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Review

Water-Saving Agricultural Technologies: Regional Hydrology Outcomes and Knowledge Gaps in the Eastern Gangetic Plains—A Review

Mohammad A. Mojid [1,*] and Mohammed Mainuddin [2]

[1] Department of Irrigation and Water Management, Bangladesh Agricultural University, Mymensingh 2022, Bangladesh
[2] CSIRO Land and Water, Black Mountain Science and Innovation Park, Canberra, ACT 2601, Australia; mohammed.mainuddin@csiro.au
* Correspondence: ma_mojid@bau.edu.bd

Abstract: Increasing food demand has exerted tremendous stress on agricultural water usages worldwide, often with a threat to sustainability in agricultural production and, hence, food security. Various resource-conservation technologies like conservation agriculture (CA) and water-saving measures are being increasingly adopted to overcome these problems. While these technologies provide some short- and long-term benefits of reduced labor costs, stabilized or increased crop yield, increased water productivity, and improved soil health at farm scale, their overall impacts on hydrology outcomes remain unclear at larger temporal and spatial scales. Although directly linked to the regional hydrological cycle, irrigation remains a less understood component. The ecological conditions arising from the hydrology outcomes of resource-conservation technologies are associated with sustainability in agricultural production. In this paper, the philosophies and benefits of resource-conservation technologies and expert perceptions on their impacts on temporal and spatial scales have been reviewed comprehensively focusing on regional hydrology outcomes in the Eastern Gangetic Plain (EGP). Due to data inadequacy and lack of knowledge-sharing among disciplines, little is yet known about actual water saving by these resource-conservation technologies and the level of their contribution in groundwater and surface water storage over large temporal and spatial scales. Inadequate knowledge of the hydrological effects of water applied in the agricultural field leads to the implementation of water management policy based on local perspectives only, often with the possibility of deteriorating the water-scarcity situation. Therefore, multidisciplinary future research should quantify regional hydrology outcomes by measuring the components of regional water balance in order to develop a proper water management policy for sustainable agricultural production.

Keywords: irrigation management; rice; percolation; scale effects; hydrologic cycle

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1. Introduction

The global demand for food, energy and water by the ever-growing population has been forecasted to increase by 50%, 50% and 30%, respectively, in 2030 compared to 2012 [1]; in the same base period, food demand will increase by 70% to 100% by 2050 [2]. The Indo-Gangetic Plains (IGP) comprising more than 250 Mha of area across Bangladesh, India, Pakistan and southern Nepal have over 100 Mha of agricultural land and host over 750 million people [3]. The Lower Gangetic Plain, called the Eastern Gangetic Plain (EGP), comprises the adjoining states of Bihar and northern West Bengal in North-eastern India, the North-West of Bangladesh and the Terai plains of Nepal (Figure 1). The EGP is characterized by the world's highest density of rural poor, persistent yield gaps, low agricultural productivity, limited crop diversification, ample water resources [4,5], and highly fertile lands [6,7] of agricultural importance [8]. The region is therefore a global priority for sustainably increasing food production [9].

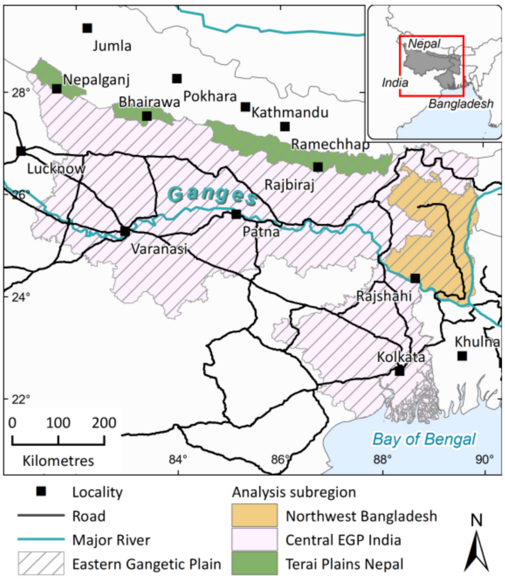

Figure 1. Location and area map of the Eastern Gangetic Plain (EGP) region.

Agricultural productivity is critically dependent on the availability of water. Adequate water supply significantly increases crop productivity [10,11] by introducing high yielding crop varieties, a better cropping pattern, and increasing cropping intensity [12]. Compared to rain-fed agriculture, irrigated agriculture produces two to four times more crop yields [13]. This contribution of irrigation increased global irrigated land by 76% between 1970 and 2012 [14]; the reliance of agricultural production on irrigation is expected to further increase in the future [15]. Farmers' capacity to access and use water is a major driving factor in obtaining the best yield and hence is an important variable for the food security index [16]. However, the growing competition for water by various sectors will affect farmers' ability to produce food [17,18]. So, making food production sustainable, while conserving diminishing water supplies, will be a great challenge in the future [19].

The Ganges basin has a tropical climate, with a distinct wet monsoon (June–September) and a dry winter (November–February); the summer is characteristically hot and humid. Except for the East and North-East hilly regions of the basin where annual rainfall often exceeds 4000 mm, the average annual rainfall in most other parts is 1500 mm. The rainfall is mostly concentrated in the monsoon season and the winter is almost rainless [20] but the main cropping season. In many parts of the IGP, agricultural drought and other climatic shocks severely affect crop production, thus, necessitating an adequate water supply to stabilize agricultural production [21,22]. Surface water is inadequate in the dry season, but groundwater plays a vital role in sustaining agricultural productivity. In India, 60% of the agricultural water requirement is satisfied from groundwater, covering over 50% of the irrigated area [23]; in Bangladesh, the corresponding quantities are 79% and 85% [24]. Of the many factors now threatening sustainability in agricultural productivity, water is the most crucial [25–33] since, without further improvement in water productivity, the amount of water needed for crop agriculture is predicted to increase by 70–90% by 2050 [34].

Several resource-conservation technologies like minimum tillage, no/zero-tillage, direct-seeding, bed-planting, laser land-leveling and residue retention [35–37], and water-saving technologies like alternate wetting and drying (AWD) and deficit irrigation methods have been developed over the past three decades and are being practiced in many parts of the world, including the EGP. In addition to the benefits from the conserved resources, these technologies can also change crop-water use and the regional water cycle [38] with negative impact on groundwater dynamics [39]. They save water by reducing water application in the fields, with resulting lower percolation and groundwater recharge. Large-scale adoption of these technologies can therefore lead to significant decline in groundwater levels [40–42], with possible degradation of soil quality and damage of vegetation [43]. In many parts of the EGP, groundwater level has declined significantly, and is now threatening sustainable water supply for irrigation and drinking [44–49] with resulting negative impacts on the economy, society and environment [50–53]. Although less than one-third of the IGP has experienced declining groundwater levels [54] the situations in high-population centers (e.g., Dhaka city) and other stressed areas (e.g., the Barind area) are potentially alarming [49].

Agriculture in the IGP is mostly dominated by irrigated rice–wheat systems, which cover 13.5 Mha and play a crucial role in the food security and livelihoods of millions of people [37,55,56]. In Bangladesh and West Bengal, rice is produced on 6.05 Mha and 5.5 Mha, respectively [57]. Both mechanized and tillage-based traditional agriculture and transplanted rice cultivation with flood irrigation requiring a huge quantity of water [58–60] are a major challenge in agriculture, in order to maintain or increase rice production. Shifting current agriculture to water-efficient ones [61–65] would conserve water from being wasted through unintended purposes and make considerable water savings [66–69] to face the challenge. Conversion of conventional agriculture to resource-conservation methods [70–72] using resource-conservation technologies and water-saving measures has been demonstrated as of particular interest in this regard [29,73–76].

When water is applied in a crop field, not all of it is consumed as illustrated in Figure 2. The local surface and sub-surface hydrological systems retain a considerable portion of the applied water, which might be reusable later by other users. Consequently, irrigation has a direct link to the regional hydrological cycle, especially in areas with shallow groundwater [54]. A large part of the applied irrigation water infiltrates below the root zone and is stored in the underlying aquifer [7,43] or in downstream surface water bodies. Figure 3 conceptualizes the flow paths of the components of water from a rice field under conventional flood irrigation with pumped groundwater. The percolated water is perceived as lost by the farmers and irrigation practitioners [77] but is a gain to the local surface and sub-surface hydrological systems. The efficiency of water usage at any separate component (e.g., crop fields, ponds) within the hydrological system may be low, but the overall efficiency of the entire system can be much higher than in the individual components. So, the general concept of water use efficiency undervalues the real efficiency of the whole hydrological system. Water recycling must be integrated into the concept of water-use efficiency to develop new realistic concepts [78]. The water flux exchanging between the aquifer and vadoze zone greatly controls the dynamics of the groundwater table [39] thus raising a valid question of how the currently advocated water-saving measures impact on the hydrological cycle of a groundwater basin. Do these water-saving measures assure proper utilization of groundwater reserves? In situations where downstream aquifers and surface water bodies are fed from upstream aquifers, what will be the effects of the water-saving measures on these downstream water resources (Figure 3)? These important issues have not yet been investigated critically on the system level; only some field-scale studies have investigated the possibilities, which are also contrasting in nature. A summary of the major previous studies assessing the impacts of various agricultural water-saving technologies on local and regional hydrology is presented in Table 1. In light of this short-coming, this paper comprehensively reviewed the available literature to evaluate the present state of knowledge and emerging knowledge-gaps on this subject so as to guide future research on this topic. Note that since rice-based cropping systems dominate the agricultural landscape of the EGP [56], this study focuses on the exchange of water flux between irrigated rice fields and the underlying aquifers. The paper is structured into five major sections in addition to an introduction and a concluding section. The benefits and impacts of conservation agriculture have been reviewed in the second section. The third section highlights the complementary and contemporary meanings of water saving while the fourth section addresses the impacts of agricultural water-saving methods on regional hydrology outcomes (i.e., links between various components of the regional hydrological cycle). The next section identifies current knowledge gaps in the key water-saving issues, including scale-effects and policy, before an overall summary and concluding section on water-saving measures and regional hydrology outcomes.

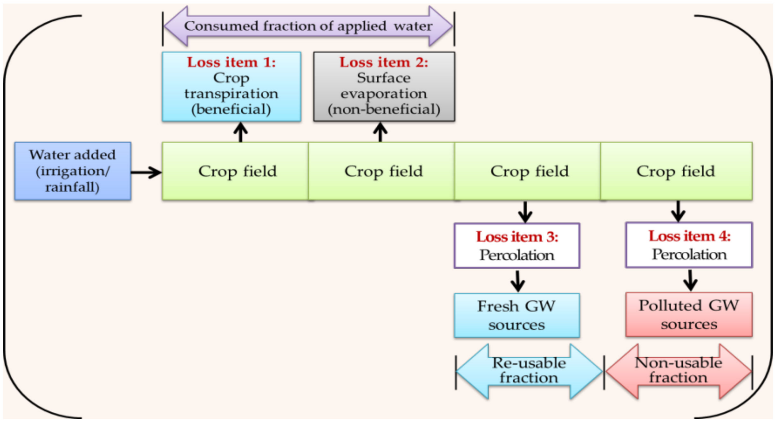

Figure 2. Utilization and fate of applied water to crop fields and hydrological links to groundwater resources.

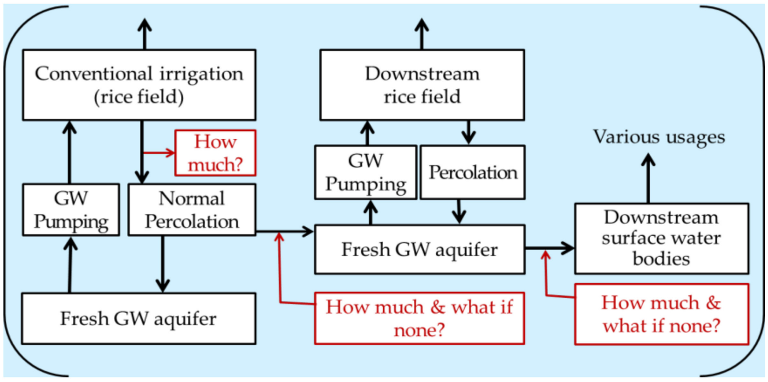

Figure 3. The pathways of the components of water from a rice field under conventional irrigation with groundwater.

2. Conservation Agriculture

2.1. Philosophies and Benefits

Conservation agriculture (CA) has been developed as a response to concerns about sustainability in agriculture [55,79–83] with basic principles of rebuilding soil, optimizing crop production inputs (resource and energy), enhancing food production and optimizing profits [84–87]. It comprises application of three inter-linked principles: (i) no or minimum mechanical soil disturbance through conservation tillage (e.g., minimum or zero-tillage), (ii) biomass mulch soil cover (e.g., crop residues), and (iii) crop diversification, as well as other practices of integrated crop management [88]. Under conservation tillage, approximately 30% of the soil surface is kept covered with crop residues, which reduces erosion of surface soil by overland flow [89,90]; a crop is planted directly into a seedbed without any tillage operation in the zero-tillage system. Cultivation of wheat under zero-tillage in the rice-wheat cropping system is an emerging CA-based technology in the IGP [91]. A CA-based sustainable intensification program was started in 2014–15 in two districts each of Nepal, Bangladesh, and Bihar and West Bengal in India [92]. Globally, the cropland under CA increased at 5.3 Mha annually since 1990 and reached 106 Mha in 2008/2009 [93] and 180 Mha in 2015/2016; 78 countries in the world have adopted CA practices.

Table 1. Summary of major previous studies assessing the impacts of agricultural water-saving technologies on local and regional hydrology. The studies are grouped by apparent and actual water saving, impacts of water-saving measures on water usage and regional water balance, gaps in current knowledge in certainty and scale-effect of water saving, and policy formulation for water resources management.

Main Findings	References
Apparent and actual water saving	
Water-saving technologies make only narrowly perceived local water saving without considering irrigation return flows.	[94,95]
Percolation from irrigated fields recharges the underlying aquifer in many groundwater basins, including the IGP basin, from where it is recoverable for reuse; so is not a loss.	[54,96–102]
Water-saving by one user may be a loss to another over large spatial scale. So, reducing percolation does not always save water.	[75,95,103,104]
Reduction in evaporation and water-flows to non-recoverable sinks (e.g., polluted water sources) makes actual water saving.	[105–107]
Impacts of water-saving measures on water usage	
Alternate wetting and drying (AWD) water management method saves between 15% and 60% of water compared to continuous standing water rice system.	[60,108–112]
Demand for water increases when technological intervention adds more value to it (e.g., reduced cost of water due to increased irrigation efficiency); this is the re-bound effect.	[75,113–116]
Re-bound effect is a potential hindrance in water resource management.	[117]
Impacts of water-saving measures on regional water balance	
Water-saving measures over regional scales cause decline in groundwater level by limiting recharge and exert stress on regional hydrology and ecology.	[38,40,77,118]
Most rivers and aquifer systems are hydraulically connected in Bangladesh and the Bengal Basin.	[119,120]
Separate management of surface and groundwater in the interconnected hydrologic systems hinders water resource allocation.	[121–123]
Knowledge gaps in certainty and scale-effect in water saving	
Impacts of water-saving technologies on the degree of actual water-savings and overall water usage in groundwater-based irrigation systems are poorly understood at larger spatial scales.	[75,95,115,116,124]
The components of water balance in the Eastern Gangetic Plain (EGP) basin have not been quantified yet.	[106,125]
Focusing on only local efficiency of water use and ignoring the return flows is a risky perception.	[126]
Knowledge gaps in formulating proper policy for water resources management	
Lack of attention, improper legislation and ineffective/less-effective institutions are the common problems in governing groundwater in many countries, especially in the face of re-bound effect.	[75,127–129]
Reliable detail information on water reserves, safe yield, water withdrawal patterns and water quality dynamics in the aquifers is lacking in most of the EGP basin.	[130]
Whether water-saving technologies can maintain sustainable development and what more need to be done for this in future remain uncertain.	[39]
Appropriate strategy for water management should be regionally suited and must establish strong regulation and policy. This is a topic of future research for the Indo-Gangetic Plains (IGP) basin.	[9,131–134]

Resource-conservation technologies have revealed some promising immediate [135–137] and long-term benefits [138–140]. They reduce field-scale irrigation, fertilizer applications, labor shortages, energy use, greenhouse gas emission, and erosion of field soil; while they increase soil organic matter and biotic activity, crop diversification, yields, and farm incomes by improving resource-use efficiency [36,37,55,75,83,91,141–146]. Tillage accelerates oxidation of soil organic matter to CO_2 and loss to the atmosphere, but CA reduces the oxidation rate [147,148]. Increased crop residues under CA and root exudation of carbon compounds into the soil cause a reversal of soil carbon from net loss to a net gain [86,149–151]. In spite of these multiple benefits [152–154] the farmers' prime interest in CA-based agriculture is mostly the monetary gain [155]. Nonetheless, CA is now emerging as a major component of farming systems for ensuring food security in South Asia [85,87].

2.2. Impacts on Soil and Water Use

The effects of conservation agriculture on soil properties vary depending on the type of chosen system, soil-type, climatic conditions, cropping history, etc. [156–158]. Soil becomes more stable and less susceptible to erosion under zero-tillage compared to conventional tillage [158,159] and provides more satisfactory physical properties for crop production [160]. Soil organic carbon increases [92,161,162] and pH decreases [163] under zero-tillage compared to a conventional tillage system over time [164,165]. Organic matter improves soil aggregation, alters pore-size distribution, reduces soil bulk density, and increases both total and effective porosities within 0–5 cm soil profile [166,167]. The increased number of 0.5–50 µm pores augments soil-water storage and 50–500 µm pores enhance water movement through the soil [92,168]. Conventional tillage creates a surface crust of high bulk density, while long-term (e.g., 8–10 years) zero-tillage helps in forming many continuous pores extending from the soil surface to the deeper layers causing significant increase in infiltration [161,166,169–171]. Zero-tillage thus increases the saturated and unsaturated hydraulic conductivity of soils [159,162,172,173]. Conservation tillage can increase the capture of rainfall and reduce runoff due to stable aggregates and increased porosity in the surface soil [174] and water-holding capacity due to increased organic matter [159] with resulting reduction in surface evaporation. The magnitudes of water-, labor- and energy-saving of some CA practices are listed in Table 2. However, generalization about such gains in water saving for all hydrological situations can provide a wrong message in many regions. In the dry season, there is not enough water on the soil surface to increase its capture in the soil within the EGP. There are only occasional relatively ample rainfall events in some areas of the EGP, in which cases CA can make more water available for plants' use and increase the precipitation-use efficiency of the production system [166]. However, water is almost always in excess of soil's saturation capacity in the wet season, thus leaving no scope for further capturing of rainfall into the soil. The important controlling factors in conserving water in the wet season are the infiltration capacity and hydraulic conductivity of the soil. However, this likelihood has not yet been investigated.

Table 2. Degree of benefits of conservation agricultural (CA) practices.

CA Practices	Benefits	Magnitude	References
Zero tillage/ laser land leveling/ bed and furrow planting	Water saving	23–45%	[175]
Zero tillage	Water saving	5–15%	[176]
Laser land leveling	Water saving	25%	[177]
Permanent bed	Water saving	10.6%	[178]
Zero-tillage	Water saving	21.8%	[178]
Direct-seeded rice	Labor saving	40–45%	[179]
Direct-seeded rice	Water saving	30–40%	[179]
Direct-seeded rice	Energy saving	60–70%	[179]

3. Agricultural Water–Saving

3.1. Water-Saving Measures

Water-saving irrigation, groundwater regulation, shifts to rain-fed agriculture, artificial recharge to groundwater, rainwater preservation, virtual water imports and indirect approaches like energy pricing and regulation are the currently available measures to reduce regional water use [134,180]. However, appropriate water-accounting is essential to identify the scope of these water-saving practices [181]. Based on the approach of reducing evaporation, runoff losses, and the extent of free water on the soil surface [182] irrigation strategies like shallow water depth associated with wetting and drying [183,184], alternate wetting and drying, AWD [108,124,185,186], semi-drying [187], aerobic rice cultivation [188,189], partial root-zone drying [190], and non-flooded mulching [191] are being practiced in different rice-growing regions. The AWD technique allows the soil to dry for a certain pre-determined number of days after depletion of the standing water in the field before the next irrigation [192]. The multiple-shallow irrigation method (1–3 cm irrigation applied frequently) can efficiently utilize rainfall and reduce percolation and surface runoff [94]. In the aerobic cultivation method, rice is grown in well-drained dry soils with supplementary irrigation, as with upland crops [188]. Furrow irrigation with raised beds, mulching, conservation tillage, deficit irrigation [193–195] and improved weed control can also achieve substantial water-saving.

3.2. Apparent and Actual Water-Saving

The impact of efficiency of water consumption and water productivity on water-saving has been investigated at field scale on several occasions e.g., [196–200]. Any effort toward improving irrigation efficiency is valuable [201], but the commonly used concepts of water-use efficiency underestimate the system-level's actual efficiency [78]. The actual fraction of the applied water that is used efficiently at a regional scale has not yet been quantified; current measurement methods are inadequate for such quantification.

All the water applied in the crop/rice fields ends up at any of, or a combination of, consumptive use, non-consumptive use, non-recoverable flow (Figure 2), and change in storage [95]. These water use-terms allow a clearer definition of various issues and options for water usage in irrigated agriculture. Water-saving through a resource-conservation technology refers to a narrow local perspective of water application by reducing percolation rates, as conceptualized in Figure 4. This water-saving does not account for return flows from the irrigated field that may be either non-recoverable outflow (e.g., to saline or otherwise polluted groundwater or surface water as schematized in Figure 5) or recoverable outflow, where it ends up in rivers or as useable groundwater source [94,95]. The return flow may be a significant contributor to groundwater recharge [131,202–204].

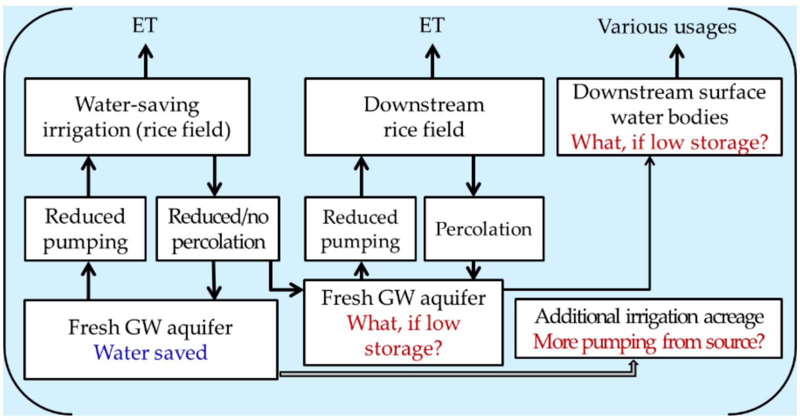

Figure 4. Conceptualizing of impacts of water-saving measures on regional surface and groundwater sources when irrigation uses groundwater.

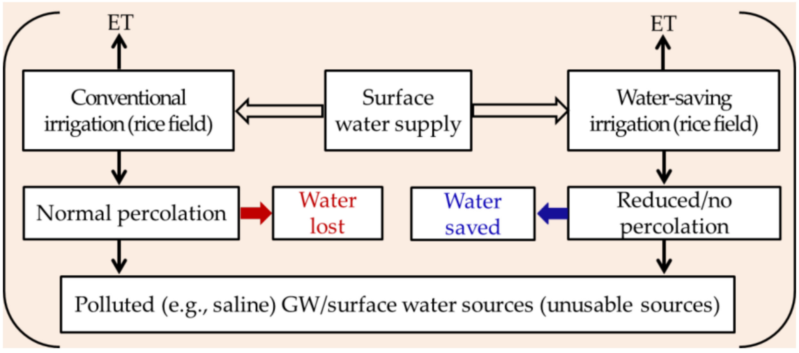

Figure 5. Water loss and water saving issues under conventional and water-saving irrigation from surface water sources when underground aquifer contains polluted water (e.g., saline).

Due to various natural calamities (e.g., seasonal storms, hailstorms, cyclonic storms, heavy rainfall and floods), dry season is the main and safe cropping season in the EGP, which has an annually renewable groundwater system. Here irrigation is predominantly done with groundwater; 79% of total irrigation in Bangladesh and more than 90% of irrigation in North-West India uses groundwater. An individual farmer considers the combined outflow of water by evapotranspiration, seepage and percolation as water usage by his/her rice field and hence actual water loss in the field. However, when considering a large spatial scale, achieving water-saving by one user may be a loss to another since the seepage and percolation from one's field enter the underlying aquifer or nearby surface water sources, from where others can reuse the water [75,103] causing no net loss to the system [205,206]. The real water-saving occurs only when the non-recoverable non-usable water losses (Figure 2) are eliminated or reduced. Avoidance of peak evaporative demand, use of short-duration varieties, cultivating less water-demanding crops, and changing from ponded to non-ponded rice culture are the potential technologies for reducing evapotranspiration [205–207]. The practicability and effects of technologies on crop yields must, however, be investigated before their large-scale field adoption.

Modifications of the water balance components by resource-conservation technologies, the fate of water saved through reduced application, and hydrologic interactions across spatial scales determine whether any reduction in water application leads to actual water-saving and reduces water usage [75]. Farmers always intend to achieve maximum output from the water resource, leading them to utilize as much water as they can have access to. Society, on the other hand, prefers utilizing scarce water to maximize profits by shifting water from agriculture to high-value economic sectors. The goals of the two entities in utilizing the scarce water are clearly opposing, and therefore appropriate terminology to describe real water-saving remains a central issue of debate [95].

Interactions between non-agricultural and agricultural water usages are scale-dependent and play a major role in water-saving [208]. At basin scale, the main interest is to reduce water usage in irrigated agriculture and transfer water to other higher-valued usages. This again implies that actual water-saving can be achieved only by reducing evaporation and water-flows to non-recoverable sinks [107]. The basin approach, instead of paying attention to individual water usage, assesses return flows, estimates water-use efficiencies at field- and basin-scales and differentiates consumptive water-saving from non-consumptive saving (Figure 2) while accounting for water and analyzing water-use efficiencies [209–213]. Despite many complexities in perceptions of water-saving, its ultimate objectives are clear and undisputable: to stop unsustainable exploitation of the available water resources and to increase the quantity of water for other essential and more beneficial usages. It is therefore essential to understand the scale-effects of water usage clearly to improve water-savings and water productivity [124,210,214–216].

3.3. Impacts on Water Use

AWD effect: Irrigation management through alternate wetting and drying is widely practiced in many countries/regions like the Philippines, Vietnam, China and EGP [217–220]. Under AWD, the percolation rate decreases leading to water-saving; the reduction in evapotranspiration plays only a minimal role [221]. Compared to the continuous standing water rice system, the levels of water-saving by the AWD method are listed in Table 3. Percolation from the crop fields controls the transport of nitrate [94], heavy metals [222], salts [223], nutrients [224], and pesticides [225] to groundwater. So, with reduced percolation the quality of groundwater remains under safeguard. The AWD method also reduces greenhouse gas emission [226,227], uptake of arsenic in rice grain [228,229], the cost of pumping water [230,231], and concentration of methyl mercury in field soil [232].

Table 3. Levels of water-saving by alternate wetting and drying (AWD) method compared to the continuous standing water rice system.

Type of Effect	Quantity	References
Water saving	23%	[108]
Water saving	15–40%	[109–111,221,233]
Water saving	30–60%	[112]
Percolation reduction	50–80%	[112]
Percolation reduction	19–28%	[60]

Bund effect: An unsaturated zone beneath standing water and a higher hydraulic conductivity zone beneath the bunds in rice fields are developed. This causes the applied irrigation water to move through the bunds and recharges the underlying aquifer [234]. The destinations of the applied irrigation in the rice fields were measured on several occasions e.g., [205,235–238] and a significant portion was reported to percolate through the field boundaries. This type of lateral seepage flow field is horizontal first and then vertical below the bunds [239]. Often rice fields of irregular shape are transformed into regular rice fields in order to improve irrigation efficiency, keeping part of the previously generated plow pan beneath the bunds of the reformed rice field [234]. Consequently, the dominant movement of water is in the horizontal direction through the bund. The seepage flux is, however, much less than the deep percolation rate [239–241] except when rice is cultivated on terraced fields, where the seepage water moves to the downstream plots through the bunds [239]. In flat rice fields, the infiltration rate below the bunds remains close to the average infiltration rate for the crop field with plow pan beneath the bunds, but may double or more without plow pan beneath the bunds [205,239]. [234] demonstrated 50% of water lost through the bunds, 25% through evapotranspiration, and 25% equally through infiltration providing an estimated annual water loss of 41 km^3 through percolation underneath the bunds of rice fields in Bangladesh. Based on this field scale estimate, sealing of bunds (e.g., by puddling) can reduce seasonal water use by 52 ± 17%. Much greater savings (~90%) can be achieved in fields with larger perimeter-to-area ratio.

Puddling effect: Puddling eliminates large pores and alters the field soils to stratified layers: a top puddled layer, muddy layer and plow pan overlying a lower layer [242,243]. A low-permeable layer, formed above the puddled layer, comprises a finer fraction of the soils in suspension [244,245]. Puddling creates a 5 to 10-cm layer of plow pan, of low hydraulic conductivity, 20–25 cm below the ground surface. The hydraulic properties of plow pan regulate the water regime in the irrigated field [236–247]. Water flow occurs under unsaturated conditions below the plow pan [243]. The percolation rate varies widely with soil texture, 3–17 mm/day for clay and 13–30 mm/day for sandy loam [245,248]. The intensity [249] and depth of puddling [250], soil-type and post-puddling time period [251], and ponding water depth [252] regulate reduction of the percolation rate in the puddled soils. The percolation rate is high during the early growth period but decreases by 35–45% with the advance of the growth stage [253–255].

Re-bound effect: The re-bound effect, a less-known proposition, suggests that when efficiency of using a resource increases, its consumption rate also increases simultaneously [113]. Jevon's contradiction/paradox in economics advocates that any technologies aimed at saving energy actually end up by achieving the contrary of what they were supposed to do. Although the re-bound effect is quite well-known in energy usage [256], it is less known in the irrigation literature. Any intervention to modernize irrigation systems will improve efficiency, reliability and flexibility of the system, with a consequent increase in demand and consumption of water, especially by progressive farmers. The re-bound effect is therefore a potential problem in water resource management as recognized by [117].

Water-saving technologies are promoted based on the supposition that a reduction in water inputs per unit of output makes a comparable water-saving. However, this assumption may not be factual for two reasons. First, whether the quantity of water spared by reducing input transforms into real water-saving depends on the destination of the saved water. A significant part of the applied irrigation water percolates to the underlying aquifer, which can be pumped by the same or other farmers for reuse (Figure 1) and hence is not lost or wasted [212]. So, there is a risk of focusing on local efficiency alone and ignoring the return flows [126]. Secondly, based on economic theory [257], water-saving technologies, by adding more value to water, may encourage farmers to use more water as observed by [114] in Pakistan and Yemen where the overall water usage increased significantly [127,258]. Contrasting evidence is also found in the central United States where new technologies reduced water usage [74].

It is crucial to quantify water extracted and water consumed separately in order to effectively investigate the re-bound effect in irrigation. The usage of extracted water can comprise a consumed part and a non-consumed part. The consumed part may comprise both beneficial and non-beneficial evapotranspiration and runoff or percolation loss that are not recoverable. The non-consumed part comprises parts of the runoff and percolation that are recoverable for further use [213,259]. So, efficiency improvements do not always reduce overall water use; these actually reduce the effective cost of net irrigation encouraging the farmers to achieve more benefit by increasing net irrigation [115,260–262].

4. Regional Hydrology Outcomes

Irrigation water is an important but as yet less characterized component of the hydrological cycle in regions with intensive agricultural irrigation, due to complexity in monitoring [263]. Appropriate differentiation of the natural inter-connection between the surface and groundwater resources is an impending problem [121]. In a highly connected hydrologic system (e.g., EGP), separate management of surface and groundwater will cause conflict in water resource allocation between various sectors (e.g., irrigation, households, industry and fisheries) and exert stress on groundwater-dependent ecosystems [121–123]. Groundwater is mostly a renewable resource in the IGP because of its recharge and depletion mechanisms associated with the regional hydrologic cycle. Water extracted from the aquifers can follow a number of pathways in the hydrologic cycle (Figures 3 and 4), with some travel only over a short distance, and may not join the aquifer [264,265]. Recharge to the aquifers occurs through rainfall, seepage and percolation from rivers and canals, and irrigation return flow [99], with rainfall and irrigation return flow remaining as the major contributors for many groundwater basins ([97,98,102]). So irrigation return flow that depends on soil hydraulic properties and irrigation management practices [266] is an important outcome of irrigated rice fields [96,100,267].

Abstraction of groundwater lowers the water table in aquifers with resulting reduction in groundwater pressure head that induces groundwater recharge by drawing down water from surface sources into aquifers [268,269]. Most rivers in the Bengal Basin, having direct hydraulic contact with aquifer systems [119,120] recharge the aquifers during March to November and receive water from the aquifers during December to February. These water exchange behaviors imply that groundwater tables can be deliberately lowered to more extent in the dry season to accommodate more recharge during the monsoon. This intervention, first put forward in the 1970s [270] and then re-examined occasionally [271], will increase groundwater reserve for irrigation during the dry season and also help control flooding during the monsoon.

Percolation from irrigated rice fields is important to the economy, environment and water resource conservation in irrigated rice-dominated South Asian countries like Bangladesh, India and Taiwan. Flooded rice fields are comparable to wetlands [101,272] and play an important role in raising groundwater level [273]. The recharge potential of rice fields is 69.2 cm for sandy loam and 37.2 cm for clay loam in India [274], between 1–2 mm/day and 7.5 mm/day in Bangladesh [275], and 21.2–23.4% of the applied irrigation water from the terraced rice fields in northern Taiwan [239]. The groundwater-dominated irrigation in Bangladesh has changed the nature of aquifer recharge and the flow patterns of groundwater with a resulting reduction in residence time of water in the aquifer, especially in the shallow aquifers [276]. Recharge from the irrigation fields can be significantly modified by changes in irrigation management practices [77,118].

Adoption of agricultural water-saving technologies at the farm level changes crop-water use and regional hydrology [38] by reducing groundwater recharge. In many groundwater irrigated areas of the EGP (e.g., the North-West region of Bangladesh) the aquifers are not currently recharged fully from other sources (e.g., rainfall and interflow from adjacent aquifers). Consequently, water-saving technologies cause decreased opportunities for groundwater irrigation. There are other factors (e.g., canal lining, reduced water diversion, leveling undulating lands) that also reduce recharge by restricting percolation with eventual decline of groundwater tables. Some countries (e.g., China) widely use mulched-drip irrigation system, which significantly modifies the dynamics of regional groundwater by changing water exchange flux between the irrigation fields and underlying aquifer [39]. The exchange flux at the groundwater table during drip irrigation period is downward and remarkably reduces after adoption of water-saving technologies [39]. Adoption of efficient water-saving measures at regional scales would significantly restrict groundwater recharge with a consequent decline in groundwater levels [40]. This will exert negative impacts on regional hydrology and ecology by degrading soil quality and deforesting, particularly in arid regions [43]. With decades of large-scale groundwater withdrawal and reduced recharge opportunity due to increasing urbanization and decreasing wetlands, water tables have already declined significantly and are continuously declining in many large urban areas (e.g., Dhaka city in Bangladesh) over time [3]. There is, however, evidence of induced groundwater recharge due to the creation of significant vertical head gradients by increasing pumping in areas with shallow water tables and permeable upper soil formation [277]. This implies that dry season abstraction of groundwater can create storage space in the aquifer that can be utilized for harvest in the monsoon. Such intervention would exert a positive contribution on overall water availability in the area [131]. The main threat in the IGP Basin is not considered to be the diminished quantity of groundwater, but the degraded water quality resulting from high arsenic and salt contents [54].

5. Gaps in Current Knowledge

5.1. Uncertainty in Water-Saving

The reported impacts of conservation agriculture on water-saving are yet to be ascertained and evaluated more rigorously [278–282]. Water moves through very complex pathways and the impacts of conservation agriculture are so far understandable only at field-scale, but not at the larger scale [75]. Puddling forms plow pan and also creates soil cracks in addition to preferential flow paths. Consequently, increasing percolation, instead of commonly reported decreasing percolation, has been also reported [283]. In groundwater-based irrigation systems, improved irrigation efficiency and consequent water-saving achieved by reducing irrigation applications with water-saving technologies are clearly understood at the field-scale [115,116]. However, due to the lack of measurement of the water balance components, these are poorly understood at a larger spatial scale [75,106,116,125]. When farmers in a region reduce percolation substantially, which would ultimately recharge a usable aquifer or join to a usable surface water body on the one hand but may also increase the irrigated area with the saved water on the other (Figure 4), the overall impact may be unintended. Instead of saving water, it can actually increase water consumption and reduce water availability for other users [95,116].

The growth period of rice with high evaporative demand can be avoided by shifting planting time. Adoption of short-duration varieties will also reduce evapotranspiration and percolation loss of water. The effects of these alternative crop technologies on water losses and crop yield have not been investigated adequately yet. If field-level estimates of water-saving are extrapolated to larger spatial scales in rice-based cropping systems that utilize recycled water or surface and groundwater conjunctively, there is a possibility of underestimating the real water-saving [284]. The concept of classical irrigation efficiency for an entire basin becomes erroneous and misleading when irrigation management is considered for the water resources of a region as a whole. The discrepancy arises since the water losses with respect to which the classical irrigation efficiency is calculated are not the actual water losses when considering the whole system. It is not possible to clearly know the extent of water-savings until the destination of the lost water is correctly known [95]. It is not yet clear how the water-saving technologies alter the dynamics of overall water balance. Whether application of water-saving technologies can maintain sustainable development and what else needs to be done for this in future are still major questions [39].

5.2. Limited Knowledge of Recharge–Discharge Interaction

Groundwater recharge occurs from several sources (e.g., rainfall, flood water, irrigation return flow, inter-basin transfer, etc.) through several processes, the complexity of which varies widely. In an inefficient surface water irrigation system, a large fraction of the applied irrigation water percolates to the underlying aquifer, causing a significant loss of water when considering irrigation efficiency. However, this irrigation system appears as one of the most efficient methods of recharging groundwater, as occurs in most parts of Bangladesh, India, Pakistan and elsewhere [54,99]. So, the common perception of more efficient irrigation systems that can reduce seepage and percolation losses must be thought about with great caution.

A reliable quantification of groundwater recharge from irrigation fields, although essential in order to know its impending impacts on the dynamics and quality of groundwater, is difficult and remains unresolved in regions with confined aquifers. The groundwater table is confounded with both recharge from irrigation fields and extraction by irrigation wells. Many factors like soil type and surface condition, vegetation, depth to groundwater level, and chemical quality of soil and irrigation water control groundwater recharge. Although groundwater flow and recharge from rice fields have been examined on many occasions e.g., [101,246,285–287], the effects of land use conditions on recharge and groundwater level are not yet clear [288]. When groundwater is abstracted from an aquifer, recharge from surface sources occurs under transient conditions. The knowledge of soil-water flux in the vadoze zone that can help understanding the transient recharge [289] is still limited [290]. Therefore, a major pre-requisite for sustainable groundwater management is to reduce the uncertainty in aquifer recharge from rice fields.

5.3. Uncertain Causes of Groundwater Decline

Large-scale withdrawal of groundwater, increased Boro rice cultivation, dry season reduction in river flow, reduction in wetland areas, declining annual rainfall, low recharge potentiality of soils, and lack of recharging of aquifers through artificial methods are regarded as the major barriers to sustainable groundwater use in the IGP basin [291]. These factors, in their various combinations, are causing decline in groundwater level in some regions in the EGP (e.g., North-West region of Bangladesh; [49]). In a groundwater irrigation system, reduced application of irrigation may be an effective way to check groundwater level depletion [292], although contrasting results were also reported [293–295]. These contrasting opinions and observations raise valid questions of how far irrigation return flow contributes to groundwater recharge.

Field-level water-savings can make water use more profitable by increasing crop-water productivity and may lead to greater total water use in the basin [75,116]. Mere adoption of resource-conservation technologies cannot guarantee overall water-saving unless the usage of saved water can be controlled by proper policies and regulations. However, regional-scale study is still scarce for the evaluation of impacts of water-saving on evaporation and groundwater levels [296]. A proper policy to achieve stabilized groundwater levels must not consider only the adoption of technology and management of users' demand; recharging the aquifer artificially and finding alternative water sources, i.e., supply side management, is also necessary in some situations [64]. To establish sustainable levels of groundwater usage and achieve maximum benefit therefrom, investigation of the feasibility of combination of demand management, recharge improvement and alternative water supplies are crucial [297].

5.4. Inadequate Understanding of Scale-Effects

Improved irrigation methods and conveyance systems are essential to increase efficiency of water use. However, water loss through deep percolation has the possibility of reuse in another region and the quality of percolated water may undergo changes during transmission through the hydrological units. It is therefore essential to account for the usages of surface water and groundwater, losses of water while being used, and interactions of various water components at the field scale and basin scale by adopting a system approach [67]. The common system approach of water accounting requires that, in closed basins, all lost water is presumed to be re-used somewhere downstream and hence any intervention to increase efficiency of water use would not make significant water-savings. So, there is hardly any scope for water-scarce regions to reduce water stress, especially through improvement in efficiency of water use. This approach has three major faults [298]. This disregards a major element of unproductive water use, values only new water without sufficiently considering water productivity in a broader aspect, and fails to account for several co-benefits arising from increasing efficiency of water use (e.g., upgraded water quality, increased reliability and less energy demand). Because of the complexity of the impacts of water-saving technologies at large scales, good approaches must integrate the conceivable spatial and temporal effects. Often a three-dimensional surface-groundwater interaction approach [299] is considered for this; but the problem remains as yet unexplored.

5.5. Weakness in Policy

In the past, agricultural water management generally concentrated attention on irrigation options and water withdrawals from rivers and aquifers. Now it dedicates more attention to managing rainwater, evapotranspiration and water reuse, and views land-use decisions as water-use decisions [103]. In current perceptions of water management, considerable water-savings can be realized if the water-saving options are assessed in terms of technical, economic and institutional aspects and selections are made based on their efficacy [67]. Although technologies play a vital role in reducing water applications per unit of crop production, the re-bound effect is always a problem. If the increase in cultivated area of a certain crop, or even the irrigated area due to the re-bound effect, can be adequately known, the regional impacts of water-saving measures could also be scientifically explainable. However, restricting the demand of water is a challenging issue [75,127] with weak institutional arrangements. In the IGP, instability in the market price of agricultural products often guides the farmers to choose crops irrespective of the set policy. The performances of water-saving technologies contrast, and their adoption is a widely debated issue. Nonetheless, promoting water-saving technologies is a popular policy for governing groundwater in many countries (e.g., Bangladesh, India, China, Spain, Mexico, and the USA). Lack of attention, proper legislation, and ineffective or less-effective institutions are the main difficulties in governing groundwater in many least-developed and developing countries [128]. In cases when aquifers extend across more than one independent country, groundwater governance becomes extremely complex [131].

When the groundwater table is very close to the surface (within capillary rise) the declining groundwater table can increase percolation rates by increasing the hydraulic gradient that would not have happened with a deeper groundwater table. It is speculated that this will offset the gains, at least to some extent, that the adopted water-saving technologies can offer. The recharge of shallow aquifers is therefore an important mechanism that needs to be well-understood for effective management of aquifers [300]. As the scale of water use extends, water loss increases, with resulting decrease in traditional irrigation efficiency. In contrast, water recycling increases with extending scale of water use, with eventual increase in net efficiency except when recycling is not feasible at the system level. This scenario of water usage suggests that the term 'irrigation efficiency' can lead policy planners to miscommunication and misunderstanding. While the problems of groundwater are clearly intuitive, the solutions are not. Enactment of wrong, flawed or misemployed concepts of efficiency in water-resource strategy and management can bring about many unexpected problems [78]. An example is the assumption that the rate of natural groundwater recharge is the safe yield of an aquifer [301]. This water budget myth ignores the factual possibility of increasing recharge and/or decreasing discharge from the aquifer due to groundwater extraction [199]. Our knowledge of the nature of interconnection between surface and groundwater systems over a large spatial scale is not yet adequate. Consequently, many water managers have been suffering in formulating strategy and establishments separately, rather than based on the linked inter-connection of surface water and groundwater. It is important that groundwater systems are treated as complex systems, which respond dynamically to abstraction-induced perturbation. A correct account of the vadoze zone in irrigation fields [302] can enable assessment of the impacts of change and of interventions to be prioritized [77].

Effective governance, although lacking in many countries, is a prerequisite for sound water resource management [129]. Because of existing political structures and systems, adopting a policy of restricting tube wells to reduce groundwater extraction in the IGP basin seems unrealistic. Several states in India have adopted regulations to prevent/minimize groundwater mining but could not implement these regulations totally [303,304]. In Bangladesh, reliable and detailed information on water reserves, safe yield, water withdrawal patterns and groundwater quality dynamics of aquifers is lacking [130]. These knowledge gaps have raised serious concerns about sustainable use of groundwater for irrigation, especially in the North-West region of the country [305]. Recently, emphasis has been placed on increasing dry season Boro rice production in the southern zone to reduce stress on groundwater use in the North-West region [306]. However, the viability of this approach remains to be cross-examined. The potential major restrictive factors are salinity problems of soil and water, weakness in synchronized water governance and the likely effects of climate change in the southern region [130,307,308]. In Bangladesh, there are specific problems in governing groundwater usage. The number of groundwater users is very large, most water users are resource-poor, and the institutional settings are mostly ineffective to ensure execution of laws and regulations. Under such a situation, enforcement of water rights and controlling access to groundwater by permit systems are probably not feasible options. A well-conceived rational and persistent strategy is appropriate for groundwater governance. Some prospective drivers of success may be engagement of users, refinements in water pricing structures, inspiring farmers to move from high to less water-demanding crops [53], in situ rainwater conservation, deficit irrigation, modifying rice–wheat areas [309], extensive investments in technology, and advancement of proactive policies and decision-making systems. Certainly, all these options will not be equally effective at all times and places since groundwater dynamics are localized; local countermeasures, such as managed aquifer recharge, can be implemented [9]. The best option(s) for governing groundwater at specific times and locations must be, however, identified through policy research [130].

Artificial recharge to aquifers through natural drains, canals and topographical depressions is a technically feasible and economically viable option [310] in the EGP. However, this option needs to be within a proper policy framework for its implementation. If groundwater-irrigated areas are not further increased, groundwater levels are expected either not to decline further or decline at much smaller rates than currently. With checked groundwater-irrigated areas, the other possibility is that groundwater levels will attain a new equilibrium that will be lower than at the current level. This proposition, yet to be considered in national policy, implies that the existing abstraction rates of groundwater can be continued and the presumed lower groundwater levels will not hamper the environment and economic and social developments [311]. However, these suggested potentials are only propositions and because of widely variable hydro-climatic, political and socio-economic conditions among the affected regions no single solution will be adequate for groundwater management. The most logical strategy would be to select, from among the available options, regionally-suited strategies and establish strong regulation and policy for management of regional water resources [131–133]. Therefore, sustainable long-term strategies that are appropriate and adaptable for individual regions need to be recognized and exchange of knowledge and actions between regions must be established. Thus, establishing region-specific strategy and communication systems [134] will be important topics for future research in the IGP basin.

6. Summary and Conclusions

Manifold attempts have been made in different regions of the world to increase food production for the rapidly growing population since the early 1960s. There has been great success in increasing food production globally but with a tremendous resulting pressure on the production-linked resources, specifically water and soil. The accelerating stress on these vital resources in the EGP raises sustainability concerns regarding agricultural production systems. Researchers and practitioners have been facing these challenges, both locally and regionally, over the last few decades. They have developed resource-conservation technologies as a response to concerns about agricultural sustainability, with basic principles of rebuilding the soil, optimizing inputs for crop production, increasing food production, and optimizing profits [84,86,87]. This review study has summarized the benefits of these technologies, and the scale-dependency and uncertainty of some of the benefits. Also identified are the gaps in current knowledge regarding the conceptual aspects of these technologies to make agriculture sustainable over a large regional scale so as to guide the future research in proper directions.

Of these resource-conservation technologies, conservation agriculture and water-saving measures are being practiced in many regions of the world, including the EGP [85,87]. Some benefits of these technologies, such as reduced energy and nutrients usage and reduced agrochemical leaching, are scale-invariant and intuitively clear [37,83]. However, the issue of water-saving remains uncertain at the system level since it is both a temporal and spatial scale-dependent element and linked to the regional hydrologic cycle [94,95]. Water saved at the farm level could otherwise join the groundwater or surface water systems to be used later by the same or other users [75,103]. Consequently, whether water-saving achieved at the farm level makes any real saving when considering the entire groundwater or river basin has not yet been adequately investigated. Furthermore, there is evidence of increasing demand for water after adding more value by technological interventions, such as increasing irrigation efficiency by adopting water-saving measures [114]; however, contrasting evidence has also been observed [74]. Whether or not the reduced extraction of groundwater, as well as reduced recharge, under resource-conservation technologies raise groundwater storage/groundwater level or reduce it remains unresolved [306]. Apparently, the reduced extraction of groundwater is expected to increase groundwater storage, but this likelihood is also uncertain since most aquifers in the Gangetic basin discharge to the rivers as base flow in the dry season. Thus, the current level of understanding of the complexity of the hydrological link to field-applied water is inadequate due to lack of measured data on the components of regional water balance. Lack of shared knowledge on the impacts of resource-conservation technologies on regional water balance among the pertinent disciplines, such as agricultural production practitioners (e.g., agronomists, economists, irrigation engineers) and hydrologists (e.g., groundwater hydrologists, surface water hydrologists), is another drawback in planning and implementing holistic approach to investigate regional hydrology outcomes. This inadequate knowledge of inter-linked water systems may lead to the implementation of wrong policy [121–123] merely based on local perspectives with eventual worsening of the water-scarcity situation. Therefore, all pertinent disciplines should adopt integrated research approaches to measure the components of local and regional water balance and quantify regional hydrology outcomes over a large temporal scale. Only then proper water management policy can be planned and implemented for sustainable agricultural production.

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