www.ThePharmaJournal.com

The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2021; SP-10(10): 118-131

www.thepharmajournal.com
Received: 25-08-2021
Accepted: 27-09-2021

RK Naresh
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

PC Jat
ICAR-Indian Institute of Farming System Research (IIFSR), Modipuram, Meerut, Uttar Pradesh, India

M Sharath Chandra
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

SK Gupta
Department of Agronomy, Bihar Agricultural University, Sabour, Bhagalpur, Bihar, India

Sandeep Gawdiya
Department of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi, India

Shivangi
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Brijesh Kumar Pandey
Department of Soil Science & Agricultural Chemistry, V.B.S. Purvanchal University, Jaunpur, Uttar Pradesh, India

SKS Chandel
Department of Soil Science & Agricultural Chemistry, Janta College Bakewar Etawah, Uttar Pradesh, India

Corresponding Author
RK Naresh
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Water-saving technologies and modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources in RWCS: A review

RK Naresh, PC Jat, M Sharath Chandra, SK Gupta, Sandeep Gawdiya, Shivangi, Brijesh Kumar Pandey and SKS Chandel

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. Though India receives a copious annual precipitation of around 4000×10^9 m^3, only around one fourth (1123×10^9 m^3) of it is utilizable. Globally, area equipped for irrigation is currently about 301 million ha of which 38% are equipped for irrigation with groundwater. Total consumptive groundwater use for irrigation is estimated at 545 km^3 yr^{-1}, or 43% of the total consumptive irrigation water use of 1277 km^3 yr^{-1}. Groundwater abstraction from the transboundary Indo-Gangetic Basin comprises 25% of global ground water withdrawals, sustaining agricultural productivity in Pakistan, India, Nepal and Bangladesh.

Recent interpretations of satellite gravity data indicate that current abstraction is unsustainable, yet these large-scale interpretations lack the spatio-temporal resolution required to govern groundwater effectively. Here new evidence from high-resolution in situ records of groundwater levels, abstraction and groundwater quality, which reveal that sustainable groundwater supplies are constrained more by extensive contamination than depletion. The volume of groundwater to 200 m depth to be >20 times the combined annual flow of the Indus, Brahmaputra and Ganges, and show the water table has been stable or rising across 70% of the aquifer between 2000 and 2012. Groundwater levels are falling in the remaining 30%, amounting to a net annual depletion of 8.0 ± 3.0 km^3. Within 60% of the aquifer, access to potable groundwater is restricted by excessive salinity or arsenic. Recent groundwater depletion in northern India has occurred within a longer history of groundwater accumulation from extensive canal leakage. Capitalizing on recent progress in evaporation measurement techniques, we can now close the water balance and directly quantify the exchange flux at the field scale, thus gain a better understanding of regional groundwater dynamics. The comprehensive observations of water balance components in an irrigated cropland were implemented. The water balance analysis showed that the exchange flux and groundwater dynamics were significantly altered by the application of water-saving irrigation. Groundwater recharge sustains groundwater discharge, including natural discharge through springs and the base flow to surface water as well as anthropogenic discharge through pumping wells. Spatial variations in groundwater recharge rates (basin-wide mean: 17 to 960 mm yr^{-1}) were estimated in the major river basins across India. The extensive plains of the Indus–Ganges–Brahmaputra (IGB) river basins are subjected to prevalence of comparatively higher recharge. This is mainly attributed to occurrence of coarse sediments, higher rainfall, and intensive irrigation-linked groundwater-abstraction inducing recharge by increasing available groundwater storage and return flows. However, precipitation rates do not significantly influence groundwater recharge in most of the river basins across India, indicating human influence in prevailing recharge rates. The spatial variability in recharge rates could provide critical input for policymakers to develop more sustainable groundwater management in India.

Keywords: consumptive water use, ecosystem water determinants, environmental sustainability

Introduction

Water is crucial to life on Earth, however, its availability in space and time is not uniform. The near utilization of surface water resources has made the public and Government to look towards groundwater resources to supplement the water supply. The ever increasing demand has resulted in the greater dependence on groundwater and consequently resulting in depletion of groundwater resources in many parts of the country.

In the era of climate change, groundwater may act as a buffering resource in the time of drought and it needs to be managed more intensively to enhance its sustainability. The change in groundwater extraction and rainfall pattern necessitate periodic revision of groundwater resources assessment. Ground Water is the backbone of India's agriculture and drinking water security in urban and rural areas. Nearly 90% of rural domestic water use is based on groundwater while 70% of water used in agriculture is pumped from aquifers. Increasing evidence points to the fact that 50% of urban water usage is groundwater. Groundwater is also important for the industrial sector in a large measure and if left unregulated may lead to serious inter-sectoral conflicts. Hence growth in both agriculture and industry is impingent on how India is able to manage her groundwater resources, particularly the aquifers in different parts of the country. A serious groundwater crisis prevails currently in India due to excessive over-extraction and groundwater contamination covering nearly 60 percent of all districts in India and posing a risk to drinking water security of the population. In addition to over-extraction and biological and chemical contamination, excess groundwater and water logging is also a serious problem in many regions, impacting livelihood security of large sections of society. The acute problems relating to groundwater warrant a change in both the perspective on our aquifers as well as the approach in the use and management of groundwater resources. It is necessary to acknowledge the hydro-geological characteristics of groundwater and its integral link to land, vegetation and surface water resources and perceive it as a 'resource' rather than a 'source'.

The relationship between these two important parameters is complex and depends upon the "aquifers" from which ground water is tapped by wells, tube wells and bore wells; and, in many cases, which supply water to springs. The fundamental basis for good ground water management is a clear understanding of aquifers, and the status of ground water accumulation and movement in these aquifers. Understanding aquifers is primarily based on a proper understanding of the geology of an area– rock types and rock structure. The geological diversity in India makes understanding aquifers challenging, but all the more important because local conditions are important in determining approaches to managing ground water resources. Moreover, these local conditions also define the implications of ground water overuse, droughts, floods etc. on how drinking water security is endangered, both in the short and the long terms. Much of the purpose of the ground water assessment in the country has revolved around the estimation of potential of ground water resources. Given the seriousness of ground water related problems, the estimation of ground water potential is no longer restricted to finding ground water but it also involves understanding aquifers. Sustain growing food demand and increasing standard of living, global water withdrawal increased by nearly 6 times from~500 $km^3\ yr^{-1}$ in1900 to~3000 $km^3\ yr^{-1}$ in 2000, of which agriculture is the dominant water user (≈70%) (Wada *et al*., 2013).

Soaring water withdrawal worsens water scarcity conditions already prevalent in semiarid and arid regions where available surface water is limited due to lower precipitation, increasing uncertainty for sustainable food production and economic development (Vörösmarty *et al*., 2010; Wada *et al*., 2011b). In these regions, the water demand often exceeds the available surface water resources due to intense irrigation which requires large volumes of water during crop growing seasons. Groundwater resources serve as a main source of such intense irrigation, supplementing the surface water deficit (Siebert *et al*., 2010; Wada *et al*., 2012a) [29]. Excessive groundwater pumping, however, often leads to overexploitation, causing ground-water depletion (Gleeson *et al*., 2012; Taylor *et al*., 2013). Moreover, Ganges river depletion is related to groundwater base flow reduction caused by ongoing observed groundwater storage depletion in the adjoining Gangetic aquifers (Ganges basin, −0.30±0.07cm/year or −2.39±0.56 $km^3\ yr^{-1}$). Our estimates show, 2016-basefow amount (~1.0×106 $m^3\ day^{-1}$) has reduced by ~59%, from the beginning of the irrigation pumping age of 1970s (2.4×106 $m^3\ day^{-1}$) in some of the lower reaches. The net Ganges river water reduction could jeopardize domestic water supply, irrigation water requirements, river transport, ecology etc. of densely populated northern Indian plains. River water reduction has direct impact on food production indicating vulnerability to more than 100 million of the population residing in the region. The results of this study could be used to decipher the groundwater-linked river water depletion as well as the regional water security in other densely populated parts of the globe.

The interactions between river water and groundwater are determined by the relative difference between groundwater level and river stage. A river is defined as "gaining" when it is maintained by groundwater seepage (base flow). It may also be defined as "losing" type if river water infiltrates the adjoining aquifer, or the two-way exchange rivers are controlled by seasonal water levels (USGS, 1990). The Ganges river has been described as a perennial, gaining river, being sustained by groundwater discharge (as base flow), specifically during the non-monsoon, dry periods (Kumar *et al*., 2007; Goldin, 2016; Mukherjee *et al*., 2015; Maurya *et al*., 2011) [12, 8, 21, 19] and with maximum flows in the 4 months (June-September) of monsoon season contributed from increased overland flow (>70% of low from rainfall) [Eriksson *et al*., 2009] [4]. In general, the river stage has been suggested to be sustained from overland flow from rainfall in basin hinterland, Himalayan glacial melt [~1500mm/year] [Savoskul and Smakhtin, 2013] [24], along with discharge from groundwater. Therefore, it is a challenging task to quantify the river water availability over the years in the densely populated region. Climate change scenario (Luo *et al*., 2018) [15] and land-use change as a consequence of population growth (Luo *et al*., 2018) [16] further aggravate the situation. In this context, we have tried to investigate the scenario using a combination of in situ, remote sensing based and numerical modeling estimates, along with chemical and isotopic signatures.

In the present assessment, the total annual ground water recharge has been estimated as 432bcm. Keeping an allocation for natural discharge, the annual extractable ground water resource is 393bcm. The total current annual ground water extraction (as in March, 2017) is 249bcm. The average stage of ground water extraction for the country as a whole works out to be about 63%. The extraction of ground water for various uses in different parts of the country is not uniform. Out of the total 6881 assessment units (Blocks/ Mandals/ Talukas/Firkas) in the country, 1186 units in various States (17%) have been categorized as 'Over-Exploited' indicating ground water extraction exceeding the annually replenishable ground water recharge. In these areas the percentage of ground water extraction is more than 100 percent. In addition, 313 units (5%) are ‘Critical’, where the stage of ground water extraction is between 90-100%. There are 972 semi-critical units (14%), where the stage of ground water extraction is between 70% and 90% and 4310 assessment units (63%) have been categorized as ‘Safe‘ where the stage of Ground water extraction is less than 70%. Apart from this, there are 100 assessment units (1%), which have been categorized, as ‘Saline’ as major part of the ground water in phreatic aquifers is brackish or saline.

The over-exploited areas are mostly concentrated in:(i) the north western part of the country including parts of Punjab, Haryana, Delhi and Western Uttar Pradesh where even though the replenishable resources are abundant, there have been indiscriminate withdrawals of ground water leading to over-exploitation; (ii) the western part of the country, particularly in parts of Rajasthan and Gujarat, where due to arid climate, ground water recharge itself is limited, leading to stress on the resource and (iii) the southern part of peninsular India including parts of Karnataka, Andhra Pradesh, Telangana and Tamil Nadu where due to inherent aquifer properties of crystalline aquifers, the ground water availability is low. In some areas of the country, good continuous rainfall and management practices like ground water augmentation and conservation measures through government and private initiatives have resulted in improvement in ground water situation. Ground water resources assessment, like other fields of science, requires continuous refinements.

Van Beek *et al*. (2011) [29] to simulate water withdrawal use and consumptive water use considering water allocation from surface water and groundwater resources and explicitly taking into account feedbacks between supply and demand. Mukherjee *et al.* (2018) [22] suggested that intricate interactions of Ganges river water with groundwater, characterized by general domination of base flow from aquifers to the river in recent times (1.0×10^6 m^3 /d in 2016), which (RI_{sim}) however, has drastically decreased (by ~59%) in comparison to the RI_{sim} values in 1970 (2.4×10^6 m^3/d). Computed response curves of potentiometric hydraulic heads (1970–2015) of the aquifers indicate a decline trend of simulated groundwater level and decrease in associated groundwater storage (GWS_{sim}) anomaly along reach E (−0.68±0.01 cm/year) (−0.64±0.02 cm/ year, Sen’s slope), reach F (−0.42±0.02 cm/year) (−0.35±0.00 cm/year, Sen’s slope), reach G (−0.70±0.05 cm/ year) (−0.53±0.03cm/year, Sen’s slope), and reach H (−0.51±0.07cm/year) (−0.27±0.04cm/year, Sen’s slope), respectively (Fig. 1a). The GWS_{sim} anomalies match well with the GWS_{obs} anomalies (1978–2015, n=540, r=0.62 to 0.96, significant with p values80%) in 2050 (1.3×103 m^3 /d) from present, while the base flow (6.1×105 m^3/d) would decrease further by 38% from present (2016) and 75% of pre-pumping regime of 1970 (Fig. 3a &3b).

The depletion in river water volume will also have profound effect on future food security in Ganges basin, typically known as the “bread-basket of South Asia” (Mukherjee *et al.*, 2015) [21]. The highly productive Indo-Gangetic basin would experience substantial reduction in food production, if groundwater is continued to be extracted in current unsustainable rate (Zaveri *et al.*, 2016) [31]. We assess that in present times, surface water irrigation for cropping account for 27% of the total irrigation in the area. Hence, the dwindling of Ganges River would also severely affect water available for surface water irrigation, with potential future decline in food production. Consequently, according to our estimate, by 2050, the total carbohydrate-based food would be unavailable for almost 1/5th (~115 million) of the >500 million inhabitants of the area. This suggests a strong need for implementing the adaptation options related to either food production or water use in agriculture in the region e.g. water efficient agricultural practices, conversion to lower-water consuming crops, reduced groundwater pumping, aquifer rejuvenation and managed recharge (Bhanja *et al.*, 2017) [1] etc.

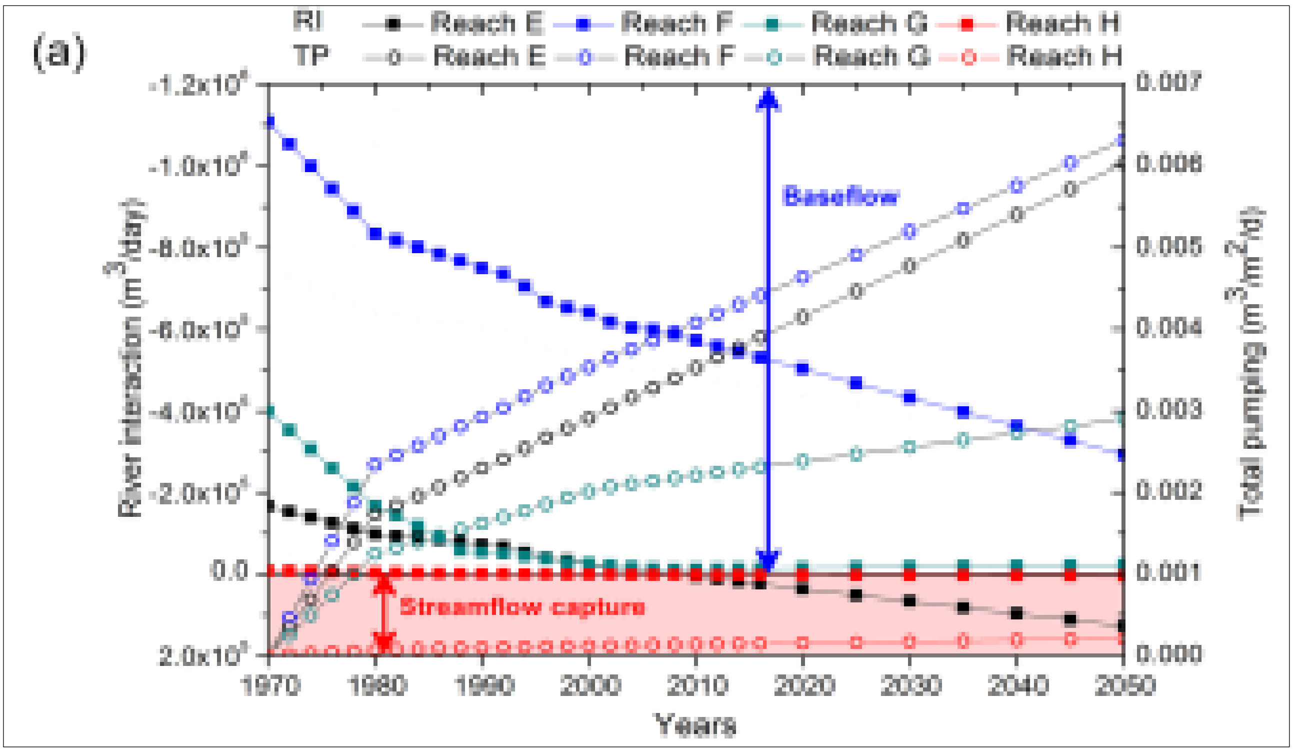


Fig 1a: Simulated response as generated simulating pre-monsoon river interaction (RI) as base flow or Stream flow capture using a hydro geologically-detailed regional groundwater flow model in the adjoining Gangetic alluvial aquifers for the Ganges River reach

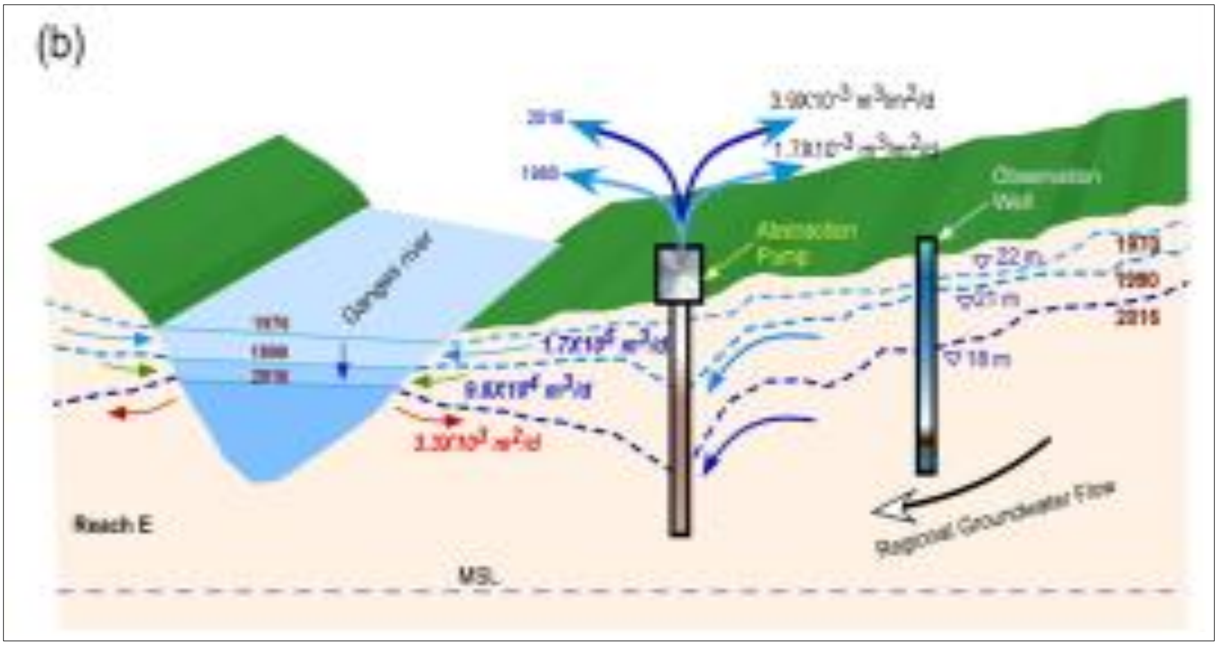


Fig 1b: Conceptual diagram summarizing the hypothetical observations at reach indicating Ganges River pre-monsoon stage decrease from 1970-2016

Wada *et al*. (2014) [30] revealed that water and groundwater withdrawal and consumption over the period 1979–2010 (Fig 2a & 2b). Global water withdrawal and consumptive water use respectively increased from ~ 2000 and ~ 1000 km^3 yr^{-1} in 1979 to ~ 3300 and ~ 1500 km^3 yr^{-1} in 2010. This increase is primarily driven by growth in the agricultural sector (mostly irrigation), accounting for as much as ~ 80% of the total. Most of industrial and domestic water that is withdrawn from surface water and groundwater returns to river systems (40–80%).

Surface water and groundwater withdrawal increased respectively from ~1350 and ~ 650 km^3 yr^{-1} in 1979 to ~ 2100 and ~ 1200 km^3 yr^{-1} in 2010. During the period 1979–1990, groundwater withdrawal increased by ~ 1% per year, while surface water use rose by ~ 2% per year. However, during the recent period 1990–2010, the rate of groundwater withdrawal increased to ~ 3% per year, while that of surface water use decreased to ~ 1%. This is likely due to the fact that surface water has been extensively exploited in response to the consistent increase of global water demands, while the construction of new (large) reservoirs has been decreasing since the 1990s (Chao *et al*., 2008). Kummu *et al*. (2010) [13], and Wada *et al*. (2012a) [29] also report an increasing dependency of consumptive water use on groundwater resources in recent decades.

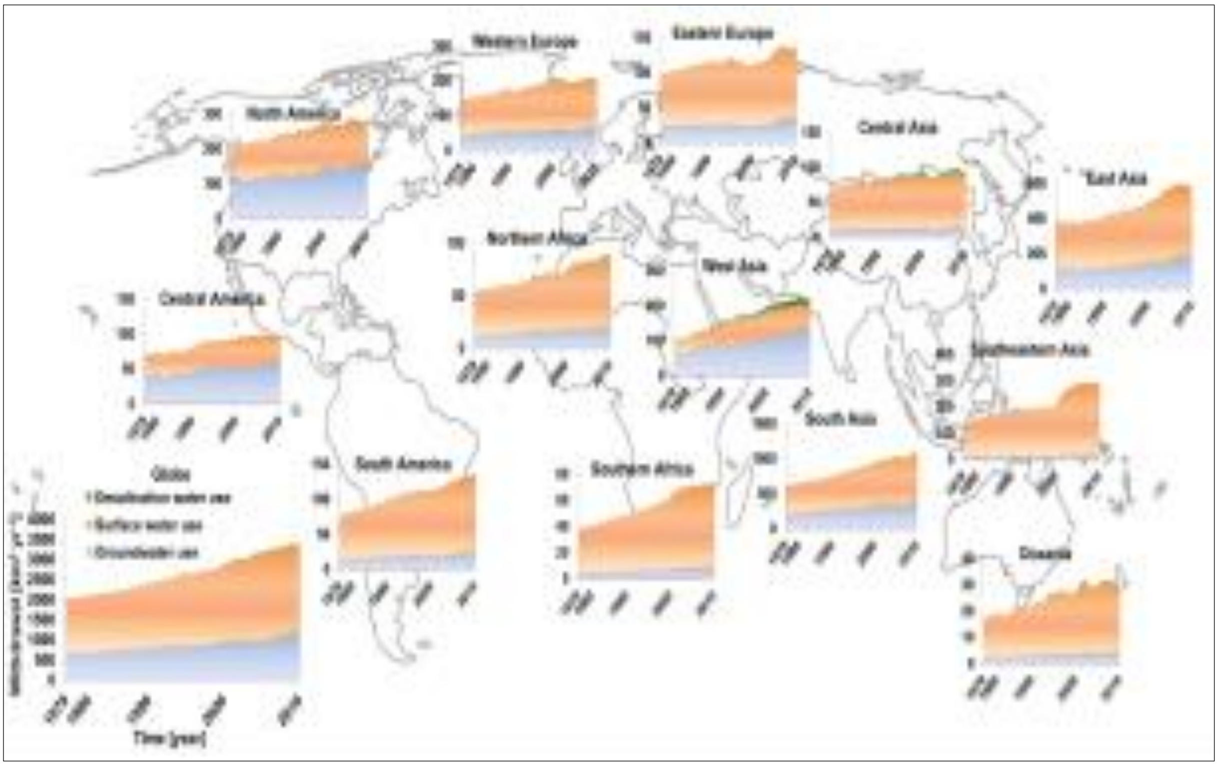


Fig 2a: Regional trends of water withdrawal per source (desalination water, surface water, and groundwater) over the period 1979–2010

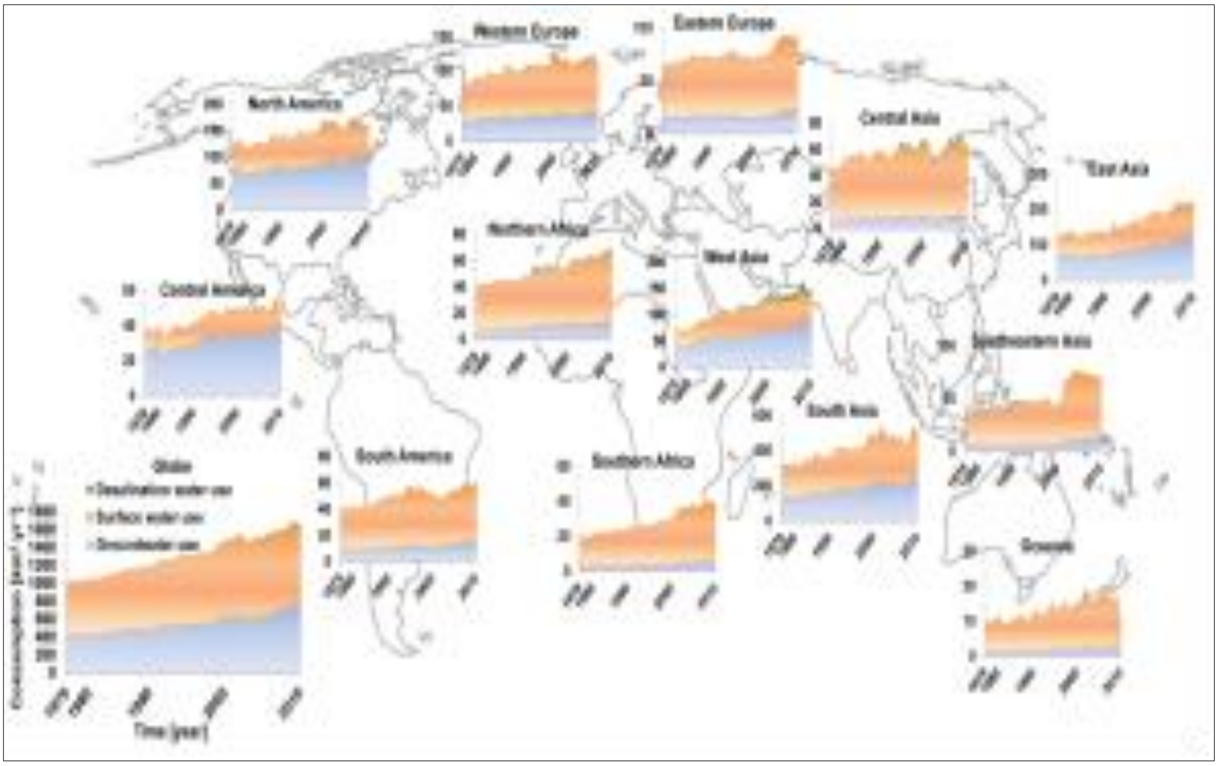


Fig 2b: Regional trends of consumptive water use per source (desalination water, surface water, and groundwater) over the period 1979–2010

Falkenmark, (2003) reported that in the catchment, the land unit within a water divide, the rainfall is shared between terrestrial and aquatic systems, and between nature and human society. This is the areal unit in which a balancing between man and nature may be carried out, as it allows simultaneous attention to the functioning of its living landscape components in terms of biotopes, etc., to human interaction with both land and water, and to water's roles in generating environmental side-effects of human landscape modifications. All the rain falling inside the water divide constitutes the shared water resource of all water-dependent activities there, human as well as ecological. After reaching the land surface, the rainwater is partitioned into the vapour form *green water flow* and the liquid form *blue water flow*. The former consists of the total evaporation, composed of one non-productive part (evaporation from soil, water or canopy), and one productive part (water taken up by plants and returned to the atmosphere as transpiration). The rest moves as blue water flow in rivers and aquifers from uphill to downhill and from land to water systems (Fig 3a).

Moreover, owing to particular water-related natural processes going on in the landscape, these interferences will be reflected in unintended side-effects. Three different water related processes in the landscape are involved in the generation of side-effects of human landscape modifications: **(i)** the *partitioning* of the incoming rainfall at the ground surface, first between flood-flow-forming overland flow and infiltration into the soil, second between evapotranspiration and groundwater recharge;

(ii) water's dissolvent capacity making it a *unique solvent on continuous move* above and below the ground, picking up everything that is water soluble and carrying it along; and

(iii) water's mobility in the *water cycle with its continuity and integrity*, producing continuity-based chain effects in terms of onwards transport from the atmosphere to the ground and the terrestrial ecosystems, then onwards to the groundwater and the rivers, lakes and aquatic ecosystems, and then onwards again to the coastal waters and their ecosystems. The consequence is that rather than assuming stability and explaining change, one needs to assume change and explain stability (Fig.3b).

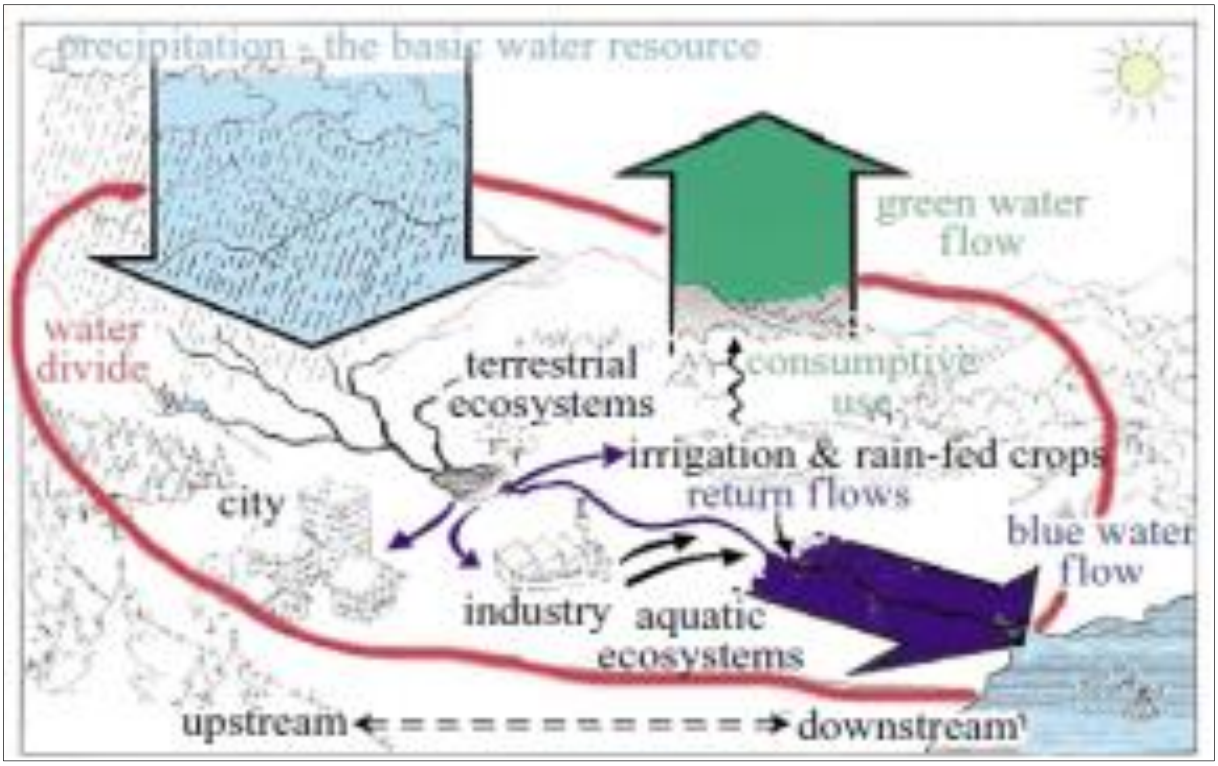


Fig 3a: The catchment allows an integrated approach to all water-related phenomena at work within the water divide

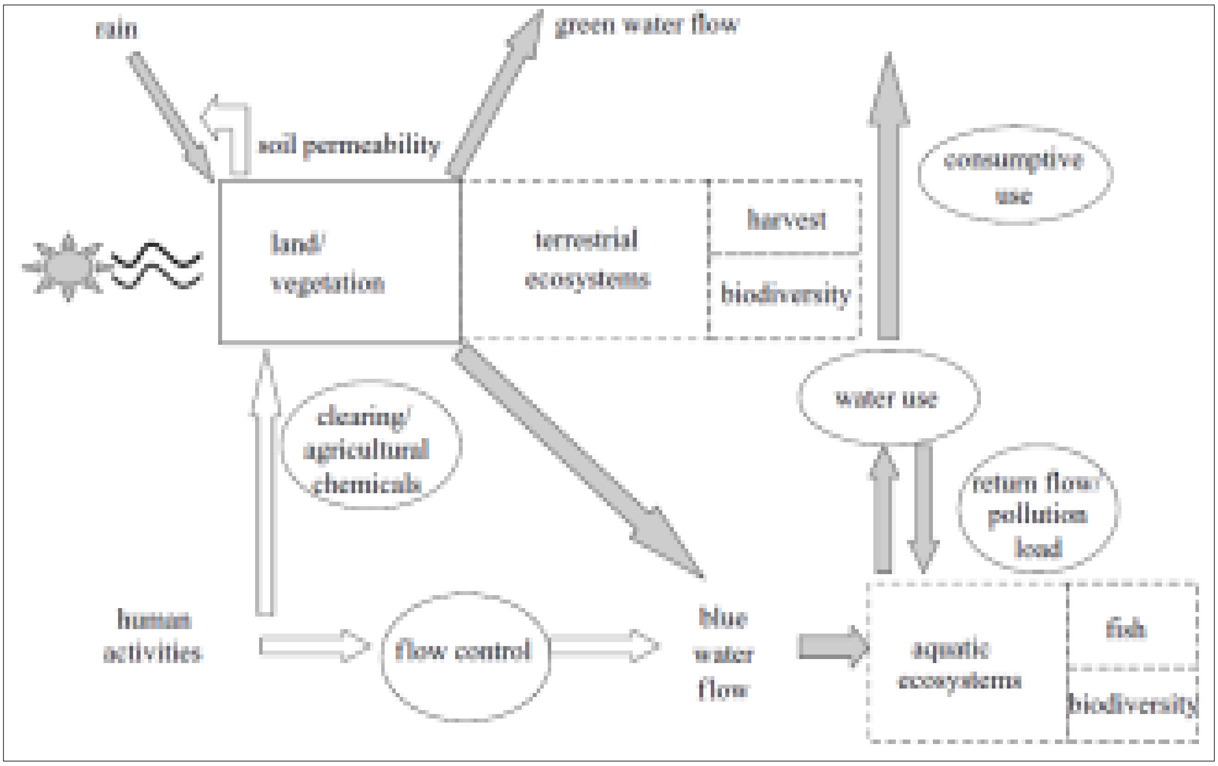


Fig 3b: Ecosystems may be impacted from three different societal entry points: by land-use activities, by water use and introduced pollution load, and by flow control measures

Bhanja *et al*. (2019) [2] reported that the unconsolidated formations of the IGB basin are highly transmissive for the water flow (transmissivity values varies from 250 to 4000 m^2 day^{-1}; Fig. 4a). Horizontal hydraulic conductivity values are found to be higher in the IGB basin (hydraulic conductivity varies from 10 to 800 m day^{-1}; Fig. 4a). As a result, intense groundwater withdrawal at a region within the IGB basin would have a profound impact on the groundwater storage on the surrounding regions (particularly the areas within the periphery of the pumping influence). This would facilitate the creation of the additional recharge space within the entire region. In contrast, comparatively lower transmissivity and hydraulic conductivity values in aquifers of western, central and southern India restrict water to flow in the horizontal direction (Fig. 4a). this inhibits the horizontal flow of water after a pumping event in those regions.

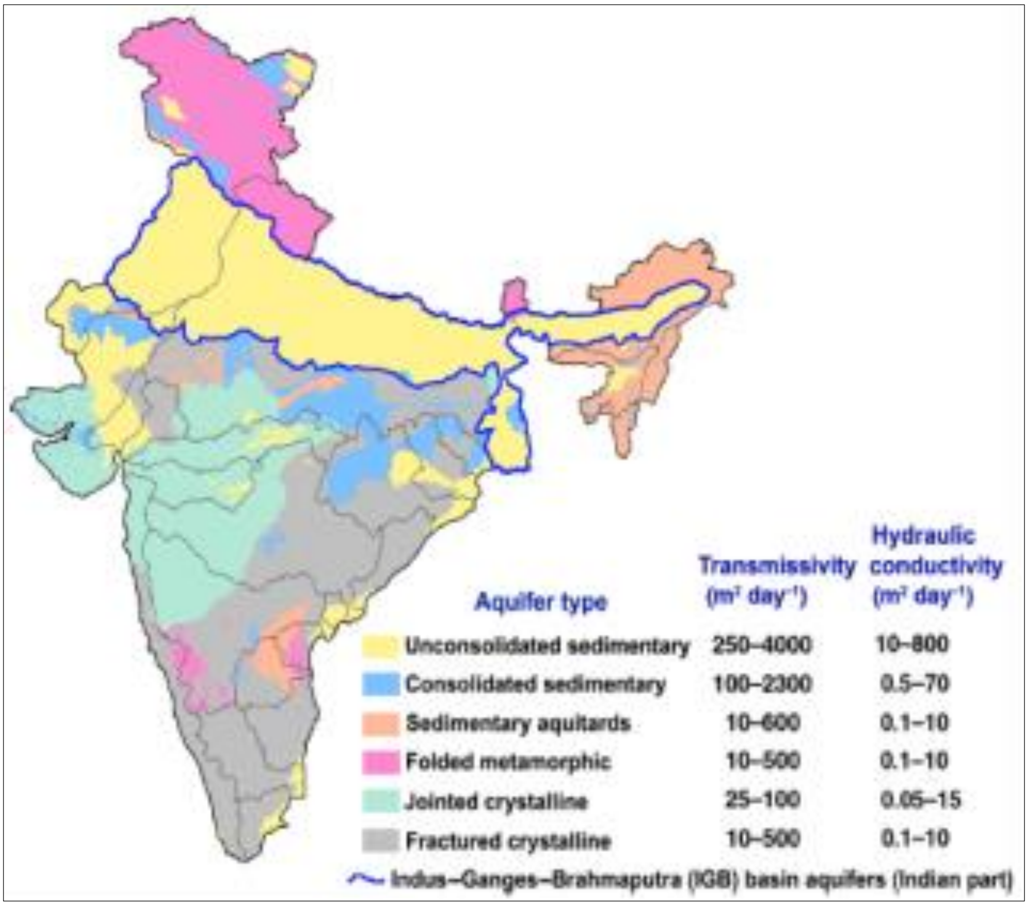


Fig 4a: Aquifer types, transmissivity (m^2 day^{-1}) and horizontal hydraulic conductivity values (m day^{-1})

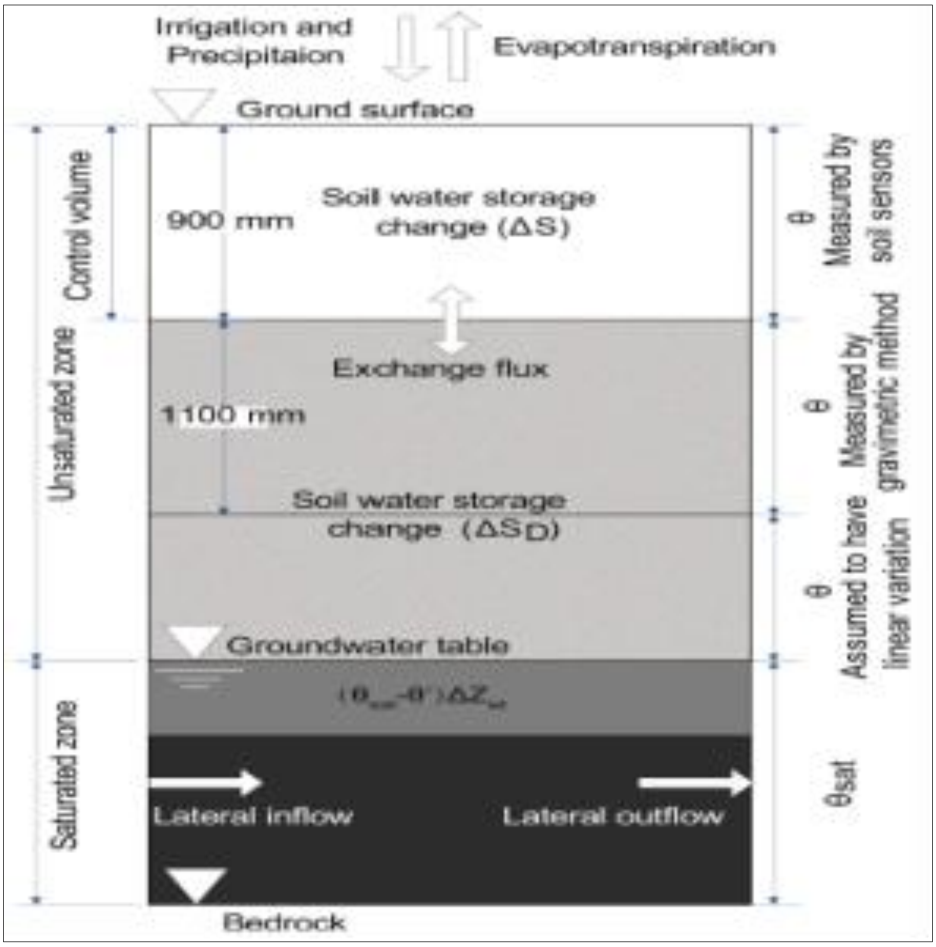


Fig 4b: Analysis zone for water balance and groundwater dynamics

Hossain and Bhatt, (2019) [9] revealed that climate smart technologies (CSTs) recommended improving the waning productivity of irrigation water in the region. However, these CSTs are not universally applicable and their performance in meeting their objective depends upon divergent soil textural class and agro-climatic conditions. In terms of effective use of irrigation water in relation to food grain production, therefore increasing water productivity is the best pointer for making an assessment of different management tools (Tuong and Bhuiyan, 1999) [26] in the area. Although, it is dependent on the performance of differentiated technologies in diverse types of soils, and also their impact must be estimated by directing more and more number of field observations. Further, supplementary food has to harvest from the natural assets. For example, land and water resources are inadequate, thus their per capita accessibility both in terms of quantity and quality deteriorated in the past three decades (Table 1). Generally, people are starved not because of lack of availability but mostly because of accessibility. In worldwide, out of total available water, only about 2.7% is fresh water, therefore it is an urgent issue for judicious use of water for enhancing water productivity in agriculture as well as other sectors also.

Table 1: Water availability (per capita) in major rice-growing countries in Asia during 1950–2050 Source: (Gardner-Outlaw and Engelman, 1997)

Country	1950	1995	2000	2005	2010a	2015a	2020a	2025a	2050a
					M^3				
China	5047	2295	2210	2134	2068	2006	1956	1927	1976
India	5831	2244	2000	1844	1717	1611	1525	1557	1292
Japan	6541	4374	4314	4292	4307	4348	4423	4528	5381
Indonesia	31,809	12,813	12,325	11,541	10,881	10,361	9952	9609	8781
Nepal	21,623	7923	6958	6245	5695	5230	4820	4470	3467
Pakistan	15,390	3435	3159	2822	2533	2277	2069	1900	1396
Phillipines	11,822	4761	4158	3778	3450	3175	2945	2754	2210
Sri Lanka	5626	2410	2302	2212	2117	2041	1990	1961	1990
South Korea	3247	1472	1424	1390	1363	1345	1336	1336	1500
Thailand	8946	3073	2871	2714	2627	2559	2505	2465	2440

Mojid and Mainuddin, (2021) [20] also reported that whenwater is applied in a crop field, not all of it is consumed Fig. 5a. 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 (MacDonald *et al*., 2016) [17]. A large part of the applied irrigation water infiltrates below the root zone and is stored in the underlying aquifer (Bhanja *et al*., 2019; Chen *et al*., 2016) [2] or in downstream surface water bodies. Fig. 5b 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 (Foster *et al*., 2003) [5] but is a gain to the local surface and sub-surface hydrological systems. The efficiency of water usage at any separate component within the hydrological system may be low, but the overall efficiency of the entire system can be much higher than in the individual components. The water flux exchanging between the aquifer and vadoze zone greatly controls the dynamics of the groundwater table (Zhang *et al*., 2014) [32] thus raising a valid question of how the currently advocated water-saving measures impact on the hydrological cycle of a groundwater basin.

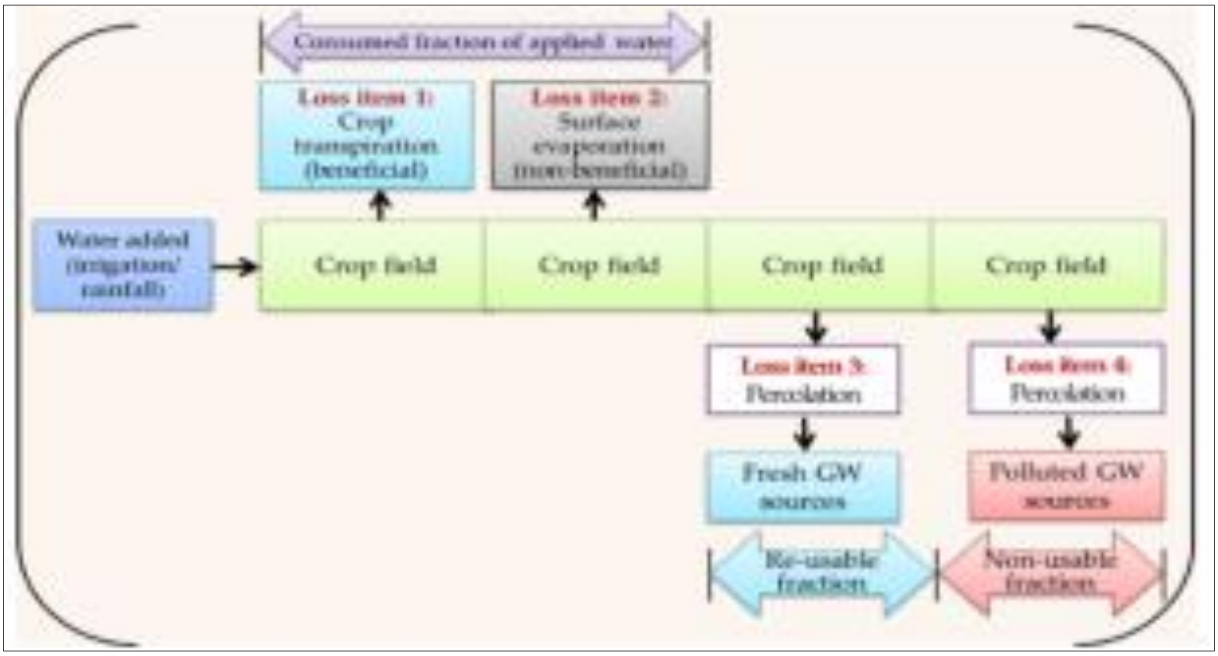


Fig 5a: Utilization and fate of applied water to crop fields and hydrological links to groundwater resources

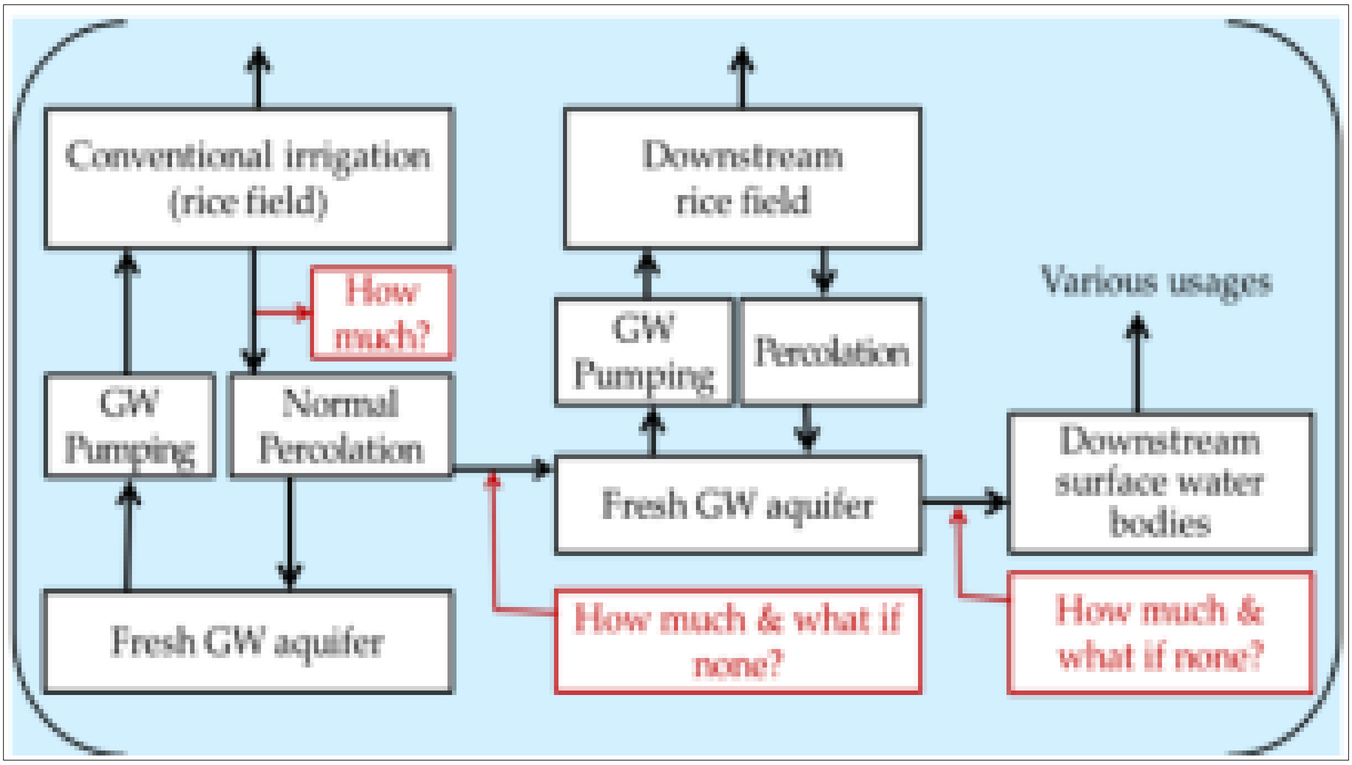
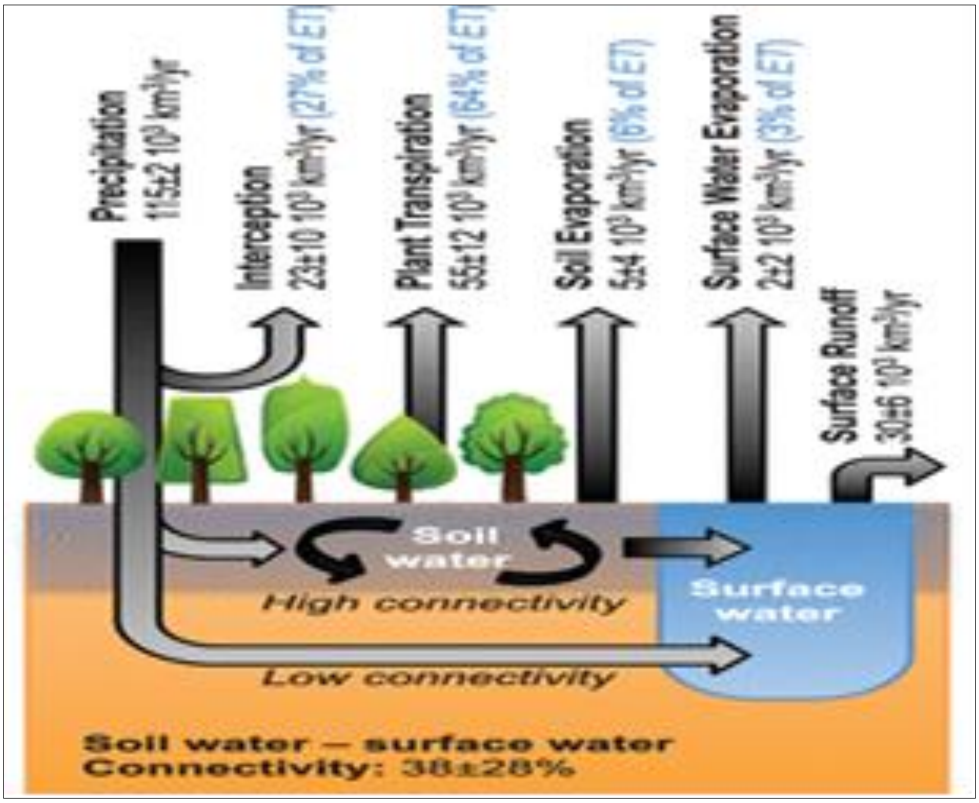


Fig 5b: The pathways of the components of water from a rice field under conventional irrigation with groundwater

Terrestrial precipitation (annual mean ± 1 SD) not intercepted by vegetation mixes into soils or flows into surface waters. Soil water is withdrawn by plant roots via transpiration, subjected to evaporation, and leaks into the surface water (Fig.6).

Of the flux entering the surface waters, our results suggest that 38% is derived from the soils, with the remainder being consistent with precipitation routed directly via preferential flow paths. Surface water that does not evaporate returns to the ocean as runoff



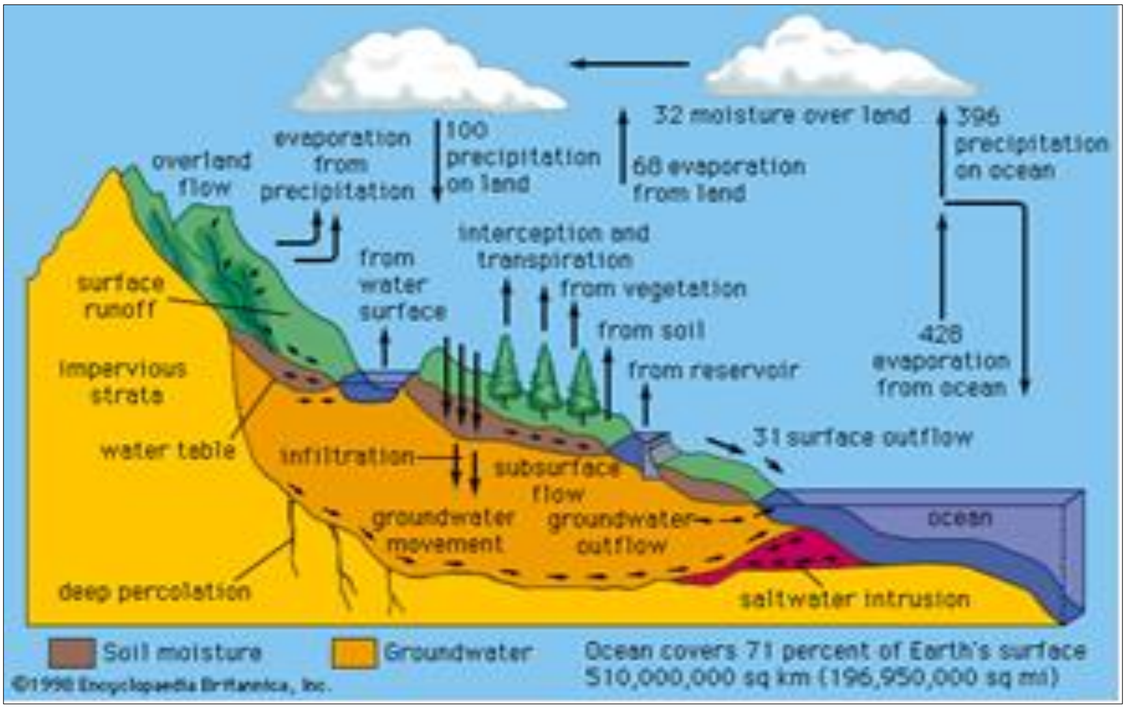


Fig 6: Partitioned continental hydrologic fluxes

Zhang *et al*. (2014) [32] reported that the regional groundwater balance clearly, representative sketches of seasonal groundwater dynamics Fig. 7a. When irrigation was implemented the groundwater table rose significantly. Then the groundwater table declined after irrigation periods and the rates gradually decreased when the water table became lower. The lateral flow out of the analysis zone was expected to be high due to the recharge caused by irrigation and the high groundwater table. However, the outflow rate indicating that the lateral flows into this zone was also significant. In fact, snowmelt happened during spring and summer, and the precipitation was also concentrated in the summer period. They resulted in significant subsurface. Similarly, the natural stage, the anthropogenic activities had limited impacts on water resources. The groundwater table did not change much and the water table was relatively deep (Fig. 7b). Oases were restricted along the river and isolated from each other. Natural factors dominated the hydrologic cycle and socio-economic development (Liu *et al*., 2014) [14]. Rivers had sufficient water to support the natural vegetation in the riparian areas. The relationship between surface water and groundwater was quite weak during this stage.

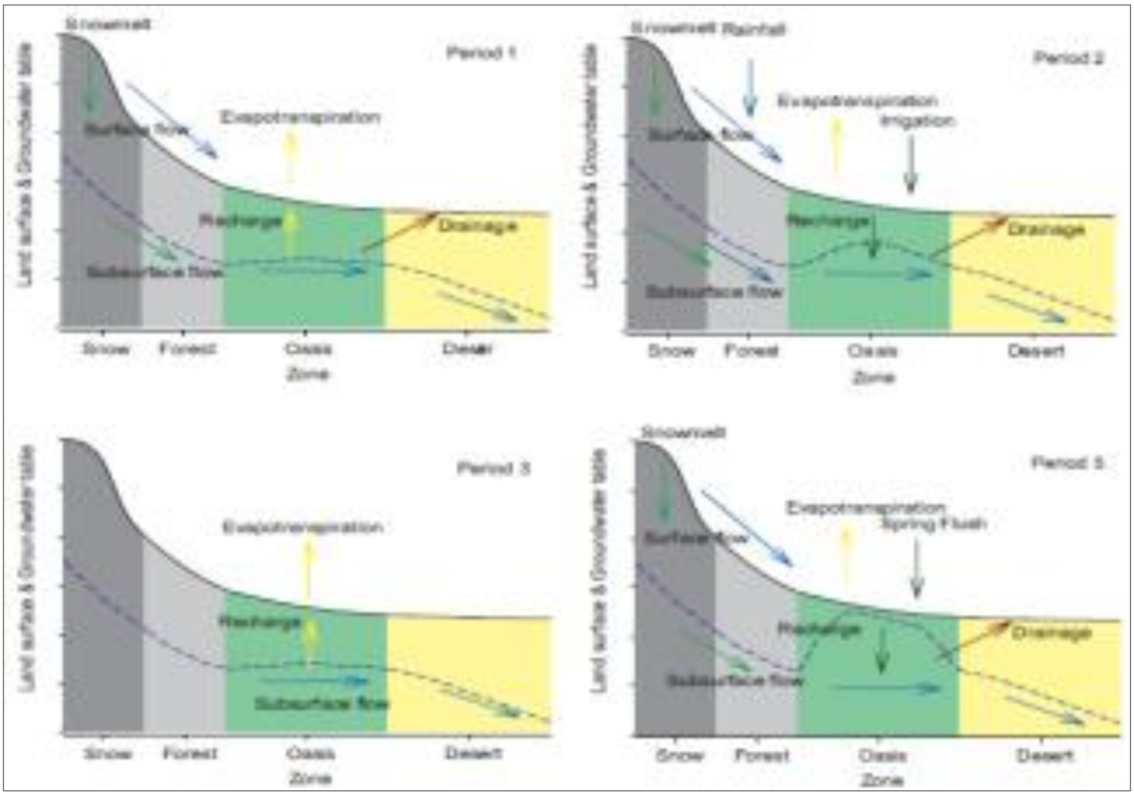


Fig 7a: Sketch of seasonal groundwater dynamics

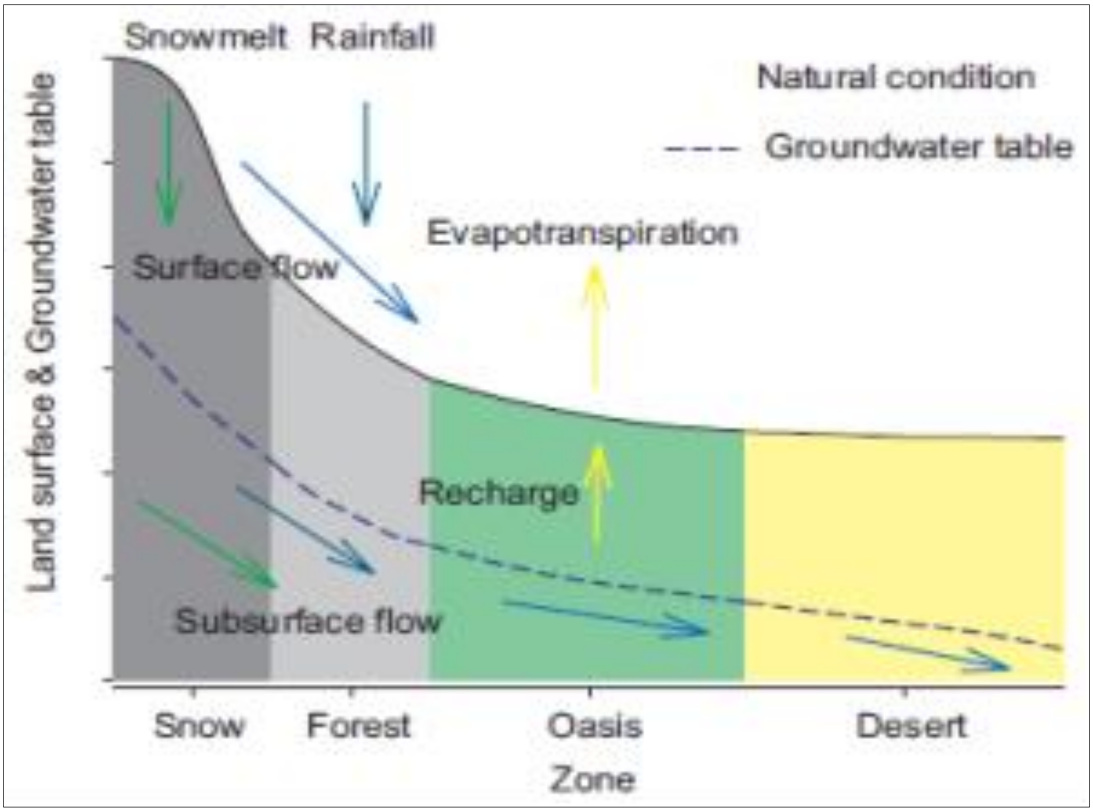


Fig 7b: Groundwater dynamics in the natural stage

The impact of efficiency of water consumption and water productivity on water saving has been investigated at field scale on several occasions (Igbadun *et al*., 2008; Karam *et al*., 2007) [10, 11]. Any effort toward improving irrigation efficiency is valuable but the commonly used concepts of water-use efficiency underestimate the system-level's actual efficiency (Seckler *et al*., 2003) [25]. 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 fields ends up at any of, or a combination of, consumptive use, non-consumptive use, non-recoverable flow and change in storage (Perry *et al*., 2017) [23]. 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 Fig.8a. This water-saving does not account for return flows from the irrigated field that may be either non-recoverable outflow Fig. 8b or recoverable outflow, where it ends up in rivers or as useable groundwater source (Perry *et al*., 2017) [23]. The return flow may be a significant contributor to groundwater recharge (Giordano, 2009; Tuong *et al*., 2005) [7, 27].

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 (Masih and Giordano, 2014) [18]. 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 (Perry *et al*., 2017) [23].

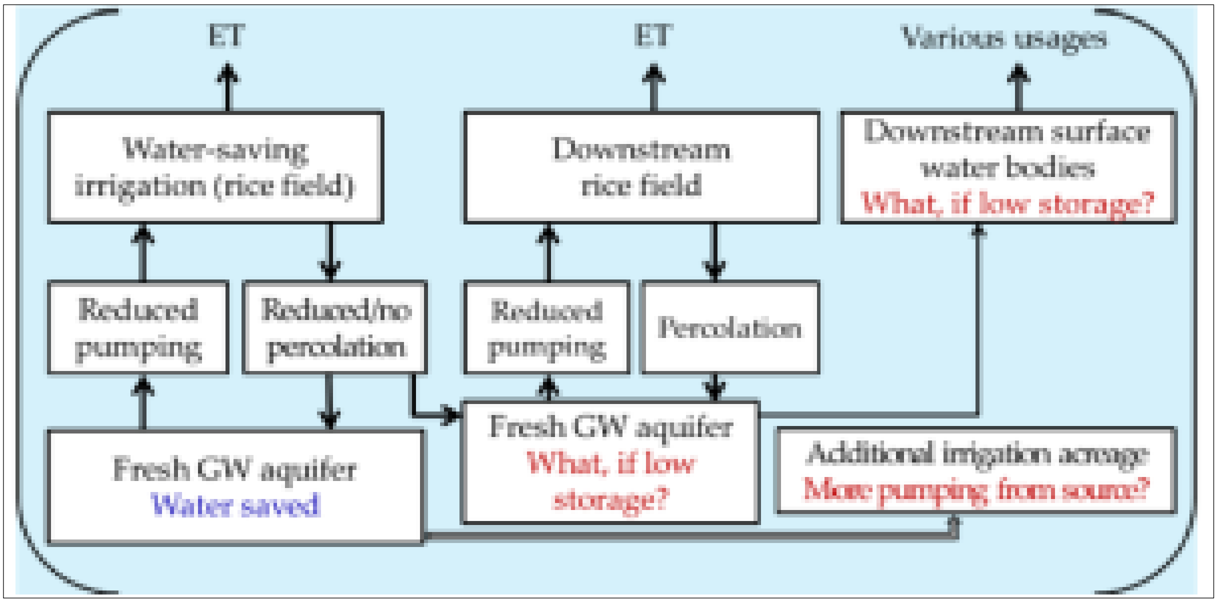


Fig 8a: Impacts of water-saving measures on regional surface and groundwater sources when irrigation uses groundwater

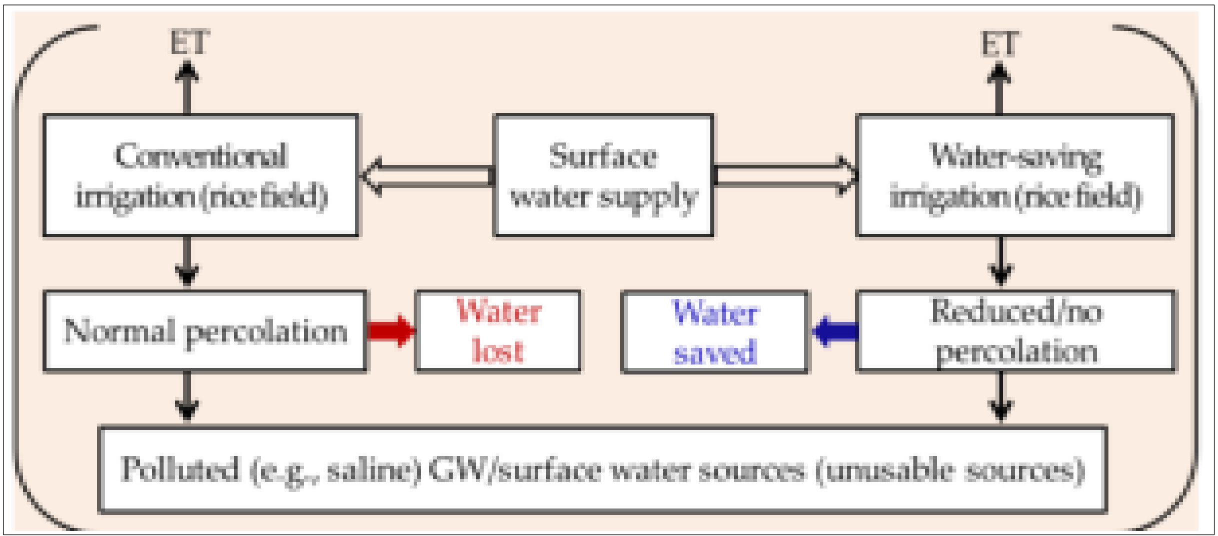


Fig 8b: Water loss and water saving issues under conventional and water-saving irrigation from surface water sources when underground aquifer contains polluted water

Conclusions

India is a country with intensive groundwater-fed irrigated agriculture; and the large extraction of groundwater for food production has created concerns about the sustainability of groundwater resources for both current and future citizens. The model identification confirm that the integrated hydrologic-groundwater use model can capture groundwater storage depletion in northwest India and therefore can serve as a promising predictive modeling tool to quantify the anthropogenic impact of irrigation on groundwater resources in the region. The assessment results suggest that, without consideration of the effect of changes in cropping patterns and irrigation water use efficiency, it is well possible that climate change will ameliorate the groundwater deficit in northwest India. However, the beneficial effect is not strong enough to reverse depletion trends. Global water withdrawal and consumptive water use respectively increased from ∼ 2000 $km^3 yr^{-1}$ and ∼ 1000 $km^3 yr^{-1}$ in 1979 to ∼ 3300 $km^3 yr^{-1}$ and ∼ 1500 $km^3 yr^{-1}$in 2010. Moreover, groundwater withdrawal increased by ∼ 1% per year, while surface water use rose by ∼ 2% per year. However, the rate of groundwater withdrawal increased to ∼ 3% per year, while that of surface water use decreased to ∼ 1%. The fact that surface water has been extensively 20 exploited in response to the consistent increase of global water demand.

In general, anthropogenic activities have significantly affected the water balance and groundwater dynamics. After the application of water-saving irrigation, the downward exchange flux is greatly reduced during irrigation periods, while the upward flux is trivial during non-irrigation periods due to the moderate groundwater table depth. Some problems such as salinization induced by shallow groundwater table are mitigated, while new challenges also emerge. The water savings resulting from water saving irrigation have not remained in the river to recharge the groundwater for ecologic use. In fact, they have instead been reused towards the expansion of irrigation croplands, resulting in even more water consumption. The continued decline of the groundwater table will lead to the destruction of the natural vegetation that relies on the groundwater and this will further result in the degradation of the whole ecosystem. In addition, the salinization risk still exists due to the insufficient leaching water under water-saving irrigation.

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. 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.

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 and hydrologists is another drawback in planning and implementing holistic approach to investigate regional hydrology outcomes.

The scientifically best developed area in relation to freshwater management is *aquatic ecosystems*, their value and what key determinants should be entered into water management. The real challenge is to find out what is the ‘best possible manipulation’, not the ‘least possible manipulation’. The scientific community should activate itself in developing a synthesized human ecology which pays adequate attention to the multitudes of roles and functions of water, the bloodstream of the biosphere. Moreover, to facilitate a mutual understanding between ecologists and water managers, ecologists need to be more limpid and specific when using the extremely broad concept ‘ecosystem’.

References

1. Bhanja SN, Abhijit Mukherjee A, Rodell M, Wada Y, Chattopadhyay S *et al*. Groundwater rejuvenation in parts of India influenced by water-policy change implementation. Sci Rep 2017;7:7453.
2. Bhanja SN, Mukherjee A, Rangarajan R, Scanlon BR, Malakar P, Verma S. Long-term groundwater recharge rates across India by in situ measurements. Hydrol. Earth Syst. Sci 2019;23:711-722.
3. Chen H, Liu Z, Huo Z, Qu Z, Xia Y, Fernald A. Impacts of agricultural water saving practice on regional groundwater and water consumption in an arid region with shallow groundwater. Environ. Earth Sci 2016;75:1204.
4. Eriksson M *et al*. The changing Himalayas: Impact of climate change on water resources and livelihoods in the greater Himalayas, ICIMOD 2009.
5. Foster S, Tuinhof A, Kemper K, Garduno H, Nanni M. Groundwater Management Strategies: Facets of the Integrated Approach; (No30091, 1). The World Bank: Washington, DC, USA 2003.
6. Gardner-Outlaw T, Engelman R. Sustaining Water, Easing Scarcity: A Second Update. Population Action International, Washington, DC 1997, 19.
7. Giordano M. Global groundwater? Issues and solutions. Annu. Rev. Environ. Resour 2009;34:153-178.
8. Goldin T. Groundwater: India’s drought below ground. Nature Geo-science 2016;9:98-98.
9. Hossain A, Bhatt R. Intervention of Climate Smart Technologies for Improving Water Productivity in an Enormous Water Use Rice-Wheat System of South-Asia. Int Lett Nat Sci 2019;75:27-35.
10. Igbadun HE, Salim BA, Tarimo AKPR, Mahoo HF. Effects of deficit irrigation scheduling on yields and soil water balance of irrigated maize. Irrig. Sci 2008;27:11-23.
11. Karam F, Lahoud R, Masaad R, Kabalan R, Breidi J, Chalita C *et al*. Evapotranspiration, seed yield and water use efficiency of drip irrigated sunflower under full and deficit irrigation conditions. Agric. Water Manag 2007;90:213-223.
12. Kumar B *et al*. Stream flow modelling of Bhagirathi River: Hydrograph separation using isotopic and Geo-chemical Techniques. Technical Report, CS/AR-2/2006-07, National Institute of Hydrology, Roorkee 2007.
13. Kummu M, Ward PJ, de Moel H, Varis O. Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia, Environ. Res. Lett 2010, 5, 034006, doi:10.1088/1748-9326/5/3/034006.
14. Liu Y, Tian F, Hu H, Sivapalan M. Socio-hydrologic perspectives of the co-evolution of humans and water in the Tarim River basin, Western China: the Taiji-Tire model, Hydrol. Earth Syst. Sci 2014;18:1289-1303.
15. Luo P *et al*. Impact of forest maintenance on water shortages: Hydrologic modeling and effects of climate change. Science of the Total Environment 2018;615:1355-1363.
16. Luo P, He B, Duan W, Takara K, Nover D. Impact assessment of rainfall scenarios and land-use change on hydrologic response using synthetic Area IDF curves. Journal of Flood Risk Management 2018;11:S84-S97.
17. MacDonald AM, Bonsor HC, Ahmed KM, Burgess WG, Basharat M, Calow RC *et al*. Groundwater Quality and Depletion in the Indo-Gangetic Basin Mapped From in Situ Observations. Nat. Geosci 2016;9:762-766.
18. Masih I, Giordano M. Constraints and opportunities for water savings and increasing productivity through Resource Conservation Technologies in Pakistan. Agric. Ecosyst. Environ 2014;187:106-115.
19. Maurya AS *et al*. Hydrograph separation and precipitation source identification using stable water isotopes and conductivity: River Ganga at Himalayan foothills. Hydrological Processes 2011;25:1521-1530.
20. Mojid MA, Mainuddin M. Water-Saving Agricultural Technologies: Regional Hydrology Outcomes and Knowledge Gaps in the Eastern Gangetic Plains-A Review. Water 2021;13:636.
21. Mukherjee A *et al*. Groundwater systems of the Indian Sub-Continent. Journal of Hydrology: Regional Studies 2015;4:1-14.
22. Mukherjee A, Bhanja SN, Wada Y. Groundwater depletion causing reduction of base flow triggering Ganges river summer drying. Sci Rep 2018;8:12049 | DOI:10.1038/s41598-018-30246-7
23. Perry C, Steduto P, Karajeh F. Does Improved Irrigation Technology Save Water? A Review of the Evidence; FAO, United Nations: Cairo, Egypt 2017, 42.
24. Savoskul OS, Smakhtin V. Glacier systems and seasonal snow cover in six major Asian river basins: hydrological role under changing climate. International Water Management Institute, IWMI Research Report 2013, 150.

25. Seckler D, Molden D, Sakthivadivel R. The concept of efficiency in water resources management and policy. Water Product. Agric. Limits Oppor. Improv 2003;1:37-51.
26. Tuong TP, Bhuiyan SI. Increasing water-use efficiency in rice production: farm-level perspectives. Agri Water Manag 1999;40(1):117-122.
27. Tuong TP, Bouman BAM, Mortimer M. More rice, less water-integrated approaches for increasing water productivity in irrigated rice based systems in Asia. Plant Product. Sci 2005;8:231-241.
28. US Geological Survey (USGS). Effects of Groundwater development on groundwater flow to and from surface-water bodies. Sustainability of Ground-Water Resources-Circular 1990, 1186.
29. Wada Y, van Beek LPH, Bierkens MFP. Nonsustainable groundwater sustaining irrigation: A global assessment, Water Resour. Res 2012a, 48, W00L06, doi: 10.1029/ 2011 WR010562.
30. Wada Y, Wisser D, Bierkens MFP. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dynam 2014;5:15-40.
31. Zaveri E *et al*. Invisible water, visible impact: groundwater use and Indian agriculture under climate change. Environmental Research Letters 2016;11:084005.
32. Zhang Z, Hu H, Tian F, Yao X, Sivapalan M. Groundwater dynamics under water-saving irrigation and implications for sustainable water management in an oasis: Tarim River basin of western China. Hydrol. Earth Syst. Sci 2014;18:3951-3967.