11/02/16 | 02/20/16 | 133 | 61 | 698 | 1297 | 641 | 14.71 | 12.50 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Onion | 11/02/16 | 02/20/16 | 113 | 40 | 565 | 1050 | 530 | 12.78 | 6.39 |
| | | | | | | | | | |
| Radish | 11/07/16 | 02/20/16 | 33 | 9 | 195 | 416 | 206 | 3.25 | 1.63 |
| | | | | | | | | | |

Table 9: Modelled evapotranspiration for main season crops grown in Madhubani using Aquacrop

| CROP | PLANTING | HARVEST | CYCLE | RAIN, MM | ETO, *MM* | GD, C.DAY | IRRI, MM | BIOMASS, TON/HA | YIELD, T/HA |
|---|---|---|---|---|---|---|---|---|---|
| Paddy | 08/15/16 | 11/15/16 | 70 | 436 | 419 | 1398 | 112 | 11.49 | 0.47 |
| Brinjal | 06/15/16 | 07/01/16 | 63 | 661 | 406 | 1253 | 64 | 8.17 | 6.94 |
| Bitter Guard | 06/15/16 | 07/01/16 | 63 | 661 | 406 | 1253 | 64 | 8.44 | 7.17 |
| Cucumber | 06/15/16 | 07/01/16 | 63 | 642 | 416 | 1253 | 93 | 8.44 | 7.17 |
| Wheat | 12/30/16 | 04/15/16 | 113 | 52 | 849 | 2413 | 981 | 13.36 | 6.41 |
| Lentil | 11/30/16 | 03/15/16 | 120 | 52 | 939 | 1458 | 816 | 15.03 | 6.77 |
| Mustard | 11/30/16 | 03/15/16 | 83 | 28 | 444 | 682 | 523 | 11.07 | 5.54 |
| Cauliflower | 11/30/16 | 12/15/16 | 133 | 49 | 888 | 1377 | 921 | 14.71 | 12.50 |
| Cabbage | 11/30/16 | 12/15/16 | 68 | 21 | 351 | 543 | 432 | 8.62 | 7.32 |
| Potato | 12/15/16 | 01/15/17 | 105 | 45 | 773 | 2054 | 952 | 15.61 | 11.71 |
| Tomato | 12/15/16 | 01/15/17 | 106 | 41 | 665 | 1310 | 749 | 12.24 | 7.71 |
| Moong Beans | 04/15/16 | 05/30/16 | 120 | 906 | 1042 | 2545 | 458 | 15.62 | 7.03 |
| Onion | 02/15/16 | 03/15/16 | 113 | 155 | 1046 | 1795 | 947 | 12.76 | 6.39 |
| Cucumber | 02/15/16 | 03/15/16 | 63 | 32 | 596 | 931 | 656 | 8.44 | 7.17 |
| Tomato | 02/15/16 | 03/15/16 | 111 | 130 | 1009 | 1951 | 970 | 12.00 | 7.56 |

For most crops, production is highly dependent on irrigation. Achieving a crop intensification is dependent on ability to efficiently manage the groundwater withdrawals coupled in some cases with surface water resources in a conjunctive use pattern. A modified planting calendar needs to be developed to enable both optimal irrigation water access and achievement of enough growing degree days for each crop (Okwany 2016).

Different production and conservation agricultural approaches also need to be considered in regional hydrological impact assessments. Case Study 3 provides two examples for West Bengal.

### 3.3.1 Case Study 3: Zero tillage production systems in West Bengal

In West Bengal, medium-long duration rice varieties such as MTU 7029 are traditionally grown, taking 145-155 days to mature, which often delays sowing of the Rabi crops. A new drought and disease resistant variety “Anjali” with shorter days to maturity was introduced to the farmers in both Dholaguri and Uttar Chakoakheti. Despite generally lower yield, Anjali matured earlier, allowing early sowing of Rabi vegetable crops which farmers preferred. Previously farmers had to harvest jute early to free land for rice planting. With Anjali, jute could be grown to full term with an early Rabi planting.

Zero tillage (ZT) in wheat and mustard was also trialled in West Bengal, allowing early seeding into residual moisture. Productivity can increase with ZT, as it is possible to sow the crop in mid to end November (15 to 20 days earlier) in rice fields, without any land preparation. Localized placement of fertilizers and chemical weed control in ZT drilled crops helps further towards better performance. Under zero till wheat, productivity levels were encouraging, and the cost of cultivation was reduced significantly.

Zero till helped to advance the sowing time by 2 weeks, which had a direct influence on crop performance. Herbicide usage replaced manual weeding, which reduced cultivation cost. The benefit-cost ratio increased from 0.67 to 1.15 when conventional tillage was replaced by zero till. Zero till also had a positive impact on mustard production, with a benefit-cost of 1.98. In some cases, a poor crop stand was achieved under zero till mustard due to excessive depth in seed placement. Notwithstanding this crop failure, farmers showed resilience, and continued zero till successfully, due to labour cost savings, timeliness and reduced irrigation water requirements.

Although case study 3 did not explicitly consider the regional hydrological impacts, the earlier sowing dates can change crop water requirements due to the earlier crop experiencing different temperatures and rainfall. This could result in some impact on the regional hydrology.

## 3.4 Water resources and irrigation systems

Dry season agriculture in the Eastern Gangetic Plains depends upon access to water reserves stored during the monsoon– namely groundwater resources, and in some cases surface storage such as ponds. Groundwater resources across the EGP are extensive. While these are under-utilised in India and Nepal, with only a fraction of the cultivable area under irrigation of dry season crops, they tend to be over exploited in parts of North West Bangladesh. In both cases, this results in limited crop diversification, food insecurity and poor nutrition.

The groundwater resource in India and Nepal is generally considered to have potential for further use, whereas in northwest Bangladesh it is generally considered likely to have reached the limit of potential use (see more extended discussion in section 6). The amount of groundwater use will be determined by irrigation development (in India and Nepal) or changed irrigation management (Bangladesh). Development or change is likely to be influenced by a range of factors including the availability of pumps, conveyancing efficiency, the type of irrigation system (with drip systems likely to lead to less non-beneficial evapotranspiration from weeds and the soil than other systems, for example), and irrigation management and optimisation based on assessment of the crop water requirement. In the following case studies, we consider these factors. In common with the other case studies, the factors considered below are at the field scale. Case studies such as these should be linked to broader regional studies in order to assess the regional hydrological impact. This will be discussed in a final case study after the case studies below on irrigation systems.

Constraints to irrigation development include limited rural electrification and severe power shortages, which have made farmers in Bihar and Nepal dependent upon more expensive diesel pumps. Technical barriers to irrigation also include inefficient pumps, poorly maintained ponds and limited technical expertise in irrigation scheduling and the operation of water efficient irrigation distribution systems.

These technical barriers to improved irrigation and water management are matched by acute socio-economic and institutional constraints. The marginal and tenant farmer majority cannot afford investment in pump sets or tubewells, and this is made worse by monopolistic pump rental markets, which further drive up the costs. Furthermore, even if cheaper pumping and distribution technologies can reduce operating costs, tenant farmers who constitute a significant proportion of farmers, have limited incentives to invest due to tenure insecurity, while small and fragmented holdings make investments unfeasible. Agrarian stress has driven many young men into the migrant labour market, paving the way for the feminisation of agriculture. The women who increasingly manage the land experience a high workload, while facing further constraints to accessing irrigation due to entrenched gender relations and limited access to resources (Schmidt et al. 2019).

## Water resources

All DSI4MTF villages have substantial groundwater resources. The water table is shallow and water quality is generally suitable for irrigation purpose. Dry season agriculture is mainly limited by inadequate irrigation infrastructure provided (Okwany et al. 2015; Okwany 2016; Schmidt et al. 2019).

### Surface Water

Surface water resources consist of small to medium size ponds while groundwater is accessed using shallow tubewells with a total depth of less than 30m. Tubewells and dug wells are not evenly distributed.

Ponds in the study sites are very small, offering limited capacity for irrigation, and are generally dry in summer due to evaporation and seepage losses. Where ponds can store water, they are usually reserved for more profitable fish production, domestic purposes and animal use. For optimal fish production, water level needs to be maintained above 1.5m. While evaporation is a consideration, excessive seepage losses through the banks and base of the pond is the main cause of drying. This is due to poor construction and maintenance of the banks and highly permeable coarse soil textures. Groundwater is seldom used to fill ponds, owing to cost of pumping.

### Groundwater

Groundwater is primarily used for irrigation and was monitored weekly during DSI4MTF using electronic sensors. Across all sites the maximum depth to groundwater occurred during the late dry season (February-April) and minimum water depths occurred towards the end of rainy season (July-September). Across all sites pre-monsoon and post-monsoon showers are received during the months of April and September, and most of the annual rainfall is received during the period May to August. In general, very low precipitation occurs during October to March. Consistent trends in rise and fall of groundwater were evident across sites. Monsoon rains raise the water table, which then declines, rapidly at first and then slowly as the hydraulic gradient reduces.

At Dholaguri minimum and maximum observed depth to water table across all sites was 0.7m and 6.6m. The seasonal change in water level was approximately 3.5m. Maximum depth of less than 9m suggests water is within the suction lift of a centrifugal pump. Small inter-seasonal range implies little impact by irrigation. In Uttar Chakoakheti the minimum and maximum depths to water table were 0.5m and 5.3m, respectively.

In Kanakpatti, the water table varies between 0.7m and 7.6m below ground level, with seasonal range of 2m-3m. In Koiladi, the seasonal range was around 1.5 m. The seasonal range in groundwater at Bhagwatipur was between 1.3m and 2m and in Mauahi between 1.2m and 1.8m.

Local measured groundwater levels were consistent with the Indian Governments Central Ground Water Board (CGWB) records reinforcing CGWB reporting that local groundwater resource in the region is underutilized (see also Section 6.2).

In all villages the groundwater levels did not appear to be impacted markedly by local pumping and generally remain within the practical suction lift of centrifugal pumps. In some cases, groundwater level dropped temporarily below the suction lift of the centrifugal pump following drawdown after a long pumping event. However, with possible large out scaling of dry season irrigated agriculture, pressure on groundwater could increase. Further research on regional hydrological impact of farm-scale water abstractions under different scenarios is therefore important.

#### Irrigation Systems

Irrigation system performance, efficiency and scheduling are key to increase crop production and reduce input costs, especially pumping cost. A series of trials were conducted across the Nepal and India sites, working with advisors and farmers, to demonstrate how simple tests could help improve irrigation performance. Selected Case Studies from the DSI4MTF project (Schmidt et al 2019) are presented below to highlight a range of farm scale options to improve water use efficiency. Regional impacts of these approaches need to be considered in hydrological modelling.

### 3.4.1 Case Study 4: Pumping Systems

The type of pumping system will impact irrigation system operation and groundwater extraction. The dominant pump type in Madhubani and West Bengal sites were 3-7 hp diesel driven, end suction, centrifugal pumps. In Saptari many farmers had access to electric pumps. Due to their light weight and portability, 5 hp capacity diesel pumps are most popular among the farming community. Smaller capacity (3 hp) pumps are generally used to pump water from ponds while higher capacity (5 hp) pumps are used to pump water from tubewells with greater discharge capacity. The pumps were typically poorly maintained.

Data on the average number of farmers served per pump indicated that in Bhagwatipur one pump served the needs of 13 farmers, whereas in neighbouring Mauahi it was 39 farmers per pump. This highlights the pressure on irrigation pump sets and illustrates that frequently it is not possible for farmers to get access to pumps for irrigation.

#### Diesel Pumps

Diesel is a major input cost and pump efficiency is impacted by pump design, maintenance and operating factors. The impact of engine speed on volume of water pumped per litre of diesel used, an indicator of pumping and fuel efficiency, was demonstrated in each site and discussed with farmers to encourage better operation. This simple test was able to identify the optimum engine speed for each pumping situation. Results showed that pumping cost could be reduced by up to 30 % simply by finding the optimum engine speed.

## Solar Pumps

Electricity and diesel prices, as well as the reliability of electricity supply, impact irrigation reliability and performance. Solar pumping has become an attractive option. Government programs and subsidies are supporting the roll out of these technologies. However, procedural difficulties constrain small and marginal farmers accessing such subsidies. Four 3hp (2.2 kW) solar systems were installed for two farmer collectives in Dholaguri and Uttar Chakoakheti (West Bengal) respectively, while they were also provided to two farmer collectives in Bhagwatipur (Madhubani). Small 80W Sunflower pumps were also provided to the farmer collectives in Saptari.

Tests were undertaken to evaluate the performance of solar systems in terms of voltage and current outputs, solar system efficiency, variation in discharge through the season and impact on water pumped and irrigable area. Tests illustrated how seasonal variation in day length and solar intensity impacts pump discharge. This is a limiting factor when required to irrigate over a 10-hour day, to meet crop water needs. As an example, the impact on water yield per day and resulting irrigable area is shown in Table 10 for a solar pump at Bhagwatipur. Based on 5 mm/day crop water requirement this equates to an irrigable area of 1.5ha in December and 2.8ha in June. The volume pumped and area served by the 3hp solar systems which typically pump < 5 l/sec over 5-8hours, is thus small compared to traditional diesel systems. Diesel systems pump 8-10 l/s over a 10hour day, equivalent to 288-360m$^3$/day and can serve an irrigation area of 5.8 – 7.2 ha. Installation of solar systems is also expensive (Rs 250,000) when compared to a diesel pump Rs 18,500. The operating cost of a diesel system is however high. The annual cost of using a diesel pump to deliver the same volume of water as the solar system at Madhubani is approximately Rs 100,000. This assumes a solar system pumping 120 m$^3$/day over 250 days, and a diesel pump with discharge (10 l/s) and operating cost of Rs120/hr. This equates to a 2.5-year payback.

The extent to which solar irrigation systems meet crop water requirements and the impact on groundwater resources following widespread adoption of these systems given generous subsidies and low running costs needs consideration.

Table 10: Water availability for dry season agriculture from a 2.2kW solar pump

| MONTH/S | WATER YIELD PER DAY (M3/DAY) FROM A SOLAR PUMP ON A CLOUD FREE DAY | IRRIGABLE AREA PER DAY (HA/DAY) FROM A SOLAR PUMP ON A CLOUD FREE DAY (BASED ON 5 MM/DAY AVERAGE APPLICATION RATE) |
|---|---|---|
| Sep-Nov | 120- 130 | 2.4 – 2.6 |
| Dec-Jan | 75-85 | 1.5 – 1.7 |
| Feb | 90-110 | 1.8 – 2.2 |
| Mar-Jun | 130-140 | 2.6 – 2.8 |

### 3.4.2 Case Study 5: Water Conveyance efficiency and loss

One of the simplest methods for transporting water from a water source to a field is an earthen channel. For large plots of land, farmers have constructed permanent channels that connect different plots, however these channels are not concreted or lined and continue to lose water with every irrigation (Schmidt, Sugden & Scobie 2020).

The significance of these losses depends on the construction of the channel and the soil parameters. To understand this loss a simple measurement can be done. The difference between the flow into the channel and the flow at a given point along the channel is the loss. Providing there are no breaks in the channel and that the measurements are taken over a short period to limit losses to evaporation, the difference is the seepage loss (Schmidt, Sugden & Scobie 2020).

Flexible polythene pipes provide an alternative to earth channels. Farmer collectives and advisors were shown how to compare the two conveyance methods and take flow readings at the pump and at the end of 100m of earthen channel (through a V-notch weir) and at the end of 100m of lay flat polythene pipe on two plots. The irrigation water loss through an earth channel was compared with the reduction in discharge when using a polythene pipe as shown in Table 11.

Table 11: Reduction in discharge at the field through earthen channel and polythene pipe (%)

| CONVEYANCE SYSTEM | FLOW RATE AT WATER SOURCE (L/S) | FLOW RATE AT V NOTCH AND AT THE END OF 100 METER PIPE (L/S) | REDUCTION IN FLOW AND CONVEYANCE EFFICIENCY (%) |
|---|---|---|---|
| Earthen open channel | 5.7 | 3.0 | 2.7 L/s (53 %) |
| Polythene pipe | 5.7 | 5.1 | 0.6 L/s (89 %) |

Discharge was reduced by 2.7l/s when using an earthen channel (conveyance efficiency of 53 %) and when lay flat pipe was used, the additional backpressure placed on the pump by the restriction of the pipe, resulted in a reduction of only 0.6 l/s (conveyance efficiency of 89 %). Results from Madhubani showed the saving in diesel pumping costs more than compensating for capital cost of the piping with a 2-year replacement.

This encouraged several groups to shift to using lay flat pipes. Farmers usually use 300 ft rolls of 3” or 4” polythene pipe which costs approximately Rs.1,600 Rs.1,900. Pipe is sometimes purchased collectively and can be resold as scrap at approximately 20 % of the original price.

It was found that there is an increase in water delivery per litre of diesel fuel when using 4” pipe over a 3” pipe, due to reduced friction loss and pumping pressure. The benefit of using 4” hose ranged between 17 % and 42 % (Table 12) depending on the speed and discharge of the pump. Tests were conducted on a range of pumps under differing conditions.

Table 12: Comparison between using a 3" and 4" water delivery pipe

| TEST NO. | RPM | WATER PUMPED WITH 1 LITRE OF DIESEL THROUGH A 3” DELIVERY PIPE (300FT) | WATER PUMPED WITH 1 LITRE OF DIESEL THROUGH A 4” DELIVERY PIPE (300FT) | BENEFIT OF USING 4” DELIVERY HOSE |
|---|---|---|---|---|
| 1 | 1,300 | 32.96 $M^3$ | 38.59 $M^3$ | 17 % |
| 2 | 1,400 | 34.67 $M^3$ | 42.31 $M^3$ | 21 % |
| 3 | 1,500 | 34.88 $M^3$ | 43.09 $M^3$ | 24 % |
| 4 | 1,600 | 35.41 $M^3$ | 50.54 $M^3$ | 42 % |

The trade-off between lay-flat hose and channel distribution system is the reduction in water loss when using piping, versus the increased pumping pressure when using piping. This pumping pressure can be reduced by increasing pipe diameter.

### 3.4.3 Case Study 6: In field drip and sprinkler irrigation system performance

Drip irrigation is gaining favour among irrigation modernisation projects due to its ability to apply water precisely, both in terms of volume of application, and in terms of placement of water close to the plant. However, drip irrigation is one of the most complex and intensive methods of irrigation. It requires significant labour and skill to install and manage and is not suitable for all crops. Drip irrigation requires that water is filtered and that filters are cleaned and maintained to ensure that operating pressures are maintained. If a drip irrigation system is not maintained, the performance and the precision that is a key advantage of the system is lost.

Drip irrigation is often considered to be a highly efficient method for irrigation, and many farmers engaged in vegetable cultivation in DSI4MTF piloted drip systems. However, if the irrigation system is not installed well and maintained, the performance and efficiency can be poor. The uniformity of water application in drip irrigated fields depends on several factors including operating pressure, extent of emitter clogging, system characteristics, lateral diameter and emitter spacing etc. In addition to system design factors, field topography and soil hydraulic properties are also important considerations. The status of uniformity of water application is generally assessed using uniformity coefficient. Irrigation systems with poor uniformity coefficient can experience reduced yields due to localised water stress and/or water logging in various parts of the field and can lead to environmental impacts due to leaching of nutrients.

The coefficient of uniformity is the most used indicator of the performance of a drip irrigation system and is based on data collected in catch cans across the field. Farmers helped collect field data to demonstrate the importance of good installation and maintenance of irrigation systems.

For example, the coefficient of uniformity was calculated for two consecutive years in the same experimental plot. The coefficient of uniformity fell from 91.5 % to 80.7 % between March 2017 and March 2018. For excellent functioning of drip systems, the uniformity coefficient should be greater than 90 %. The results illustrated the need to maintain drip irrigation systems, with a focus on filtration units and emitter clogging.

Sprinkler irrigation systems were also piloted through the project. In this instance the distribution uniformity (DU) was used since it is more commonly used when evaluating sprinkler system uniformity. Results at Madhubani showed an increase in DU of a sprinkler irrigation system from 78.6 % in 2017 to 90.9 % in 2018. The improvement was due to better operating pressure and favourable prevailing wind conditions during the assessment in 2018. Results helped farmers understand the impact of pump operating pressure and wind on droplet distribution.

Modernisation of irrigation systems comes with many challenges but can also realise water savings and productivity improvements. The impact on farm-scale water balance can be readily modelled, as shown further in Section 5 on APSIM. Translating this to regional hydrological impacts is a further consideration, which we will explore in Section 4 on groundwater and Section 6 on water balances.

### 3.4.4 Case Study 7: Adoption of drip Irrigation by marginal farmers.

Prior to the DSI4MTF project farmers, in the Kanakpatti village of Saptari, depended on monsoon water for irrigation and used flood and basin irrigation techniques. Whether a crop had been irrigated adequately was determined visually. Farmers believed that the crops would grow well if they irrigated in abundance and so they often ended up over-irrigating the crops.

Farmers in each collective had limited knowledge of efficient irrigation techniques, as well as limited access to tube wells or pumps. Drip irrigation technologies were entirely new when the project introduced them.

Small drip systems covering 50 square meters were introduced with the capacity of a 50-litre drum, which suffices for about 80 plants. In both sites, farmers were advised to use solar pumps with drip system together. Farmers were generally satisfied with the drip technology, as it saved time, labour, water, and cost, and allowed crops to be grown during dry season. Drip systems reduced weed problems. While farmers found the drip system easy to use, several farmers in Bihar indicated difficulty reading the pressure gauge to monitor the flow and pressure in the irrigation pipes, and additional training was required to resolve that challenge.

Farmers participated in water use efficiency tests which showed a water efficiency of 90 % in Saptari and 30-35 % saving of water in comparison to the furrow method of irrigation in Bihar, considerable improvements over canal or flood-based irrigation. Fertilizer efficiency has also increased by mixing fertilizer with water in the drum, reducing the time needed to manually apply as well as the amount of fertilizer required. Realizing the benefits of drip irrigation, farmers in Nepal have invested in bigger drip systems for subsequent seasons.

Drip systems show potential for improving irrigation efficiency in water scare areas, however, there is a need for this equipment to be promoted by local agricultural development agencies, who can facilitate supply of materials and offer technical support.

### 3.4.5 Case Study 8: Irrigation scheduling using the DSI scheduler tool

Irrigation scheduling is important to optimise the timing and depth of irrigation and supporting farmers with this was a priority. Several tools and techniques were evaluated as summarised as part of DSI4MTF (Schmidt et al 2019). Mini evaporation pans proved useful to demonstrate seasonal changes in evaporation demand. Soil moisture sensors, including Chameleon sensors and tensiometers, helped demonstrate the change in moisture being drawn from different depths. Technical challenges limited the usefulness of these systems for marginal farmers.

Soil moisture budgeting, using FAO56 approaches, and a purpose-built web App (DSI Scheduler) allowed integration of, weather, soil and crop information to guide irrigation timing and depth of application. The DSI Scheduler was also used as a storage hub and repository for seasonal irrigation data.

Crop evapotranspiration was computed from solar radiation, temperature, humidity and wind speed data for each site using FAO56 methods. Temperature loggers were installed in each village and other parameters were taken from regional weather sources or long-term averages.

Figure 9 *s*hows an example soil water balance using the DSI Scheduler for field B2F04 (Bhagwatipur Site 2 Field 4). The green line shows the daily soil moisture balance in a wheat crop. The timing of the first irrigation (orange bar) is perfect, within one or two days of the soil moisture depleting to the refill point, an irrigation was applied. The volume of this irrigation was satisfactory (but not perfect, as it did not adequately refill the profile). The second irrigation however was too late, and the crop would have been suffering from water stress. Unfortunately, this was compounded as the second irrigation was also insufficient in volume to refill the profile. Maintaining soil moisture is less important in the latter stages of growth for cereal crops where ripening and drying off is required and late rainfall (blue bars) would have had minimal effect on yield. Visualisation of the soil water balance helped interpret whether the timing and volume of irrigation was suitable to meet crop water requirement.

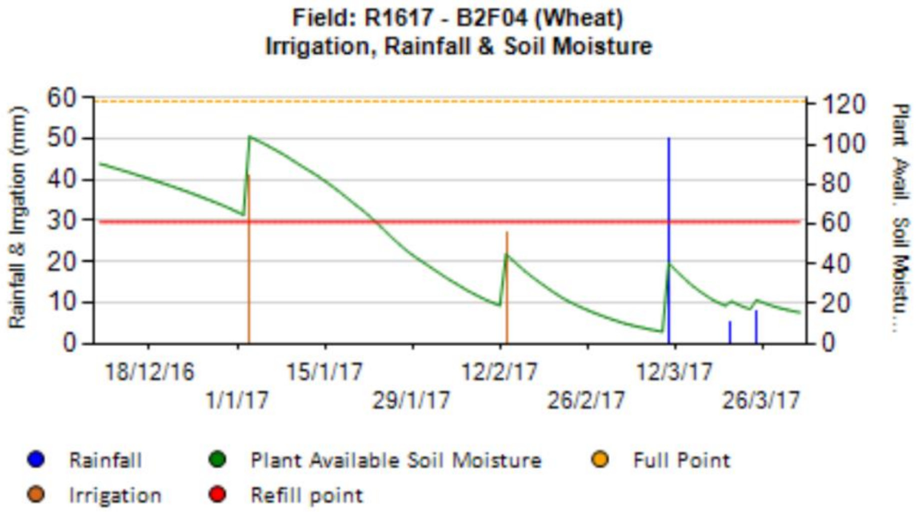


Figure 9: Example of the DSI Scheduler soil moisture balance for wheat crop in Bhagwatipur, Madhubani, India

Figure 10 shows that irrigation was well managed for a brinjal (eggplant) crop on field B1F08. Soil moisture was maintained during the growing and fruiting phases of plant development, and then allowed to dry down towards harvest.

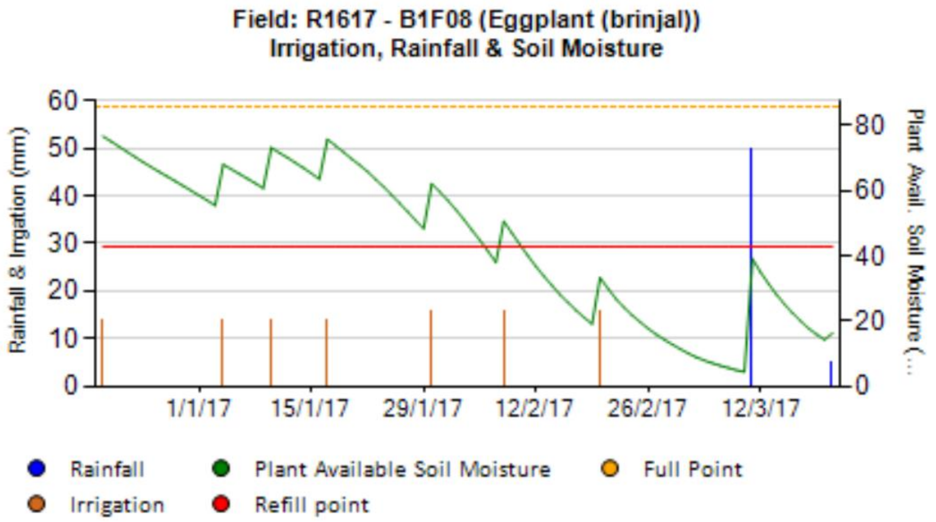


Figure 10: Soil moisture balance including rainfall and irrigation for Brinjal in Rabi 16/17 in Bhagwatipur, Madhubani, India

Figure 11 shows cumulative seasonal totals for the Brinjal crop of potential evapotranspiration (ETc), modelled actual ETc (somewhat reduced as this crop was water stressed from late January until harvest) as well as accumulated in season rainfall and irrigation. The crop required 275 mm of water for optimum growth, however, insufficient irrigation created a water stress condition and the crop was only able to utilise 190 mm of moisture. The cumulative total for irrigation and effective rainfall was approximately 145 mm, which means that the crop was able to extract 45 mm of moisture from the soil profile.

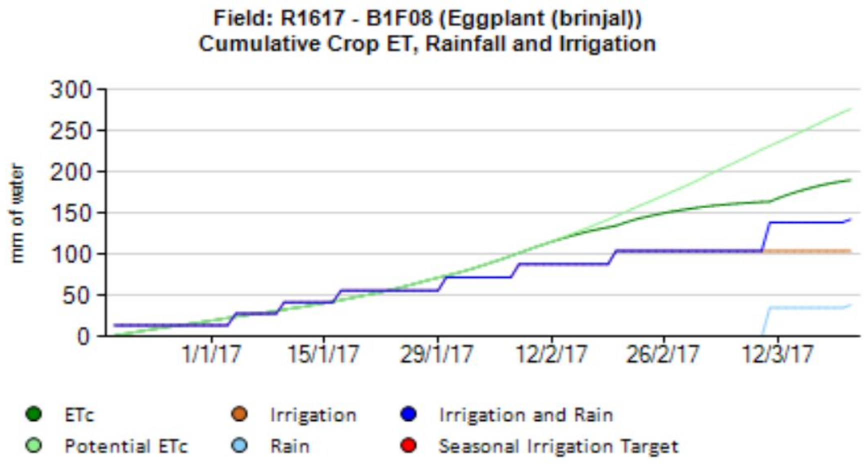


Figure 11: Individual field seasonal summary from DSI Scheduler showing total crop water requirement, irrigation applied and rainfall

The field scale water balance approach described was an important focus of the study and helped advise field staff and farmers and improve irrigation management and scheduling decisions.

### 3.4.6 Case Study 9: Crop water requirement

The water balance approach also helped estimate the irrigation required to meet crop evapotranspiration, as illustrated in Table 13 for a range of crops in the 2016/2017 Rabi season. Red and green shading represents high and low irrigation requirement respectively. The Brinjal crop of B1F08 planted 20/12/2016 and harvested 21/03/17 required 275 mm of water to meet potential evapotranspiration of which 39mm was met by effective rainfall and 236 mm was required through irrigation. Irrigation water requirements vary based on crop type and plant and harvest dates. For example, the radish crop grown for just 55 days required only 135 mm of irrigation. There is also a difference in crop water requirement between four wheat crops with a difference in planting dates of 3 weeks.

Table 13: Irrigation requirement as a function of total crop water requirement and effective rainfall

| SITE | CROP | PLANT DATE | HARVEST DATE | EVAPOTRANSPIRATION ETC (MM) | EFFECTIVE IN CROP RAINFALL (MM) | IRRIGATION REQUIRED (MM) |
|---|---|---|---|---|---|---|
| B1 | Radish | 3/11/2016 | 28/12/2016 | 135 | 0 | 135 |
| B1 | Brinjal | 20/12/2016 | 21/03/2017 | 275 | 39 | 236 |
| B1 | Spinach | 14/12/2016 | 20/02/2017 | 162 | 0 | 162 |
| B4 | Spinach | 15/12/2016 | 10/03/2017 | 240 | 0 | 240 |
| B1 | Wheat | 14/12/2016 | 1/04/2017 | 345 | 44 | 301 |
| B2 | Wheat | 6/12/2016 | 1/04/2017 | 360 | 44 | 316 |
| B3 | Wheat | 24/11/2016 | 1/04/2017 | 390 | 44 | 346 |
| B4 | Wheat | 19/12/2016 | 28/04/2017 | 395 | 51 | 344 |
| B1 | Potato | 4/11/2016 | 4/02/2017 | 220 | 0 | 220 |
| B2 | Potato | 12/11/2016 | 6/02/2017 | 190 | 0 | 190 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **B3** | Potato | 20/11/2016 | 5/02/2017 | 175 | 0 | 175 |
| **B4** | Potato | 8/11/2016 | 4/02/2017 | 210 | 0 | 210 |
| **B2** | Lentil | 8/11/2016 | 5/03/2017 | 280 | 0 | 280 |
| **B3** | Lentil | 5/12/2016 | 18/03/2017 | 270 | 35 | 235 |

The water productivity (yield per unit of water), and the extent to which crop water requirements were met by irrigation were also assessed. Figure 12 shows an output from the DSI Scheduler tool for irrigation, rainfall and water productivity information for a selection of plots in Bhagwatipur for the Rabi 16/17 season. For the brinjal crop of field B1F08, a total of only 104mm irrigation was applied by farmers, well below 236mm required. The yield was only 52 kg/ha with a low water productivity in terms of yield per cubic meters of water used by the crop.

DSI4MTF Scheduler

*R1617 - B1* *Detailed Report* *18 March 2019*

This report provides a summary of data inputs and results for Fields R1617 - B1F06, R1617 - B1F07, R1617 - B1F08, R1617 - B1F12, R1617 - B1F13, R1617 - B1F17 and R1617 - B1F20 at R1617 - B1 located near Bhagwatipur (Bihar, India).

***Yield and Irrigation Summary***

| Field | Crop | Rain gauge used | Soil | Plant Available Water (mm) | Refill Point (% PAW, mm) | Plant Date | Harvest Date | Yield (/ha) | Water Productivity (kg/m3) | Total In-season Rain (mm) | Effective Rain (mm) | Total Irrig. Applied (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R1617 - B1F06 | Peas | Bhagwatipur | Sandy Loam | 72 | 50 (36mm) | 14/12/2016 | 07/03/2017 | 4915 kg | 9.1 | 0 | 0 | 0 |
| R1617 - B1F07 | Radish | Bhagwatipur | Sandy Loam | 36 | 50 (18mm) | 03/11/2016 | 28/12/2016 | 6906 kg | 25.6 | 0 | 0 | 0 |
| R1617 - B1F08 | Eggplant (brinjal) | Bhagwatipur | Sandy Loam | 85.5 | 50 (43mm) | 20/12/2016 | 21/03/2017 | 52 kg | 0.03 | 55 | 39 | 104 |
| R1617 - B1F12 | Spinach | Bhagwatipur | Sandy Loam | 36 | 50 (18mm) | 14/12/2016 | 20/02/2017 | 1934 kg | 3.79 | 0 | 0 | 24 |
| R1617 - B1F13 | Wheat | Bhagwatipur | Sandy Loam | 121.5 | 50 (61mm) | 14/12/2016 | 01/04/2017 | 2051 kg | 1.14 | 63 | 44 | 59 |
| R1617 - B1F17 | Potato | Bhagwatipur | Sandy Loam | 45 | 50 (22mm) | 04/11/2016 | 04/02/2017 | 11713 kg | 12.1 | 0 | 0 | 63 |
| R1617 - B1F20 | Gourd (luffa) | Bhagwatipur | Sandy Loam | 72 | 50 (36mm) | 20/12/2016 | 01/04/2017 | 0 kg | 0 | 63 | 44 | 84 |

Notes

Plant Available Water - the amount of water (mm) that is available in the plant root zone.

Refill point - user defined point at which irrigation should be applied i.e. 20% means that the user is willing to allow 20% of the soil moisture to be removed before applying irrigation.

Water Productivity - units of production per m3 of crop evapotraspiration.

Total In-season rainfall - cumulative total of all rainfall between plant and harvest dates.

Effective rainfall - the amount of rainfall that enters the root zone and is available for the plant to use.

Figure 12: DSI scheduler interpretation of water productivity kg yield per m3 water used by the crop (effective rainfall, plus applied irrigation, plus extracted soil moisture)

This information can be used to explore broader trends. Daily soil moisture data was aligned into four growing stages 1) initial, 2) developing, 3) mid and 4) late. Daily soil moisture levels from each of the intervention sites over eight cropping seasons (Kharif 2015 – Rabi 17/18) totalling 1,638 individual crops were modelled to determine the time spent in a water stressed position for all crops (Figure 13), potato only (Figure 14) and wheat only (Figure 15). **A general trend was the tendency to over irrigate young crops and under irrigate mature crops.**

Figure 13 shows that water stress became more common as the crop developed. Farmers were less likely to allow the crops to become water stressed at the early stages of development. This is likely because young plants require less water and farmers can more easily recognise water stress in young plants. This may also be related to the irrigation systems type and the lack of ability to apply small amounts of water through surface irrigation techniques.

Figure 14 shows for potato similar trends (more water stress in the later stages of crop growth), however there was a higher proportion of crops stressed in the earlier stages of growth. This is likely due to potato being a newly introduced crop in Bihar and Saptari (potato is very common in West Bengal) and new farmers may not have developed a good understanding of crop water requirements and were not able to recognise signs of crop stress in the early stages.

Figure 15 shows for that water management for wheat crops was relatively good. There were no crops that were water stressed in the initial stages of growth and the extent of water stress in the developing stage is also quite low, but high in mid and late growth stages.

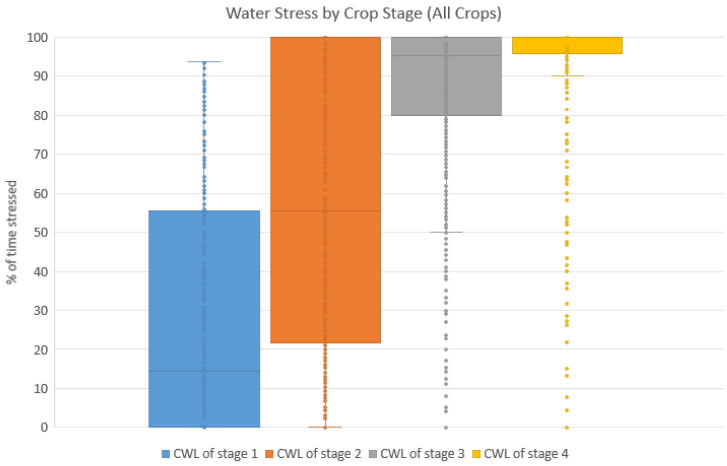


Figure 13: Percentage of time that each crop was water stressed (all crops)

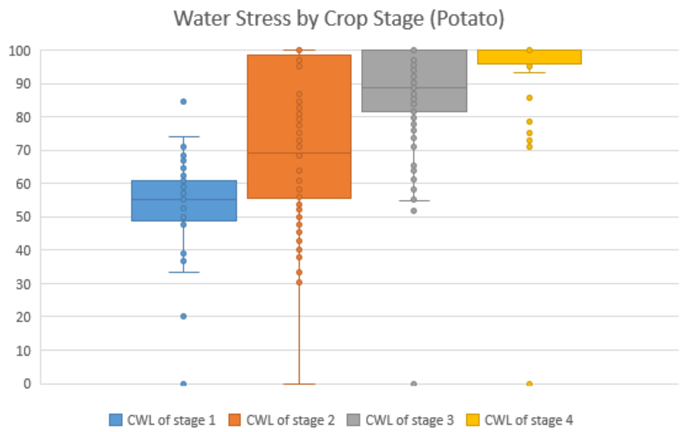


Figure 14: Percentage of time that each crop was water stressed (Potato)

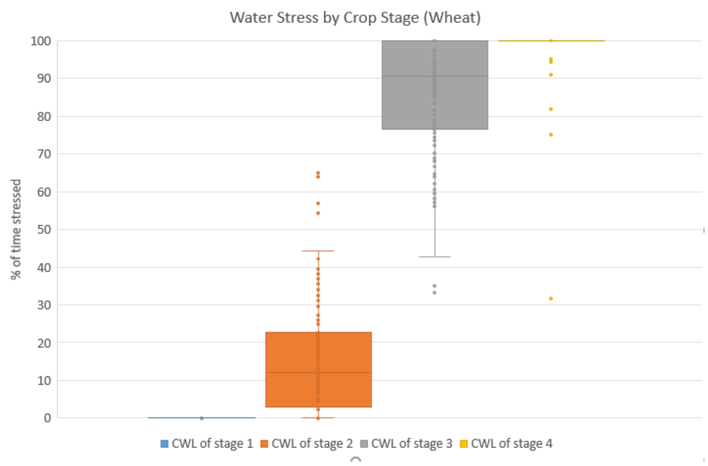


Figure 15: Percentage of time that each crop was water stressed (Wheat)

The water balance approach has helped improve the understanding of crop water requirements across different crops, growth stages and seasons, which is important to manage irrigation scheduling to meet crop water requirements and maximise crop and water productivity. Field scale assessments are key to validating regional scale models.

## 3.5 Linking Regional Hydrology models to farm scale improvements

Regional hydrology models can be used to inform government policy as well as operations of local and informal water management institutions. However, it is the farmer that makes ultimate decisions on farm therefore adoption of model recommendations need to be farmer centric.

### 3.5.1 Data collection

The technical components of the DSI4MTF project successfully introduced a range of improved irrigation systems and management practices. Technologies piloted included drip irrigation, solar pumping, alternative wetting and drying, irrigation scheduling as well as low technology systems, such as improved surface irrigation and water conveyance through poly-pipes.

A range of measurements and assessments were undertaken to determine the performance of the interventions from technical and engineering perspective. These results from these assessments were then provided to the farmers with discussion on the options for optimisation or improvement. Farmers were involved in the data collection and analysis where appropriate. At the completion of the assessment farmers were engaged in discussion on the results and findings.

### 3.5.2 Digital data collection

Regional hydrological models require suitable temporal and spatial scale data for calibration and validation. Mobile phones, particularly internet connected smartphones prove to be efficient tools for sending and receiving information in the field. The DSI4MTF project developed a range of simple applets to capture data, process it and/or instantaneously send it to cloud databases for processing and storage (Schmidt et al. 2019).

A simple data collection process of logging the location of village tube wells evolved into a cloud based spatial dataset linked to a series of integrated, mobile friendly, front end applets (Schmidt, Sugden & Scobie 2020).

### 3.5.3 Case Study 10: development of a digital hub for field data collection

Initial stages of the DSI4MTF project saw a range of data being collected using notebooks that were then transcribed into spreadsheets, which were then emailed to project staff to be analysed using routine analysis techniques. At each step of this data transfer there was potential for delays and lost data. A digital hub was needed to store data digitally. With the hub came a series of interfaces to enter and query the data. This system stemmed from a series of questions raised by various stakeholders. This data collection system proved highly valuable and saved a great deal of time and avoided potential error. However, there was significant effort to design, build and train users to ensure that quality data was collected.

In addition to point in time data collection of water and irrigation monitoring, the DSI4MTF project also undertook significant economic and gross margin analysis at the plot scale. The time and cost associated with every agri-input was recorded and analysed for every plot and every season over the duration of the project. This process was streamlined by the development of spreadsheet proformas that could be uploaded into cloud data storages. A series of bespoke tools were developed to then spatially analysis the data at the end of each season. These tools were integrated where possible and a rich data set of information was used to quantify the actual and potential impact of the water management intervention. A schematic diagram of the integration of the spatial data and applets developed for the project are shown below in Figure 16.

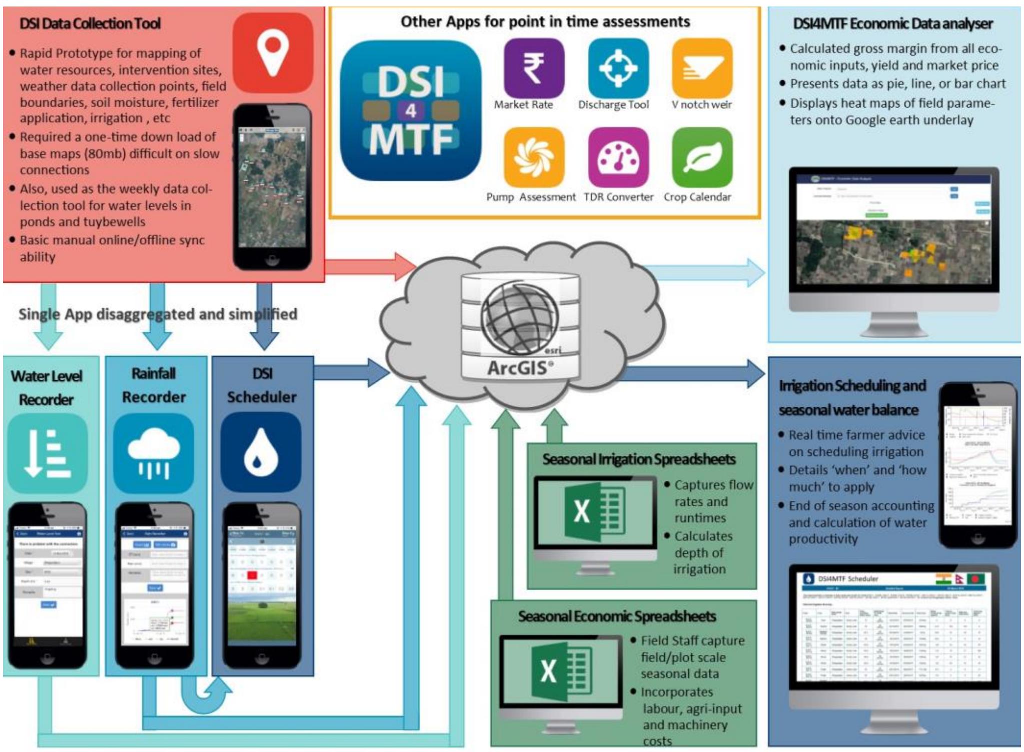


Figure 16: Data collection, integration and analysis using tools developed for the DSI4MTF project

Utility of Farm scale data

The DSI4MTF project involved working with farmers that have had little exposure to irrigation technologies and extension information of water management improvements. This was a key consideration when delivering advice and extension. The project team were able to undertake a range of assessments, but the issue was how this was related to the farmer and how they could use the information to make practice changes.

Farm scale data is necessary to better inform regional scale models but should also be an opportunity to interact and provide feedback to farmers. These opportunities provide an interface between the modelling and farmers and are an entry point for building trust and rapport which will lead to better success in uptake of modelling recommendations.

## 3.6 Policies and Institutions for sustainable water use

Earlier sections have given technical examples of the irrigation and cropping systems used by marginal farmers in the DSI4MTF study sites and approaches to improve water use and crop profitability and productivity. However, the technical considerations need to be considered within the local and policy context. Policy and institutional constraints mediate access to surface and groundwater irrigation and impact the ability of marginal farmers to improve water use for dry season agriculture. Relevant policies for the study sites, were documented by Bastakoti et al. (2017) and summarised by Schmidt et al. (2019). Key aspects are discussed below.

### 3.6.1 Policies

For surface water, providing year-round irrigation through development of small-scale irrigation infrastructure, has been a key policy focus. Another major emphasis has been on participatory irrigation management, ensuring active participation of local users through water users' association (WUA). Policies have promoted community-based institutions and acknowledged the roles of local institutions in managing the small-scale surface irrigation infrastructure, although these are often not well implemented in practice. The policy emphasis is currently on groundwater irrigation. Subsidies for shallow tubewells and pumps has been an important policy instrument to facilitate its expansion.

Policy frameworks developed in the EGP region have emphasised participatory management of both surface and groundwater resources. The key outcome is formation of a water users' committee to ensure active involvement in planning, implementation, and monitoring and evaluation.

Another key policy has been the provision of subsidies and support services to enhance the access to surface and groundwater resources. However, users are required to follow complex procedures and guidelines to avail such services which are not readily accessible by marginal farmers, particularly women. Facilitating linkages between farmers and relevant government and non-government agencies to ensure they benefit from such provisions is an important requirement.

### 3.6.2 Water management institutions

Local institutions were analysed by Bastakoti et al. (2017) through interviews with district level officials and community focus group discussions. While several formal/informal institutions exist in each village, they are generally insufficient to significantly enhance access to resources. Institutions include the village development committee, water user's committee, village Panchayat, farmer's cooperative or club and self-help groups.

Management of water access is mainly informal and on a first come first served, or priority needs basis. There are typically informal markets to sell water from a tubewell, with charge rate generally based on number of hours pumped and size of pump. For those who cannot access groundwater, public canals are available, yet their coverage is limited in the study area. There are also surface ponds, yet these primarily support fish farming and farmers seldom access pond water for irrigation purposes.

Some villages have received support from government agencies for installation of tubewells and purchase of pumps. In all villages studies reviewed under DSI4MTF, except for Dholaguri, existing water sources (tubewells and ponds) were insufficient to meet irrigation needs, resulting in large areas of fallow land in the dry season months.

Farmers are generally aware of various government support services but were unable to access them due to lack of awareness of application procedures and poor local coordination with authorities. While policy and institutional frameworks exist at different levels, and include provision for subsidies and other support, national policies do not trickle down effectively to local levels.

### 3.6.3 Strengthening Institutions for sustainable water use

Technical interventions to support sustainable intensification will be unsuccessful if they are not accompanied by institutional innovations, which can overcome structural barriers to adopting new technology and irrigation methods (Schmidt et al 2019).

Alternative models of farming which can support smallholders, most notable of which is group farming (whereby collectives of farmers pool land, labour, capital and skills to create larger units of production) were shown by Sugden et al. (2020) to be foundational for sustainable agricultural intensification by marginal farmers. Strategies to sustain these collectives and build their scalability have been proposed in Schmidt, Sugden and Scobie (2020). These include the need to harness existing cohesion within communities, the importance of expanding to form larger plots, and the critical role played by ethical community engagement in ensuring buy in from communities.

Equally important is the alignment of farmer groups, or collectives with existing programmes and institutions operating at a local level. This will strengthen the collectives themselves, while also supporting their out-scaling locally to neighbouring communities. Buy in from larger programmes meanwhile, also opens opportunities to upscale the models, so they can in the future become part of the larger policy landscape. Alignment is required with both the government and private sector as outlined below and in Schmidt, Sugden and Scobie (2020).

### 3.6.4 Government Sector

By far the most important institution is that of local government agencies. In Nepal the new Federal governance structure is taking shape, and local government institutions are evolving rapidly. This presents a unique opportunity for Nepal to integrate collective farming models in local level policy and planning which are in formulation process. For example, the newly formed rural municipalities bring together multiple line agencies, and develop their own agricultural policies using a budget allocated by the centre. There is considerable potential to advocate to include collective farming models within their plans, offering outstanding opportunities for local level out-scaling.

At a district level, key line agencies include the Krishi Gyan Kendra (KGK) which was the District Agriculture Office prior to restructuring. The KGK is an agricultural knowledge centre established to demonstrate new agricultural technology and promote technology transfers. Strong links with KGK can help sustain collectives after project ends with support in capacity building, agricultural extension services and subsidies.

In Indian sites of Bihar and West Bengal, where the local governance landscape is more established, strong linkages should be developed with the Block Development Office (BDO), which fulfils a similar role to the rural municipalities. There is also considerable opportunity for institutionalizing the collectives through the wide range of state-run programs available locally. In Uttar Chakoakheti and Dholaguri, the Govt. Of West Bengal, Office of the Assistant Director of Agriculture (ADA), is one of the key local line agencies for agricultural support. They assist farmers with accessing seeds, fertilisers, medicines, and farm machinery while offering training on seasonal crops. Other important agencies in both Bihar and West Bengal include the Agricultural Technology Management Agency (ATMA). In West Bengal it has provided assistance through offering mini kits for Boro paddy for farmers, and training on apiculture including bee box, and the Krishi Vigyan Kendra (KVK), which in West Bengal has offered skill based training on vermicompost, and support in provision of seeds.

### 3.6.5 Private Sector

Beyond the government, there are also private sector institutions which can also open opportunities for marginal farmers. For example, in Madhubani, Agri-evolution (De-Haat) is a start-up company which provide services to farmers from seeds up to marketing of their produce, while offering hand holding support to rural entrepreneurs. Another important field for private sector engagement is crop insurance. Where project sites are flood prone, marginal farmers are disproportionately affected. Since, it is difficult for marginal and tenant farmers to obtain insurance for crops in smaller land plots, any umbrella organisation associated with collectives can facilitate group crop insurance.

One of the components for collectives to function well requires establishing and maintaining effective value chains. In future work, working with a broader range of stakeholders at different stages of the agricultural value chain is important to understand relation between farm productivity and farmer livelihoods on one hand and capture implications of collective farming on the other. Strengthening linkages with value chain actors such as banks, agronomic equipment suppliers, agrovets should be pursued.

## 3.7 Gaps in Current Knowledge

Many projects have been designed and delivered using conservation agriculture as a vehicle for sustainable improvement of farmers' livelihoods. However, irrigation and farm level water management must not be overlooked as a key component to increasing production. While it is widely accepted that efficient irrigation is the goal, there are many nuances around how that is achieved at the farm level. Issues arise between the ability to measure (crop requirement, irrigation application, water use efficiency) versus the ability for the farmer to act at a scale or resolution that will have an impact.

Farmers need to have access to both better information and knowledge as well as better technologies to act on the information. For example, a farmer knowing that the weekly crop water requirement is

48mm, but only having access to a poorly levelled irrigation basin means that their ability to uniformly and accurately apply millimetre precise irrigation is impossible.

The following section highlights knowledge gaps for intensification and diversification in the EGP with a specific focus on small scale irrigated farming systems. While these gaps have been categorised into several groupings, a multidisciplinary systems approach is required to address these research gaps.

## Risk

- Better understanding of the risk imposed on marginal farmers and their ability to manage this risk when introducing irrigated dry season crops. Intensification and diversification can increase risk, especially for small farmers who are not well resourced, and are poorly connected to support services such as agronomic, insurance and technical support.
- Better understanding of marketing and supply chain linkages for vegetable crops.

## Farming Systems

- Understanding models for potential for integrated farming systems for small holder production, including the role of alternative cropping, fisheries and livestock production and impact on water resources.
- Economic, environmental and social impact of alternative crop combinations, including hydrological and other agronomic and social constraints of multi crop system.
- Production constraints of soils (eg nutrients and acidification) and approaches to maintain soil productivity and health under irrigation intensive systems.
- Understanding nutrition sensitive agriculture and better understanding on how intensification and diversification lead to improved nutritional outcomes.

## Irrigation and water use

- Better understanding of water and energy use by alternative cropping systems and irrigation practices.
- Impact of diversification and intensification on the sustainable yields of the groundwater aquifer.
- Improved farmer understanding of suitability of various irrigation systems.
- Optimisation of cropping systems for best water productivity and profitability.

## Data collection and information transfer

- The best methods to implement irrigation system management and water resource monitoring programs through government programs, the private sector and NGO’s.
- Better understanding on the most useful suite of ‘measure to manage’ tools and assessments in each element in a farm scale irrigation and water management system.
- Improved models and modelling approaches for scaling the impacts of farm scale irrigation on regional water resources.
- Methods to downscale and upscale information between farm/field studies and catchment decisions.
- Potential for smart phone and other technology and social media platforms to improve the farming in the EGP.

### Adoption, implementation and knowledge

- Better technical support and knowledge sharing for small scale farmers and improved linkages with public and private sector.
- Local institutional strengthening to improve farmer access to information on markets, inputs and advisory services.
- Better understanding of the decision-making process in adoption of new technologies/cropping systems management.
- Understanding the preferred approach for delivery of irrigation and water management advice for farmers, and the scalability of each delivery option.

# 4 APSIM modelling, particularly focussing on the impact of landuse change and changes to soil / landscape infiltration properties

The APSIM cropping systems framework (Keating et al., 2003; Holzworth et al., 2014) is a model with a proven track record in modelling the performance of diverse cropping systems, rotations, fallowing, crop and environmental dynamics (Turpin et al., 1996; Carberry and Arbrecht, 1991; Robertson et al., 2001; Verburg and Bond, 2003; Whitbread et al., 2010; Hochman et al., 2007; Gaydon et al., 2017). A distinctive innovation and philosophical departure from most other 'crop models' is APSIM's primary focus on simulating crop resource supply (rather than a primary focus on resource demand, ie crop growth), with the soil forming the central simulation component. Crops, with their own resource demands impacted by weather and management, find the soil in one condition, and leave it in another condition for the next crop (McCown et al., 1996). This emphasis on simulation of soil resource dynamics positions APSIM strongly in comparison with other models for investigations into long-term changes to soil conditions, water -balance terms, and sustainability associated with different cropping strategies and practices. With particular focus on research into Conservation Agriculture (CT) and other adaptation strategies, another notable strength of the APSIM model is it's unique capacity to capture intricate detail and subtleties of dynamic farmer management practices through a highly flexible 'Manager' Module allowing the user to specify detailed farmer decision-trees in simple 'if-then-else' logic (Holzworth et al., 2014). APSIM has recently been enhanced to simulate rice-based cropping systems and environmental dynamics of ponded systems (Gaydon et al., 2012a, 2012b). APSIM can simulate different tillage and residue practices, as well as other components of CA like alternate-wetting-and-drying (AWD) irrigation, and assess the impacts on crop production, water use, and other system balance terms (soil carbon, nitrogen and moisture). Of course, APSIM can likewise capture the effect of conventional tillage practices.

## 4.1 APSIM modelling method

The method for modelling Conventional Tillage (CT) as distinct from Conservation Agriculture (CA) is described below:

When soils are puddled prior to the rice phase, then later tilled prior to the wheat phase in conventional rice-wheat, rice-maize and similar systems, significant inter-seasonal changes occur in soil properties (Gathala et al., 2011). Puddling reduces the effective Ks and bulk density (BD) of affected layers, whereas tillage after the rice phase increases effective Ks by breaking the plow-pan. BD of surface soil layers is decreased. These are significant input parameters in sensibly simulating rice-wheat system performance (Gaydon et al., 2012a), however APSIM does not currently simulate these parameter changes in response to specified tillage events. For the relevant simulated datasets in this study, we found it was necessary to employ APSIM-Manager to specify an increase in Ks of the plow-pan layer by 100 % (a doubling), and a decrease in BD by 5 % following post-rice tillage, and apply the reverse change to these parameters upon puddling at the start of the subsequent rice phase (following findings of Gathala et al., 2011). Bund height (APSIM resettable parameter max_pond) was also reset to zero via APSIM-Manager on the date of rice field drainage (representing opening of the bunds), and then again set to the actual experimental bund-height on the occasion of bund establishment pre-crop. Once again, these are not simulated in APSIM, they are specified by the user. APSIM does however simulate the effect of tillage on soil roughness and therefore runoff and water retained on the soil surface and available for infiltration - by automatically reducing the USDA curve number, as per specified parameters. As an example, we found it necessary to reduce curve number by 10 in the case of each discing, and by 5 for harrowing. The curve number was reset to the default curve number when at least 40 mm of water was added to soil (by rain or irrigation) to simulate the collapse/smoothing of a freshly cultivated soil surface as a result of saturation and rainfall impact (Balwinder Singh et al., 2015a, b).

The water balance and all component terms (rainfall, irrigation, change in soil water storage, runoff, drainage, soil evaporation, crop transpiration) are calculated by APSIM on a daily basis, based on inputs of daily climate data (max, min temps, rainfall, solar radiation) as well as imposed farmer management (details of agronomy, sowing dates, crops, irrigation amounts, fertiliser, tillage etc..). APSIM is a dynamic daily time-step model that combines biophysical and management modules within a central engine to simulate cropping systems. The model is capable of simulating soil water, C, N and P dynamics and their interactions within crop/management systems. Daily potential production for a range of crop species is calculated using stage-related radiation-use efficiency (RUE) constrained by climate and available leaf area. The potential production is then limited to actual above-ground biomass production on a daily basis by soil water, nitrogen and (for some crop modules) phosphorus availability (Keating et al., 2003). The soil water balance (SOILWAT) module uses a multi-layer, cascading approach for the soil water balance following CERES (Jones and Kiniry, 1986), however a more process-based soil water-balance module is also available (SWIM3; Huth et al., 2012). The SURFACEOM module simulates the fate of the above-ground crop residues that can be removed from the system, incorporated into the soil or left to decompose on the soil surface. The SOILN module simulates the transformations of C and N in the soil. These include organic matter decomposition, N immobilization, urea hydrolysis, ammonification, nitrification and denitrification. The soil fresh organic matter (FOM) pool constitutes crop residues tilled into the soil together with roots from the previous crop. This pool can decompose to form the BIOM (microbial biomass), HUM (humus), and mineral N (NO3 and NH4) pools. The BIOM pool notionally represents the more labile soil microbial biomass and microbial products, whilst the more stable HUM pool represents the rest of the soil organic matter (SOM) (Probert et al., 1998). APSIM crop modules seek information regarding water and N availability directly from SOILWAT and SOILN modules, for limitation of crop growth on a daily basis. Biological and chemical processes occurring in ponded rice fields are simulated using the POND module within APSIM (APSIM-Pond, Gaydon et al., 2012b). Crop modules specifically relevant to the evaluation presented in this paper are APSIM-Oryza (Gaydon et al., 2012a), APSIM-Wheat (Wang et al., 2003), APSIM-Maize (Carberry and Abrecht, 1991), APSIM-Ozcot (Hearn, 1994); APSIM-Soybean (Robertson et al., 2001; Robertson and Carberry, 1998) and APSIM-Canola (used also for mustard; Robertson et al., 1999; Robertson and Lilley, 2016). APSIM-Oryza was recently improved to simulate rice crop response to soil salinity (Radanielson et al., 2018). APSIM-Wheat simulates salinity effect in a more simplistic way (focussing on water-availability effects only; Hochman et al., 2007) however none of the other APSIM crop modules attempt to simulate crop response to saline soil conditions.

To simulate CA in the EGP, general rules followed in specifying the different practices are shown in Table 14.

Table 14. Differentiating CA vs CT management in APSIM

| System component | Conservation Agriculture (CA) | Conventional Tillage (CT) |
|---|---|---|
| **Residue management** | 75 % removed after harvest of each crop<br>25 % retained on soil surface | 90 % removed after harvest of each crop<br>Remaining residues incorporated into top 100mm soil layer during preparation for next crop |
| **Tillage** | No tillage, no puddling, zero-till (ZT) drill seeding in row | Full tillage: 4 tillage passes followed by drill seeding in row |
| **Irrigation** | WHEAT and MAIZE : Irrigation of 40mm triggered by a soil water deficit of 40mm in top 1m of soil<br>BORO RICE: alternate wetting-and-drying (AWD), re-flooding after 2 days of non-ponded conditions | WHEAT and MAIZE: as per CA<br>BORO RICE: continuously ponded conditions maintained. Field re-flooded as soon as pond disappears. |
| **Fertiliser** | Varies between sites as per local recommendations, but same between CT and CA | Varies between sites as per local recommendations, but same between CT and CA |

## 4.2 APSIM modelling results

Results of simulated water-balance studies for selected sites (please see the locations in Figure 25 in the next Chapter) in the EGP (Table 15) are given below. The APSIM model for all sites was robustly calibrated and validated during the ACIAR-SRFSI project (https://www.aciar.gov.au/project/CSE-2011-077 ). In this water-balance study, we compared the performance of CA vs CT, and present here figures for the individual sites for Rice-Maize, Rice-Wheat, and Rice-Rice (Boro) rotations (Figure 17 to Figure 20), followed by the averaged figures across the 4 sites (Figure 21 to Figure 24).

Table 15. EGP sites and crop rotations used in analysis

| Country | District | Node | Latitude | Longitude | Cropping systems simulated | Climatic period |
|---|---|---|---|---|---|---|
| **Bangladesh** | Rajshahi | Premtoli | 24.40691 | 88.43403 | Rice-wheat<br>Rice-maize<br>Rice-Boro rice | 1/06/2000-31/05/2017 |
| **India (West Bengal)** | Coochbehar | Falimari | 26.40823 | 89.77732 | Rice-wheat<br>Rice-maize | As above |
| **India (Bihar)** | Purnea | Dogachi | 25.51621 | 87.33464 | Rice-wheat<br>Rice-maize<br>Rice-Boro rice | As above |
| **Nepal** | Sunsari | NARC Tarahara | 26.705 | 87.256 | Rice-wheat<br>Rice-maize | As above |

As CA implicitly includes AWD irrigation in Boro rice, in combination with no puddling and the associated increase in saturated percolation rate, irrigation water savings were not evident in comparison with CT Boro rice – largely driven by the 2x factor reduction in percolation rate from puddling. In order to examine the impact of AWD in isolation, we conducted an additional analysis for Premtoli, Rajshahi, Bangladesh, in which we simulated CT (puddled) Boro rice with both continuous ponding, and AWD.

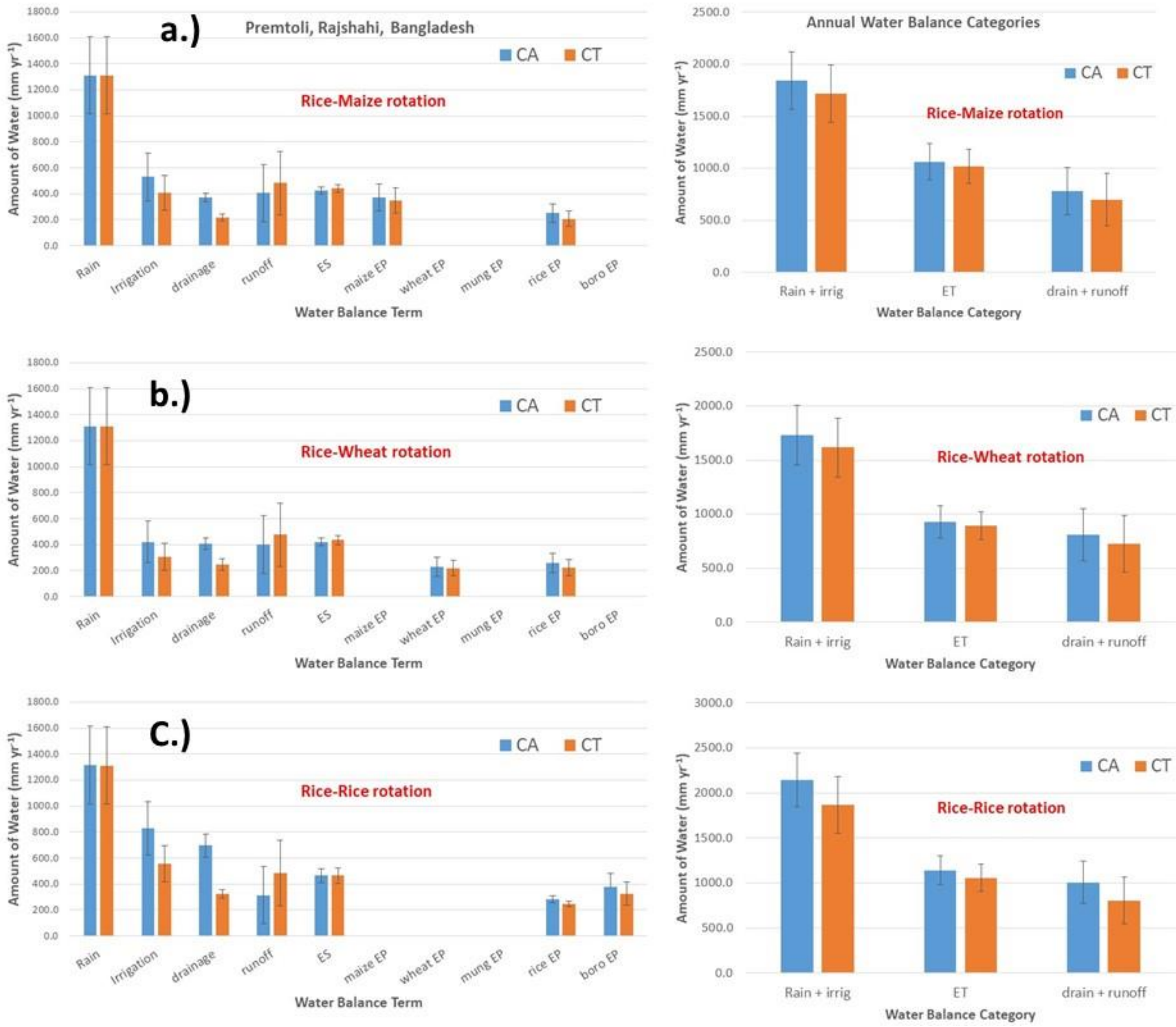


Figure 17. Annual average simulated water balance terms at Premtoli, Rajshahi, Bangladesh (2000-2017) (left side), plus water balance categories (combining several of the individual terms from the left) (right side), for a.) a rice maize system; b.) a rice-wheat system; and c.) a rice-rice system, showing the impacts of farmers following CT or CA cropping practices. ES is evaporation (including both from the soil surface or pond when present); EP is crop transpiration. Mung is mungbean, Boro is Rabi season irrigated rice; rice refers to Kharif season monsoon rice.

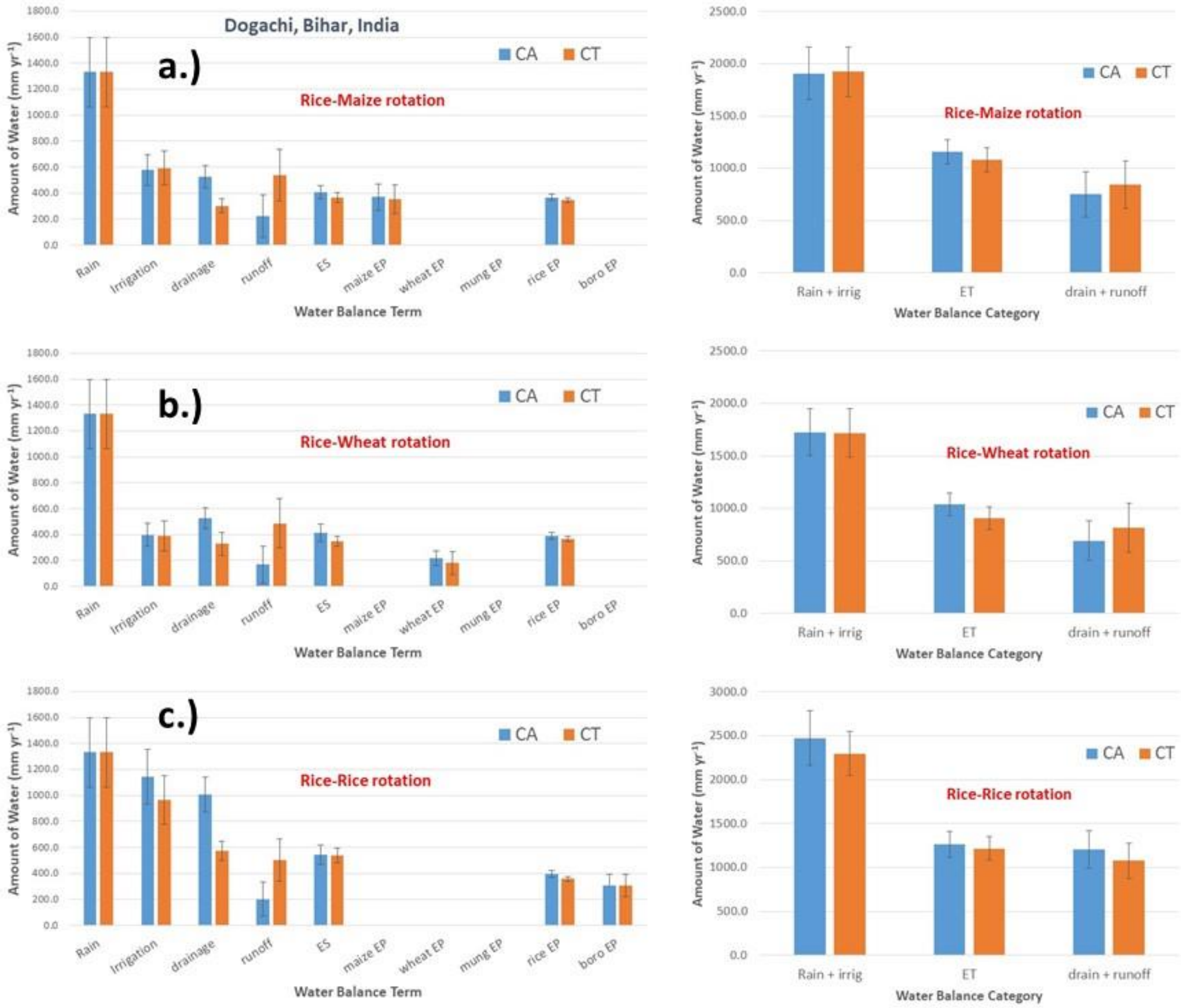


Figure 18. Annual average simulated water balance terms at Dogachi, Bihar, India (2000-2017) (left side), plus water balance categories (combining several of the individual terms from the left) (right side), for a.) a rice maize system; b.) a rice-wheat system; and c.) a rice-rice system, showing the impacts of farmers following CT or CA cropping practices. ES is evaporation (including both from the soil surface or pond when present); EP is crop transpiration. Mung is mungbean, Boro is Rabi season irrigated rice; rice refers to Kharif season monsoon rice.

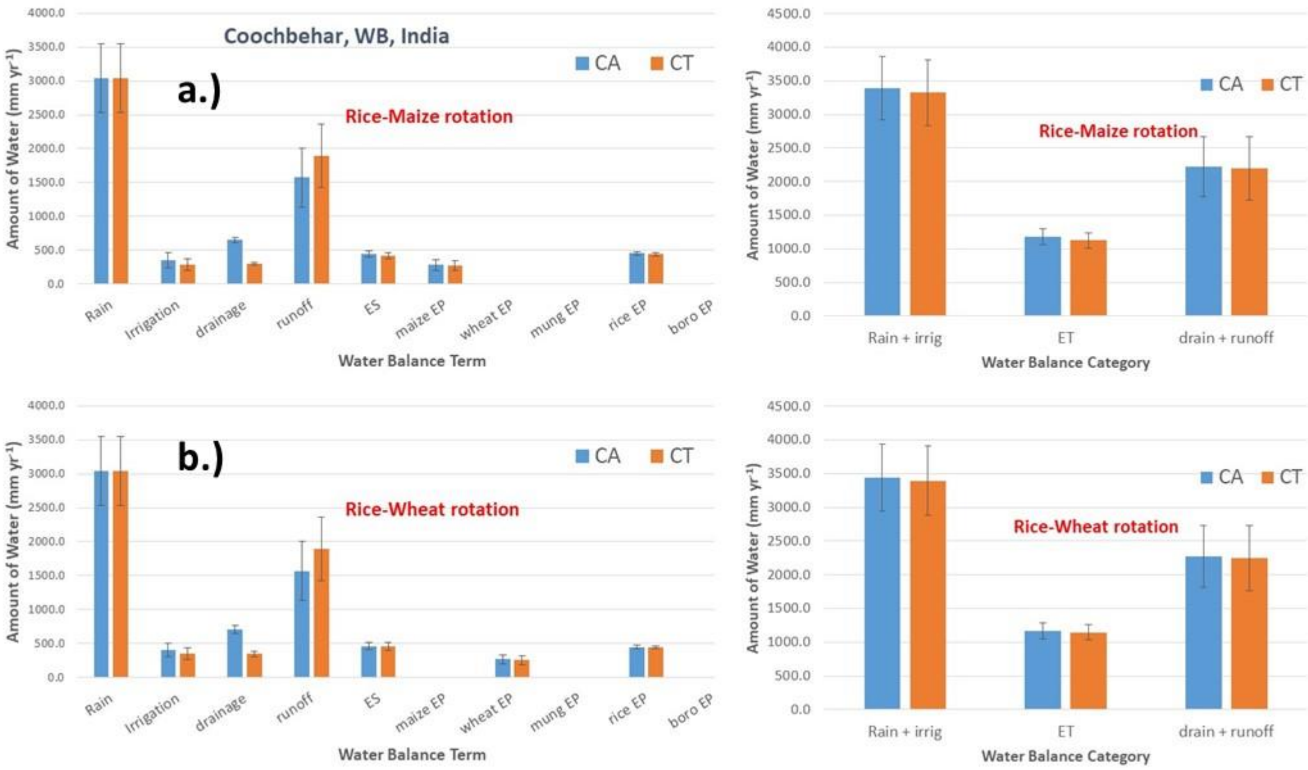


Figure 19. Annual average simulated water balance terms at Coochbehar, West Bengal, India (2000-2017) (left side), plus water balance categories (combining several of the individual terms from the left) (right side), for a.) a rice maize system; and b.) a rice-wheat system showing the impacts of farmers following CT or CA cropping practices. ES is evaporation (including both from the soil surface or pond when present); EP is crop transpiration. Mung is mungbean, Boro is Rabi season irrigated rice; rice refers to Kharif season monsoon rice.

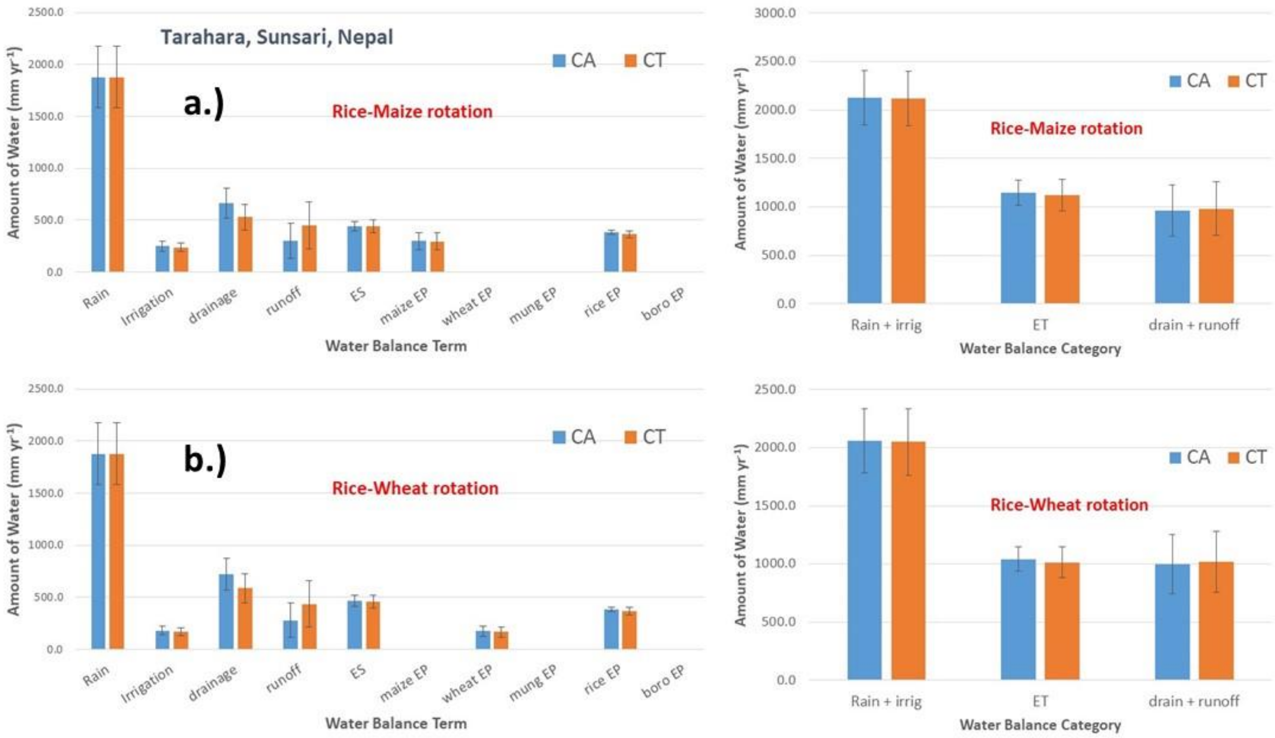


Figure 20. Annual average (2000-2017) simulated water balance terms at Tarahara, Sunsari, Nepal (left side), plus water balance categories (combining several of the individual terms from the left) (right side), for a.) a rice maize system; and b.) a rice-wheat system, showing the impacts of farmers following CT or CA cropping practices. ES is evaporation (including both from the soil surface or pond when present); EP is crop transpiration. Mung is mungbean, Boro is Rabi season irrigated rice; rice refers to Kharif season monsoon rice.

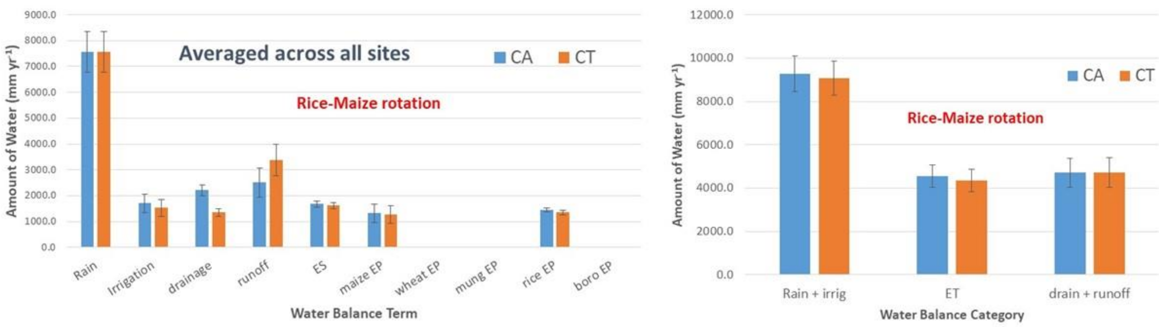


Figure 21. Annual average simulated water balance terms, rice-maize rotation, averaged across sites (2000-2017), (left side) plus water balance categories (combining several of the individual terms from the left) (right side), for a rice-maize system, showing the impacts of farmers following CT or CA cropping practices. ES is evaporation (including both from the soil surface or pond when present); EP is crop transpiration. Mung is mungbean, Boro is Rabi season irrigated rice; rice refers to Kharif season monsoon rice.

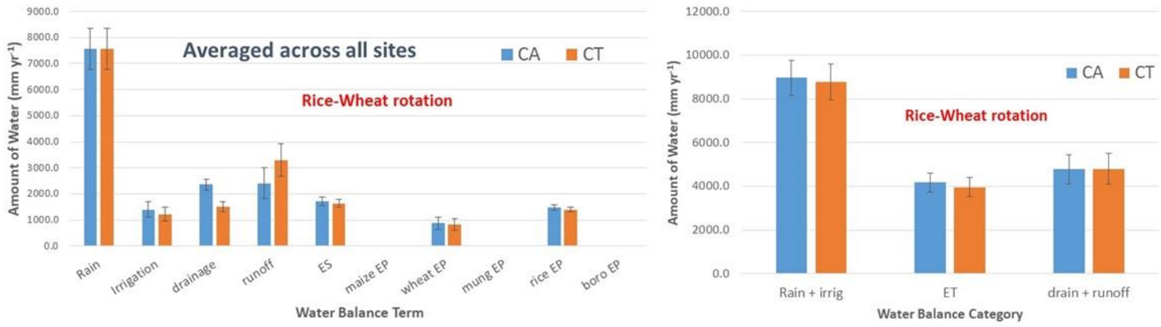


Figure 22. Annual average simulated water balance terms, rice-wheat rotation, averaged across sites (2000-2017), (left side) plus water balance categories (combining several of the individual terms from the left) (right side), for a rice-wheat system, showing the impacts of farmers following CT or CA cropping practices. ES is evaporation (including both from the soil surface or pond when present); EP is crop transpiration. Mung is mungbean, Boro is Rabi season irrigated rice; rice refers to Kharif season monsoon rice.

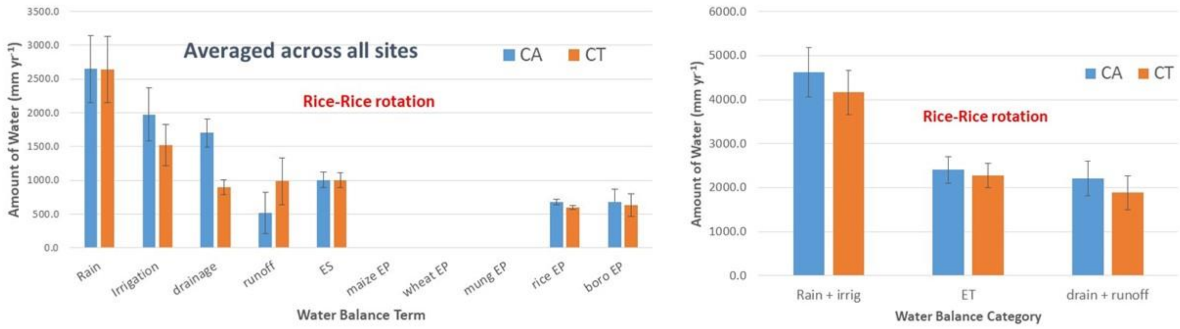


Figure 23. Annual average simulated water balance terms, rice-rice rotation, averaged across sites (2000-2017), (left side) plus water balance categories (combining several of the individual terms from the left) (right side), for a rice-rice system, showing the impacts of farmers following CT or CA cropping practices. ES is evaporation (including both from the soil surface or pond when present); EP is crop transpiration. Mung is mungbean, Boro is Rabi season irrigated rice; rice refers to Kharif season monsoon rice.

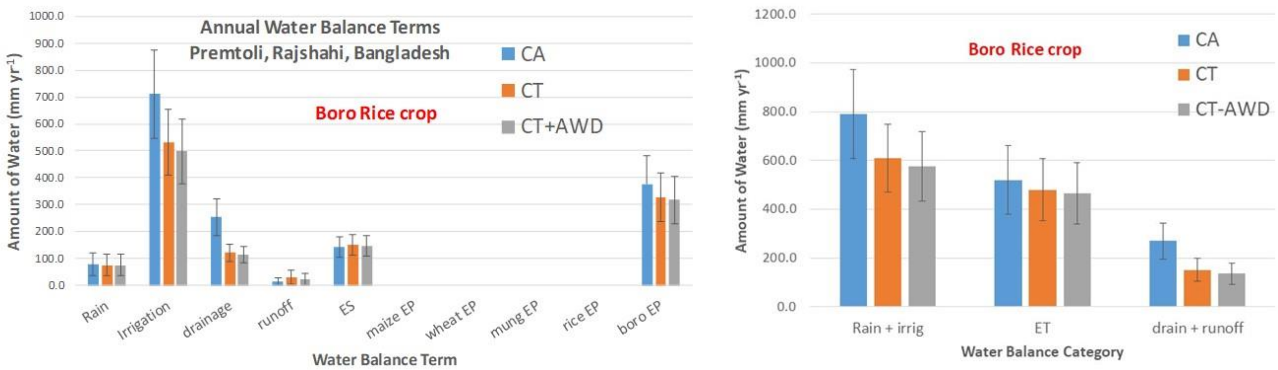


Figure 24. Annual average simulated water balance terms, Boro rice crop, Premtoli, Rajshahi, Bangladesh (2000-2017), (left side) plus water balance categories (combining several of the individual terms from the left) (right side), for a rice-rice system, showing the impacts of farmers following CT or CA cropping practices. ES is evaporation (including both from the soil surface or pond when present); EP is crop transpiration. Note that the results are those for Boro rice only, not the system.

Major discussion points from the analysis:

- Across all sites (with annual rainfalls ranging from 1300 mm up to 300 0mm, a diversity of soils, and three different cropping systems) the same conclusions can be drawn. Conservation agriculture has a significant effect on irrigation requirement, but not on total ET (soil and pond evaporation (Es) + crop transpiration (Ep)). It is understood that in recirculating aquifer-based hydrological systems like the EGP, ET is the key variable of a system which impacts the net groundwater drawdown (Humphreys et al., 2010). From our limited point-based analyses therefore, there appears little difference between CA and CT management in terms of overall water-table drawdown.
- CA systems decreased or maintained similar Es to CT systems, but with increased Ep (due to more productive crop production)
- CA systems required increased irrigation water. This was driven by the increased saturated percolation of water in CA systems (doubled over CT systems) during kharif rice cropping phases, which required supplementary irrigation in our APSIM simulations. During Maize and Wheat crops, CA required slightly less irrigation water due to reduced ES losses from the soil resulting from higher residue retention rates. But this irrigation water savings disappeared at a systems level, as it was over-ridden by increased irrigation water needed in the rice phase. If the rice phase is not supplementally irrigated, then CA systems will require less irrigation water, but considerable kharif rice production losses may result due to increased water stress during that phase, due to quicker disappearance of ponded water.
- Water use by CA Boro rice crops was different from CT Boro rice crops due to two main reasons: (i) AWD reduced time ponded, and (ii) lack of puddling increased the percolation rate by a factor of 2x. The net result of these two factors was that CA Boro rice crops required considerably more irrigation water than CT Boro rice crops at all locations. The increased irrigation water requirement due to the increased percolation rate (now plow-pan) overshadowed the savings from AWD. Due to this confounding of factors, the original analysis alone was unable to define the impact of AWD itself. For that reason, we conducted an additional investigation of the impact of implementing AWD in a fully puddled CT system (Figure 24). This indicated that AWD (we imposed 2 days gap between re-flooding) saved irrigation water requirement (by around 6 %), but the effect on ET was considerably less (around half of that, 3 % saving).

## 4.3 Implications for regional hydrology

There are a limited number of cropping systems modelling papers focussing on CA vs CT in the literature, but our searches only found crop-production-focussed studies and none reporting water-balance terms or differences.

The implications for the hydrological system of the EGP, where much of the deep drainage and runoff re-enter the aquifers (from which irrigation water is drawn) and hence are not ‘losses’ from the system, are that the key comparisons between cropping systems options (eg CT vs CA) should be based on total evapotranspiration (ET = soil evaporation (Es) + crop transpiration (Ep)), not on amount of irrigation water applied (or pumped) and its subsequent drainage component. Our simulations thus far, in rice-wheat, rice-maize and rice-rice systems, indicate that there is very little difference in overall ET between CT and CA practices. If anything, CA is likely to result in higher ET due to enhanced rooting and better Rabi crop production (due to the associated higher crop transpiration Ep).

In this sense, claims that CA will result in reduced groundwater drawdown in the EGP would likely be baseless. However, greater Rabi crop production and increased farmer profit is likely to result, which is a good thing. Such gains will be based mostly upon labour savings and better crop rooting due to elimination of the puddling-derived plough pan – not due to water savings. This reinforces some of the findings in the case studies in Section 3.

Our study indicated that CA reduces erosion and runoff and increases soil moisture-holding capabilities and surface soil organic matter. This is supported by several reports in the literature (Palm et al., 2014). However, our preliminary study has additionally shown that the reduced runoff in CA is matched roughly by increased drainage below the crop roots in CA compared with CT. Both drainage and runoff waters are likely to ultimately re-enter the water tables and aquifers and hence are not system water losses in any case.

## 4.4 Gaps in current knowledge

Gaps in knowledge, particularly around cropping system management and its effects on the water balance are numerous. As noted earlier, there is effectively nothing in the literature in this regard for either the EGP or South Asia generally. Some of the principle gaps which need to be explored in effectively managing water resources in this agricultural region are:

1. to what extent does land use change lead to changes in landscape infiltration properties? For example, does an increase in the area dry season irrigated rice and the accompanying puddling reduce infiltration? The examples provided in this SRA project report indicate that the impacts of CA technologies on the water balance vary considerably with cropping environment and management (climate, soil, water-table dynamics, farmer practices, etc). Although we see this pattern in several discrete examples, they do not give us a wholistic picture of the regional story with regard to CA technologies and their overall impact on the water balance for the EGP. For that, a future comprehensive study will require geographically broad (GIS-based) data on soils, climate, water-tables, salinity dynamics, etc., which should be scaled-up using APSIM-simulated data at representative points to provide a reginal perspective.
2. Better information on regional water tables and their dynamics must be incorporated into future APSIM modelling efforts.
3. It is likely that additional crop varieties and species may need to be incorporated and calibrated/validated for APSIM, in order to adequately represent the whole EGP region.
4. Projected future climate and water-table dynamics data is needed across the EGP.
5. A methodology for linking APSIM to both GIS-based systems and regional groundwater models will need to be developed in order to make regional assessments.

# 5 Simple indicative water balance studies in different parts of the Eastern Gangetic Plains

## 5.1 Introduction

In this Section, we describe simple, indicative water balances in several parts of the region. The water balances in northwest Bangladesh were developed in the Sustainable Development Initiative Portfolio project and have been published in reports, with some aspects also published in scientific journals (Peña-Arancibia et al., 2020). The water balances in Bihar, Uttar Pradesh and West Bengal described below were developed for this scoping study, and are less complete than those for Bangladesh; nevertheless, they offer insights as to the likely issues and where the concerns noted above are likely to become manifest. They also offer insights about data availability, data quality and the requirements in a detailed project for dealing with and extending the available data.

### Locations for the study

We chose eight districts within the EGP, as shown in Figure 25. The choice of the districts was based on:

1. Cooch Behar in West Bengal (DSI4MTF project has sites there);
2. Kurigram in northwest Bangladesh (SDIP Bangladesh project);
3. Rajshahi in northwest Bangladesh (SDIP Bangladesh project);
4. South 24 Parganas in West Bengal (Cropping intensification in the coastal zone project has been working at Gosaba Island, part of South 24 Parganas);
5. Madhubani in Bihar (DSI4MTF project has sites there);

with the remaining districts chosen to cover the geographical range of the EGP.

The districts cover the region from E to W and N to S. That is also roughly the rainfall / ET gradient. Cooch Behar has an excess of rainfall over potential ET, whereas Kanpur, Bhojpur and Lakhimpur Kheri have a deficit. All other things being equal (which they aren't), that would make for differences in recharge and runoff. One key regard in which other things are not equal is the proximity to a large river. Kanpur and Bhojpur are at the confluence of the Ganges and a tributary (Yamuna for Kanpur and Sone for Bhojpur), and Lakhimpur Kheri borders the Ghaghara, and the Sarda, a tributary of the Ghaghara, runs through the district. That difference too might make for considerable differences in recharge and hence groundwater behaviour. The choice of districts was with this sort of contrast in mind.

While the list does not include a location in Nepal, the districts of Madhubani, Purba Champara and Lakhimpur Kheri all border the Terai region. The surface water balances in these three districts are likely to be similar to those in the adjacent parts of the Terai.

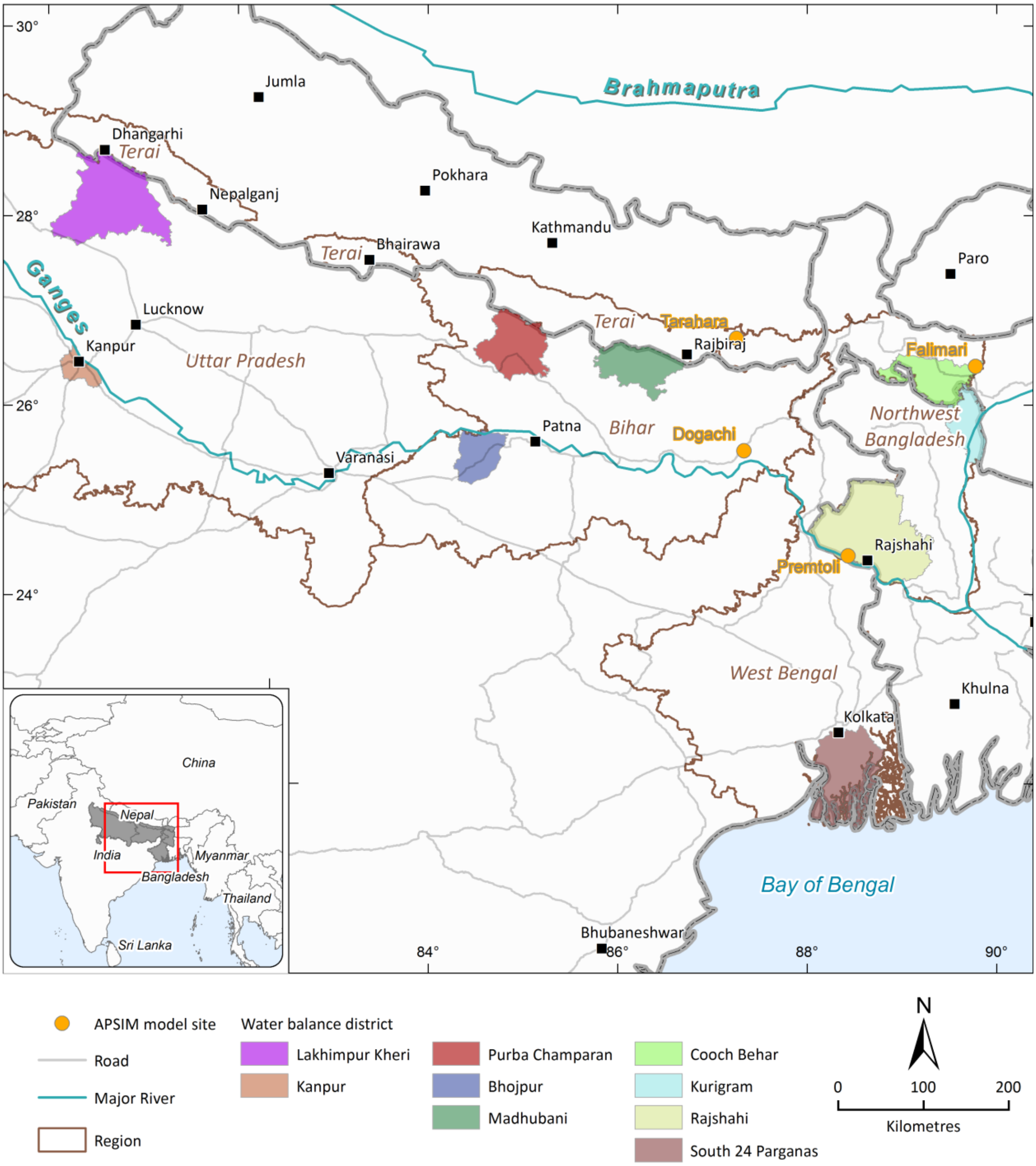


Figure 25. Districts assessed in the simple water balance study.

## 5.2 Simple water balances: method

We used the surface water balance approach of Ahmad (2002) and Ahmad et al. (2005), as modified by Ahmad et al. (2020a, 2020b, 2021). Ahmad (2002) and Ahmad et al. (2005) suggested that the net groundwater use in an irrigation area, *Ingw*, could be computed as the deficit implied by a water balance of the land surface, given by:

$$Ingw = ETa - Pn - Icw + dW/dt \quad (1)$$

where $ETa$ is the water lost by evapotranspiration of crops and other vegetation, $Pn$ is the water gained from precipitation (considered as a net term, after losses to runoff), $Icw$ is the diversion of water into the area via canals, and $dW/dt$ is the change in water stored in the area (in the soil, but also in other surface storages) over the period being considered.

The advantage of the surface water balance approach is that it does not require detailed groundwater modelling or assessment, and does not require information or assumptions about lateral groundwater flows.

Ahmad et al. (2005) applied the method to the Rechna Doab region of Pakistan, using spatially explicit estimates of ETa derived from remotely sensed satellite data.

Ahmad et al. (2020a, 2020b, 2021) modified the idea slightly to look at a lumped surface water balance (of the canal commands in Pakistan) given by:

$$0 = ETa - P - Icw - Ingw + B \quad (2)$$

where $P$ is the total rainfall and $B$ is a balance term that is the difference between the sum of the other terms (and thus forces equation (2) to sum to zero).

In modifying equation (1) to derive equation (2), the soil water storage term, $dW/dt$ is absent, and is implicit in the difference or balance term, $B$. We deal here with annual water balances. The change in the annual soil water storage, while it may be significant from year to year, is likely to be insignificant over a period of many years. Since we will use the annual water balances to identify trends in the water balance over a 38 year period, the change in the soil water storage as a trend (rather than an annual variation) is likely to contribute little to the interpretation. In any event, as pointed out, the term is not absent, but is implicit in another term.

Here, we do not have access at this scoping study stage to time-series estimates of the actual evapotranspiration or canal deliveries of irrigation water. We therefore modified the approach and the equation to

$$0 = P + Ingw - ETo + B \quad (3)$$

where $ETo$ is the potential evapotranspiration. We have reversed the signs of the terms from equation (2), because (as we will discuss later) the meaning of trends in the balance term, $B$, become more intuitive; a positive trend in the balance term with the sign convention of equation (3) is an indication of a trend to a more sustainable water balance, which intuitively we think of as a positive outcome. Equation (3) is not strictly a water balance, because the potential evapotranspiration is not strictly the actual amount of water that is lost by evapotranspiration. However, the equation can be viewed as indicating the balance between supply (rainfall plus groundwater use) and demand (potential evapotranspiration). Where supply is in excess of demand, there is likely to be runoff, and modest need for irrigation. Where supply is less than demand, there is likely to be little runoff, and irrigation would lead to greater crop production.

In the wetter locations in this study, the actual evapotranspiration is likely to be only a little less than the potential evapotranspiration. As we will show in the results, in the two locations in northwest Bangladesh the actual evapotranspiration is 88 % and 93 % of the potential evapotranspiration. Therefore, in the wetter locations, results based on equation (3) may be close to the actual water balance.

Leaving the canal water term out of equation (3) is unlikely to be a concern in several of the locations in this scoping study, since there is probably little use of canal water. Our previous work has identified that 97 % of irrigation water in northwest Bangladesh is sourced from groundwater. Where supply is less than demand, it is possible that the deficit is made up by canal water diverted from the rivers. However, canal water use should be estimated in any follow-on study.

Following Ahmad et al. (2020a, 2020b, 2021), we calculated the net groundwater use term as the annual change in groundwater levels, assessed from a regression through all the groundwater data in a district, done separately for pre-monsoon and monsoon data. For this study, in which annual water balances are used, we used the average of the pre-monsoon and monsoon trends. The slope of the regression line was multiplied by the specific yield, assumed to be 0.1, to convert change in depth to the water table to an equivalent change in depth of water stored. If the groundwater recharge and discharge is strictly one-dimensional, the calculation of net groundwater use as the annual change in groundwater levels is correct (though the estimates may nevertheless be subject to measurement error). It is probable that most recharge of the groundwater occurs through rainfall in the northern parts of the Eastern Gangetic Plains, and so is largely one-dimensional. This may not be true in the districts near the Ganges, where subsurface lateral groundwater flow may allow drainage into or recharge from the river. Any subsurface lateral flows in the groundwater appear as an unaccounted loss or gain in the difference or balance term.

The difference or balance term is a composite term that includes unaccounted losses and gains (such as surface runoff, or lateral subsurface flows that contribute to the change in groundwater levels and are thus implicit in the net groundwater use term), plus the difference between actual evapotranspiration and potential evapotranspiration, plus observation errors in the other terms. In calculating the balance term, we assumed that the groundwater trend from 1996 (in the Indian states) can be extrapolated back to 1980.

## Data

As noted for Figure 2, crop area data was obtained as follows: Indian states from https://data.gov.in/catalog/district-wise-season-wise-crop-production-statistics; Bangladesh compiled in previous CSIRO projects from various sources, and published in a summary form by Peña-Arancibia et al. (2020). The Bangladesh data have been “cleaned” to remove errors in formatting and actual values. The Indian data have not been cleaned other than to remove a few obvious gross errors; Bihar has some obvious missing data in the first few years (Figure 2).

Rainfall and potential evapotranspiration data were taken from the CRU_TS4.03 dataset, available at https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.03/, and described by Harris et al. (2014). Note that the Harris paper strictly refers to an earlier version of the CRU dataset. The dataset has rainfall and potential evapotranspiration gridded at 0.5˚ intervals across the land surfaces of the globe, from 1900 to 2018. The nearest grid point to the centre of each district was selected, and the data from 1980 to 2018 extracted for use.

Groundwater data were obtained as follows: Indian states from the Central Groundwater Board at http://cgwb.gov.in/GW-data-access.html (click on Ground Water Data Download, then select the state and district of interest); Bangladesh compiled in previous CSIRO projects from Bangladesh Water Development Board data. In the earlier CSIRO work on Bangladesh, borehole records were screened, and the data cleaned to remove errors. For some applications, surfaces were fitted to the groundwater level data for each period and the average depth to the surface calculated. We use those data here. The data for India have not been screened and cleaned, and are simply used “as is”. Regressions were fitted to all the pre-monsoon data points and to all the monsoon data points. For all districts, we converted a change in the groundwater level to an equivalent change in the depth of water stored by multiplying by an assumed specific yield of 0.1.

## 5.3 Simple water balances: results

### Rainfall

The annual rainfall from 1980 to 2018 for each district is shown in Figure 26, summarised in Table 1.

The annual average rainfall varies from over 2600 mm in Cooch Behar in the northeast of the region, to 818 mm in Kanpur in the west and south. In the eastern part of the study region, the rainfall declines from Cooch Behar in the north, to Kurigram, to Rajshahi in the centre, and then rises again towards the coast in South 24 Parganas. The rainfall in a year varied from 1961 to 3506 mm in Cooch Behar, to 536 to 1075 mm in Kanpur. The rainfall declined slightly in all districts, up to a maximum decline of about 7 mm per year (using a regression line) in Kurigram; a decline of 7 mm per year is equivalent to a decrease of 266 mm over the full period. However, the decrease is statistically significant only in South 24 Parganas, Rajshahi and Kurigram; while the trend is statistically significant in South 24 Parganas, the actual decrease is not, amounting to a decrease of only 11 mm over the 38 years.

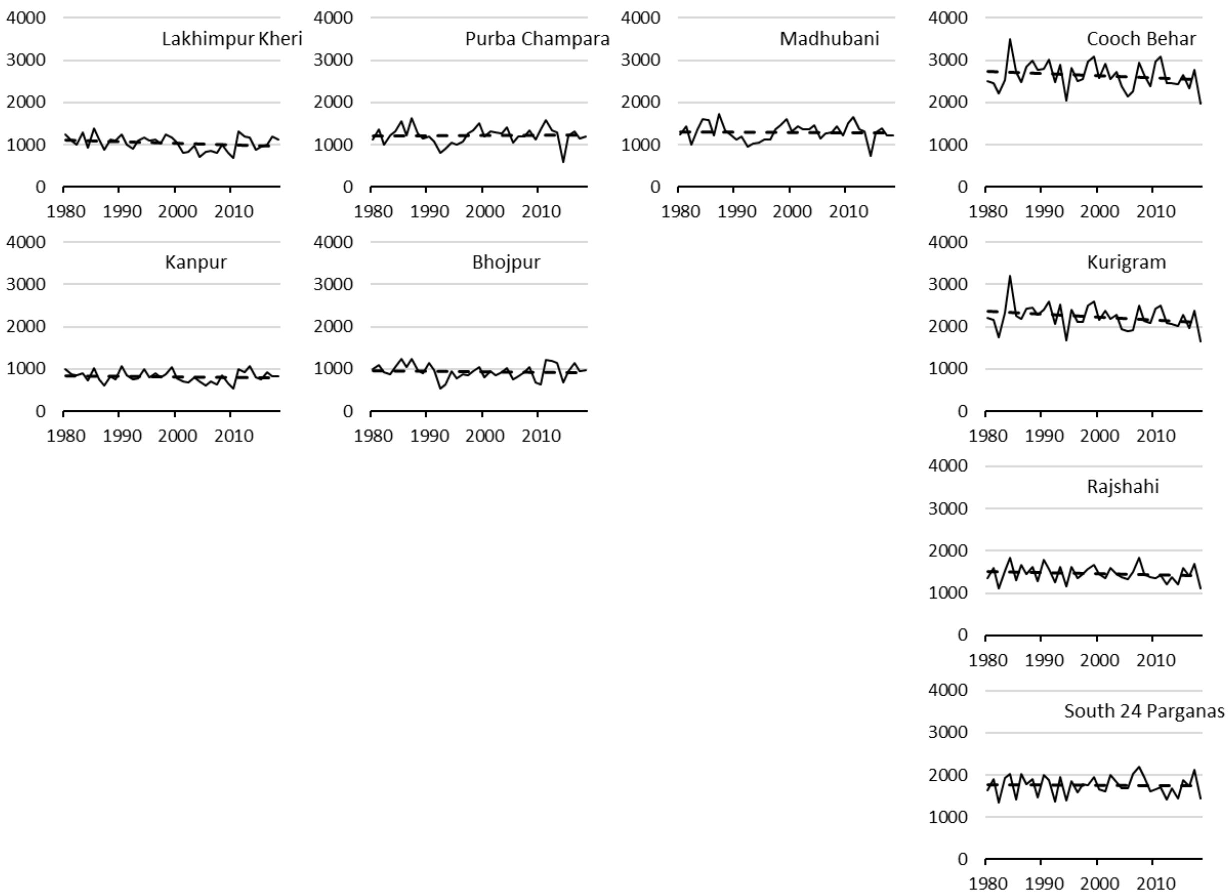


Figure 26. Annual rainfall in mm from 1980 to 2018 in the nine districts. The graphs are arranged so that the districts are in a west to east order from left to right, and a north to south order from top to bottom. This has the effect of scanning from most rainfall in the top right graph to least in the bottom left.

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Table 16. Summary water balance results. The columns are arranged so that the districts are in a west to east order from left to right, and a south to north order in the four groups as plotted in Figure 26. This has the effect of scanning from most rainfall in the right column to least in the left.

| | Kanpur | Lakhimpur Kheri | Bhojpur | Purba Champara | Madhabani | South 24 Parganas | Rajshahi | Kurigram | Cooch Behar |
|---|---|---|---|---|---|---|---|---|---|
| Average, mm/yr | | | | | | | | | |
| Rain | 818 | 1035 | 939 | 1219 | 1301 | 1754 | 1458 | 2232 | 2638 |
| PET | 1593 | 1510 | 1477 | 1263 | 1225 | 1329 | 1309 | 1192 | 1169 |
| dGW | 13 | 2 | -10 | 1 | -3 | -13 | -21 | -3 | -1 |
| Balance | -776 | -476 | -528 | -45 | 79 | 437 | 171 | 1044 | 1470 |
| | | | | | | | | | |
| Trend, mm/yr | | | | | | | | | |
| Rain | -2 | -4 | -1 | 0 | -1 | -0.3 | -3 | -7 | -6 |
| PET | 1 | 2 | 1 | 1 | 0 | -0.4 | 0.2 | 0.1 | 0 |
| Balance | -3 | -6 | -3 | 0 | -1 | 0.1 | -3 | -7 | -6 |
| | | | | | | | | | |
| Significant trend? | | | | | | | | | |
| Rain | no | no | no | no | no | yes | yes | yes | no |
| PET | yes | yes | yes | no | no | yes | yes | yes | no |
| dGW (monsoon) | yes | no | yes | yes | no | yes | yes | yes | no |
| dGW (pre-monsoon) | yes | yes | yes | no | yes | yes | yes | yes | no |
| Balance | no | yes | no | no | no | yes | yes | yes | no |

## Potential evapotranspiration

The annual potential evapotranspiration from 1980 to 2018 for each district is shown in Figure 27, summarised in Table 16. The annual average potential evapotranspiration varies from 1169 mm in Cooch Behar in the northeast of the region, to 1593 mm in Kanpur in the west and south. The potential evapotranspiration in a year varied from 1117 to 1235 mm in Cooch Behar, and from 1524 to 1652 mm in Kanpur. The variation across the region and from year to year is much less than it is for rainfall. The potential evapotranspiration increased slightly in all districts except one, with a maximum increase of about 2 mm per year (76 mm over the whole period).

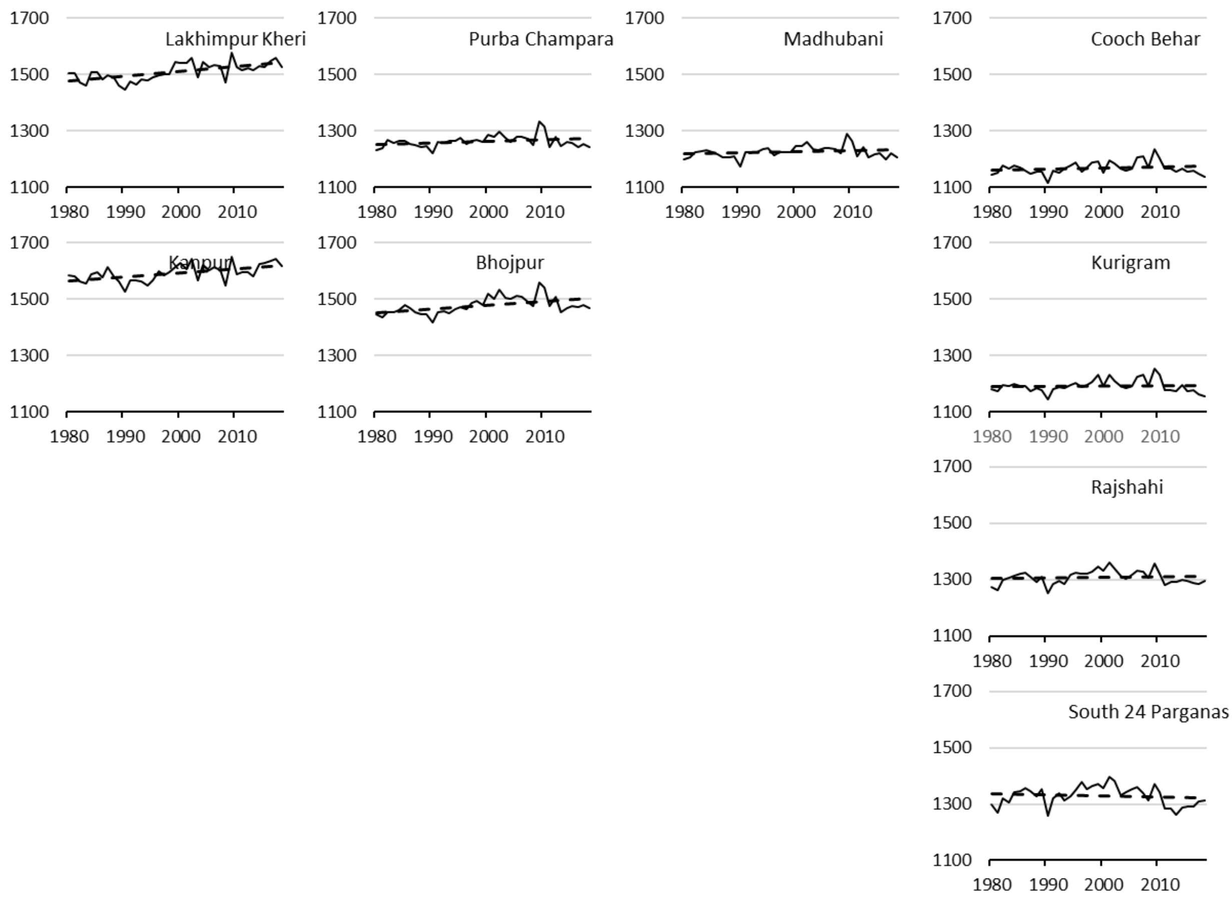
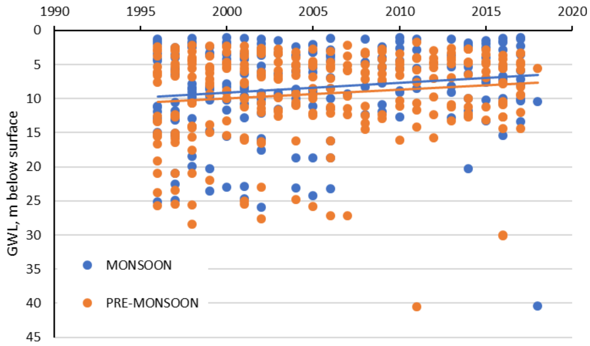



Figure 27. Annual potential evapotranspiration in mm from 1980 to 2018 in the nine districts. The graphs are arranged so that the districts are in a west to east order from left to right, and a north to south order from top to bottom. This has the effect of scanning from least potential evapotranspiration in the top right graph to most in the bottom left.

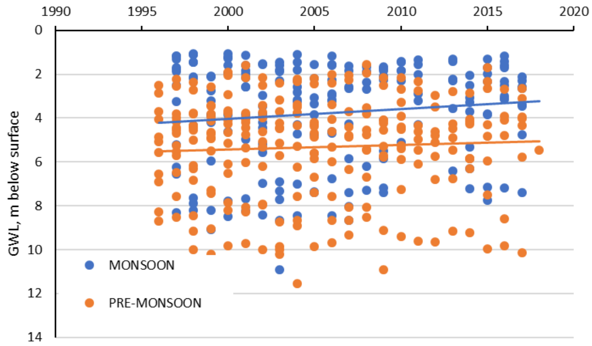
## Groundwater change

As noted in the methods section, a decline in the groundwater level represents a supply to the surface; this is true for a strictly one-dimensional situation, and likely to be largely true for many other situations in which groundwater recharge is dominated by rainfall. The annual average change in groundwater levels from 1980 to 2018 for each district is summarised in Table 16. What is most obvious about the groundwater change is that it represents a very small contribution to the overall surface water balance. This result would not be materially changed by alternative plausible assumed specific yields. The groundwater levels of the districts are shown in Figure 28. Bhojpur and Rajshahi both have obvious, large declines in groundwater levels, both pre-monsoon and monsoon.

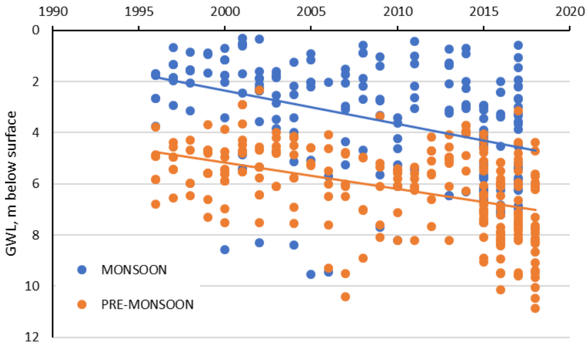
Kanpur



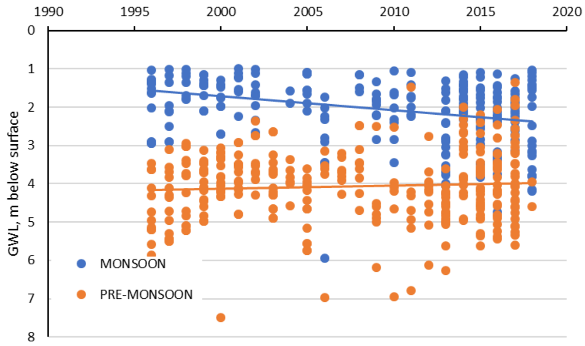

Lakhimpur Kheri



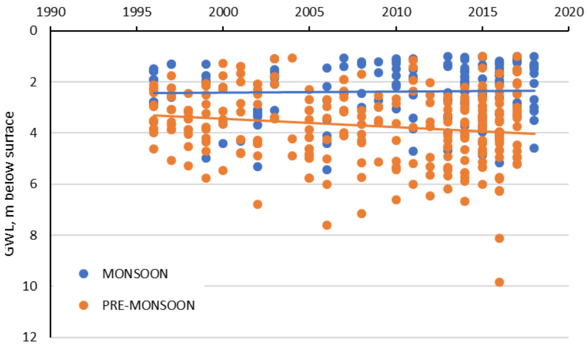

Bhojpur



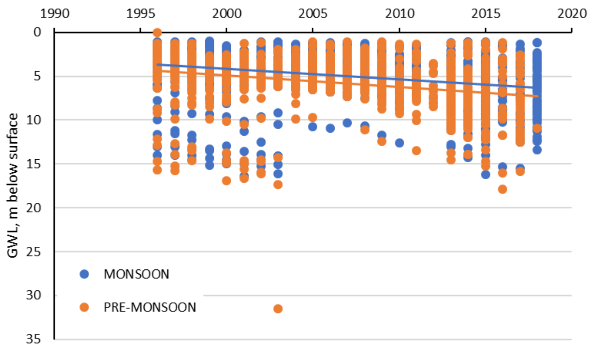

Purba Champara



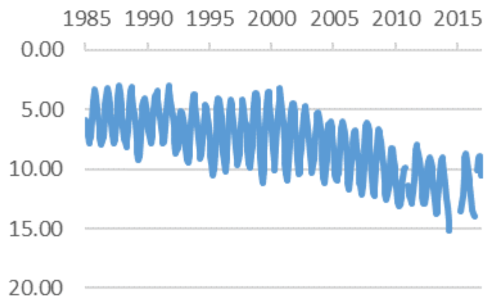

Madhubani



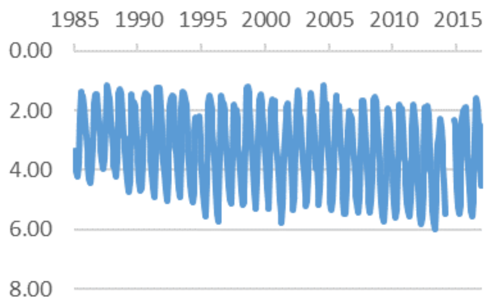

South 24 Parganas




Rajshahi



Kurigram




Cooch Behar

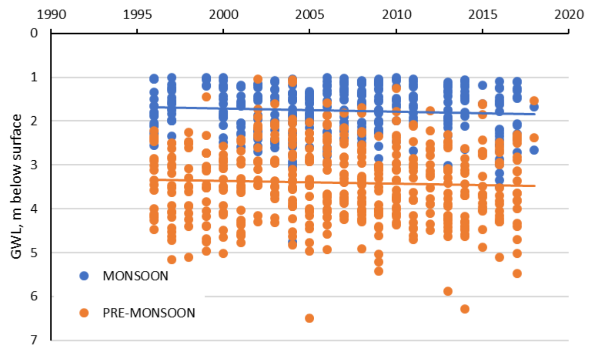



Figure 28. Groundwater levels in the nine districts in m, from 1996 to 2018 (Indian districts) or 1985 to 2016 (Rajshahi and Kurigram in Bangladesh). The graphs are arranged so that the districts are in a west to east order from top to bottom, and a south to north order in the four groups as plotted in Figure 26. This has the effect of scanning from greatest water deficit (of rain minus potential evapotranspiration) in the top left graph to least (or greatest surplus of rain over potential evapotranspiration) in the bottom right.

## The balance term: excess or deficit of water supply over potential demand

The annual balance term represents the excess or deficit of water supply over potential demand (plus errors in the estimated rainfall and potential evapotranspiration, and in the groundwater trends) from 1980 to 2018 for each district is shown in Figure 29, summarised in Table 16.

The annual average balance varies from an excess of 1470 mm in Cooch Behar in the northeast to a deficit of 776 mm in Kanpur in the west and south. The excess in a year varied from 824 to 2329 mm in Cooch Behar, whereas the deficit varied from 450 to 1053 mm in Kanpur. Cooch Behar, Kurigram and South 24 Parganas have large excesses (positive balances) with no year in deficit (no negative balance). Kanpur, Lakhimpur Kheri and Bhojpur have large deficits (negative balances) with no year in excess (no positive balance). Purba Champara, Madhubani and Rajshahi all have excesses in some years and deficits in others, and are on average close to zero.

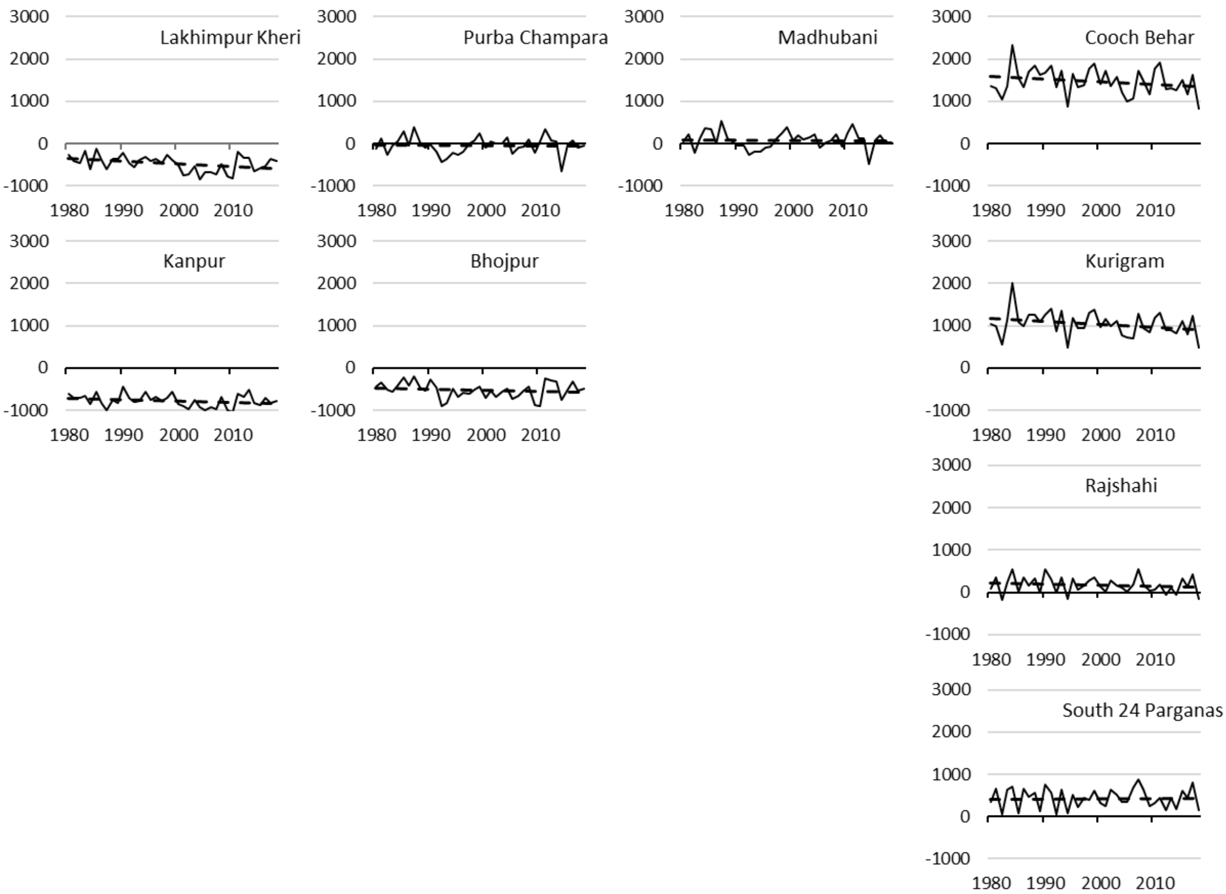



Figure 29. Annual balance (excess or deficit of supply over potential demand) in the nine districts in m, from 1996 to 2018 (Indian districts) or 1985 to 2016 (Rajshahi and Kurigram in Bangladesh). The graphs are arranged so that the districts are in a west to east order from left to right, and a north to south order from top to bottom. This has the effect of scanning from greatest excess (positive balance) in the top right graph to the greatest deficit (negative balance) in the bottom left.

## 5.4 Discussion

### 5.4.1 Potential impacts of farm-scale water saving measures

As noted in Section 2.3, water saving measures may not actually save water unless they reduce the consumption of water as evapotranspiration. The discussion in Section 2.3 suggests that in searching for impacts, we should carefully define what we mean. From the point of view of the farmer, any reduction in the use of irrigation water is a saving which will reduce costs and, provided yields and quality are not affected, will enhance profitability. The trend from an excess of annual supply over demand in the northeast of the Eastern Gangetic Plains (Cooch Behar and Kurigram) to a deficit in the west (Kanpur) means that there is less incentive for the farmer to save water in the northeast. Conversely, there is more to be gained from water saving measures in the west.

Impacts of water saving on regional hydrology, however, can only come from actual reductions in water consumption as evapotranspiration (as discussed in the Section 2.3), or from changing the source of irrigation water and the destination of unused water. Similar to the farmer perspective, there is likely to be less impact in either of these senses on the regional hydrology in the northeast of the Eastern Gangetic Plains (Cooch Behar and Kurigram) than in the west.

Although the annual supply in the northeast exceeds potential evapotranspiration, there are nevertheless periods in the dry season when there is a deficit, so irrigation is useful at critical times of crop growth. However, the amount of water required is not great and, if taken from groundwater, is likely to be readily replenished in the following wet season. Hence, there is limited scope in the northeast for impact on irrigation water volumes of reducing water consumption as evapotranspiration, or from changing the source of irrigation water.

As the excess of annual supply over potential evapotranspiration periods diminishes with progression south and west, the dry season deficit grows and its period lengthen, so more irrigation is required for crop growth. This is the situation in Rajshahi, where irrigation is associated with groundwater level declines (Figure 28). Here, a reduction in water consumption as evapotranspiration would lessen the requirement for pumping and might arrest or reverse declining groundwater tables. However, since other factors may be partly responsible for the declining groundwater levels (Peña-Arancibia et al, 2020), water saving measures which would lessen evapotranspiration might not be as effective as hoped. The conclusions of Rushton et al. (2020) suggest that saving water by preventing deep drainage might be counter-productive and possibly lead to more rapidly declining groundwater levels.

The Bangladesh Government, owing to concerns over unsustainable groundwater use, is pursuing a policy of promoting surface water use (ie river water use) for irrigation and discouraging groundwater use. This changes the source of irrigation water, which might change the regional hydrology by allowing the recovery of groundwater levels in places such as Rajshahi. Again, the impact may be less than hoped (Peña-Arancibia et al., 2020).

Further west, in Bhojpur, Lakhimpur Kheri and Kanpur, all of which have large deficits of rain to satisfy potential demand and therefore more requirement for irrigation water, there is increasing scope for impact on regional hydrology of reducing water consumption as evapotranspiration, or from changing the source of irrigation water.

Finally, South 24 Parganas, especially in locations close to the coast, is a special case. As shown by our work in Gosaba Island (in South 24 Parganas) and other locations in the coastal zone of the Ganges delta, a key aspect of management for crop production is the management of salt (Mainuddin et al., 2019c, 2020b). Here, water saving measures are important because water of sufficient freshness becomes scarce in the later part of the dry season. Water saving through mulching and other techniques may be important. Here preventing deep drainage (such as less pumping, AWD method) is real water saving even they may not reduce evapotranspiration as the underlying groundwater is saline. Irrigation is done using fresh or less saline surface water stored in canal, ponds, or from river. The impact of these measures on regional hydrology has less to do with water quantity than water quality.

### 5.4.2 Potential impacts of climate change

Kirby et al. (2016) and Mainuddin et al. (in preparation, report on DFAT funded SDIP project) examined the potential impacts of climate change on the water balance in the northwest of Bangladesh. (Kirby et al., 2016, also examined the effects in other regions of Bangladesh.) While potential evapotranspiration is generally expected to increase with rising temperatures under most climate change models and scenarios, there is greater uncertainty about rainfall which could increase or decrease (Karim et al., 2020).

In the northern part of northwest Bangladesh, an area with an excess of rain to satisfy the potential demand, Mainuddin at el. (in preparation) found that groundwater levels are projected to be not much affected by projected climate change. This is similar to the expectation discussed above that water saving measures are not likely to much affect regional hydrology where there is an excess of rain. Indeed, Mainuddin et al. (in preparation) also found that groundwater levels are projected to be not much affected by irrigation development or changes to crop areas.

Conversely, in the southern part of northwest Bangladesh, Mainuddin et al. (in preparation) found that groundwater levels are projected to be considerably affected by projected climate change, irrigation development or changes to crop areas. With wetter climate change scenarios, the declining groundwater levels observed in this region were projected to decline less or even increase, with use thus becoming more sustainable. However, with drier climate change scenarios, declining trends were projected to increase, with use thus becoming less sustainable.

While these results are for northwest Bangladesh only, they are consistent with the expectations discussed above that regional hydrology is likely to be more affected by external changes in the areas of a deficit of rainfall to satisfy potential demand. The impact on regional hydrology of potential climate change in the Easter Gangetic Plains is thus likely to be most felt in the west of the region. However, there is considerable uncertainty as to the direction of change.

## 5.5 Conclusions and gaps in current knowledge

The analysis of the balance of supply and potential demand developed here is an incomplete but useful assessment of the likely water balance in the Eastern Gangetic Plains. It allows an initial assessment of the likely impacts of water savings on regional hydrology, and how the impacts are likely to differ across the region.

Identifying whether a water saving measure has impact, and how much, requires a careful evaluation of whether the measure has actually saved water. For example, a measure that reduces groundwater pumping for irrigation but does not reduce the actual evapotranspiration of the crop probably isn’t saving water. Rather, the less pumping is very likely being balanced by less drainage from the root zone back into the aquifer.

The northeast of the region, around Cooch Behar, has a large excess (about 1500 mm) of rainfall over potential evapotranspiration. The groundwater in these areas is generally quite shallow. While there will be some benefit in irrigation in the dry season, the quantities required for additional evapotranspiration are likely to be small. In this part of the region, water saving measures are not likely to have a large impact on the regional hydrology.

The southwest part of the region, around Kanpur, has a deficit (of about 750 mm) of rainfall to satisfy potential evapotranspiration. There will be considerable benefit in irrigation, particularly in the dry season, and the quantities required for additional evapotranspiration are large. In this part of the region, water saving measures are likely to have a large impact on the regional hydrology (if they reduce evapotranspiration), by reducing the use of groundwater or river water or both.

In the coastal part of the region, around South 24 Parganas, the major issue for cropping is salt management. Water saving measures here should be viewed in terms of their impact on salinity. Reducing irrigation application to the field is real water savings here even if they don’t reduce evapotranspiration as the underlying groundwater is saline. For example, application of soil mulch to reduce evaporation might result in a delay in increasing soil salinity as it dries out.

### Gaps in current knowledge

As noted, the water balances developed here are not complete water balances; rather they are an indication of the balance of supply and demand. To develop complete water balances, time-series actual evapotranspiration data will be required. This could come from crop water use modelling in the wetter part of the region (cf our work in NW Bangladesh, where we showed good agreement between crop water use modelling and remotes sensing estimates, Peña-Arancibia et al., 2020, discussed further in Section 7), but remote sensing would be better especially in the drier districts such as Kanpur and Bhojpur. We have previously found crop modelling to work less well in the more arid climate of the canal commands of Pakistan,  so we used only remote sensing estimates in studies there. Crop modelling works less well in such environments because the approach is not suited for estimating water use of non-irrigated parts of the landscape (which make up part of the regional water balance) in a dry climate. In the wetter climate of the more easterly parts of the region, especially when underlain by shallow water tables, this is less of a concern; the evapotranspiration of non-irrigated parts of the landscape is generally close to potential, and its estimation is relatively easy.

For groundwater, proper trend analyses will be required, either borehole by borehole, or by generating surfaces for each period and then assessing trends in surfaces (or average depths derived from surfaces). In the simple water balances above, the trend analyses for Rajshahi and Kurigram are more reliable than those from the other locations.

For all data, there is a compelling need for data cleaning – the removal of errors in formatting and values, dealing with spurious values, etc. This is not a trivial task.

Water balance modelling, as we did in Bangladesh (Kirby et al., 2015), or direct analysis of the inflows, outflows and unaccounted gains and losses, as we did in Pakistan (Ahmad et al, 2020a, 2020b, 2021), would further enhance the usefulness of water balances.

Finally, in all studies, there is a need to incorporate the potential impacts of climate change.

# 6 A review of groundwater trends and issues in the Eastern Gangetic Plains

Groundwater is a major source of irrigation water in the Eastern Gangetic Plains. Groundwater is sourced primarily from the alluvial aquifer of the Ganga Basin. Thus, overexploitation for irrigation can have a direct impact on the sustainability of the groundwater resource. Conversely, water conservation approaches are expected to have a direct positive impact on sustainability of these aquifers. The effectiveness of water conservation approaches in improving sustainable use however depends on the status quo of groundwater resource and how water conservation measures interfere with the current cycle of groundwater recharge and discharge. For example, if the current recharge is less than potential maximum in an area due to a shallow water table, there may be opportunity for more groundwater development without impacting sustainability and in such areas water conservation measures may not be useful in conserving water resource. On the other hand, if groundwater mining is happening in some areas because of over exploitation, water conservation measures in agriculture may have a positive impact on groundwater sustainability. Groundwater trends and flow dynamics analyses can be used to assess the status quo of the resources and investigate long-term trends that provides insights into whether current use is unsustainable in parts of whole of the region. Investigation of groundwater balance and different components of inflow and outflow and predictive analysis of changes in recharge and discharge components (like groundwater contribution to ET) can be used to inform whether conservation agriculture will be effective in areas of interest.

In this section of the report, we explore the status of groundwater resource in the Eastern Gangetic Plains by analysing major components of groundwater balance available from past studies as well as our preliminary modelling analysis. The groundwater balance is explored by classifying the EGP into the subregions that fall within the Terai plains of Nepal, Indian Ganga Basin and northwest Bangladesh region (Figure 30). At a finer scale, four districts are also analysed to assess feasibility of a full-scale analysis in terms of data-availability and quality and also to investigate readily recognizable trends in groundwater levels. These districts were selected from different parts of the basin and within the three countries involved.

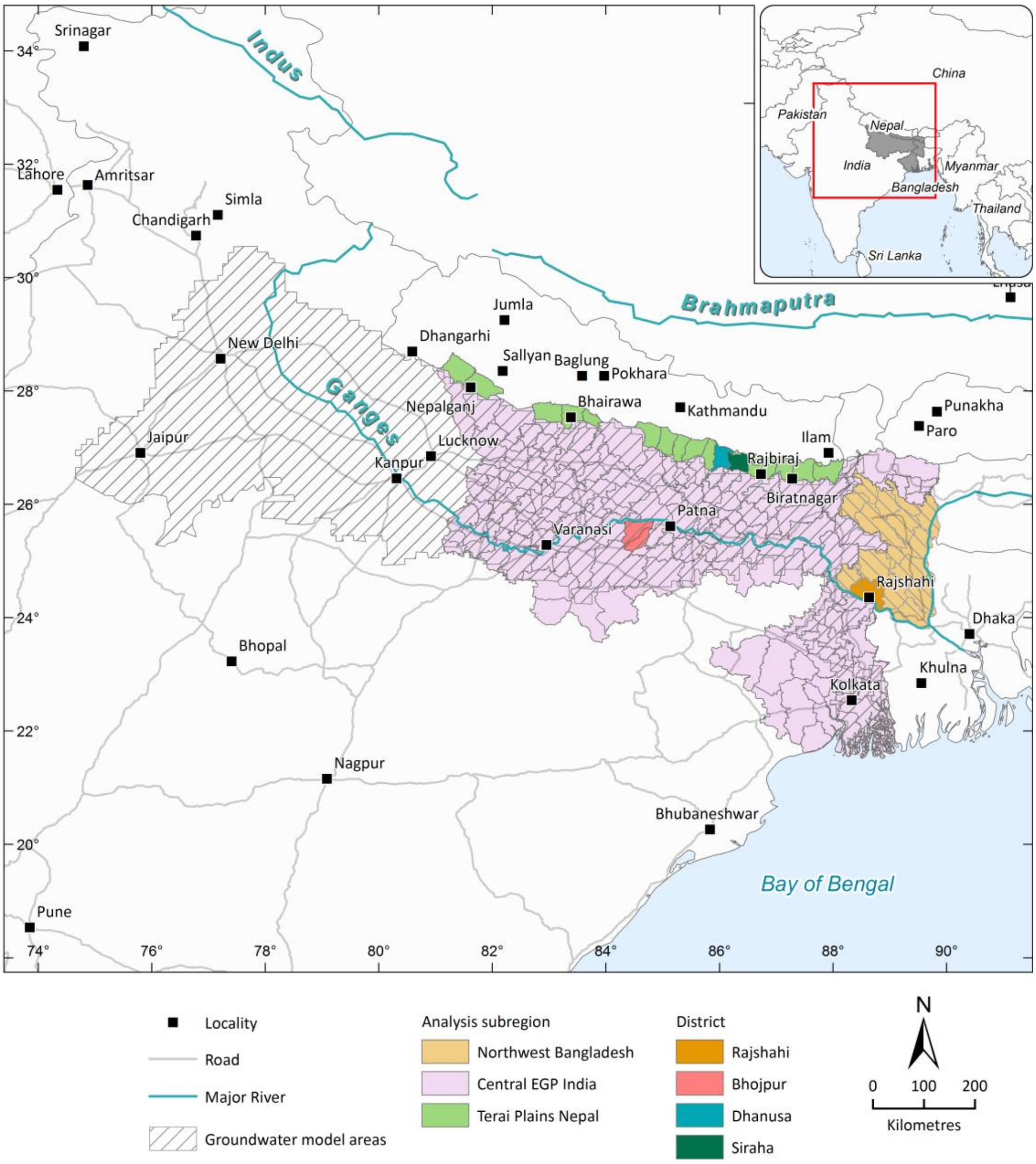



Figure 30: The sub-regions and districts considered for groundwater analysis and the extent of groundwater models used for water balance analysis

## 6.1 Groundwater trends in selected districts of EGP

Four representative districts were selected from the EGP to do a district-scale analysis of groundwater balance. This district-scale analysis was undertaken to identify the types, quality and variability of data sets available at the district scale should detailed district scale analyses need to be carried out in a full-scale project. Two districts, Dhanusa and Siraha were selected from the Terai Plains of Nepal, primarily because of the availability of data sets for the analyses from the SDIP phase II research for the Kamala Basin. These two districts correspond to an area in the upper areas of the groundwater basin. Groundwater development is relatively low in this area. Another one is Bhojpur district from Bihar state of India and is a district where groundwater table is generally shallow and does not experience significant groundwater quantity problems, although parts of this district has groundwater quality concerns caused by high arsenic levels. The fourth district selected was Rajshahi in northwest Bangladesh and is representative of areas already experiencing groundwater stress caused potentially by over exploitation.

Northwest Bangladesh region had the groundwater level data sets available at the finest temporal resolution with weekly groundwater levels from over 350 bores since 1985. Groundwater level data set available for the Indian states in EGP were primarily from the regional monitoring network of the Central Groundwater Board. This data set provides seasonal groundwater level records published from 1996. The available groundwater level data for the Terai plains of Nepal were from published technical reports of Groundwater Resource Development Board.

### Groundwater in the Dhanusa and Siraha districts of Nepal

Dhanusa and Siraha districts are located largely within the Terai plains of Nepal although parts of the districts lies in the northern Siwalic ranges. The altitude varies from 70 m in the Terai plains to 1000 m in the northern areas (Shresta, 1992). There are several rivers that flow through these districts including the major river Kamala. Areas within these districts have a subtropical climate and receives 85% of the total annual rainfall of 1700 mm in the months between June and September. The crops grown in these areas include rice, wheat, maize, oil seeds, pulses and others.

Sedimentary depoits of this area is classified into two groups for hydrologic and lithologic purposes (Shreshta ,1992). The Bhabhar deposits form the sediments at the foot of the Siwalik Hills. It is a principal recharge area for the broader Ganga Basin. Bhabhar deposits are poorly sorted and contains large fraction of coarse material. The Terai Plain deposits are formed by a thick sequence of clastic sediments. The sediments of the Terai plains are finer grained ranging from clay to gravel. Their thickness exceed 1000 m closer to the Indian border and forms important aquifers of the region.

A limited amount of groundwater level data from the Dhanusa and Siraha districts of Terai plains was available from the past CSIRO studies in the region (SDIP-II). This data set comprised intermittent groundwater level observations from 25 and 23 shallow bores respectively from the Dhanusa and Siraha districts between 2004 and 2013. The aquifer assignment of these bores were not available.

Annually groundwater in the shallow aquifer in Dhanusa district fluctuates up to 7m. The groundwater table of the shallow aquifer was found to be 0 m below ground level (bgl) to 4 m bgl. Previous studies in the Dhanusa district also reports that water table is shallow in the Dhanusa district (GDC, 1994). In Siraha district the annual groundwater fluctuation of shallow aquifer is reported to vary from 2 to 12 m between the months of September to May. Analysis of available groundwater level data in the Dhanusa and Siraha districts also indicated that groundwater varies in the range 0.1 m to 7.5 m below ground level ($5^{th}$ to $95^{th}$ percentile range) between monsoon and summer months. The $25^{th}$, $50^{th}$ and $75^{th}$ quartiles of available groundwater level data in Dhanusa and Siraha districts are shown in Figure 31 and Figure 32 respectively.

The observed water level indicated that water level is always shallow within 1 to 4 meters below ground level in Dhanusa district. In the period between 2004 and 2009, the water levels are more or less steady. An abrupt increase in depth to water table is observable in after 2009 in the median, lower and upper quartiles. This could be likely because of a datum error or reflective of climatic conditions in the 4-year period. More investigation into longer term data set will be needed to conclusively interpret long-term groundwater trends.

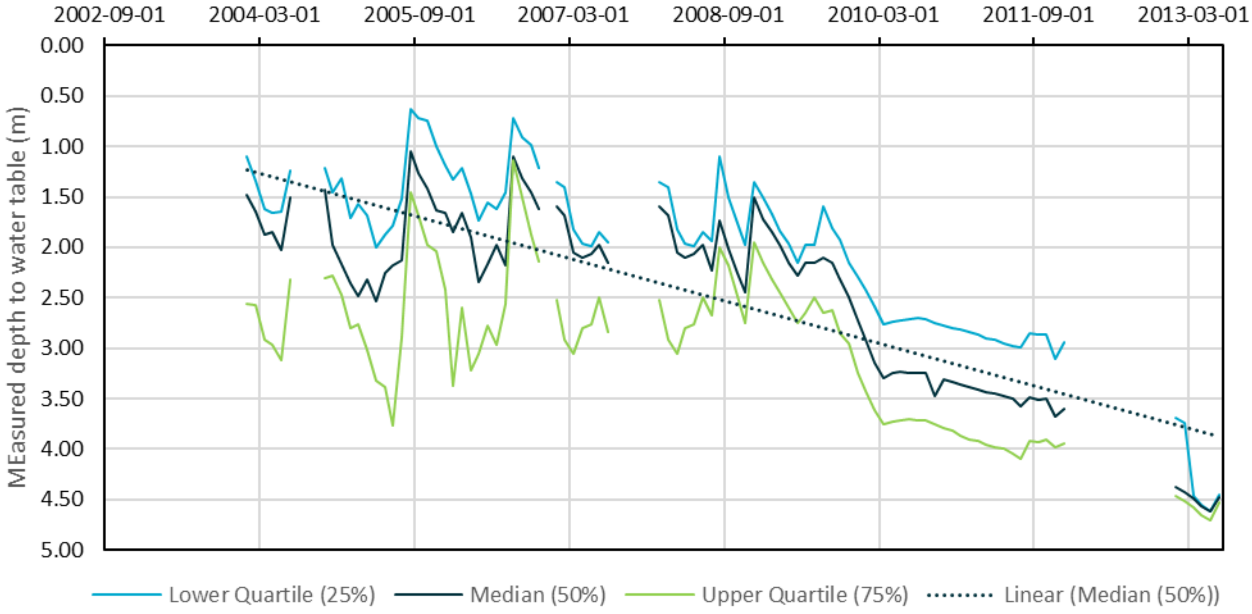



Figure 31: Median and quartiles of observed groundwater levels from 25 observation bores in the Dhanusa district of Terai plains

Groundwater levels in Siraha district is also similar with water level varying between 1 to 4 metres below ground level. During the monsoon season, groundwater levels rise very close to the ground surface up to 1 metre below the ground. The median, upper and lower quartiles of depth to groundwater shown in Figure 32 shows a moderate increasing trend. While groundwater levels are more or less steady between 2004 and 2009, the increasing trend is evident between 2009 and 2013, similar to that observed in Dhanusa district. Identifying the causal factors of this trend will need more investigations about trends in climatic factors and groundwater use in the district.

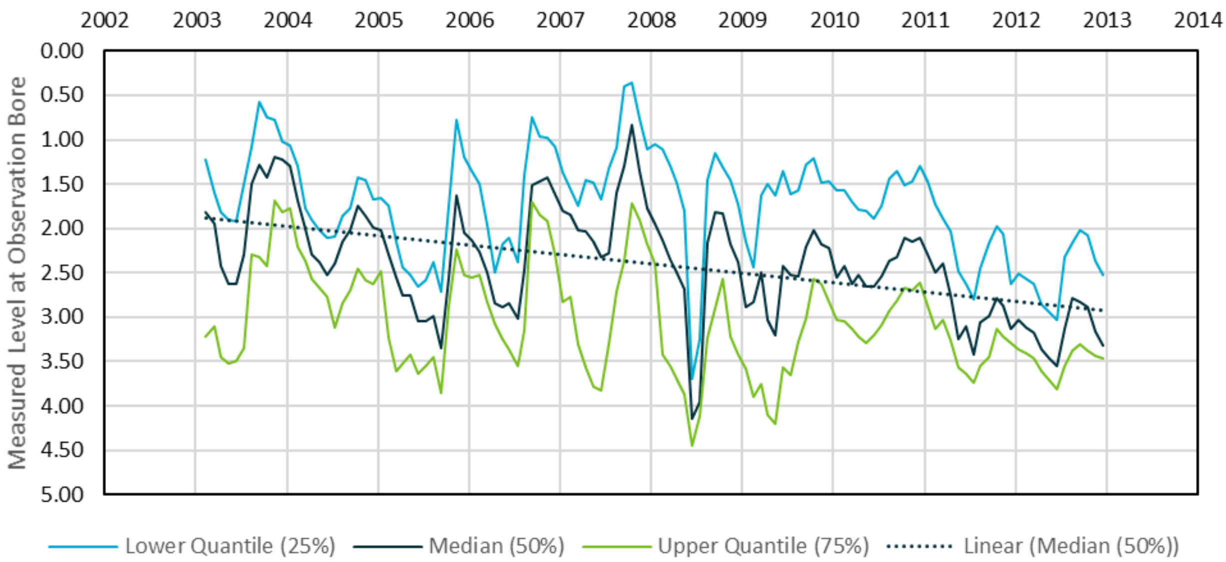



Figure 32: Median and quartiles of observed groundwater levels from 25 observation bores in the Siraha district of Terai plains

## Groundwater in the Bhojpur district of Bihar, India

Bhojpur district is located in the western part of the State of Bihar in India. It lies between 25º10’ and 25º40’ North latitudes and 83º 45’ and 84º 45’ East longitudes with total population of 27, 20,155 as per Census, 2011. The district is bounded by Ganga river in north and Son river in east. The entire district consisting of 14 blocks forms an interfluves zone of Ganga and Son rivers. The study area has warm and humid climate. The maximum temperature in the district is 39ºC during the month of May, whereas minimum temperature decreases up to 6.3ºC during the month of January. The monsoon season starts in the month of June and continues up to September. The normal rainfall of the district is reported to be 1080 mm/yr and the annual rainfall varies from 1025 mm to 1106 mm (CGWB, 2019). The monsoon period receives about 85.6 % of the total annual rainfall and the rest is received in the non-monsoon period (November-May).

The geological characteristics of the district are alluvial in nature consisting of younger and older Gangetic alluvium which forms the potential aquifers. The northern and northeast parts of the district form younger alluvium whereas the southern and central parts are formed with older alluvium (Fig. 1). The top layer within 30 m bgl is an aquitard (in fact it works as an unconfined aquifer) which is composed of sand, silt and hardpans and generally this layer is contaminated with arsenic. The study area has a common slope towards the north and northeast. The common elevation with respect to mean sea level is 50-90 m and gradient is 0.6 m/km from south to north. The district in general possesses alluvium soil and the soils are of poorly drained type. The area adjoining the rivers Ganga, Son, Dharmawati, and Gangi consists of sandy loam, loamy sand and sand, whereas, the area away from the river channels consist of silty sand to sandy silt. The soils in common are fine textured away from the river course and rivulets and coarse textured along their courses.

The groundwater level data (2015- 2018) was collected from representative monitoring bores of the Central Ground Water Board (CGWB) and spatial behaviour of water levels along with flow direction was analysed the Bhojpur district (Figure 33). The depth to water level in pre-monsoon season (year 2018) varies from 3.0 to 9.0 m bgl with minimum and maximum values observed in south western part and north eastern part of the district. The hydraulic gradient indicated groundwater movement towards the river Ganga (Figure 33a). It is observed that there is likely a small declining trend of groundwater level as shown in the long-term groundwater level data for a representative bore (Figure 34), however, significant fluctuation of groundwater level can be noticed between pre and post monsoon season which indicate that natural recharge is good in the area.

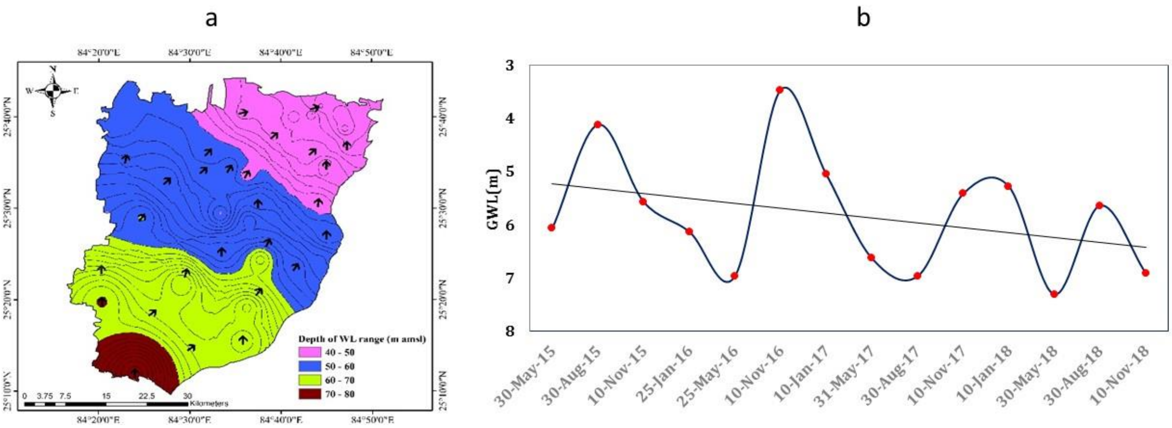



Figure 33: a) Water table contour map showing flow direction for the Bhojpur district and b) groundwater hydrograph for a representative monitoring bore in the district

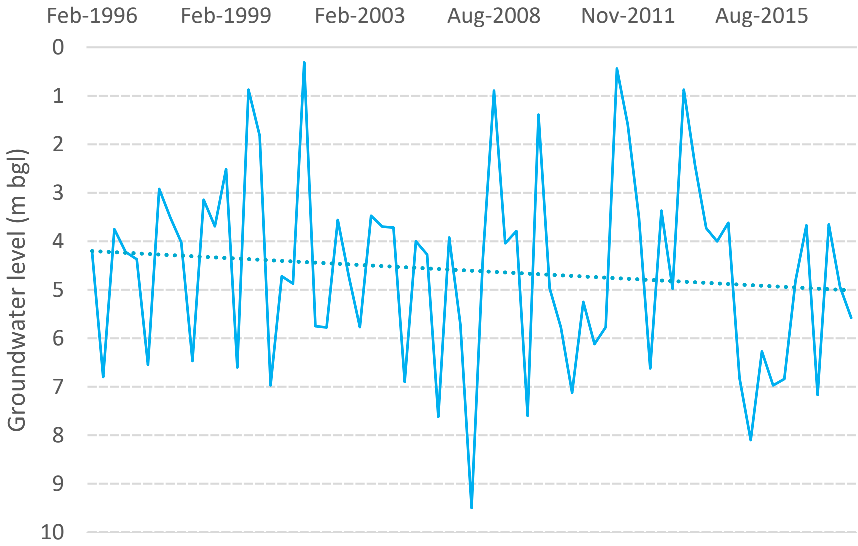



Figure 34: Long-term trend in groundwater level record in a monitoring bore in the Barhara block in Bhojpur district

## Groundwater in the Rajshahi district, northwest Bangladesh

Rajshahi district is in the southern extent of the northwest Bangladesh region and is bounded by the Padma river (known as Ganga in India) in the south. This district is covered by the flood plains of the Padma river but is also characterized by the High Barind Tract a distinctive physiographic unit comprising of uplifted blocks of terraced land. With a comparatively low rainfall (1250 mm) and temperature regularly exceeding 40$^{o}$ C, this area is considered as semi-arid and drought prone. Extensive development of groundwater by means of shallow and deep tube wells has occurred in Rajshahi since 1990s due to the increase in the cultivation of Boro rice crop that is irrigated with groundwater. Declining trends have been reported in the Rajshahi district. Groundwater level trends observed in four representative bores in the Rajshahi district is shown in Figure 35. Significant declining trends are observed in many bores in the districts although steady trends are observed in some bores.

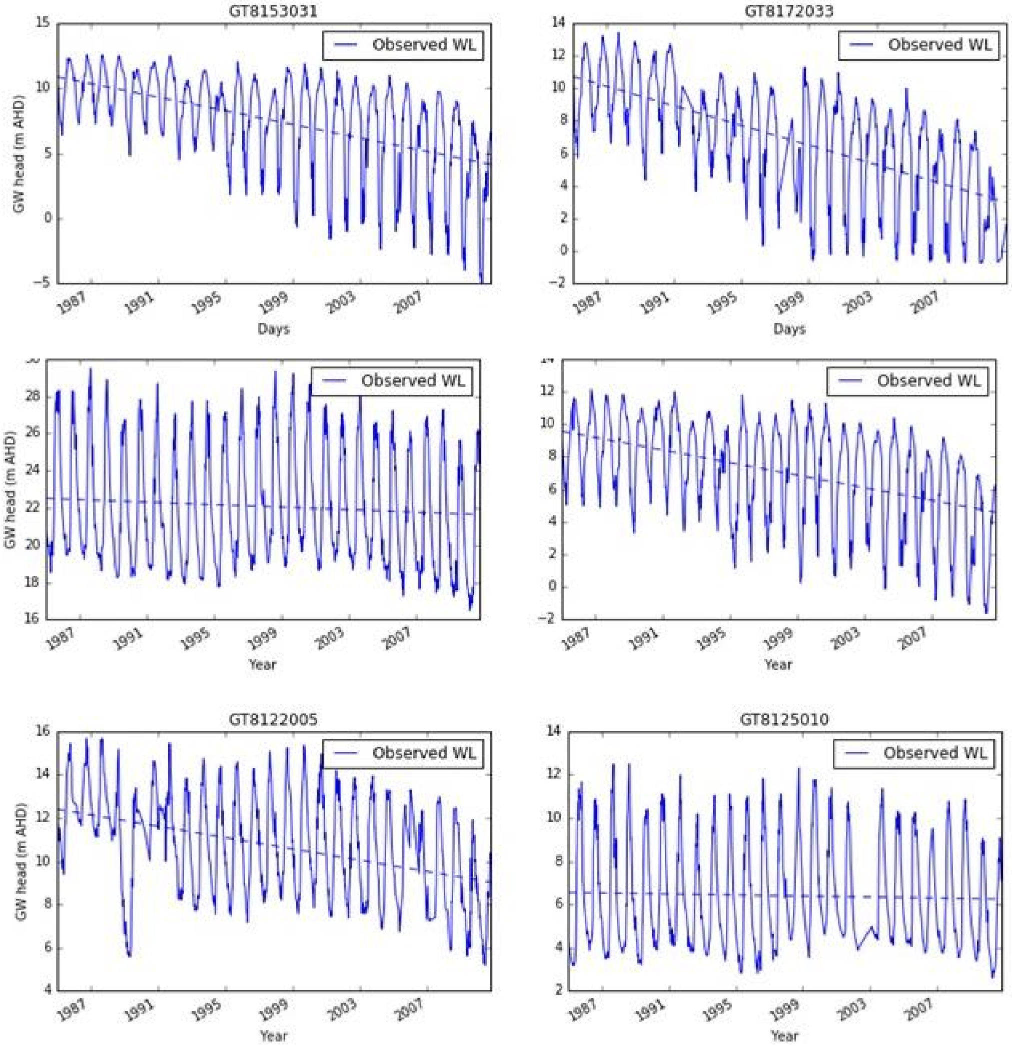



Figure 35: Long-term trend in representative groundwater observation bores in Rajshahi district of northwest Bangladesh

## 6.2 Regional overview of groundwater balance in the EGP

The most important source of groundwater in the Easter Gangetic Plains is the aquifers of the Ganga Basin. Multiple aquifer systems in the Ganga basin extending to a depth of about 2000 m holds one of the largest ground water reservoirs in the world (CGWB,1996). This groundwater system extends from the Terai Plains of Nepal in the north, a central part extending over the states of UP, Bihar and West Bengal in India, and all across the extent of Eastern Gangetic Plains in Bangladesh. Groundwater resource is held in the unconsolidated formations of quaternary alluvium, Palaeozoic-Mesozoic and Cenozioc semi-consolidated formations and deeper consolidated formations. Based on the characteristics of the geographies, administrative boundaries and state of groundwater development we report the groundwater resource analysis separately for the Terai plains of Nepal, EGP subregion in India and northwest Bangladesh.

### 6.2.1 Groundwater in the Terai plains of Nepal

#### Hydrogeology

The hydrogeology of the Terai plains in Nepal is composed by two major depositional units – the Bhabhar zone (towards the north) and the Southern Zone (Shreshta et al, 2018). The Bhabhar zone is situated in the foothill of the Chure consisting of alluvial and colluvial coarse sediments. The Bhabhar zone has unconfined aquifer with generally deep water table. Intersection of the Bhabhar zone of the Chure Hills and the Terai plain marks the northern boundary of the Ganga basin. The Southern Zone is underlain by recent alluvium with an average thickness of 1500 m formed by the deposition of sediments in the rivers running from the North. The rivers and streams frequently shift along the plain, sometimes over kilometres. Consequentially, the sediments are cross-bedded, eroded, reworked and redeposited resulting in aquifers that provide valuable groundwater resource. The depth profiles in the region comprising of alternating sand and gravel of various sizes mixed with clay favours high groundwater potential.

### Recharge

The confined aquifer of the Terai plains is believed to be recharged from the Bhabhar zone at the foot of the Chure Hills (Rao et al, 1996; Shreshta et al, 2018). Diffuse recharge from rainfall and river-aquifer interactions would also be contributing to the annual recharge of the shallow groundwater system. The paleo channels of the Terai plain are also considered as active recharge zones. Duba (1982) estimated 9629 MCM of total annual recharge in Terai based on rainfall data and attributed almost one-third of this recharge to the Bhabhar zone and the rest to diffuse recharge across the Terai plain Other studies have also estimated the recharge for the Terai plains in the range 5800 MCM to 10,745 MCM (Mukherjee, 2018).

### Aquifers

Major investigations about the aquifers of the Terai plains have been undertaken through several initiatives since 1980s. The aquifer system of the Terai plain comprises both unconfined (to semi-confined) shallow aquifers and confined deep aquifers. The shallow unconfined aquifer material is considered to have good groundwater potential in many zones, with transmissivity values ranging between 10 to 10,000 $m^2$/day (UNDP, 1992).

### Groundwater balance

Groundwater forms a significant component of the total water resource in the Terai plains. Almost half of the population of Nepal, who resides in the Terai plains, depend on groundwater for domestic needs. Groundwater is also used for irrigation, although this utilization is much lower than potential in most areas. Groundwater contributes for meeting evapotranspiration requirements of natural and irrigated vegetation, and discharge, contributing to summer flows in streams.

According to the Groundwater Resources Development Board’s recent study, the Terai plain has a dynamic groundwater reserve of 8800 MCM out of which 756 MCM is currently abstracted for irrigation and industrial purposes and 297 MCM for drinking water use (GWRDB, 2019). Accordingly, there is a groundwater surplus of 7747 MCM which may be potentially developed for irrigation (Figure 36). A more detailed analysis is required to generate the complete groundwater balance for the Terai plains including all recharge and discharge components. This was not possible for the Terai sub-region within the scope of this SRA, given the effort required to collate, synthesise and analyse the data with appropriate modelling tools.

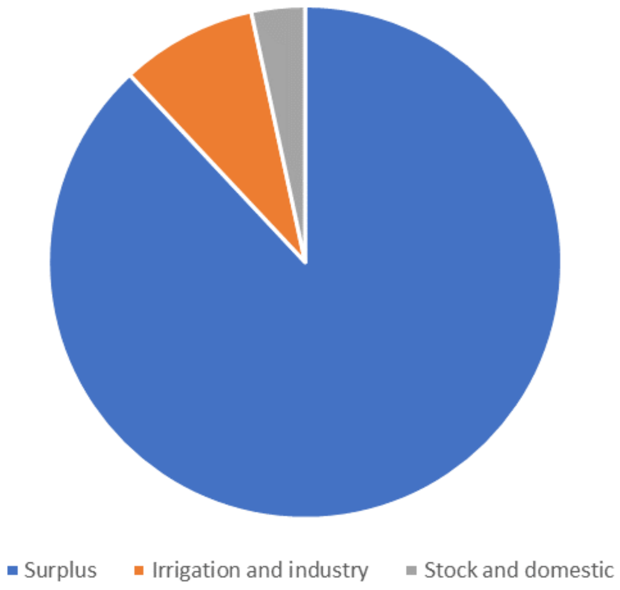



Figure 36: Groundwater balance for the Terai Plains reported by GWRDB (2019)

Thus, the Terai plains represents a sub-region in the EGP where there is immense potential for groundwater development. GWRDB reported that 7,26,000 ha of land has good potential for shallow tube wells (STW) and 1,90,000 ha of land has good potential for deep tube wells (DTW) in the Terai plains to expand groundwater irrigation.

### 6.2.2 Groundwater in the central EGP region within India

The sub-region of EGP that spans the states of Bihar and West Bengal and parts of Uttar Pradesh in India are considered as a separate sub-region in this analysis. This region is characteristically distinct from the Terai Plains. Groundwater is much more extensively developed for irrigation in this region, however, massive declining trends as observed in northwest Bangladesh is not observed in many parts of this sub-region. Hence, this sub-region is analysed in this study distinctly from the Terai plains and northwest Bangladesh. Unconsolidated formations in the sub-region comprises of Recent Alluvium, Older Alluvium and the Coastal Alluvium of Bay of Bengal (IIT, 2014). A detailed description of the hydrogeology of the Ganga Basin is available from IIT (2014). Groundwater development in this subregion largely occurs from these alluvial formations. Groundwater is extensively used for irrigation in this region. Estimated district-wise groundwater use (CGWB, 2019) in the modelled area within this subregion is shown in Figure 37.

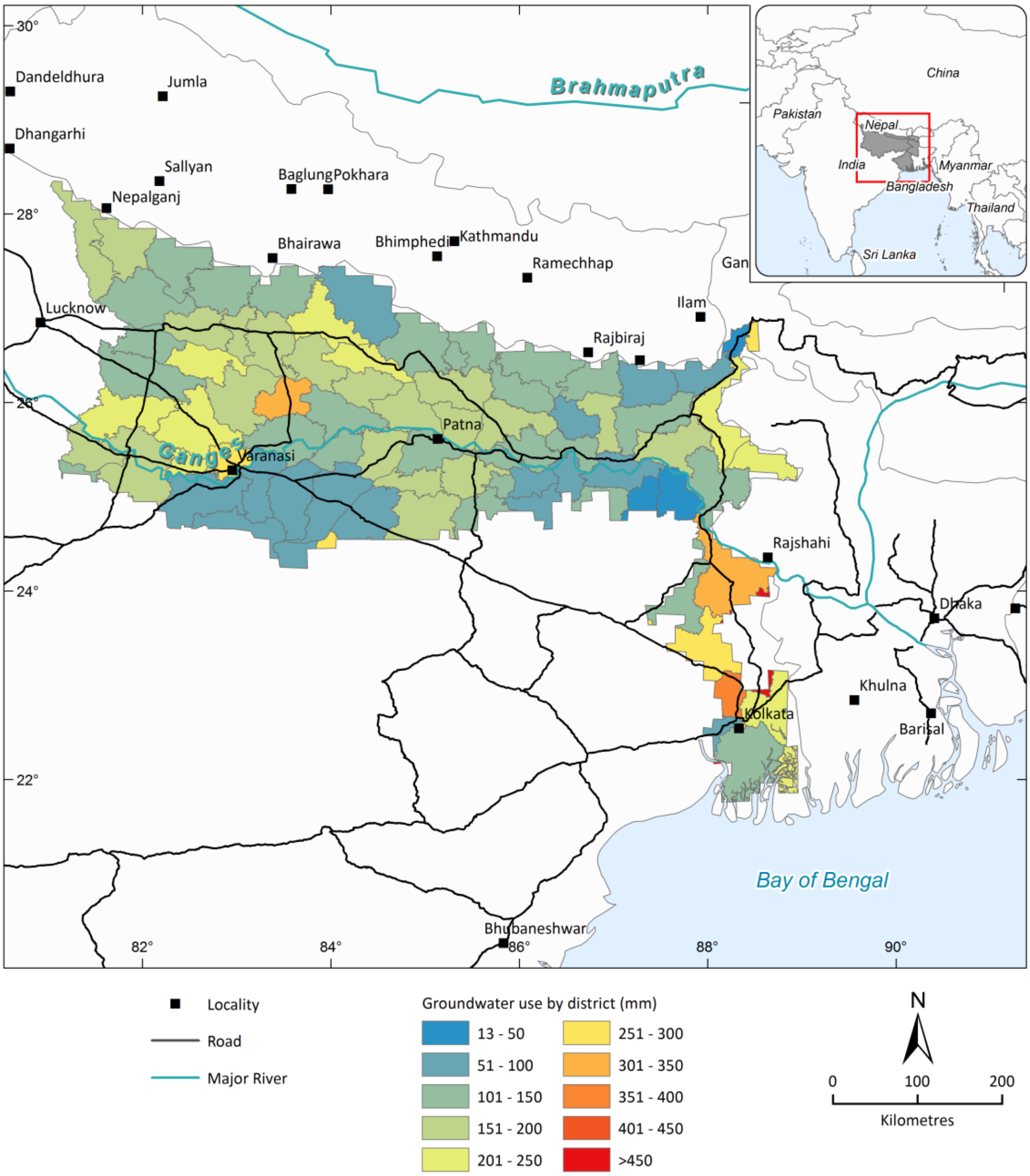



Figure 37: Estimated groundwater use in the districts of the central EGP sub-region within India

## Groundwater balance modelling

In this study we used a regional scale numerical groundwater model of the Ganga Basin alluvial aquifer built and calibrated by Sreekanth et al (2020) to do a preliminary quantification of the groundwater balance and groundwater level trends in the central EGP region in India. The regional scale model represented the alluvial aquifer system of the Ganga basin in a single-layer numerical groundwater model built using the MODFLOW code. The model area is discretised into finite difference cells in 322 rows and 665 columns. Each cell is 2500 m wide and 2500 m long in the X-Y directions. Vertically the aquifer is represented in a single layer that extends from the land surface to 500 m below the ground. The model area was chosen to extend beyond the alluvial aquifer extent of the Indian Ganga Basin in the west and south, and by the country borders in north and east. The model boundaries were specified with MODFLOW general head boundary conditions to account for the groundwater inflow and outflow across these borders. The representation of major water balance components recharge, groundwater use for consumptive demand (irrigation and crop water use), and SW-GW interaction is described in the following.

## Recharge

The spatial distribution of groundwater recharge was assumed to be proportional to the rainfall distribution across the region. Recharge was estimated by the model as a fraction of rainfall as spatially distributed and transient groundwater recharge was estimated while calibrating the model to historical groundwater level observations across the region. In the Indian Ganga Basin region, topography slopes from the northwest to the southeast and rainfall distribution also, in general, increases from the west to east. Recharge zones were identified based on these spatial characteristics. The recharge and discharge from and to the river stretches was dynamically simulated in the model using the river package. The details of these boundary conditions are available from Sreekanth et al (2020).

## Evapotranspiration

One of the major mechanisms of groundwater discharge in the Ganga Basin is groundwater use for evapotranspiration in addition to the regional flow towards the east and southeast that ends up in significant quantities of discharge into the Bay of Bengal. Evapotranspiration comprises the root water uptake by the native vegetation as well as groundwater use by irrigated agriculture. Spatially and temporally variable groundwater contribution to evapotranspiration and consumptive demand was modelled as a fraction of the total evapotranspiration estimate and was estimated by constraining the model to observed groundwater levels. In the EGP region in India, groundwater use for irrigation is largely unmetered and hence, reliable estimates of groundwater use for irrigation is unavailable. Past studies have provided estimates of groundwater pumping. Due to varying irrigation efficiencies in the region, there is a likelihood that a considerable portion of pumped water is returned to the water table as irrigation excess. On the other hand, farm-scale studies conducted in several areas, indicate that several crops are under-irrigated in many parts of the region. Thus, extrapolation of limited number of pumping estimates to quantify groundwater use over the region will result in large uncertainties leading to significant over or under estimating of groundwater use in regional models.

Hence, evapotranspiration estimates obtained using the Global Land Data Assimilation System (GLDAS) based Noah land surface model was used in Sreekanth et al (2020) to constrain the groundwater contribution to evapotranspiration and consumptive demand. In the EGP region, evapotranspiration signals have seasonal characteristics with two distinct peaks corresponding to high ET firstly during the monsoon season coinciding with the Kharif cropping and a second and smaller peak during the Rabi cropping season. Both these high ET periods, will have considerable groundwater contribution due to different mechanisms. While shallow groundwater table results in natural groundwater contribution to ET by root uptake in the monsoon season, groundwater pumping results in significant groundwater contribution to ET during the Rabi season. Hence, we hypothesise that apportioning groundwater as a fraction of total ET and calibrating it using observed groundwater levels is an efficient way to quantify groundwater use in such data-sparse areas. This approach, if integrated and refined with more local scale and field estimates of groundwater use and evapotranspiration from representative areas from distinct parts of the EGP will be very useful to test the hypothesis put forth by this scoping study.

## Hydraulic characteristics

The uncertainty in the regional variability of hydraulic characteristics like hydraulic conductivity and specific yield of the alluvial aquifer system was characterised by representing them as spatially variable parameters in the regional scale model. The spatial parameterisation devise called pilot points was used for this. The pilot points of hydraulic conductivity and specific yield were included as parameters for model calibration. The property values for each model cell are interpolated from the pilot point values. This approach enabled to calibrate and estimate the hydraulic property around each pilot point by history matching to the observed groundwater levels in the vicinity.

## Groundwater levels and water balance

The Central Groundwater Board of India collects groundwater data using dedicated monitoring bores and these data sets are publicly accessible through their web portals. These data sets include groundwater level monitored 4 times during the year. In this study we used observed groundwater levels between 2001 and 2012 for the Ganga basin to analysis the trends and calibrate the groundwater model. In the calibration process parameters governing the recharge, evapotranspiration, SW-GW interaction and hydraulic properties were adjusted to calibrate the model.

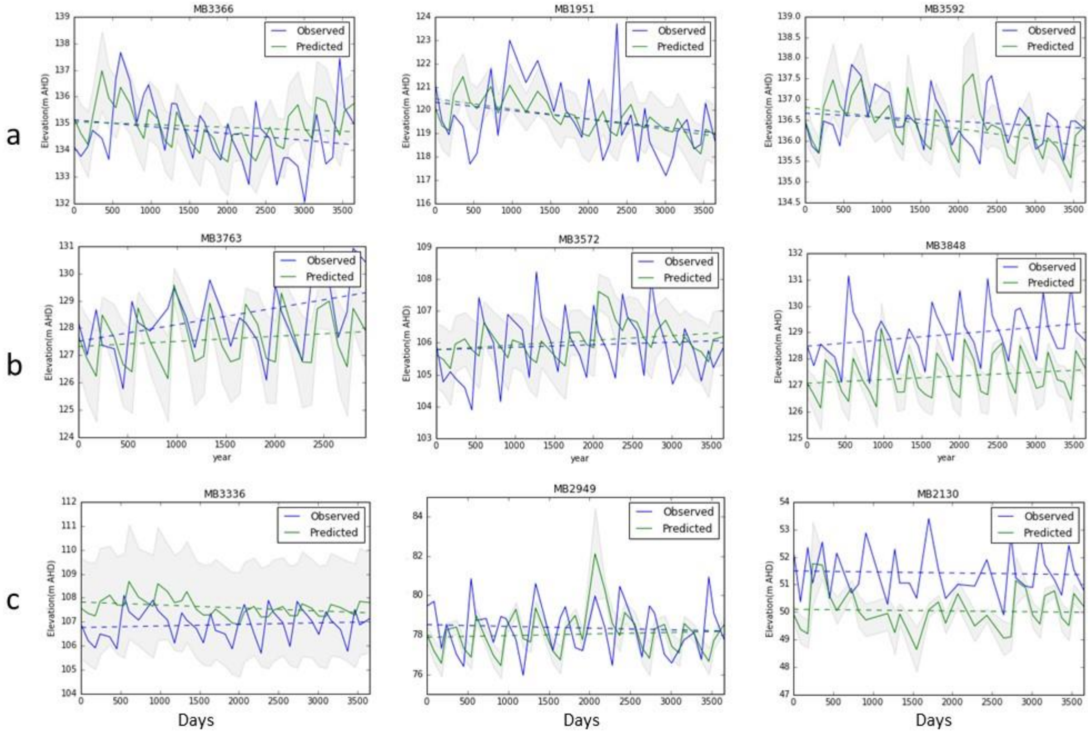



Figure 38: Observed and simulated groundwater levels in 9 example bores for the period between 2001 and 2012 a) showing declining trends b) showing increasing trends and c) showing more or less stable trends. The grey area demarcates the upper and lower bounds of groundwater level prediction uncertainty obtained using one standard deviation

Across the central region of EGP in India groundwater level trends showed three distinct patterns. A large number of bores in this region showed moderate declining trends in water levels. The rest of the observation bores in the region shows either stable or moderately increasing trends in water levels. Examples of these trends are shown in Figure 38. A summary of groundwater level trends in selected districts of India and Bangladesh are further investigated in Section 5. These responses could arise from a combined effect of groundwater abstraction and changes in recharge patterns triggered by climate variability and needs to be further explored.

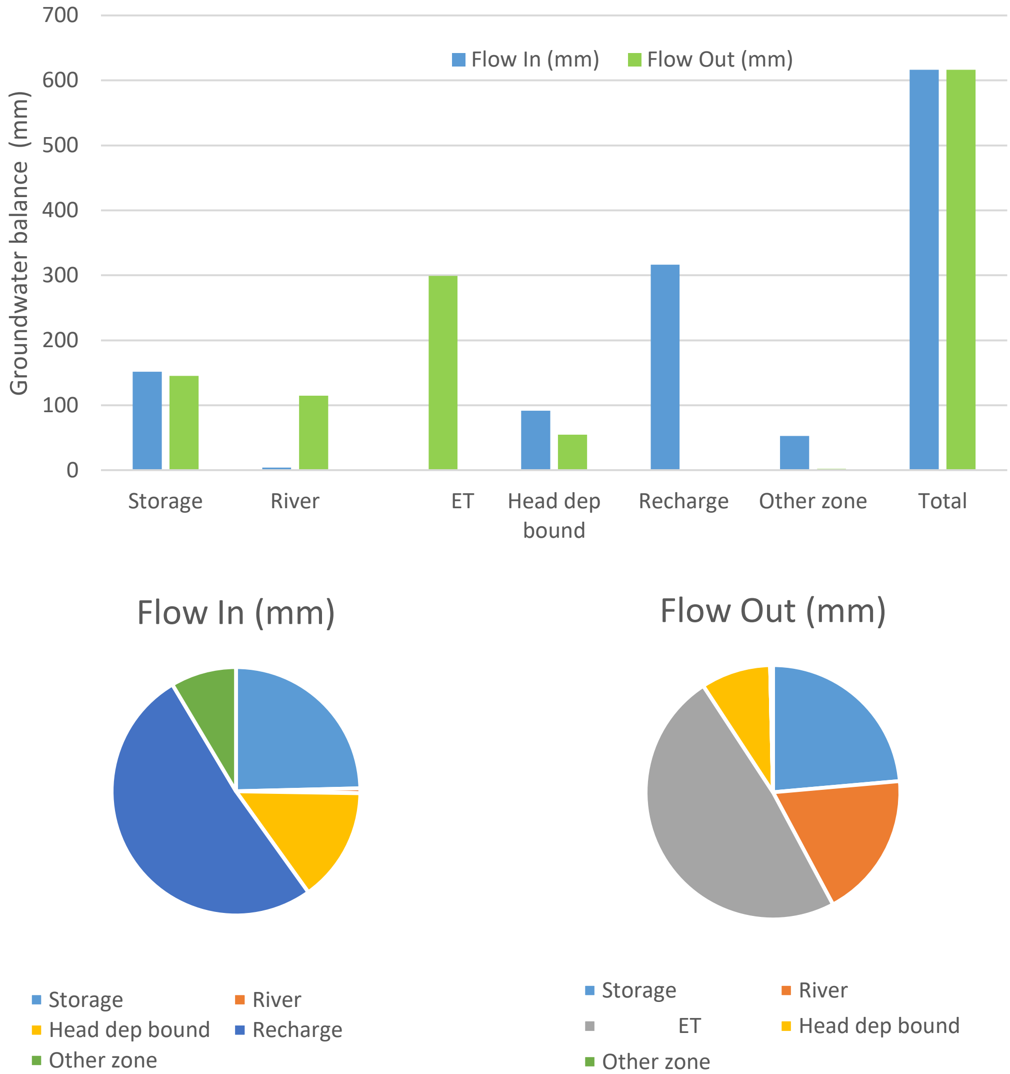



Figure 39: One realization of annual groundwater balance simulated by the calibrated MODFLOW model

The groundwater balance for the central EGP region in India estimated using the numerical groundwater flow model is shown in Figure 39. It indicates that diffuse recharge from rainfall (and irrigation excess) is the major component of inflow and groundwater used for meeting evapotranspiration requirement is the major component of groundwater outflow. These two components are indicated to be very close to each other indicating that groundwater use is nearly equal to the net recharge available annually. In addition to this, groundwater also serves the purpose to base flow into the river indicated by the significantly higher amount of groundwater flow out into the river compared to the inflow into the aquifer from losing stretches of the river. The storage terms in the water balance indicates the dynamic flow of groundwater into and out of aquifer storage. The two components are nearly equal in this water balance indicating that there is no massive depletion or large accumulation of storage that occurred over the 11 year period considered for the water balance analysis. The head dependent boundary fluxes (indicated as head dep bound in the bar chart) represent the inflow and outflow across the model boundaries. The head dependent inflow is higher given the larger influx of water across the Terai plains on the norther boundary of the model.

### 6.2.3 Groundwater in northwest Bangladesh

Similar to the central EGP region in India, we undertook an indicative groundwater balance and water level trend analysis using a numerical groundwater flow model constrained with observed groundwater levels.

The numerical model built using the MODFLOW code was developed as part of CSIRO's project in Bangladesh for the SDIP-II program with the aim of exploring predictive uncertainties in conjunction with a detailed MIKE SHE model for integrated SW-GW interaction simulation for the northwest Bangladesh. In this study the calibrated MODFLOW model is used to quantify groundwater balance in the northwest. The salient features of the model are briefly described in the following and subsequently an overview of groundwater level trends and water balance is presented. For a detailed description of the model development readers may refer to the groundwater modelling report (Sreekanth et al, 2020).

### Recharge

A district scale representation of the groundwater recharge was represented in the MODFLOW model as a function of deep drainage estimated by the companion study (Mainuddin et al, 2021) in the SDIP-II Bangladesh project. Temporally variable deep drainage was available from that study and groundwater recharge was estimated as a fraction of that and calibrated to observed groundwater levels in each district. Recharge from losing reaches of the rivers in northwest region was represented using river package of MODFLOW.

### Evapotranspiration

Similar to the approach used earlier, regional groundwater use for irrigation was represented in this model using evapotranspiration package of MODFLOW. However, remote sensing estimates of ET from GLDAS was not used as an input into the model to represent the spatial and temporal trend in ET. Instead, district-scale ETa estimates from water balance study (Mainuddin et al, 2021) was used to represent the spatio-temporal patterns of actual ET across the region. Then, the groundwater contribution to ET was estimated as a fraction of this, after calibrating the model to observed groundwater levels.

### Groundwater balance and water level trends

The trends in groundwater levels analysed for selected districts is reported in Section 5. In this section, trends in observed and simulated groundwater levels are used for constraining groundwater balance of northwest region. Trends for example bores are shown in Figure 40. Declining trend is observable in many bores in the northwest region especially in the Barind tract area. The groundwater model was calibrated to match these declining trends and then the model was used for simulating the groundwater balance for the northwest. One realization of the groundwater balance from many plausible ones is shown in Figure 41. This groundwater balance is one of the many plausible realisations, because the available groundwater level observation data alone is not sufficient to resolve all uncertainties in water balance. Yet this water balance reveal insights about various water balance components. As was the case with the central EGP region in India, the two major components of are diffuse groundwater recharge for the inflow and evapotranspiration for outflow. For the simulated groundwater level trends to mimic the observed ones by the calibrated model, evapotranspiration is roughly equal to or moderately higher than recharge. This indicates that it is unlikely that the northwest region has significant surplus groundwater unlike the Terai plains. Also the simulation indicated that the long-term average groundwater use is likely to deplete the storage which in turn results in declining groundwater levels, if the depletion in storage is not compensated in increase recharge, for example from the losing stretches of the river.

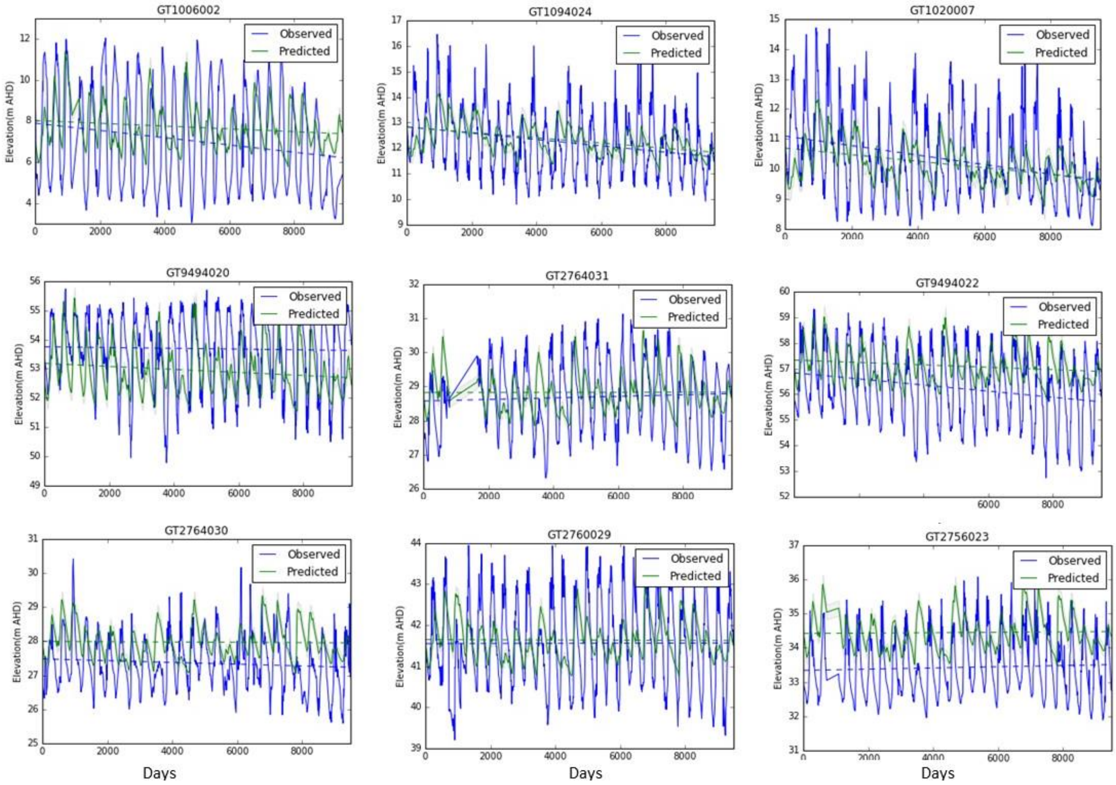



Figure 40: Examples of groundwater level trends in the northwest region.

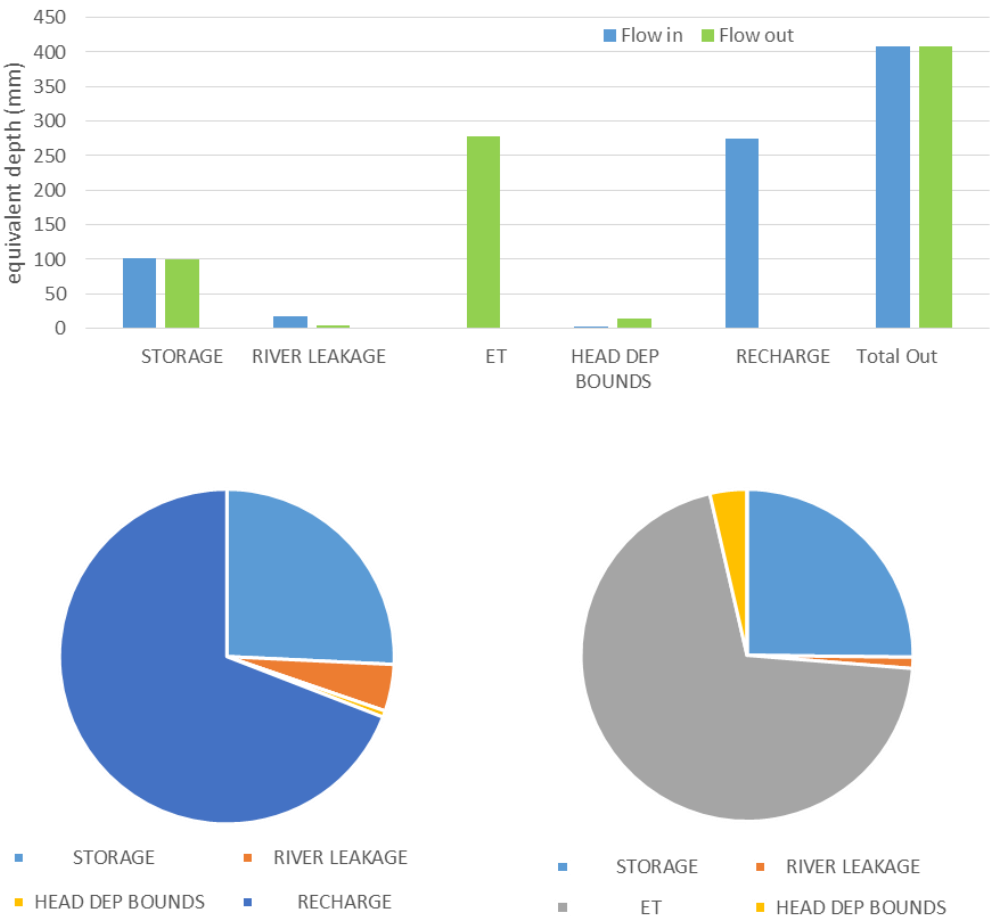



Figure 41: One plausible realisation of groundwater balance for the northwest region

## 6.3 Discussion

We analysed groundwater level trends and groundwater balance in three different sub-regions of the EGP based on the geography and political boundaries. It revealed that the state of groundwater exploitation and use is considerably different across the region. For example, the limited analysis and literature review reveals that the Terai plains may have large amounts of surplus groundwater that may be developed for irrigated agriculture whereas the northwest region of Bangladesh is likely to have reached a potential maximum of sustainable groundwater use. The analysis also revealed that there may be multiple confounding factors that affects the status  of groundwater resource in the region. For example, despite having significant amount of groundwater resources, several observation bores in the Dhanusa and Siraha districts of Terai, shows some declining trends in water levels. It is very likely that confounding effects of groundwater use, climate variability and change and dynamically evolving groundwater balance in the region cumulatively produce the trends in observed parameters. This also suggests that any single, consistent approach to groundwater management, for example encouragement of water conservation measures, alone may not be suitable to resolve groundwater management challenges in the region.

Limited analysis of groundwater balance in the Indian and northwest Bangladesh regions of the Ganga basin indicates some similarities and differences. The long-term storage changes in both regions indicate small rates of groundwater depletion. This is potentially indicative of the stress on the regional groundwater system induced by the combination of large-scale irrigation water use and other factors like changes in rainfall patterns. Considerable differences are seen between the components of individual water balances. However, these individual water balance components like the river, recharge and ET fluxes are not independently constrained by relevant observations other than the groundwater levels. More comprehensive probabilistic approaches to water balance need to be employed before conclusive inferences are made about these individual components.

## 6.4 Gaps in current knowledge

*What will be required for resolving uncertainties in the regional scale groundwater balance?*

There is large amount of groundwater level observation data available for the EGP region, predominantly in the northwest region of Bangladesh as well as in India. However, estimates of volumes of groundwater use for irrigation and other purposes is largely absent in the region. While, measurements and metered data are available at the local scale, extrapolating it to the regional scale will exacerbate the uncertainties in water balance analysis. It was also found that the field-scale data sets were of variable quality across the region and are variable in terms of the ease of access and use. However, other data sets like remotely sensed or independently estimated data pertaining to processes like evapotranspiration and recharge can be consistently and easily obtained for the whole region. Such secondary data sets can be very useful in reducing predictive uncertainty in the regional scale models that are used for understanding the regional hydrological impacts of water saving measures. Such data sets and analyses that bridges the gap in data availability between the two scales – local and regional is key to test the hypothesis put forth by this study.

*How do we resolve the effects of multiple stressors on the groundwater system?*

Declining groundwater levels is often attributed to over exploitation of groundwater resource. However multiple stressors including climate, evolving land use and rapid urbanisation, changes in river flow etc that are present in the Eastern Gangetic Plains region can interfere with the dynamics of the groundwater resource. A two-way approach that explores the system from local-to-regional and regional-to-local is needed to investigate and explore these effects. Integration of field/local scale data and coarser scale remote sensing data sets in scalable models is required for this.

# 7 Remote sensing for mapping crops and estimating their water use

## 7.1 Introduction

Understanding the retrospective dynamics of agriculture is essential in areas of the Eastern Gangetic Plains (EGP) where water limitation becomes a major constraint to irrigation (Ladha et al 2003). Mapping crop types and their water use in the EGP on a season-to-season basis and at policy relevant scales is particularly important because of the potential impact of conservation agriculture projects on water use and regional hydrology. Recent technological advances in satellite earth observation and image processing have enabled the mapping of crop types and their water use from farm (< 1 ha) to regional scales (i.e. >100,000 km$^2$). Remote sensing (RS) actual evapotranspiration ($ET_a$) models underpinned by satellite imagery and global-scale meteorological data can provide estimates for the entire EGP at policy relevant scales (from 8-daily to monthly and ~500 m spatial resolution, e.g. Mu et al 2011, Zhang et al 2019). Also, multi-temporal satellite imagery, geospatial processing such as Google Earth Engine (Gorelick et al 2017) and machine learning algorithms can potentially identify crop types , yield and their water use efficiency.

Areas were conservation agriculture projects have been stablished for some years can therefore be assessed using RS, in terms of their cropping mix and net water use and changes over time. Water saving techniques (e.g. drip irrigation and lining of canals) may reduce the bulk application of irrigation water, but only reductions in $ET_a$, considered as the net water use, are real water savings. Conservation agriculture will therefore have achieved the water conservation aims if $ET_a$ from areas under conservation agriculture is generally less than under typical agricultural systems.

The remainder of this Section summarises the potential contribution of RS to assess conservation agriculture water use, highlighting studies previously undertaken to estimate $ET_a$ and crop types, with an emphasis on work carried on by CSIRO in the region.

## 7.2 Estimation of remote sensing actual evapotranspiration

Methods to estimate $ET_a$ using RS can be classified in: (i) vegetation states physical models (Zhang et al 2019) (ii) vegetation-index (VI) methods (Glenn et al 2011, Yebra et al 2013), (iii) thermal methods (Kalma et al 2008) and (iv) hybrid methods that combine information about vegetation vigour and environmental moisture, including machine learning (Guerschman et al 2009, Jung et al 2009).

The different methods have their strengths and weaknesses. For example, vegetation states physical models can describe specific components of $ET_a$ (transpiration, soil evaporation and interception) but require more RS, meteorological and land cover input data. VI methods rely on degrees of 'greenness' as observed by RS data and are generally easy to implement but have their limitations during dry periods, when plants possibly close their stomata even though they still look 'green' according to RS data. Thermal methods can overcome this issue since the RS temperature data indicate periods of water stress, but they need manual calibration and parameters are region specific. Hybrid approaches can make use of several VIS and meteorological data and vary from linear or non-linear equations combining VIS and meteorological data to supervised machine learning approaches enabled through large training datasets. The simple equations can resemble VI methods and possess their weaknesses , whilst more complex equations may suffer from equifinality (Beven 2006) and in the case of machine learning, $ET_a$ causality is difficult (or impossible) to establish.

As can be inferred from the above paragraph, RS $ET_a$ methods rely on satellite optical reflectance data to be able to 'see' vegetation states (as indicated by VIs or other RS-derived products such as leaf area index). Cloud cover in parts of the EGP is prevalent during the Indian monsoon (Tang & Chen 2006). The latter would limit optical RS methods for satellites with a low temporal frequency, for example, the high spatial resolution (30 m) but low temporal frequency (16 days) Landsat satellites TM-ET+/OLI (Goward et al 2006). A resolution of 30 m is desirable for the fragmented agricultural landscapes in the EGP, but most current RS $ET_a$ products use reflectance data from the Terra and Aqua satellites' Moderate Resolution Imaging Spectroradiometer (MODIS), with a spatial resolution of 500 m and daily temporal frequency. There are ways to make use of the high temporal frequency of MODIS with the high spatial resolution of Landsat to obtain monthly or 16-day $ET_a$ estimates with Landsat resolution (30 m) using a blending approach. This is exemplified by two recent studies, in which the CMRSET (Csiro Modis ReScaled EvapoTranspiration) $ET_a$ model (Guerschman et al 2009) was implemented with Landsat data in south-eastern Australia (McVicar et al 2017) and northern Australia (Van Niel et al 2017). Blending in south-eastern Australia was performed using ESTARFM (Zhu et al 2010). In northern Australia, as outlined in Van Niel et al (2017), the blending approach was an extension of a geostatistical method that analytically relates the variance of a spatio-temporal dataset into its spatial and temporal variance components (Sun et al 2010). The Landsat-MODIS blend $ET_a$ data produced accurate estimates when compared to flux towers and long-term catchment $ET_a$ (obtained by subtracting *P*-*Q* over the long-term, where *P* is catchment averaged precipitation and *Q* is catchment averaged runoff).

### 7.2.1 CSIRO's remote sensing actual evapotranspiration work in the EGP region

Within the EGP domain, Peña-Arancibia et al (2020) used the CMRSET model to estimate $ET_a$ at a monthly temporal resolution and spatial resolution of 500 m for the 2000–2016 period in 16 districts in northwest Bangladesh (34,540 $km^2$). Monthly $ET_a$ was estimated by scaling Priestley-Taylor potential evapotranspiration ($ET_p$) via a remote sensing-based crop factor ($K_c$), which is obtained from two indices: the Enhanced Vegetation Index (EVI, Huete et al 2002) and the Global Vegetation Moisture Index (GVMI, Ceccato et al 2002). EVI and GVMI monthly composites were obtained via Google Earth Engine (Gorelick et al 2017) from the daily Moderate Resolution Imaging Spectroradiometer (MODIS) surface spectral reflectance product (MOD09GA, collection 6). The average pixel value was selected within the monthly composite, while minimising cloud cover and nulls. Using EVI and GVMI allows discrimination of open water and bare soils when EVI is low and GVMI is high, and to detect vegetation water content when EVI is high. CMRSET uses a single set of parameters (i.e. does not need an auxiliary land cover map and does not require a complex calibration). In addition, CMRSET can estimate $ET_a$ in lakes and floodplains.

The remote sensing $ET_a$ estimates (in million cubic meters, mcm) were visually compared to crop (and other vegetation) coefficient model $ET_c$ estimates aggregated at the district level from survey crop statistics (Figure 42). The Pearson's correlation coefficient (*r*), the mean percentage bias (*MPB*) and the root-mean-squared-error (*RMSE*) between remote sensing $ET_a$ ($ET_a$ RS) and crop coefficient $ET_a$ ($ET_a$ Crop) were used as goodness-of-fit metrics to assess the differences in both estimates. The comparisons have correlation coefficients between 0.75 in the worst case, and 0.89 in the best, with the greatest difference in mean monthly actual evapotranspiration is 5.4 %. The absolute MPB is less than 5 % in 14 districts, and less the 10 % in the remaining two (Kurigram and Rangpur, Figure 42e and n), with no visible systematic under- or overestimation. The mean RMSE for the entire period is between 19.7 and 73.4 mcm (average of 41 mcm), which was only about 2 % of the mean annual $ET_a$ for the period (2380 mcm).

Although not an independent evaluation but a comparison of models, the similar results provide confidence in their use as inputs to other hydrological modelling such as water balance at the district-scale such as those reported in Peña-Arancibia et al (2020).

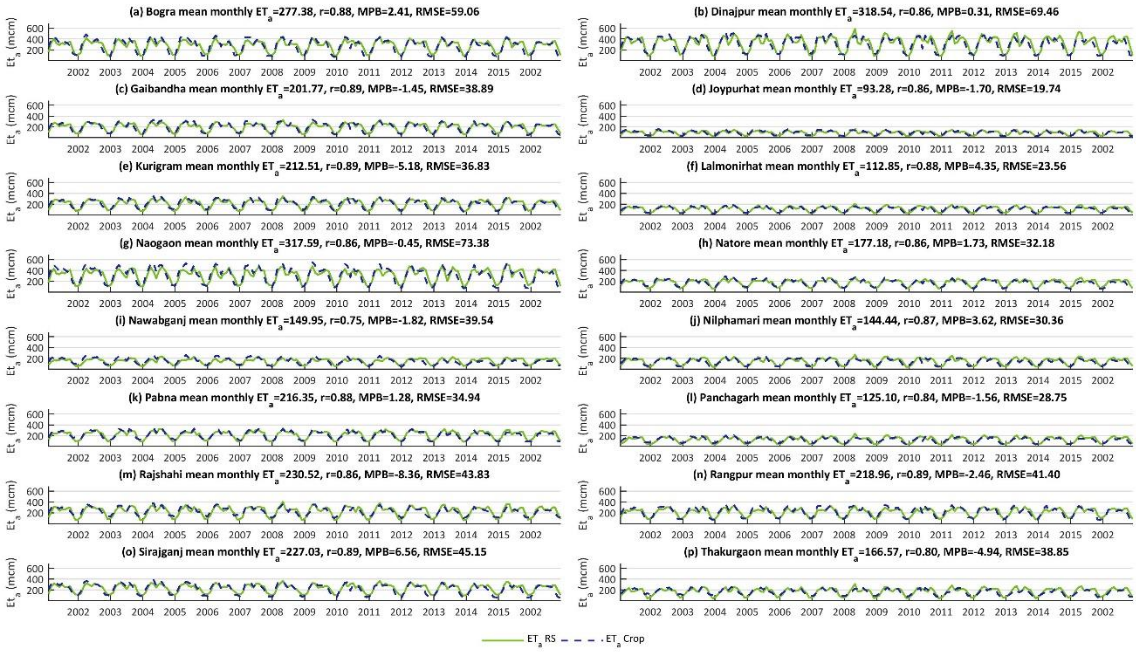


Figure 42 Monthly time-series for the remote sensing $ET_a$ and crop coefficient $ET_a$ (remote sensing: $ET_a$ RS, green solid line; crop coefficient: $ET_a$ Crop, blue dashed line) for the 16 districts from February 2000 to December 2015 (period when both time-series overlapped). Comparison statistics are shown above each plot and include the mean monthly ETa for both estimates, the correlation coefficient (r), the mean percentage bias (MPB) and the normalised root-mean-squared-error (NRMSE) (Peña-Arancibia et al 2020).

### 7.2.2 Implementation of remote sensing evapotranspiration models in the EGP region

In a recent multi-model global-scale model comparison, Pan et al (2020) assessed the magnitudes, seasonality and trends of selected $ET_a$ RS physical and hybrid models (all machine learning). On a global scale, the period from 1982 to 2011 suggested increasing trends in global $ET_a$ for ensembles of both model types. There was high uncertainty amongst model types in mean annual $ET_a$ (>200 mm/year) in large areas of the EGP (see Figure S2 in Pan et al. 2020), which the authors attributed to differences in meteorological forcing data and the semi-arid characteristics of the region. It would thus be desirable that RS $ET_a$ estimates in the EGP undergo a verification against independent data if available (including catchment water balance data, flux tower and lysimeter data, or other locally calibrated RS $ET_a$ models) to assess their spatial and temporal accuracy. Currently there are only a couple of RS $ET_a$ models that provide estimates at MODIS 500 m resolution, the PML-CSIRO model (Zhang et al 2019) and the MOD16 model (Mu et al 2011). The CMRSET model can also be straightforwardly implemented in the EGP at 500 m as described in Section 7.2.1, and oversampled to Landsat 30 m resolution using blending or bias correction methods, which is a more suitable resolution for assessing water use in conservation agriculture areas.

As an example of $ET_a$ spatial dynamics in northwest Bangladesh, Figure 43 shows the annual $ET_a$ spatial characteristics for the 2000–2016 period using the CMRSET $ET_a$ model, including the period mean, linear trend and coefficient of variation (the ratio of the standard deviation to the mean). Mean annual $ET_a$ estimates are generally >1000 mm, with areas below this value in bare/urban areas and along riverbanks and/or riverbeds (Figure 43a). $ET_a$ is mostly increasing (>5 mm per year) during this period in areas along the Barind tract (> 20 mm per year) and many areas in Dinajpur, Panchagarh and Thakurgaon (Figure 43b), whereas it is mostly decreasing in districts in the east (>5 mm per year) and in riverbank areas along the Brahmaputra (>10 mm per year). The coefficient of variation (CV) shows that overall variability is low (<5 %), except for areas along the (> 5 %) and along riverbanks and/or riverbeds (Figure 43c).

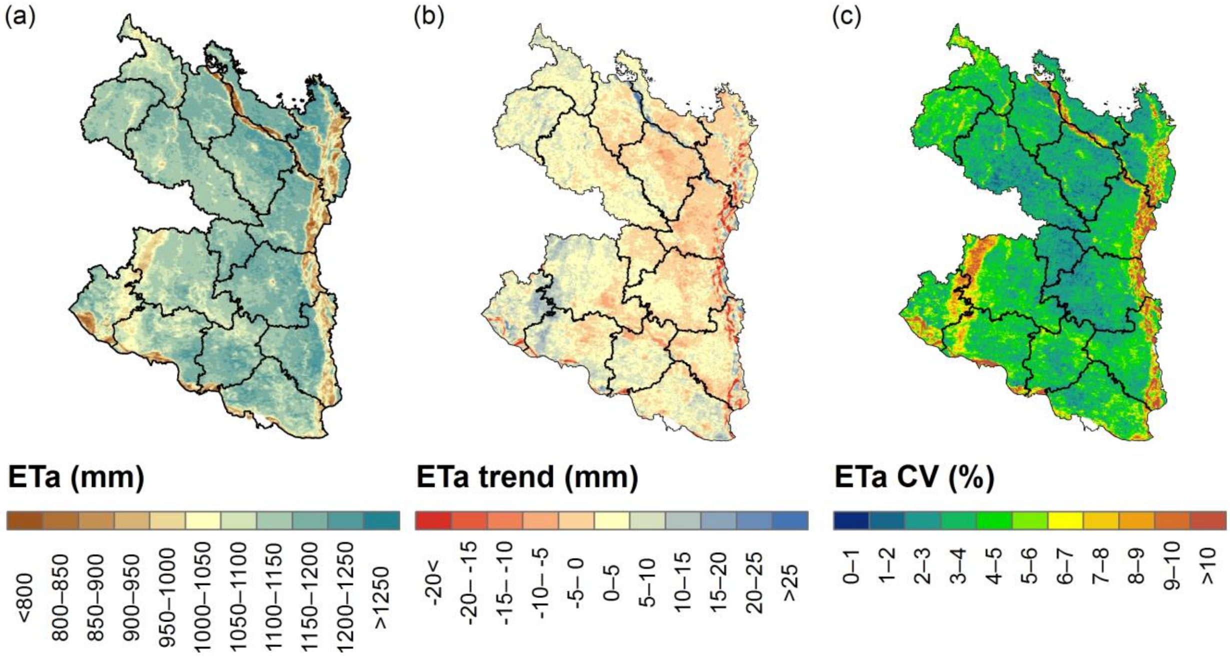



Figure 43 Spatial characteristics of (a) mean annual $ET_a$, (b) annual trends and (c) coefficient of variation for the 2000–2016 period. District boundaries are in black.

## 7.3 Crop mapping using remote sensing and machine learning

Multi-temporal RS analysis using VIs from optical satellite data or Synthetic Aperture Radar (SAR) signatures through phenology-based approaches can be successful in mapping important EGP crops such as rice (Dong and Xiao 2016, Mosleh et al 2015). RS data from the petabyte archive of Landsat reflectance available via Google Earth Engine (Gorelick et al 2017, Woodcock et al 2008) can be coupled with advances in geospatial techniques, including blending (mentioned in the previous section), to filter clouds and fill gaps in RS imagery (Cao et al 2018, Wang et al 2012, Zhou et al 2015). This can provide quality time-series VIs data useful to assess vegetation condition. The idea behind is that VIs time-series can capture crop developmental stages for the main crop types. Expert knowledge on crop calendars and field level data aided by very high resolution (i.e. ≤30 m) Google Earth Imagery can be used to interpret crop monthly phenology. Subsequently machine learning algorithms can further group the different land cover phenologies into crop and other land cover types. A ‘trained’ learner that ingests the characteristic cropping dynamics in time and space within a region can therefore efficiently identify crop types every season and every year, as long as the cropping dynamics in the region have not varied much in any given year/season. If the cropping dynamics have changed, the characteristics of these changes need to be included in the ‘training’ dataset.

There are several studies that have followed similar machine learning approaches to map land cover types including crops in time and space (Li et al 2019, Ozdogan & Gutman 2008, Ozdogan et al 2010, Thenkabail et al 2009, Xu et al 2020). But there are limitations of an *ad hoc* implementation in the EGP: (i) the trade-off between spatial and temporal resolution in satellite data (e.g. MODIS and Landsat), (ii) complex cropping systems that require expert knowledge of crop calendars for their understanding, and (iii) prevalent cloud cover during the Indian monsoon.

CSIRO has mapped the main rice types in northwest Bangladesh following a semi-supervised machine learning approach and used both expert knowledge and geostatistics to overcome some of the above mentioned limitations (Peña-Arancibia et al., 2021). The following section summarises the methods and results of the mapping.

### 7.3.1 CSIRO's remote sensing crop mapping work in the EGP region

In northwest Bangladesh, Peña-Arancibia et al (under review) used EVI and GVMI phenology time-series in a semi-supervised approach to map rice types and other land cover of importance for environmental monitoring from 1989 to 2016. The mapping was performed for the largely irrigated dry season *Boro* rice, and the largely rainfed *Aman* rice. These two rice types currently comprise about 80 % of the agricultural land in northwest Bangladesh and have experienced a 300 % areal increase since the 1980s.

In the first instance, 79 Aman and 61 Boro rice field level data were visually assessed to understand their salient features and the advantages of using the complementarity of the two VIs (see Section 7.2 for details). An example of monthly time-series in the form of violin plots of EVI and GVMI extracted from Landsat data are shown in Figure 44, alongside a conceptual model of *Boro* and *Aman* rice types growth phases from the International Rice Research Institute (IRRI 2020). The salient features of other land cover types including other vegetated areas, water, water non-permanent and bare areas were also examined in this way.

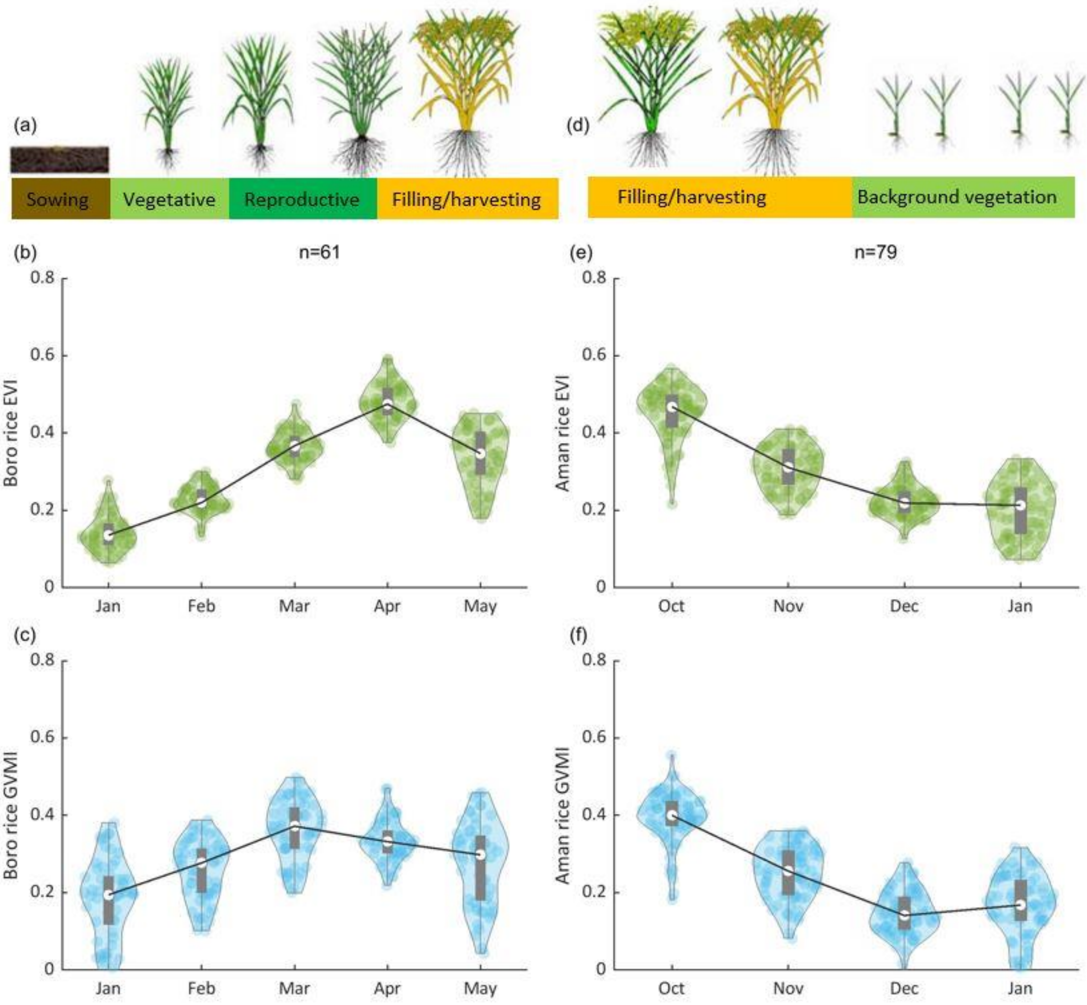



Figure 44 Crop mapping with remote sensing, Boro and Aman rice examples.: (a) and (d) conceptual models of *Boro* and *Aman* growth phases sourced from the International Rice Research Institute (IRRI 2020); (b) and (c) monthly time-series in the form of violin plots of EVI and GVMI phenological sequences for the 61 *Boro* and (e) and (f) 79 *Aman* rice fields obtained in 2015–2016, respectively. All data points are represented by a kernel density estimate of the data inside the

violin plots for each respective month, the associated box and whisker plots are show inside each violin plot (Peña-Arancibia et al under review)

K-means clustering (Lloyd 1982) was performed for the time-series of EVI and GVMI for October to January (*Aman* season) and January to May period (*Boro* season). The clustering was performed for the two VIs simultaneously, i.e., a joint 'time-series' is constructed using the monthly sequence of EVI values followed by the monthly sequence of GVMI values. The clusters were grouped visually through expert knowledge by assigning EVI and GVMI pixel time-series density plots (similar to those in Figure 44) to a land cover type 'label'. This manual aggregation was performed for the *Boro* season and *Aman* season in the years 1991–1992, 1998–1999, 2006–2007, 2010–2011 and 2015–2016 in order to capture different land cover dynamics over time.

The 'labelled' data was used to construct 'training' data to train two Random Forest (RF) learners (Breiman 2001, Ho 1998), for the *Boro* season and *Aman* season.The RF models used additional explanatory covariates (other than the monthly VIs) to map the two main rice types and other land cover types from 1989 to 2016. Other covariates extracted from the monthly data that were considered in the training data included: (i) the monthly rate of change (i.e., the slope of the line subtending two consecutive months), (ii) the area under the curve for EVI and GVMI and (iii) the ratio of EVI to GVMI for the first months in the sequence (January for *Boro* and October for *Aman*). The latter covariate is chosen to capture the ponding phase of *Boro* rice, when the EVI value is expected to be lower than the GVMI value.

Results show that the expansion in areas is captured by the RF model (Figure 45a to d), with most of the years (19 out of 23 for a total of 108 years assessed, i.e. 27 years in four modelling domains) with absolute percentage difference < 20 % in four modelling domains (NE=Northeast, NW=Northwest, SE=Southeast, SW=Southwest). The overall absolute differences are within 20 % for both *Boro* and *Aman* in all modelling domains, except for a 26 % absolute difference in the October to January mapping period in the SE modelling domain.

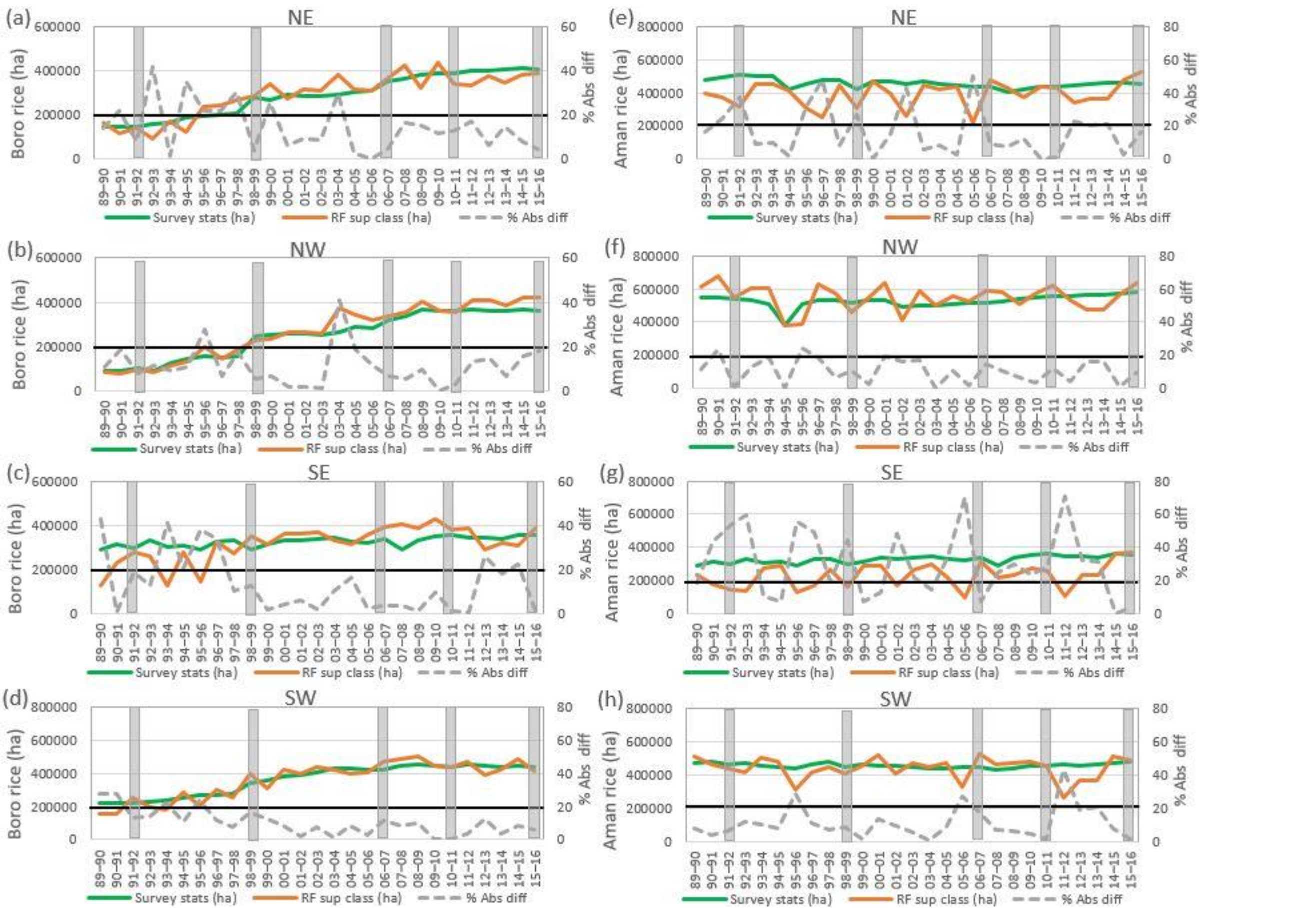


Figure 45 Crop area time -series. Survey statistics (green line) and results of the RF supervised classification mapping (orange line) and associated absolute percentage difference (dashed grey line) for the four modelling domains: (a)–(d) the January to May mapping period (corresponding to *Boro*), (e)–(h) idem. for the October to January mapping period (corresponding to *Aman*). The black horizontal thick line corresponds to an absolute error of 20 %. The grey bars denote the years from which the training dataset was obtained (Peña-Arancibia et al under review)

As an example, historical maps of *Boro* rice from 1989 to 2016 at 30 m resolution are shown in Figure 46, showcasing the extent and location of the expansion of *Boro* rice across northwest Bangladesh.

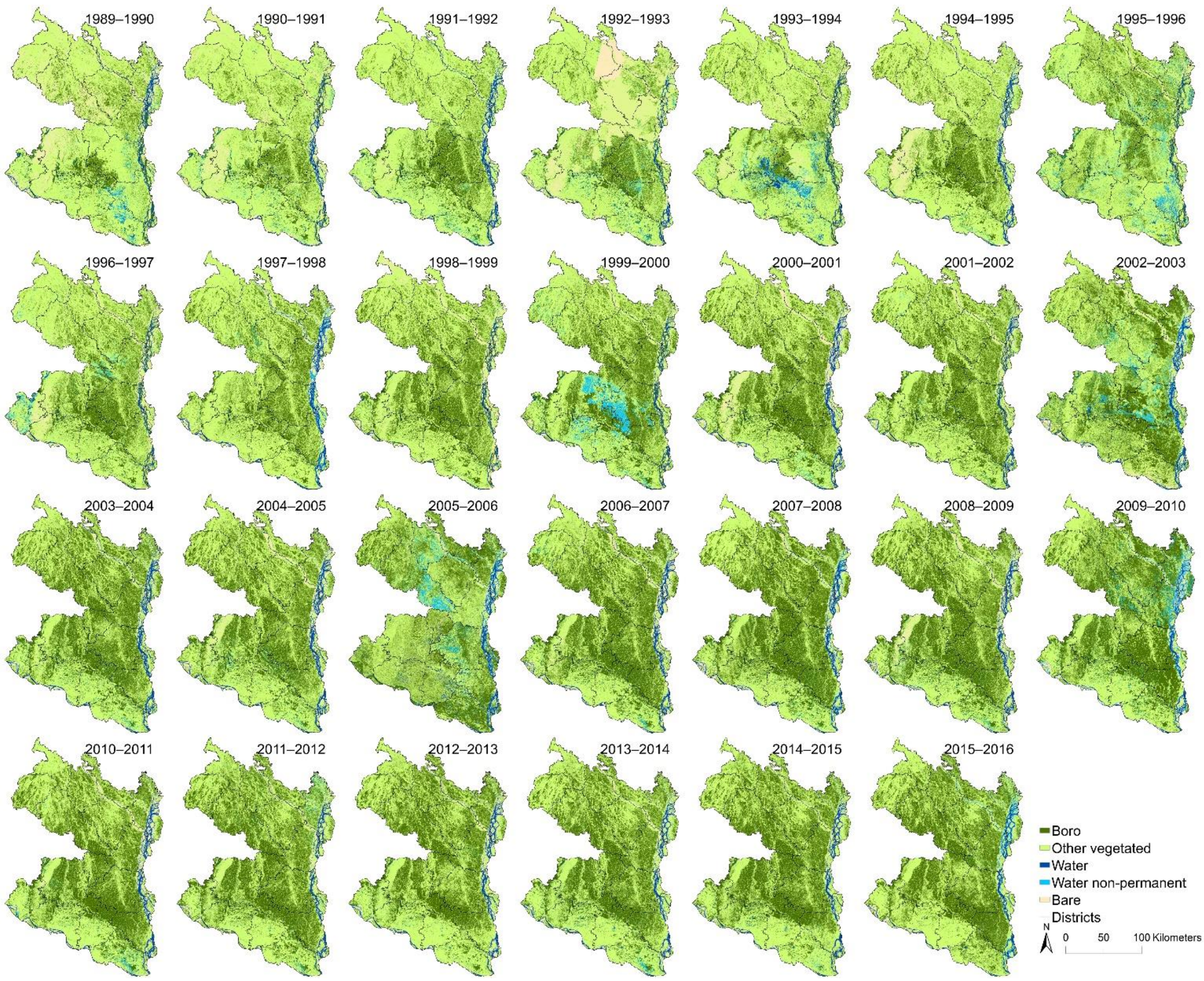



Figure 46 Historical maps for the *Boro* cropping season in northwest Bangladesh from 1989 to 2016

### 7.3.2 Implementation of remote sensing land cover mapping models in the EGP region

As outlined previously, a similar approach to map land cover types can be implemented in the EGP. For historical maps going back to the 1980s, Landsat TM/ETM+/OLI TOA reflectance data are the only alternative with a suitable resolution to understand changes in the crop mix in this fragmented landscape. The prevailing cloud cover over the monsoon season will required gap-filling or blending methods to maximise the availability of data. For more recent years, advances in image and geostatistical processing and more recent RS data (optical and microwave) can be used to solve this issue. Methods tested by CSIRO include blending of VIs using coarser but more frequent RS data (Emelyanova et al 2013, Zhou & Zhong 2020). It is possible to also use of microwave data or a combination of optical and microwave data to overcome paucity of data due to cloud cover.

## 7.4 Gaps in current knowledge

The previous sections described methods already applied in parts of the EGP to estimate net water use (in terms of $ET_a$) and associate this use to crops or other land cover types using land cover mapping techniques. With additional work, some of the questions relevant to conservation agriculture and water saving techniques in the EGP can be addressed using RS as follows:

- Methods to improve the spatial resolution (≤30 m) and frequency (≤ monthly) of $ET_a$ estimates render the evaluation of net water use at the farm scale.
- The spatiotemporal assessment of past $ET_a$ estimates and land cover mapping (including rainfed and irrigated crops) provide an indication of prevailing agricultural practices, including cropping mix and net water use and changes over time. This can answer the question of degree of cropping expansion and intensification.
- If secondary data on locations in which water saving measures (e.g. conservation agriculture) have occurred, RS can be used to identify the impact of farm level water saving measures (i.e. reduction of $ET_a$).
- The spatiotemporal characteristics of $ET_a$ can be used as direct inputs to regional hydrological models (such as water balance models as described in Section 4 or groundwater models as described in Section 5), or as inputs to parametrise prognostic $ET_a$ models (e.g., crop factor models) in such regional hydrological models to test the impacts of climate change and development.
- The spatiotemporal characteristics of $ET_a$ and cropping practices can be used to parameterise crop models (cf Section 4 on APSIM) to further test the crop water balance response to water saving techniques and their impacts on crop production and yields.

# 8 Conclusions and recommendations

## 8.1 Conclusions

We conclude that:

1. With a growing population and growing demand for food, there is likely to be continuing development of irrigation in the Eastern Gangetic Plains. Much of the development will likely be based on groundwater, and there will be growing concerns about whether its use is sustainable, adding to the concerns already present in some parts of the region with heavy use of groundwater (northwest Bangladesh).
2. Conservation agriculture and other measures to reduce water use at the farm level will likely be beneficial for farmers. The cost of irrigation is reduced and there may be other benefits such as improved soil quality; farm profitability is often increased.
3. However, farm-scale water saving measures often do not translate to water saving at a regional scale. Only measures which result in reduced evapotranspiration on the farm will save water for the region. Many water saving measures reduce the amount of water applied (which is a saving from the perspective of the farmer), but not the evapotranspiration from the field. However, the farm water saving measures may include altering the source of irrigation water or the destination of water drained (by surface or subsurface drainage) from the farm, and this may have an impact at regional scale.
4. While the principles governing the link between farm scale water use and regional hydrology are well known, there is a lack of studies and some key data in the Eastern Gangetic Plains that clearly establish a farm – to – region water balance. Time-series spatial data on actual evapotranspiration is particularly lacking. Studies at a range of scales, from farm to region, are required to determine the impact of farm-scale water saving measures on regional hydrology.
5. While explicit studies are lacking, there is evidence to suppose that the impact of water use at the farm scale is less likely to impact regional hydrology the northeastern part of the region where rainfall exceeds evaporative demand to the western part of the region where rainfall is insufficient to meet evaporative demand. There is also evidence to suppose that more groundwater use could be developed in parts of India and Nepal, whereas in parts of northwest Bangladesh the use may already have reached its potential.

## 8.2 Recommendations

Based on the conclusion above, it is important to have a comprehensive understanding of the EGP's groundwater resources and their future sustainability. While there are localized studies with various degrees of details in different parts of the basin, there is a lack for basin wide studies particularly linking farm scale activities with the regional or basin scale modelling. The advances in remote sensing technologies and machine learning (as described in chapter 7) and the numerical groundwater modelling (as described in Chapters 6) can be effectively used for developing such comprehensive understanding linking field or catchment scale analysis as described in Chapters 3, 4, and 5. The aim of this analysis will be to provide options for sustainable groundwater management for irrigated crop production in the EGP considering future scenarios (such as population growth, economic development, climate change, etc.) and thus improve the livelihood of the farming communities including women and marginal farmers. The objectives of such a study would be to:

1. Develop a field scale understanding of the different 'water savings' and 'conservation practices' and their likely impacts on the local and regional water balance and groundwater recharge.
2. Develop a detailed understanding of 'effective water savings measures' and ways of enhancing recharge into aquifer for long-term sustainability of the groundwater irrigation in the EGP
3. Suggest policy and options for sustainable groundwater management for future food security and livelihoods of the farmers including women and marginal farmers.

The study could be based on 4 main components as given below:

1. Field-based measurements: Set up field experiments with precision measurements of field water balance components:

- Set up experiments to measure the recharge rate from the rice fields under various management conditions
- Use water balance and/or APSIM model for scenarios analysis.

Ideally, field-based measurements would be conducted at four or five sites across the region, spanning the range identified in section 5 (regional water balance) from the northeastern part of the region where rainfall exceeds evaporative demand to the western part of the region where rainfall is insufficient to meet evaporative demand. While four or five field sites will not encompass the full variation in environments and farm practices, the APSIM modelling (calibrated at the field sites) can be used to estimate water balance behaviour in a wider range of cases.

2. Water balance modelling / aquifer numerical modelling. Even with good data availability, an advanced numerical model is resource intensive, and the expenditure on it may not be commensurate with the resource requirements of other components of the project. Simpler water balance modelling may be more appropriate. Irrespective of which approach is preferred, remote sensing estimation of actual evapotranspiration will prove invaluable. There will also be a need to estimate other water balance components such as canal water use for irrigation.

3. Socio-economic / behavioural assessments: how quickly is irrigation development likely to proceed in India and Nepal? There, and in Bangladesh (where there are areas of unsustainable groundwater use), what is the likely farmer response to water savings measures? What measures might lead to farmer responses that avoid undesirable impacts on the regional groundwater resources?

4. Scenario exploration: project the consequences of uptake of alternative water savings measures *and* policies to manage water resources at large scale, including under projected climate change.

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