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Financial Feasibility of Water Conservation in Agriculture

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Key Points:

- A novel method compares the costs of water conservation measures with the added value that reallocation of water in agriculture generates
- Only 10%–20% of potential water savings would be realized in the Indo-Gangetic plain if financial feasibility is taken into account
- Despite the modest expansion of irrigation it would accommodate, investing in water conservation can add significant profit to agriculture

Supporting Information:

- Figure S1

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Abstract Global water use for food production needs to be reduced to remain within planetary boundaries, yet the financial feasibility of crucial measures to reduce water use is poorly quantified. Here, we introduce a novel method to compare the costs of water conservation measures with the added value that reallocation of water savings might generate if used for expansion of irrigation. Based on detailed water accounting through the use of a high-resolution hydrology-crop model, we modify the traditional cost curve approach with an improved estimation of demand and increasing marginal cost per water conservation measure combination, adding a correction to control for impacts on downstream water availability. We apply the method to three major river basins in the Indo-Gangetic plain (Indus, Ganges and Brahmaputra), a major global food producing region but increasingly water stressed. Our analysis shows that at basin level only about 10% (Brahmaputra) to just over 20% (Indus and Ganges) of potential water savings would be realized; the equilibrium price for water is too low to make the majority of water conservation measures cost effective. The associated expansion of irrigated area is moderate, about 7% in the Indus basin, 5% in the Ganges and negligible in the Brahmaputra, but farmers' gross profit increases more substantially, by 11%. Increasing the volumetric cost of irrigation water influences supply and demand in a similar way and has little influence on water reallocation. Controlling for the impact on return flows is important and more than halves the amount of water available for reallocation.

Plain Language Summary A number of water conservation measures in agriculture have been proposed to produce more food with less water. However, the extent to which the benefits—the value of additional crop production supported by water savings—compensate the costs of these measures is poorly quantified. A complicating factor is that losses from inefficient use of water upstream are often reused downstream so that benefits of water conservation measures tend to be overstated. We used detailed model simulations to trace the impact of various measures on all irrigation water fluxes, including these losses, and crop production and its value. We then compared the cost of water conservation with the demand for water in three major river basins; the Indus, Ganges and Brahmaputra. We show that only just over 20% of potential water savings would be realized if financial feasibility is taken into account; the majority of water conservation measures are simply too costly. Despite these limited water savings and the modest expansion of irrigation they would allow, their implementation would improve farm profits in a region where the profitability of farming is low.

1. Introduction

The world faces a major challenge to reconcile demand and supply and ensure that there is water at the right location and the right time, at a cost that people can afford and are willing to pay (Hanemann, 2006). Without corrective action, high population growth, urbanization, and industrialization will further increase water demand (Godfray et al., 2010), undermining natural capital and water-dependent environmental processes. Agriculture, the sector that consumes by far the largest share of water especially in many low income countries, is under pressure to produce more food using less water: food production needs to rise by 50% by 2050 while global water use needs to be reduced to remain within planetary boundaries (Gerten

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et al., 2020). Given the magnitude of the challenge, a major transition in water use is required to ensure future water and food security (Rockström et al., 2009).

A range of supply and demand-side measures are proposed as part of this transition, from large centralized river interlinkage schemes to increase supply (Bagla, 2014) to on-farm methods such as drip irrigation systems that aim to reduce demand (Gleick, 2002). At large scales, the literature tends to focus on model-based assessments of biophysical potential of various measures both regionally (e.g. Huang et al., 2020) and globally (Jägermeyr et al., 2016; Gerten et al., 2020; Rosa, Chiarelli, Rulli et al., 2020). Jägermeyr et al. (2016) simulate integrated on-farm water management strategies to examine how they could increase global production by 41% while reducing consumptive water losses. Rosa, Chiarelli, Rulli et al. (2020) find that sustainable expansion of supplemental irrigation globally on currently rainfed cropland could increase yields by enough to feed an additional 840 million people.

A comprehensive assessment of the financial feasibility of the types of water conservation measures required to achieve these gains, is lacking. Yet, economic appraisals of individual measures often highlight affordability as a barrier to implementation (Ali & Dkhar, 2019; Fox et al., 2005; Srinivarao et al., 2017), especially in sub-Saharan Africa and South Asia where agricultural profit margins are generally low (Bhalla & Singh, 2009; Hira, 2009; Narayanamoorthy, 2013; Nadkarni, 2018). Larger-scale hydro-economic optimization approaches illustrate basin wide trade-offs between multiple measures and operational management strategies, however, applications tend to be restricted to large, supply side measures within the river network, such as dams, diversions and irrigation expansion (e.g. R. T. Geressu and Harou, 2015; Jeuland et al., 2014; Siderius, Van Walsum, et al., 2016; Wu et al., 2013), with few considering demand-side strategies such as improvements in irrigation efficiency (R. Geressu et al., 2020), or land management strategies (Siderius, Biemans, et al., 2016). Optimization approaches remain computationally demanding, limiting possibilities to asses a multitude of spatial unit-measure combinations in interlinked river systems. Integrated Assessment Models generally do feature scenarios of technological change that include demand-side measures, but the technologies on which these changes are based are often implemented through highly aggregated "management factors" clustered over large spatial units covering whole countries or river basins (e.g. the IMAGE model by Doelman et al., 2018; Van Vuuren et al., 2019 and the IMPACT model by Robinson et al., 2015).

Cost curves provide a way to identify the most cost-effective way to close an anticipated imbalance between supply and demand and to illustrate trade-offs and choices. A cost curve combines the marginal costs of measures—in the case of water, the cost to provide one additional cubic meter of water—with the expected total amount of extra water a measure can conserve, and ranks these measures from low to high marginal costs, avoiding the computational demands of the above mentioned approaches. A cost curve for the whole of India produced by the 2030 Water Resources group of the World Bank suggested that expected additional demand for water could largely be met by agricultural measures with a maximum average marginal cost of 0.04 USD m^{-3} (Addams et al., 2009). While used widely in recent years and applied to water (Addams et al., 2009; Hellegers et al., 2013), carbon reduction (McGlade & Ekins, 2015), and increasing food supply (Steduto et al., 2017), cost curves have limitations. First, cost per measure is generally presented as a constant unit cost whereas in reality, marginal costs for the same measure vary spatially because of biophysical and socio-economic heterogeneity. Second, measures are presented individually and are not mutually exclusive or combined, while in reality farmers or water managers might opt for a best portfolio of measures. Third, upstream-downstream effects are often ignored, despite the knowledge that efficiency-oriented measures upstream also reduce the return flows that downstream farmers rely on due to spillover effects upstream. For example, in practice farmers often expand or intensify production and consume more water when moving to more efficient types of irrigation like drip or sprinkler, thereby reducing rather than increasing downstream supply (Grafton et al., 2018; Perry, 2007; Scott et al., 2014; van Halsema & Vincent, 2012).

Finally, the demand for water is generally presented as a given volume, a fixed threshold, presenting a "gap" that needs to be filled, lacking the micro-economic fundamentals that characterize the cost, or supply side. Valuing water, to estimate demand, is difficult and contentious owing to water's economic, physical, and political characteristics (Garrick et al., 2017; Hanemann, 2006). Farmers all value water differently, as they do not have perfect knowledge, do not all possess the same resource base, plant different crops for a variety of reasons (some for a financial return on land instead of water and others for subsistence), practice

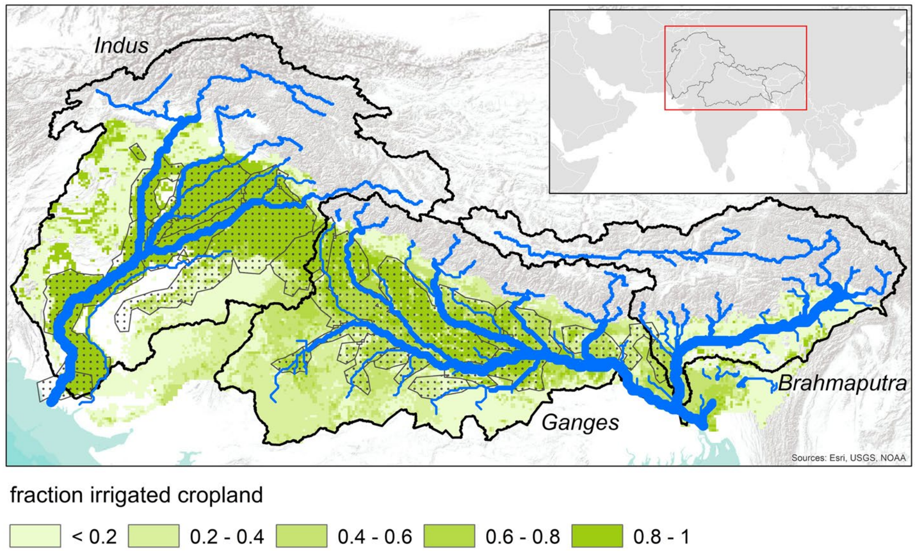

Figure 1. IGB (Indus, Ganges, and Brahmaputra) case study area with irrigated cropland as a fraction of total cell area, for all areas below 500 m above mean sea level. Dotted shapes outline the major irrigation command areas.

different crop rotations and are possibly risk averse (Hellegers & Davidson, 2010). Moreover, in the absence of a proper water market or actual water pricing, a value of water is difficult to measure, although its shadow price can be estimated (Bierkens et al., 2019; Johansson, 2005; Liu et al., 2009; R. A. Young, 2005; Ziolkowska, 2015). Bierkens et al. (2019) for example, used production functions to determine the shadow price of water used for irrigation in important groundwater-depleting countries, relating groundwater input to crop yield. Others (Hellegers & Davidson, 2010; Hellegers et al., 2013; D'Odorico et al., 2020) have based the shadow price on the residual value, the value of a marginal product of a non-priced input (R. A. Young, 2005) which, in the case of irrigation water, is derived by subtracting all non-water related estimated costs of production from the total value of output and then dividing this residual by the amount of water applied.

Here, to better assess the financial feasibility of water conservation measures, we expand the traditional cost curve approach with an improved estimation of demand, based on the marginal value of reallocating water savings, and incorporate increasing marginal cost per measure combination while correcting for changes in downstream water availability. We use model-based assessment at high-resolution (~8 km by 8 km) of crop production and irrigation water use, combined with detailed input at sub-national level of the cost of production and price of crop produce at multiple scales (cell/village and river basin). We apply our method to the Indus, Ganges and Brahmaputra rivers in South Asia (IGB, Figure 1).

South Asia has been identified as a water stress (FAO, 2020; Gerten et al., 2020; Wada et al., 2011) and climate change (De Souza et al., 2015) hotspot. Transecting the Indo-Gangetic plain, the three rivers provide water to one of the most important food producing regions in the world. The river basins are similar in agronomic conditions, though with varying dependence on irrigation and sources of irrigation water (Biemans et al., 2019). Irrigated agriculture is extensive with water use supporting almost 10% of global rice and 12% of global wheat production (FAO, 2018). Groundwater is overexploited, especially in the Punjab and the eastern part of the Ganges basin (Rodell et al., 2009; Shah, 2010; Tiwari et al., 2009; Wada et al., 2012). Salinization and waterlogging affect large areas within the lower Indus basin (A. S. Qureshi et al., 2008). Partly fed by glacier and snowmelt in the Hindu Kush Himalayan region, irrigation water supply and food production in the Indo-Gangetic Plain is anticipated to be increasingly affected by higher temperatures, changing precipitation patterns and shifts in mountain runoff (Biemans et al., 2019; Immerzeel et al., 2020). It is also a region very sensitive to potential improvements in agricultural water management (Jägermeyr et al., 2016), however, realizing these improvements faces many operational challenges, not least identifying the right economic conditions to promote uptake of water conservation measures at scale.

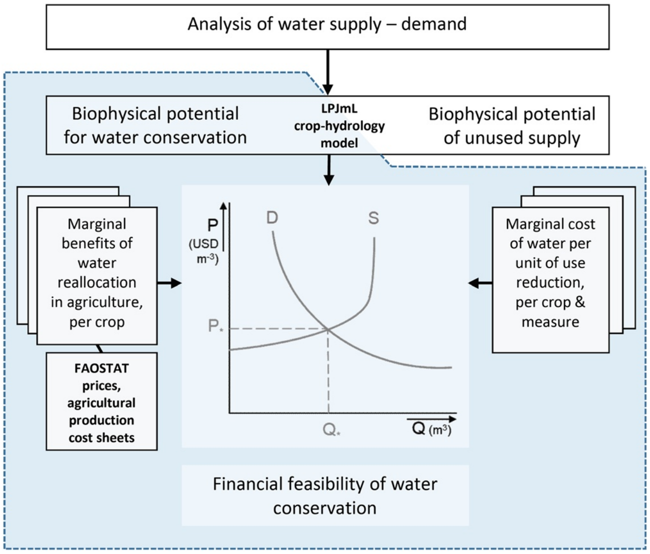

Figure 2. Conceptual framework to assess water conservation and reallocation potential in the IGB. Components enclosed by the gray box are addressed in this paper. With D, the demand curve for water, representing the marginal value of water, sloping downwards indicating that users allocate water to the highest value uses first and subsequently to lower value uses; and S the supply curve for water, representing the full marginal cost, sloping upwards indicating that the marginal costs of water provision through water conservation increase with the quantity supplied. After matching supply and demand, the equilibrium price of water P_* is the price (in USD m^{-3}) at which marginal benefits are equal to marginal cost. Q_* is the equilibrium volume (in m^3). IGB, Indus, Ganges, and Brahmaputra.

2. Methodology

We focus on the financial feasibility of widely proposed water conservation measures in irrigation to address a growing shortage between water supply and demand. Feasibility here is defined as a water conservation measure for which the marginal benefit, the additional farm revenue (on the same farm or elsewhere), exceeds the marginal cost of implementing the measure. Water supply and demand curves can be used to explore in conceptual terms how water imbalances can be addressed (Figure 2). In closed river basins, where water resources are almost fully allocated, such as in the Indus basin and seasonally in the Ganges basin, additional water supply is mainly through efficiency improvements leading to local water savings—if financially feasible—that can be reallocated for agricultural use elsewhere, or for other purposes.

We consider savings in irrigation to be a reduction in the non-beneficial consumed fraction; the evaporation from soil and water surfaces such as irrigation canals and interception losses from vegetation canopies. While it is difficult to separate or measure changes in these water balance terms empirically—though not impossible, with advances in remote sensing, see e.g. Simons et al. (2020), mechanistic models that simulate river routing, the soil water balance and irrigation water partitioning can. One such model, the crop-hydrology model LPJmL (Jägermeyr et al., 2015; Schaphoff et al., 2017) we apply here. We simulate and track water withdrawn and applied for irrigation, water consumption (evaporation and transpiration) and changes in the associated returns flow, i.e. surface or subsurface runoff or seepage from irrigation canals. In this way, we can estimate the net savings of each measure; the amount that can be reallocated for other use without impacting downstream users (for details on the water accounting, see Jägermeyr et al., 2015). We examine measures under current climate conditions.

2.1. Deriving Supply Demand Curves for Irrigation Water Conservation

2.1.1. Supply Curve

Cost of land-based measures such as new irrigation technologies or land management practices are often expressed per hectare, which we convert first into annualized capital costs and then into volumetric costs using the model simulated irrigation amounts that they conserve, compared to the baseline. As a result, while cost per hectare for a particular measure is assumed constant, volumetric costs vary spatially and per crop, depending on local climate and soil conditions. To derive marginal costs, we iteratively rank per crop and per cell all combinations of measures, from low to high marginal volumetric cost, deselecting those options that do not conserve additional water:

$$Cmarg_{cr,i} = \frac{\left(Q_{cr,i-1} * C_{cr,i-1}\right) - \left(Q_{cr,i} * C_{cr,i}\right)}{\left(Q_{cr,i-1}\right) - \left(Q_{cr,i}\right)}, \tag{1}$$

With

$$C_{cr,i} = Cinv_{cr,i} - Cm3 * \frac{Qgross_{cr,i}}{Q_{cr,i}},$$

where *Cmarg* is the marginal costs (USD m^{-3}) for crop *cr* and water conservation option *i*, based on the volumetric cost, *C*, with *Q* the net volume of water saved and with C_{i-1} (Q_{i-1}) the volumetric cost (volume saved) of the previous best option. C is based on the volumetric investment costs, $Cinv$, and the operating cost for a farmer to apply a cubic meter of water, $Cm3$, e.g. a payment of water charges to the irrigation department and/or for electricity or diesel to run a pump. Farmers would forego these costs in cases where they apply water conservation measures, hence the negative sign.

We correct for impacts on irrigation return flows by taking the net volume of water savings, Q, whereby Q is the savings in irrigation water applied (gross savings, $Qgross$) minus any reduction in surface runoff, soil drainage or canal conveyance return flows (seepage) which downstream users might rely on. Not only does this reduce the expected amount of water saved, it also increases the volumetric investment costs thereby making measures that reduce return flows less attractive (as compared to those that reduce mainly evaporative losses). This does not apply to operating costs, since the farmer foregoes these costs on the gross amount of irrigation water saved—the amount applied on their field. To account for this in our net marginal costs, we adjust the volumetric operational costs ($Cm3$) by multiplying them with the fraction of gross over net water savings.

Combining and ordering the remaining crop-measure combinations by their marginal costs gives the supply curve, or cost curve. Earlier studies (Hellegers et al., 2013) have drawn stylized cost curves for countries or river basins based on aggregated and average values of water savings and costs. Here, we draw cost curves per cell (8.5 by 8.5 km resolution), each containing up to 13 crops and 12 combinations of measures, where costs vary based on climate, soil and socio-economic characteristics that define the cost of production. Aggregating from this highly disaggregated scale we can then derive cost curves for every delineation, be it a village, a command area, basin or an administrative boundary.

2.1.2. Demand Curve

From the value of water, a demand curve for additional irrigation can be derived. A farmer's willingness to pay for water and invest in irrigation expansion is based on the value that additional water can generate, minus the costs to make use of that additional water, e.g. in the form of land conversion and irrigation infrastructure and in water charges—similar costs that underlie the supply side.

Economists have proposed several analytical approaches to assess the value of irrigation water including surface water and groundwater sources (e.g. Hussain et al., 2007; M. E. Qureshi et al., 2012; R. A. Young, 2005). The Residual Method is a special case of the well-known process of performing farm budget or cost and return analysis and identifies the incremental contribution of each input to the value of the total output and is the most widely used methodology for valuing irrigation water (e.g. Hellegers & Davidson, 2010; M. E. Qureshi et al., 2018; R. A. Young, 2005). All costs of inputs (including labor, fertilizer, pesticide, machinery, value of land) except water, are subtracted from the value of production and the remaining (or residual) value provides an estimate of the value (or productivity) of water in irrigation. This value can be assumed to be the net or marginal value per unit of irrigation water (Johansson, 2005) for an individual crop once the residual value is divided by the water applied to that particular crop. The approach relies on the assumption that the maximum value to a producer from producing a good is exactly exhausted by the summation of the values of the inputs required to produce it. This assumes constant returns to scale, which allows Euler's Theorem on homogeneous functions of degree one to be applied. It infers the marginal value of water if water is the only unpriced resource. Mostly, total value is based on crop yield multiplied by its price (e.g. Hellegers & Davidson, 2010). However, in areas where rainfall is significant and rainfed production is an alternative, attributing all yield to irrigation water will overestimate its value. Instead, we propose as a better estimate the "Residual Value of irrigation" (RVi, Equation 3), which attributes only the additional yield over rainfed to irrigation. Correspondingly, only those input costs are subtracted that are needed to generate this additional yield:

$$RVi = \frac{Yi * p - \left(Cprod * \frac{Yi}{Ytot}\right)}{I}, \tag{2}$$

with

$$Yi = Ytot - Yrf,$$

where Yi is the additional yield due to irrigation (ton ha^{-1}), with Yrf is the yield under rainfed conditions (ton ha^{-1}) and $Ytot$ is the total yield (ton ha^{-1}). p is the price of a ton of yield (USD ton^{-1}) and I is the amount of irrigation applied (in m^3 ha^{-1}). $Cprod$ is the costs of production (in USD ha^{-1}). Here, we assume the distribution of costs between rainfed and irrigation to be proportional to their contribution to total yield, e.g. replicating the increased use of more fertilizers or more labor with irrigation.

The RVi under contemporary irrigation conditions and land management practices provides a single estimate of the value of water, but this is just one realization. Irrigation improvements, like drip irrigation, alter the value of water by requiring less irrigation water to be applied. These measures come at a cost, and so to reflect the willingness of a farmer to pay for any additional water, it is the *marginal net value* (*Vi,* or marginal net profit)—the RVI minus the annualized volumetric investment cost of any type of irrigation expansion ($Cinv_{cr,i}$) and the volumetric operational cost of irrigation water ($Cm3$)—that needs to be taken into account:

$$Vi_{cr,i} = RVi_{cr,i} - Cinv_{cr,i} - Cm3. \tag{3}$$

Starting from the option that adds most net value per cubic meter we can then add those that have a lower net value per cubic meter, but overall would add some additional total value when more water would be available. These options are less efficient in water use but also less costly overall to implement (think of surface compared to drip irrigation). The marginal net value of water conservation, per crop, is calculated as:

$$Vmarg_{cr,i} = \frac{\left(Vi_{cr,i-1} * Q_{cr,i-1}\right) - \left(Vi_{cr,i} * Q_{cr,i}\right)}{Q_{cr,i-1} - Q_{cr,i}}, \tag{4}$$

where Vi is the value (USD/m^3) for option i, with $Vi_{cr,i-1}$ the higher value of the previous option and $Q_{cr,i-1}$ is the volume of that higher value option (in m^3), for crop *cr*. A demand curve is then constructed by combining and ordering by marginal net value, whereby the volume of water demand is scaled to the cropping pattern and area available for irrigation expansion in a cell.

To scale, we rely on three assumptions. First, we aim to largely maintain the existing cropping pattern and base our demand curve in each cell on the irrigated land use mix in that cell, assuming those crops represent a varied diet, and reflect local preferences and socio-economic conditions like market access. However, only those crops with a marginal value higher than the equilibrium price will be selected, thus—through the expansion—altering the cropping pattern toward higher (water) value crops. Other demand "curves" could be designed, like attributing all available land and water to the crop and water management combination with the highest marginal value, or imposing policy choices such as excluding sugarcane (expansion) from the demand curve. Second, irrigation expansion can only take place on land currently in agricultural use, that is, under rainfed production, assuming the current cropland extent is already maximized given soil conditions and the level of urbanization (W. J. Young et al., 2019). Finally, conversion to irrigation on rainfed lands will only happen if the simulated gross profit of irrigated yield for a certain crop-measure combination is higher than that of the existing rainfed yield, and if the net benefit of the irrigated crop-measure combination is higher than that of any water conservation measure on rainfed land (see Section 2.2 for the measures).

2.1.3. Matching Supply and Demand

To estimate the amount of water that can be saved, and the increase in production value that would generate, supply and demand is matched at two geographic scales:

1. the village level, i.e. cell by cell supply demand curves: here, farmers have to pay for the cost of efficiency improvements on their land or that of their neighbors to receive water to expand irrigation. Obviously, crop-measure combinations that cost more than the marginal value they generate will not be implemented. Local limitations in land use expansion play a large role at the local level, with irrigation intensity

Table 1
Selection of Water (and Soil) Management Measures Evaluated in This Study

Water conservation measure	Components	Applicability	Parameterization
Irrigation system	Surface irrigation, sprinkler, drip	Irrigated	Surface irrigation: conveyance losses 20%–30% based on soil type, additional amount of water necessary to distribute irrigation uniformly ~ 115% (distribution uniformity, "DU" parameter 1.15, (Jägermeyr et al., 2015)) Sprinkler: conveyance losses 5%, DU 0.55 **Drip**: conveyance losses 5%, DU 0.05
Land management	Mulching (organic residues, plastic films), conservation tillage	Irrigated/rainfed	Soil evaporation during growing season reduced by 25%
In situ water harvesting	Pitting, terracing, mulching	Irrigated/rainfed	Infiltration parameter, as in Jägermeyr et al. (2016), multiplied by two
Ex situ water harvesting	Rainwater harvesting and storage in tanks, farm ponds or small reservoirs	Rainfed	Surface runoff during growing season collected on 50% of cropland (storage capacity 200 mm), suppl. irrigation if soil moisture<40% of field capacity

already high, especially in the Indus and Ganges basins. As a result, in cells where there is much water to save, there might actually be no demand for conservation measures

2. the basin level: here, we bring together basin-wide demand and supply, which gives an estimate of the idealized maximum potential of water that can be reallocated. Supply options will be selected that have costs less than the marginal value this water creates anywhere else in the basin. This would require a social planner to coordinate and or to find a mechanism to finance the costs of efficiency improvements, either transferring those costs directly to downstream farmers, e.g. through increased water abstraction costs for new irrigation, or covering it by subsidies paid for by society, which could potentially be compensated by higher tax returns. This would require presence of infrastructure and operational management capable of reallocating water across the basin

Additional demand for water by other sectors is excluded from this analysis. We assume that irrigation expansion and increased production do not affect the price of produce and cost of inputs. By basing the demand curve on the existing irrigated crop mix we increase overall production but avoid strong changes in relative production levels between crops and hence the need to take into account price distortions.

2.2. Water Conservation Measures

We selected the most important water conservation measures based on Jägermeyr et al. (2016), who identified potentially achievable measures relating to the type of irrigation system, land management, in situ water harvesting and ex situ water harvesting (Table 1). They represent the major pathways through which irrigation water can be conserved and reallocated; capture more rainfall to reduce the amount of irrigation required, reduce evaporative losses from the soil, and reduce evaporative losses from the irrigation supply system.

The type of irrigation system strongly determines the efficiency of water use, with differences in field application and transport to the field resulting in varying amounts of productive water consumption, non-productive losses and return flows (Irmak et al., 2011; Jägermeyr et al., 2015). Surface irrigation, whereby the field is flooded to a certain depth with each irrigation application with water supplied through open channels, is the default system in the IGB. Canal conveyance losses are between 20% and 30%, depending on the soil type. Sprinkler irrigation uses pressurized water transport through pipes, with conveyance losses estimated at 5%, and applies water closer to the plant and distributes it more evenly leading to lower application losses. In drip systems application water is applied right into the rootzone of the plant, eliminating leaf interception evaporation losses and further reducing soil evaporation.

Land management techniques such as mulching (covering the soil with crop residues or plastic film) reduce non-beneficial soil evaporation. Taking into account current practices in the IGB where mainly crop residues are used, we have used the low-end estimate of Jägermeyr et al. (2016) which assumes this measure

Table 2
Biophysical and Technical Irrigation System Suitability by Crop Type, Informed by Sauer et al. (2010), and Jägermeyr et al. (2015), and Cropped Area per Basin

	Irrigation system		
Crop type	Surface	Sprinkler	Drip
Temperate cereals (wheat, barley)	x	x	–
Rice	x	x	–
Maize	x	x	–
Tropical cereals (millet, sorghum)	x	x	–
Pulses (field peas)	x	x	x
Temperate roots (sugar beet, potato)	x	X	x
Tropical roots (cassava)	x	X	x
Sunflower	x	X	x
Soybean	x	X	x
Groundnut	x	X	x
Rapeseed	x	X	–
Sugarcane	x	X	–
Others (cotton, vine, citrus)	x	X	x

Note. Drip irrigation is restricted to row crops.

reduces soil evaporation by 25%. In-situ water harvesting relates to techniques to increase on field infiltration such as pitting and terracing as well as mulching. This increases soil water content and reduces the need for additional irrigation water. Infiltration, a non-linear process, approximately doubles at higher soil moisture contents when applying this type of measure.

In addition, on rainfed lands, harvesting surface runoff from nearby land (ex situ) in local reservoirs – in India also called tanks or ponds – provides supplemental irrigation in dry periods (Palanisami & Easter, 1987; Siderius et al., 2015). In our simulations we assume that the water is harvested during the growing season only, on 50% of the rainfed cropland in each grid cell. Subsequently it is collected in reservoirs and applied on the same fields where it was collected from, when soil moisture drops below the 40% of field capacity (Jägermeyr et al., 2016). While in this paper we focus on irrigation water conservation and reallocation, we will evaluate the benefits of irrigation expansion against the alternatives on rainfed land, ruling irrigation expansion out if the same or higher increase in net benefits could be achieved by water harvesting or any of the previous measures.

Combining these measures leads to a total of 12 unique combinations on irrigated land (in case of suitability for drip irrigation (Table 2), else eight) and eight on rainfed. With 12 crops simulated (excluding grasslands and a category "other"), this leads to a potential total of 120 unique crop-measure combinations in irrigation, per cell, although irrigated land use in a cell is mostly dominated by two or three staple crops. We assume that no measures have been implemented as in South Asia, methods like drip or sprinkler are yet to be applied at scale. Water harvesting measures and local storage have been more widely implemented, but require regular rehabilitation (Glendenning et al., 2012). For convenience, we assume rehabilitation equals construction costs. We did not include large infrastructure options like reservoirs in the main river system. The scope for building more big dams in the IGB is limited because of lack of suitable options and the scale of negative externalities involved (Nadkarni, 2018).

2.3. Data

2.3.1. Hydrology and Crop Data

To simulate the building blocks for our analysis (that is, gridded irrigation water withdrawn, applied and return flows and crop production, with and without irrigation), we use an adjusted version of the LPJmL model which simulates a coupled hydrology and carbon cycle, which makes it a suitable tool to study the interactions between water availability and food production (Gerten et al., 2011). The version of LPJmL used in this study simulates a double cropping system, distinguishing between monsoon-season crops and winter-season crops (Biemans et al., 2016) and includes an IGB specific delineation of irrigation command areas (Biemans et al., 2019). The model does not simulate groundwaterflow between gridcells. Daily irrigation demand for an irrigated crop in a cell is calculated as the minimum amount of water needed to fill the soil to field capacity and the amount needed to fulfill the atmospheric evaporative demand. Subsequently, the withdrawal demand is calculated by accounting for losses during conveyance, distribution and application of water, depending on the type of irrigation system installed (surface, sprinkler, or drip) and the soil type of the irrigated cell (Jägermeyr et al., 2015).

Rain-fed and irrigated crop growth for 12 crops (including wheat, rice, cotton and sugarcane) is simulated based on daily assimilation of carbon. In case of crop water stress, the allocation of carbon to the storage organs is decreased, leading to reduced yields. Crops are harvested when either maturity or the maximum number of growing days is reached (Bondeau et al., 2007; Fader et al., 2010). Calibrated yields for the most important food crops and sugarcane and cotton matched well with subnational (for India and Pakistan) and national (Bangladesh, Nepal) agricultural statistics (see Biemans et al., 2016 for calibration results).

2.3.2. Agronomic Data

Annual prices of crop produce for the period 2000–2018 were taken from FAOSTAT, and corrected for inflation to 2018 price levels. National-level, crop-based weighted averages were calculated, with weights assigned based on the years before present, thereby giving higher importance to more recent price levels while at the same time accounting for historic price fluctuations. For India, FAOSTAT price data stops after 2009, at a time of strong price hikes. Time series were supplemented with Minimum Support Prices as reported by the Indian government for the period 2009–2019. For Pakistan, recent price information for pulses was provided by Pakistan's Agricultural Research Council. We checked FAOSTAT prices for consistency; in cases where year to year fluctuations in price exceeded 100% we explored national agricultural statistics yearbooks. This led to the exclusion of Pakistan sugarcane data from before 2011 and the reclassification of Pakistan cotton prices from cotton lint to raw cotton.

Cost of production data at state/province-level are routinely collected by national agricultural statistics departments to support Minimum Support Price level setting. They provide, per crop, costs of the main production factors, labor, machinery, land, water and other inputs such as fertilizer and seeds. Here we used the Indian "A2" price level for fixed costs, which includes all basic input costs and the rent paid for leased land, but no rental value of owned land or the imputed value of family labor (Sen & Bhatia, 2004). As such, it is a lower-end estimate of the actual cost of production but one routinely used by for example the Indian government. In addition, costs of irrigation charges were excluded from the A2 estimate, since this is an explicit cost parameter in our model and based on simulated water applied. For India, costs sheets for the period 2004–2017 were available. For Pakistan, data were available for the period 2013–2016, for the main staple and commercial crops rice, wheat, cotton and sugarcane. For other crops, average India values were used. The relatively small production area of Bangladesh was assigned the value of the neighboring Indian state of West Bengal, while Nepal was assigned the values of neighboring Indian state of Himachal Pradesh which has similar climate and orographic characteristics. To infill data gaps in the time-series, data were interpolated with a Kalman filter, corrected for inflation to 2018 price levels, averaged, and converted to USD. If less than three years of data were available (in a minority of cases) we simply averaged over the available years.

Irrigation costs as a percentage of total costs vary per crop and state. Officially, farmers pay for the use of water, with varying pricing mechanisms by country, state or province, by type of water application (canal/pump) and by technology (Cornish et al., 2004). Costs comprise annual costs such as irrigation charges and labor and energy costs for pumping (Webber et al., 2008), as well as investment and maintenance costs for irrigation infrastructure. Volumetric estimates are difficult to derive. Irrigation charges are often low (Cornish et al., 2004), with irrigated area-based costs mostly a token value and volumetric-based abstraction fees difficult to monitor. Energy use for pumping, be it diesel or electricity, is heavily subsidized (Shah, 2010) though not completely free of costs, such as annual maintenance, labor costs and—especially in areas with rapidly falling groundwater levels—repeated investments. Payment of bribes to secure timely surface water delivery represent another cost in canal-fed systems (Wade, 1982), but it is unclear to what extent these old practices are still common. Given the uncertainty and multiple types of costs, we estimate the price of water through a sensitivity analysis. We start with a uniform, commonly used volumetric cost of water use of 0.01 USD m^{-3}, and test for a range of volumetric costs from 0 to 0.04 USD m^{-3}.

2.3.3. Cost of Water Conservation Measures and Irrigation Expansion

Estimates for annualized, area-based costs of various measures were derived from literature (Table 3). In cases where no literature-based estimate was found, estimates by Pakistan's Agricultural Research Council (PARC) were used. Costs vary greatly with drip which is the most expensive method, and mulching

Table 3
Cost of Measures per Hectare and Sources

	A. investment cost (USD ha^{-1})	B. Estimated lifetime (year)	C. Running cost (USD ha^{-1} $year^{-1}$)	Annualized cost (A/B + C) (USD ha^{-1} $year^{-1}$)	Reference (Cost in USD ha^{-1})
Sprinkler	2,600	15–19	–	173	Chukalla et al. (2017)
Drip	3,400	10	–	340	Yavuz et al. (2018): 388, Elnesr et al. (2015): 230–260, PARC: 340, (M. E. Qureshi et al., 2018): 247
Evaporation reduction (Mulching)	240	15	48	64	PARC: 64, Mehmood et al. (2018): 38, Jabran et al. (2016): 125
In-situ water harvesting	1,000	15	–	67	PARC
Ex-situ rainwater harvesting	1,231	15	1.5	81	Srinivarao et al. (2017)
Land preparation for irrigation expansion	799	15	–	53	IWMI (Inocencio, 2007)

(using locally sourced organic materials) which is the cheapest per ha. Costs for sprinkler and drip correspond with the 2030 Water Resource Group estimates, who found that the majority of the costs of agricultural water management measures are in the range of 0.02 USD m^{-3} to 0.03 USD m^{-3}, which, assuming a water saving of 500 mm–1,000 mm per hectare, gives a cost range of 100–300 USD ha^{-1} yr^{-1}. Costs for a combination of measures were derived by adding up each individual cost. To estimate the cost of land preparation for irrigation expansion, we took the cost of land preparation for irrigation for "successful" projects in South Asia as reported by IWMI (Inocencio, 2007), but without the hardware costs, assuming that most expansion areas in the IGB are already connected to/close to an irrigation command area.

3. Results

3.1. Cost of Water Conservation

As expected, we find a gradually upward sloping supply curve when combining the marginal costs of water conservation across each basin (Figure 3). Costs are generally lowest in the Indus and higher in the Ganges and Brahmaputra basins. In the Indus basin, irrigated areas are mostly in semi-arid regions with low precipitation and high irrigation water requirements. With water conservation proportional to irrigation water withdrawn, identical area-based costs translate into lower volumetric investment costs. This even leads to negative costs, mainly when switching to drip, whereby foregone operational costs for irrigation charges (saving 0.01 USD m^{-3} applied) compensate for the investment. In the Brahmaputra, a smaller irrigated area with relatively low irrigation volumes due to higher rainfall leads to much lower potential conservation and at higher marginal cost.

Most water conservation is achieved by a switch to sprinkler irrigation without any additional measures. In the Indus basin, evaporation reducing or infiltration enhancing methods start to become relevant at costs of around 0.02 USD m^{-3} while in the Ganges basin these measures are more dominant in the mid-range of the cost curve, at around 0.12 USD m^{-3}. Although relatively cheap per ha, the water conservation potential of these land management practices is not as high as that of sprinkler or drip. In the Brahmaputra, a conversion to sprinkler dominates the cost curve, also because the main crop here is rice for which we excluded a conversion to drip. Combinations of sprinkler and other measures can conserve marginally more water but at increasingly high costs. As Figure 3 illustrates, at the level of the river basin, cost per type of measure can vary greatly, depending on the crop, soil and climatic conditions.

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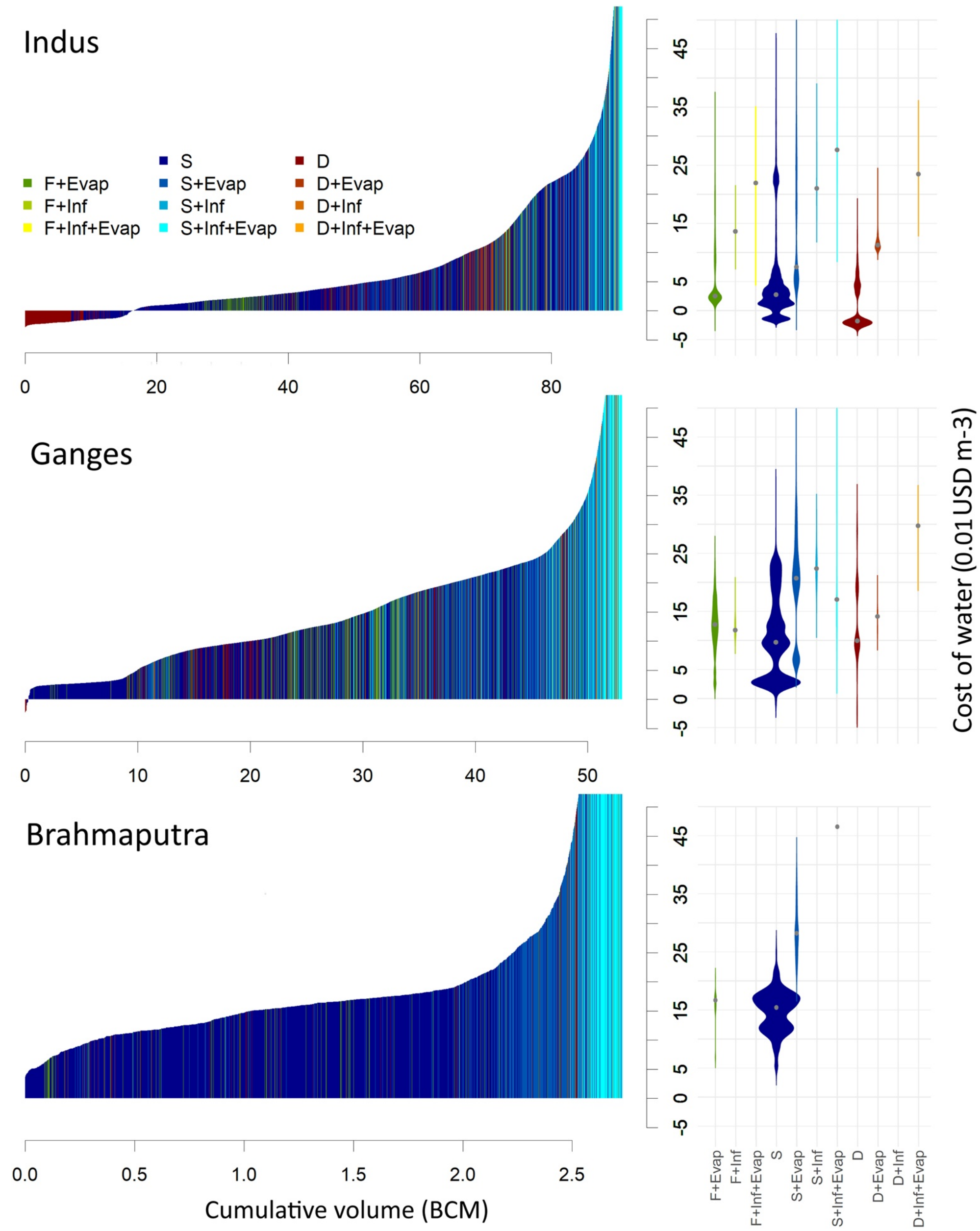

Figure 3. Cost curve for water conservation measures, for the Indus, Ganges and Brahmaputra basins. Twelve different measure combinations are evaluated. Due to biophysical and socio-economic heterogeneity in the basins the marginal cost of water conservation for a single measure combination varies, as is represented by the distribution of the colored bars. F stands for surface irrigation (furrow or flood irrigation), S for sprinkler and D for drip, Evap is evaporation reducing measures like mulching while Inf stands for Infiltration enhancing measures. Violin plots show the median value and distribution for each measure combination. BCM stands for billion cubic meters. Note different *x*-axis scales. *Y*-axis is cut-off at 0.5 USD m^{-3} for readability. BCM, billion cubic meter.

3.2. Value of Water

The value of irrigation water varies across our study area (Figure 4). Of the two dominant food staple crops, the added value of a cubic meter of irrigation water is higher for wheat than for rice. Pulses, another important group of food crops, are generally not irrigated but if they were they would on average provide the highest value of these three food crops due to their low input cost, a relatively high price and a large difference between rainfed and irrigated yield (for other crops, see Figure S1). Over large areas, rice has a negative

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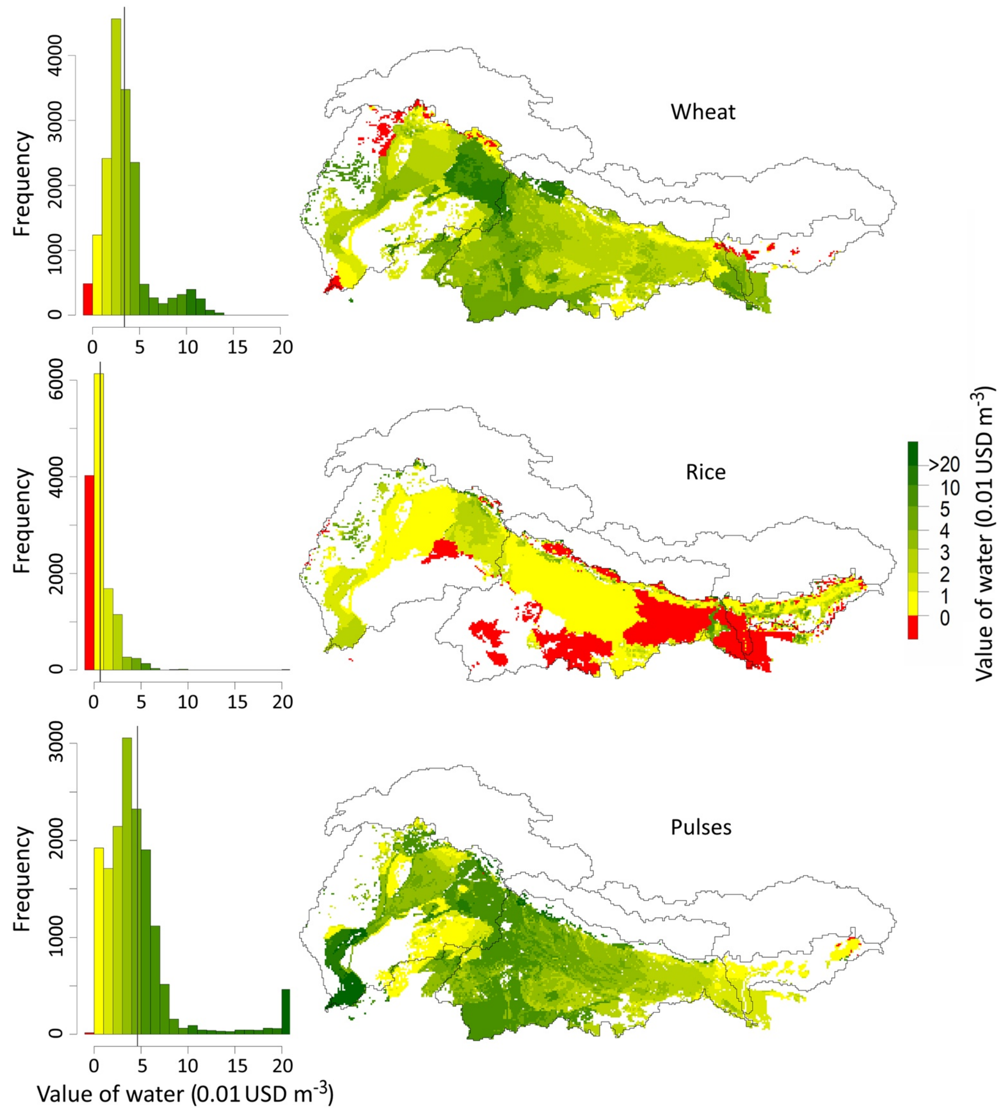

Figure 4. Residual value of irrigation water in the IGB for three main food crops (in USD m^{-3}), with median value plotted in the frequency distribution panels. IGB, Indus, Ganges, and Brahmaputra.

value; costs of production are higher than the yield it generates, even when ignoring the rental value of owned land or the value of family labor. In many regions, rice is grown for household use, and there are few alternatives during the monsoon season when the rainfall leaves large parts of the plains partially flooded especially in the downstream part of the Ganges basin—conditions which generally only rice can withstand. Still, these negative values are indicative of the low profitability of irrigated agriculture in the region.

Subtracting from the residual value the costs of expanding irrigation, and the volumetric costs of irrigation water (here assumed 0.01 USD m^{-3}), gives the net value of water of a crop at a particular location and, when combined, the overall demand curve (Figure 5). The demand curve, has a similar shape for the Indus and Ganges basin, though value tends to be higher in the Indus. Maize, when irrigated, returns high value in the Indus followed by wheat and other tropical cereals, while rapeseed is among the dominant high value crops in the Ganges. Rice is in both basins concentrated at the lower end of the demand curve yielding very limited value. The Brahmaputra basin stands out with a cropping pattern dominated by tropical cereals and rice. Here, the value of water for rice is generally higher, because relatively small amounts of additional irrigation water are needed to supplement rainfall and increase crop production considerably.

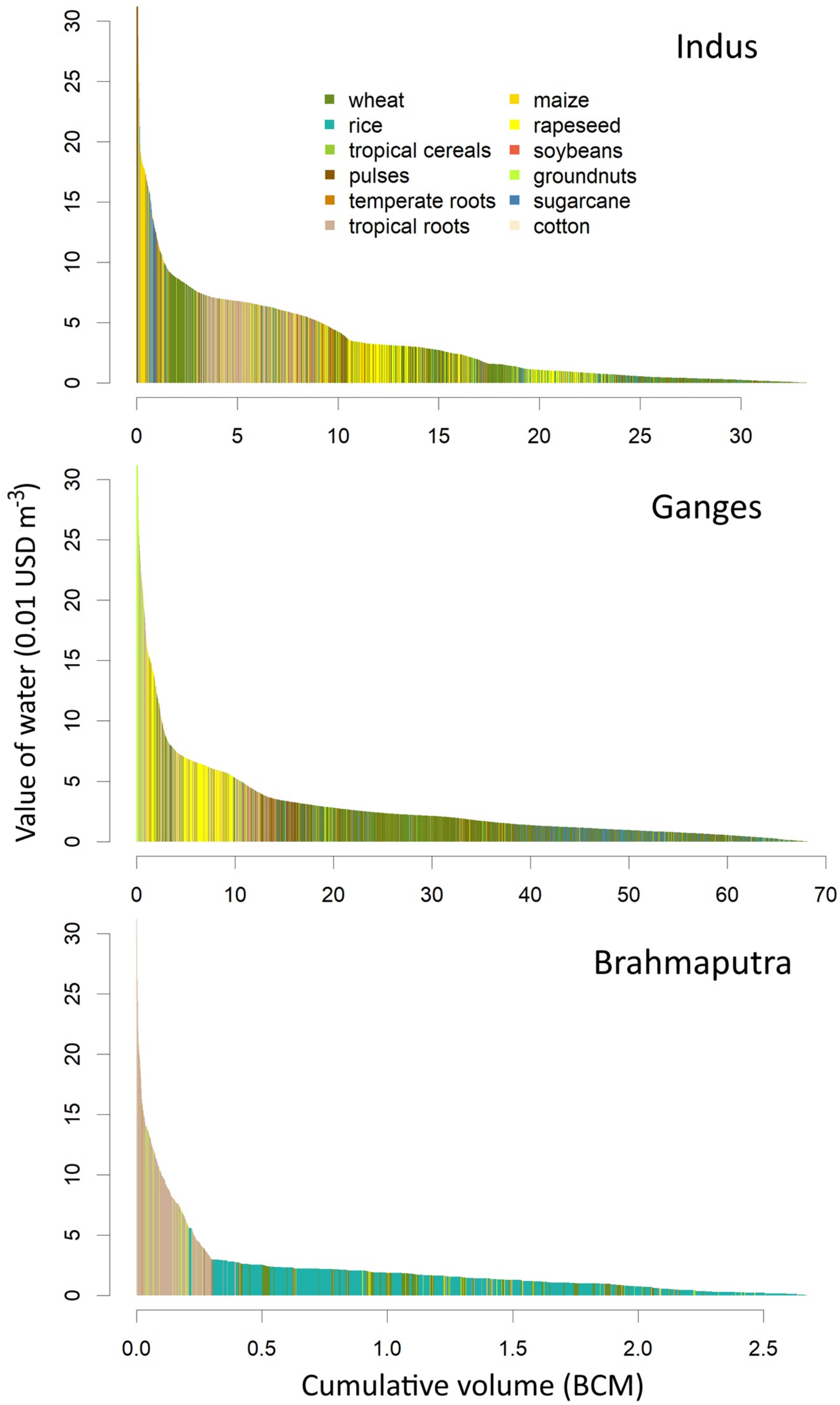

Figure 5. Demand curves for water to expand irrigation, for lower Indus, Ganges and Brahmaputra, ranking crops on their net marginal value (assuming a volumetric cost of irrigation water of 0.01 USD m^{-3}). Due to biophysical and socio-economic heterogeneity in the basins, including the 12 different water conservation measures possible on irrigated lands, the value of water varies, as is represented by the spread of the colored bars. Note different *x*-axis scales. *Y*-axis is cut-off at 0.3 USD m^{-3} for readability.

3.3. Local Equilibria

Measures taken on sugarcane and rice fields provide the most supply in the core irrigated areas of the Indo-Gangetic plain; these crops require large amounts of irrigation water and occupy a considerable fraction

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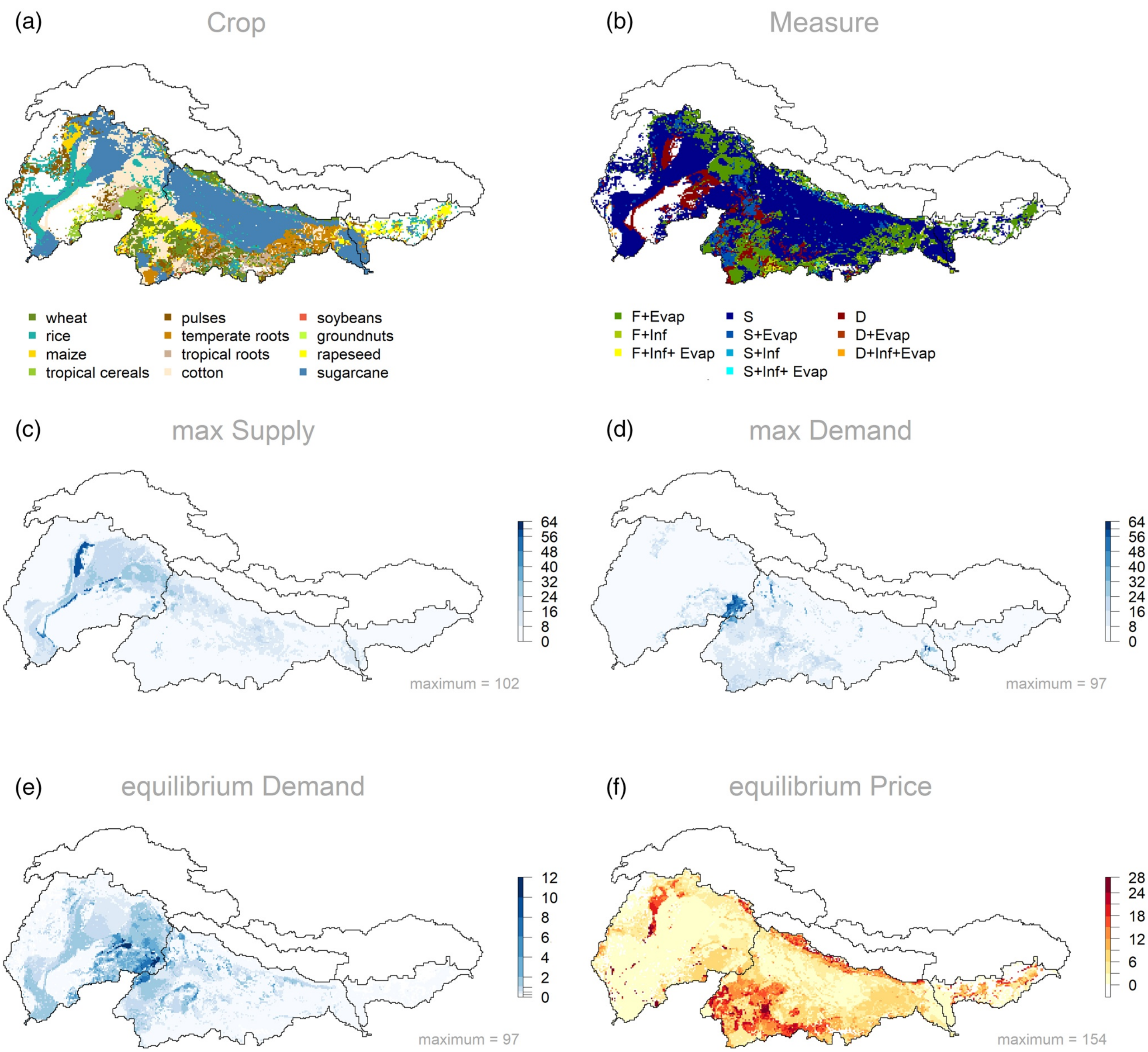

Figure 6. Crops (a) and conservation measures (b) that supply most water per cell, maximum volume of potential supply through water conservation (c) and demand (d) in MCM, and the equilibrium demand in MCM (e) and price in 0.01 USD m^{-3} (f) based on the cell-level equilibrium.

of cropped area (Figure 6a). On sugarcane and rice, drip irrigation is deemed infeasible and so a switch to sprinkler irrigation is the dominant option that provides the largest amount of water conservation (Figure 6b). On the fringes of the core irrigated areas, where a larger proportion of other types of crops is grown, drip irrigation is the dominant option, while in some locations, especially where cotton is grown, evaporation reducing methods are the most dominant.

At the village or cell-level, the spatial pattern of supply by water conservation does not meet demand (Figure 6c and 6d). Large volumes of water can be made available in cells where a high fraction of the area is irrigated, but often there is limited area available for further expansion of irrigation. Conversely, there are areas where farmers have land that could be brought under irrigation, such as in the south-eastern part of the Indus basin, or the southern part of the Ganges basin (the Chambal tributary), but here the extent of irrigation is limited and so is water conservation from existing irrigated land. As a result, the equilibrium price (Figure 6f) tends to vary from as low as 0 to almost 1 USD m^{-3}; low in cells with high potential supply,

Table 4
Equilibrium Volumes at (Accumulated) Cell and Basin Scale, With (net), and Without (Gross) Controlling for the Impact on Return Flows

	Net: Controlled for return flow impact (BCM)		GROSS: Return flow impact ignored (BCM)	
Basin	Basin	Cell	Basin	Cell
Indus	21	8.4	55	16
Ganges	10	3.9	22	9.4
Brahmaputra	0.2	0.01	0.2	0.1

BCM, billion cubic meter.

and high where there is specific demand from high value crops, but hardly any supply. The volume of water that can be reallocated by matching supply and demand at this price equilibrium is generally low at a village level (Figure 6e); aggregating all local reallocated water savings to the basin level leads to reallocation of just 8 billion cubic meter (BCM) in the Indus basin, below four BCM in the Ganges basin and a negligible amount in the Brahmaputra (see Table 4).

3.4. Matching Water Supply & Demand at Basin Level

Coordinating supply and demand over larger geographical regions can increase the amount of water savings. However, our analysis shows that savings of only about 10% (Brahmaputra) to little more than 20% (Indus and Ganges) of potential supply would be reallocated, when taking into account financial feasibility (Figure 7). The equilibrium price in the Indus basin is a low 0.01 USD m^{-3}, giving an equilibrium volume of 21 BCM, after which the costs of water conservation become higher than the value they can generate. In the Ganges and Brahmaputra, the equilibrium price is higher (0.05 USD m^{-3} and 0.08 USD m^{-3}, respectively), but the equilibrium volume as a fraction of total supply is lower because of a steeper supply curve.

The associated expansion of irrigated area at which the marginal benefit of additional conservation equals the marginal cost is moderate, about 7% in the Indus basin, 5% in the Ganges and negligible in the

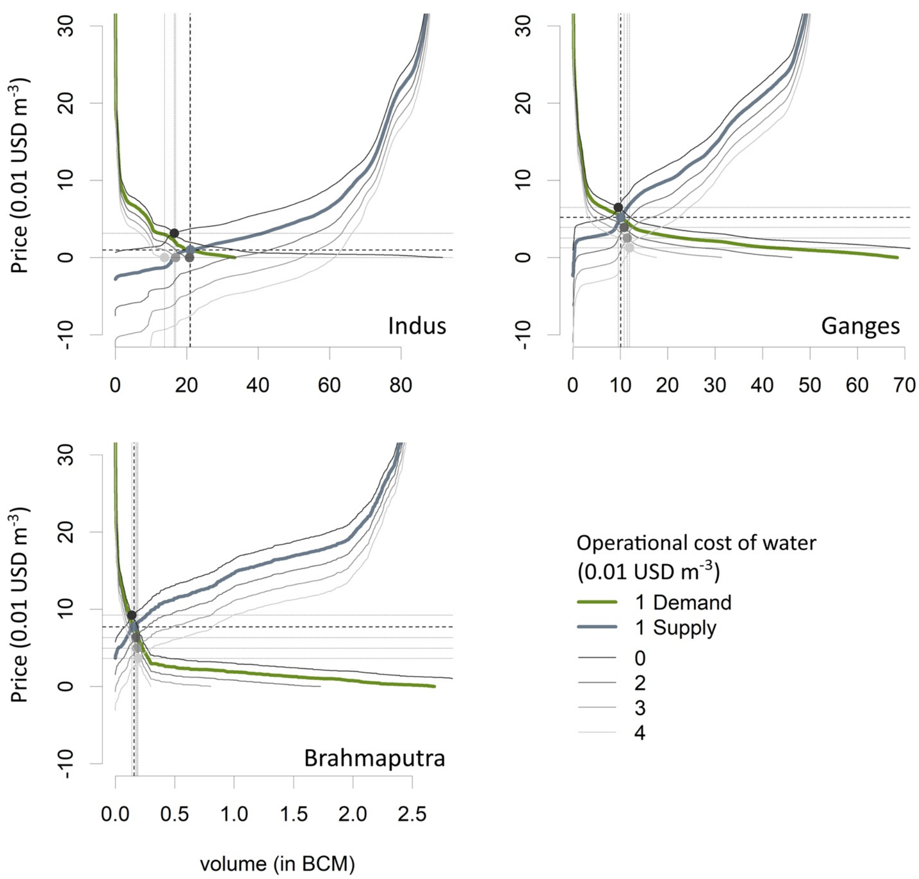

Figure 7. Supply and demand equilibria for the three basins given different volumetric operational costs (in 0.01 USD m^{-3}).

Brahmaputra. Total yield increases are similar to those for the expansion in irrigation, with irrigated yields on previously rainfed lands approximately doubling the rainfed yield they replace, though these are not necessarily the same crops. Our assumptions about the demand curve preserving the existing cropping pattern, influence this estimate. If we would base additional demand only on the cropped area distribution of crops that yield a positive margin, the equilibrium price in the Indus basin would rise to almost 0.04 USD m^{-3}. The equilibrium volume would double, leading to irrigated area to expand more than 10%, accommodated by water conservation over a much larger area. While we consider this less realistic—it is questionable whether there is a market for a strong increase in the production of crops such as tropical roots, and it would likely affect the price—it does illustrate the potential for additional demand for water savings if agricultural profit margins and, thus, the value of irrigation, would be higher. Similar relative differences were found for the Brahmaputra. In the Ganges basin, changing assumptions about the demand curve has limited impact due to a steep supply curve around the equilibrium.

Increasing the operational cost of irrigation water, e.g. representing higher water charges, has little influence on the equilibrium price and volume (Figure 7). It affects both the supply and demand side similarly (though not equally), increasing foregone costs when conserving water but also lowering the expected value of water made available through water conservation. When both the supply and demand curve slope below zero, under higher volumetric water charges, the equilibrium price reaches zero as supply outstrips demand. Farmers are better off investing in water conservation measures to avoid the higher operational costs. While there would be no agricultural demand for this increased supply, such water savings could support downstream environmental flows or reduce the overexploitation of groundwater.

Controlling for the impact on return flows is important. Table 4 shows the difference in equilibrium volumes between gross and net water savings, at both cell and basin level, indicating a reusable fraction of the reduction in irrigation applied by farmers of only 40%–50%. If farmers would ignore the impact their measures have on return flows, and thereby on farmers downstream, and use all the water they for their own benefit, double the amount of water would be available to them (e.g. in the Indus not 8.4 BCM but 16 BCM). At the basin level, this difference between equilibria based on gross and net savings is even larger as there are more opportunities to match supply with higher value demand.

3.5. Increased Margins in Irrigated Agriculture

The lower costs of production due to more efficient use of water on irrigated lands and the increased yields on rainfed lands now supplied with irrigation, raise the annual gross profit that farmers receive in the three basins. In the Indus basin, a 7% conversion of rainfed croplands to irrigation leads to a two billion USD increase in gross profit, to 13.7 billion USD, an increase in irrigated gross profit of 17%. However, it replaces rainfed agriculture with a gross profit of about 600 million USD resulting in a net increase of 1.4 billion USD. And when we subtract the approximate 200 million USD these farmers would pay other farmers annually for receiving this water (assuming here for simplicity a direct compensation transaction to pay for the costs of installing water conservation measures) this gives a surplus of 1.2 billion USD, an increase in gross profit of 10%. In the Ganges we estimate a net increase of 11% while in the Brahmaputra it increases by 25%. Increased profit margins can be used to import food and compensate for local limitations to increase production thereby increasing food security. While water savings, the irrigated area expansion it accommodates and the associated increases in production are comparatively modest, the additional total GM that this irrigation generates is more substantial.

4. Discussion

In this study, we analyzed the financial feasibility of water conservation measures, expanding the traditional cost curve approach with an improved estimation of demand that incorporates increasing marginal cost per measure while correcting for changes in downstream water availability. The use of a cost curve is limited to comparing the financial costs of measures to the benefits that can or need be gained. It is important to note that these estimates might be different from the economic costs for society as a whole, which also include externality costs, opportunity costs, subsidies etc. By not taking such costs into consideration, measures with low financial cost but high economic costs—like measures that use highly subsidized energy—might appear to be cost-effective, whereas in reality they are not economically attractive for wider society. Financial cost is not the only basis on which choices are made. Hence, our analysis is not prescriptive, but should be considered as a guide for comparing the financial costs of measures at multiple scales, within and across basins, to inform decision-making.

Comparison of the value of water estimates obtained here with other studies gives confidence in our water demand estimates. While low, our shadow prices for water confirm estimates of previous studies using different methodologies (Bierkens et al., 2019; Hellegers & Davidson, 2010; W. J. Young et al., 2019). D'Odorico et al. (2020) report somewhat higher water values for South Asia, based on irrigation water withdrawn and price data for the year 2000, for rice, maize and soybean (between 0.05 and 0.08 USD m^{-3}), but they assume the incremental costs of non-water related inputs to be negligible which is not generally the case in the IGB. We have used average price levels over the 2000–2018 period while W. J. Young et al. (2019) found that the economic return from irrigation water in Pakistan has almost doubled over the last 30 years to an average 0.06 USD m^{-3} in Sindh province and 0.08 USD m^{-3} in Punjab, attributed to increased groundwater use, increased use of fertilizer and mechanization, and some improvements in water management. Expanding cost curves by accounting for variability or trends in both prices and costs would be an interesting next step.

Without perceived and real economic benefits, farmers are unlikely to conserve water and estimates purely based on biophysical characteristics might turn out overly optimistic. We show that financially feasible water conservation is only a fraction—10%–20%—of potential supply. These savings, and the expansion of irrigated cropland they could support, however, do add considerable value to total agricultural production. Higher value demand, e.g. from industry, for domestic use or for sustaining essential ecosystem services, not included in this study, would likely warrant further water conservation beyond the agricultural equilibria presented here.

The median costs of our measures are similar to the average costs reported for India by the World Bank (Addams et al., 2009), who give a range from negative to a maximum of almost 0.04 USD m^{-3} for agricultural measures. We show there is a large spread around the median depending on location and the type of crop.

Several assumptions shape our results, and there are opportunities for improvement. First, on the demand side, we have assumed that irrigation expansion requires investments in new irrigation infrastructure. However, water savings might also serve existing irrigation command areas that already operate on a deficit, especially in years with below average precipitation. Here, one would avoid the cost for land conversion, which increases the net value of irrigation water and thereby the equilibrium price and volume. Spatially delineating such deficit areas could refine our analysis and support more tailored policy advice.

Second, we kept maximum simulated yields constrained by current–day management practices. In future, advances in crop genetics, better fertilizer use and improved applications of pesticides and herbicides could raise yields and thereby the value of crop produce. This will increase the equilibrium price of water savings, reducing the difference between the biophysical potential supply and what is financially feasible. At the same time, there will be downward pressures on yield, such as ongoing salinization or increased heat stress (Battisti & Naylor, 2009), pest incidence (Gregory et al., 2009) and water stress due to changing precipitation patterns (Rojas et al., 2019; Rosa et al., 2020b) and shifts in snow melt in a changing climate (Biemans et al., 2019; Qin et al., 2020).

Third, on the supply side, we compared irrigation application methods, and examined different levels of operational costs but did not distinguish explicitly between the types of energy used. Solar pumps have higher investment but lower running costs than electric or diesel pumps. Varying types and rates of energy subsidies, usually set by states and provinces, lead to a spatial differentiation in costs to farmers. As we show, higher water charges would stimulate further water conservation even without matching demand. However, higher costs still affect farm revenues and in an agricultural sector marked by low profitability such distributional effects should be carefully considered.

Finally, we took into account the changes in return flows to control for impacts on downstream users—recognized as essential when evaluating efficiency improvements (Grafton et al., 2018; van der Kooij et al., 2013). We thereby assume each cubic meter of water reaching a downstream user is the same, regardless of what pathway it takes, and ignore water quality limitations to reuse. High salt, pesticide and fertilizer concentrations reduce water's value downstream (Hanemann, 2006). In extreme cases return flows are being left to evaporate when salt levels are too high, as is happening in parts of the Indus basin (A. S. Qureshi et al., 2008). Under these conditions, each cubic meter of application saved is an actual saving. Distinguishing between reusable and non-reusable return flows based on drainage water quality indicators would improve our understanding of the effectiveness of efficiency measures. Efficient use of water does lead to lower operational costs (which is based on water applied, not water saved) and so there is an incentive—in reality, and also in our method—to go for the higher efficiency option, other things being equal. Given these assumptions, our estimates of the feasibility of water conservation in agriculture likely represent a lower-bound.

At an institutional level, accounting for the impact on return flows requires both monitoring capacity and motivation. We assume a central planner such as the Indus River System Authority and provincial irrigation departments will have the capacity to monitor changes in return flows and a motivation to avoid unwanted downstream impacts. In a basin like the Indus, with it is sequential ordering of interwoven command areas and relatively high storage and control capacity this might be feasible. The Ganges basin has a more dendritic structure which limits savings that cross subcatchment boundaries, although coordination to optimize combined upstream and downstream water use remains feasible.

Rather than charging farmers to incentivize them to use less, which is difficult given the inelasticity of demand at current price levels (e.g. Webber et al., 2008) and the low profitability of agriculture, here we explore what it would take to pay farmers to use less. We assume that at the basin level, the costs of efficiency improvements could be charged directly to beneficiaries, e.g. through increased water abstraction costs for areas brought newly under irrigation, or indirectly by offsetting subsidies with expected higher tax revenues. Obviously, this requires proper taxation or new forms of subsidies. In the Indian part of the Indus basin, a small pilot is currently paying farmers when they use less than their allocated share of energy and, thus, water (Punjab State Power Corporation Limited, 2019).

Low profitability in agriculture limits the capacity to finance water conservation measures. In the Indus basin, Pakistan's past approaches ranged from supporting the adoption of individual technological solutions (e.g. laser land leveling, solar powered irrigation systems) to management practices (e.g. deficit irrigation, or optimizing planting dates). Recently, more integrated programmes such as the "National Program for the Conservation and Efficient Use of Irrigation Water through High Efficiency Irrigation Systems" have been introduced which focus on both technological innovation and improving local socio-economic conditions, combined with improved monitoring of water use.

The need to reduce water use in agriculture while producing more food has been made repeatedly. However, the gap between potential water savings and what is actually feasible suggests that expectations of autonomous development should be treated with caution. Here, we show increases in the total gross profit of production of 10% (Indus) to 11% (Ganges) through on-farm demand-side measures. While significant, this is still lower than what would be required to support the widely cited 50% increase in food required globally by 2050 (Gerten et al., 2020). Water conservation measures in irrigation are one component of adaptation that also needs to include other strategies such as food waste reduction and modifying production and consumption patterns.

5. Conclusions

We analyzed the financial feasibility of water conservation measures, comparing the costs of water conservation measures with the added value that reallocation of water savings might generate if used for expansion of irrigation. The value of irrigation water for the main food crops is generally low throughout the IGB basins, limiting the ability to compensate for water conservation costs. Our results suggest that only 10%–20% of potential water savings would be realized if financial feasibility is taken into account. Despite limited water savings and the modest expansion of irrigation it accommodates, this does add significant gross profit to agriculture in these basins of about 11%. A shift to a more profitable agriculture will provide incentive for more water conservation and reduce the gap between biophysical potential and financial feasibility of water conservation.

Data Availability Statement

The crop-hydrological model LPJmL is open source (it can be downloaded from www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml/versions, together with model description and parameterization). The economic data are open source and can be downloaded from FAOSTAT (prices; http://www.fao.org/faostat/en/#data/PP) and national databases (cost of production, for India; eands.dacnet.nic.in/Cost_of_Cultivation.htm, and for Pakistan; http://www.amis.pk/Surveys.aspx).

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