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Basin-wide water accounting based on remote sensing data: an application for the Indus Basin

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Abstract. The paper demonstrates the application of a new water accounting plus (WA+) framework to produce information on depletion of water resources, storage change, and land and water productivity in the Indus basin. It shows how satellite-derived estimates of land use, rainfall, evaporation (E), transpiration (T), interception (I) and biomass production can be used in addition to measured basin outflow, for water accounting with WA+. It is demonstrated how the accounting results can be interpreted to identify existing issues and examine solutions for the future. The results for one selected year (2007) showed that total annual water depletion in the basin (501 km^3) plus outflows (21 km^3) exceeded total precipitation (482 km^3). The water storage systems that were effected are groundwater storage (30 km^3), surface water storage (9 km^3), and glaciers and snow storage (2 km^3). Evapotranspiration of rainfall or "landscape ET" was 344 km^3 (69 % of total depletion). "Incremental ET" due to utilized flow was 157 km^3 (31 % of total depletion). Agriculture depleted 297 km^3, or 59 % of the total depletion, of which 85 % (254 km^3) was through irrigated agriculture and the remaining 15 % (44 km^3) through rainfed systems. Due to excessive soil evaporation in agricultural areas, half of all water depletion in the basin was non-beneficial. Based on the results of this accounting exercise loss of storage, low beneficial depletion, and low land and water productivity were identified as the main water resources management issues. Future scenarios to address these issues were chosen and their impacts on the Indus Basin water accounts were tested using the new WA+ framework.

1 Introduction

The aim of water accounting is to track inflows and outflows, assets, liabilities, stocks and reserves for a particular area over a period of time. Outcomes are essential for both current and future water management decisions. Water accounting principles are described in detail by for instance Godfrey and Chalmers (2012). Availability of data on water flows and consumption is a major constraint for reliable accounting in river basins worldwide. For this reason, data intensive water accounting frameworks such as the United Nations System for Environmental and Economic Accounting for Water (SEEAW) (UN, 2007), which tracks water withdrawal by different sectors, are not commonly implemented (Karimi et al., 2012).

Water accounting plus (WA+) (Karimi et al., 2013) presents water accounts of river basins using four sheets including (i) a resource base sheet, (ii) an evapotranspiration sheet, (iii) a productivity sheet, and (iv) a withdrawal sheet. The *resource base sheet* gives information on water volumes. Water supply and water depletion processes are presented. The *evapotranspiration sheet* shows how beneficial the water depletion is. The *productivity sheet* shows links between water depletion and biomass production, carbon sequestration, crop production and water productivity. The *withdrawal sheet* provides information on water withdrawals and reuse. The latter sheet is relevant for managing the water cycle and meeting water allocation agreements. Every sheet has a set of indicators that summarizes the overall water resources situation. WA+ explicitly recognizes the influence of land use on the water cycle. To provide the link between water balance, land use and water use, and management options to modify it, WA+ groups land use classes with common management characteristics into the following: conserved land use (CLU), utilized land use (ULU), modified land use (MLU), and managed water use (MWU). CLU includes National Parks and other protected areas, ULU is land use with intensive ecosystem services, MLU is land with human influences such as the cultivation of rainfed crops, plantations and soil treatment. Withdrawals in the MWU class is by means of man-made infrastructure (diversion dams, canals, ditches, pumping stations, gates, weirs, pipes, etc).

The large Indus basin, with many challenging water problems (Eastham et al., 2010; Qureshi, 2011), was selected to illustrate the WA+ applications. The fundamental data on water resources and distributed flows in basins such as the Indus basin are limited and the majority of the basin is ungauged. The size of the basin, budget constraints and its transboundary nature hamper the establishment of a comprehensive measurement network. For example, less than four rain gauge stations are available per 10 000 km^2. The situation is worse for in situ soil moisture and evapotranspiration measurements. Information on land use and crop rotation systems is similarly scant. Available databases are old, coarse and do not cover the entire basin. Satellite-derived data can improve such inadequacies. The application of WA+ in the basin is described using an "accounting period" of one year. The year 2007 was selected due to availability of remote sensing (RS) data (Cheema, 2012). The objective of this paper is thus to demonstrate how WA+ can contribute to describing the water resources conditions of a basin and how it can be used to identify and assess the impact of potential solutions to the water problems. It is important to note that, since this study is only based on one year accounting, results should be treated with caution and it would be premature to use them to formulate recommendations to the agencies of the Indus Basin.

2 The Indus basin

The Indus basin (Fig. 1) occupies an area of 1 160 000 km^2 in total. It is shared by Pakistan, India, China, and Afghanistan, each respectively occupying 53, 33, 8, and 6 % of the basin area. With a population of about 250 million, the basin is among three major highly populated river basins in South Asia alongside the Ganges and Brahmaputra basins. The climate is primarily arid and semi-arid. Hence rainfed agriculture is insufficient to feed the growing population, and food production relies on irrigation. The basin is home to one of the biggest and most intensive irrigation schemes in the world: the Indus Basin irrigation system (IBIS) with an estimated command area of approximately 16 000 000 ha. Including the Indian part of the Indus basin, the total irrigated area is 26 000 000 ha, comprising 22 % of the total area of the basin.

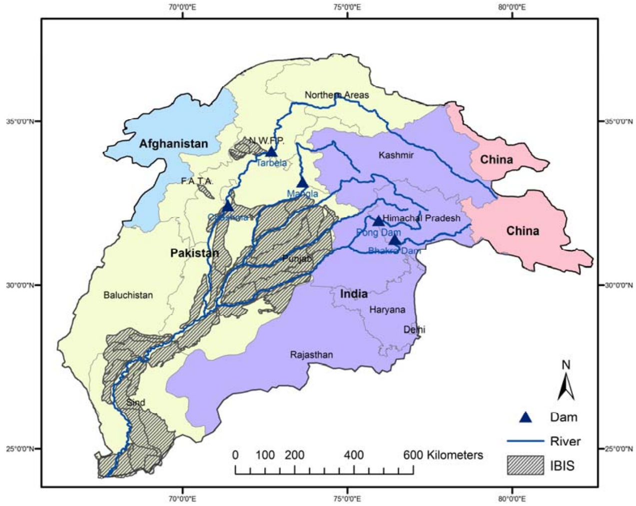

Fig. 1. The Indus basin.

The basin hydrology is complex due to the high variability in climatic and geomorphic features. The basin population is highly dependent on extensive irrigation agriculture, which long ago exceeded the threshold for sustainable water consumption (Habib, 2000). The irrigation practices run on the expense of rapidly decreasing groundwater resources. Siebert et al. (2010) and Wada et al. (2010) indicated independently that the Indus basin has one of the most over-exploited groundwater systems worldwide. Besides the unsustainable use of groundwater, the other major challenges that the basin faces include the increasing gap between supply and demand, water logging in poorly drained areas, climate change impacts, environmental degradation, soil salinization, and above all, political disagreements among riparian countries (Qureshi, 2011).

3 Data

3.1 Land use and land cover

Land use and land cover (LULC) affect the water balance, as well as the benefits and services for society and for the environment. Spatially distributed information on LULC is thus the key information required by WA+. Whereas LU relates to a specific use of land (e.g. production pasture), LC describes the physical state of that particular land surface (e.g. grass). There are a number of global and regional land cover databases based on remotely sensed data using different algorithms (e.g. Bartholomé and Belward, 2005; Bontemps et al., 2010; Friedl et al., 2010; Thenkabail et al., 2005). These products mainly provide LC data and information related to LU is limited.

An existing LULC map of the Indus, developed by Cheema and Bastiaanssen (2010), was used for this study. It is based on the seasonal phenological variations of 27 classes from temporal profiles of NDVI from SPOT Vegetation. Different crop classes were identified and verified through ground truth campaigns. The LULC classes have been re-grouped into four major clusters that differ in terms of water management: conserved land use (CLU), utilized land use (ULU), managed land use (MLU) and managed water use (MWU). The area under CLU is 83 081 km^2, ULU is 612 184 km^2, MLU is 174 100 km^2 and MWU is 278 279 km^2.

To define protected areas, the International Union for Conservation of Nature (IUCN) and United Nation Environment Programme (UNEP) database for protected areas was used. These bodies publish digital boundaries of conserved land use classes (e.g. http://www.protectedplanet.net/).

3.2 Precipitation

WA+ uses gross precipitation as the primary input. Precipitation products such as the Tropical Rainfall Measurement Mission (TRMM), the Climate Prediction Center Morphing Technique (CMORPH) (Joyce et al., 2004), and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) (Sorooshian et al., 2000), provide free global precipitation data with different spatial and temporal resolutions.

Rainfall data from the calibrated TRMM map was used for this accounting procedure. Cheema and Bastiaanssen (2012) calibrated TRMM rainfall for the Indus basin with two methods including (a) a regression analysis against rain gauges and (b) a geographical differential analysis (GDA). Using the Nash–Sutcliffe efficiency (NSE) and standard error of estimates (SEE) they concluded that calibration with the GDA method resulted in a closer correlation with rain gauge data than a simple regression equation. Both calibrations in general showed a reasonable accuracy however (NSE > 0.8). The quality of the GDA method is highly dependent on the distribution of rain gauges in the network. In the Indus basin the majority of stations are located in the low altitude plains, whereas most of the precipitation occurs in the mountainous ungauged part of the basin. The GDA method is thus likely to underestimate rainfall in the northern mountains and highlands. For these reasons, and to overcome the issue of underestimation of the rainfall by the GDA method, a new map was produced which combines the result of the two calibrations. The resulting map is shown in Fig. 2a. The annual rainfall in the basin (using the combined method) was 415 $mm\,yr^{-1}$ (i.e. a volume of 482 km^3) in 2007. Laghari et al. (2012) reported an average long-term annual precipitation in the Indus basin of 446 to 497 km^3 based on two datasets (GWSP, 2008; Hijmans et al., 2005) and figures provided by various authors (Immerzeel et al., 2010; Karim and Veizer, 2002; Mitchell and Jones, 2005). The range compares well with our estimate, especially seeing that 2007 was a wet year (PBS, 2008).

3.3 Evapotranspiration and biomass production

Various methods and algorithms to estimate actual evapotranspiration (ET) through satellite measurements have been developed over the past decades. Methods such as SEBAL (Bastiaanssen et al., 1998), SEBS (Su, 2002), TSEB (Norman et al., 2000), METRIC (Allen et al., 2007), Alexi (Anderson et al., 2007) and ETWatch (Wu et al., 2012), amongst others are used widely to estimate ET and are increasingly accepted (e.g. Kalma et al., 2008; Verstraeten et al., 2005). Products such as MOD 16 (http://modis.gsfc.nasa.gov) offer daily ET data at 1 km^2 resolution that can be downloaded by users for free.

For showing the proof of concept of WA+ in a complex basin, ET data of the Indus basin for 2007 was taken from the new ETLook algorithm (Bastiaanssen et al., 2012). ETLook is a two-layer surface energy balance model that adopts microwave-based soil moisture data to solve the partitioning of net radiation into latent heat flux, sensible heat flux and soil heat flux. ETLook computes evaporation (E) and transpiration (T) separately using leaf area index to partition total net radiation into canopy and soil components. ETLook also provides spatially distributed data for interception (I) and a special subroutine for open water evaporation. Figures 2c and 1d show the annual E and T values respectively, of the Indus basin. The total ET of the basin in 2007 was 501 km^3, of which T accounted for 229 km^3 and E and I for 272 km^3. The data were compared against field measurements of lysimeters, Bowen ratio flux towers, and water balance data in Pakistan (Bastiaanssen et al., 2012). The RMSE was 0.29 $mm\,d^{-1}$, R^2 was 0.76, and bias was 6.5 %.

The ETLook model also computes biomass production. The magnitude of Transpiration (T) is related to the stomatal and canopy resistances. The stomatal resistance model for transpiration was used together with the Absorbed Photosynthetic Active Radiation (APAR) and Light Use Efficiency (LUE) to compute biomass production of vegetation, see Fig. 2b. More background information on biomass production is explained in Bastiaanssen and Ali (2003).

3.4 Storage change

WA+ divides total water storage in a river basin into three groups, namely surface water storage, groundwater storage, and glacier reserves.

3.4.1 Surface water storage

Information on surface storage changes (ΔS_{sw}) was acquired from dam operation agencies in Pakistan. Surface storage changes in the main reservoirs for this study were estimated by coupling water level fluctuation data with the size of the reservoir (see Table 1). A total surface storage depletion,

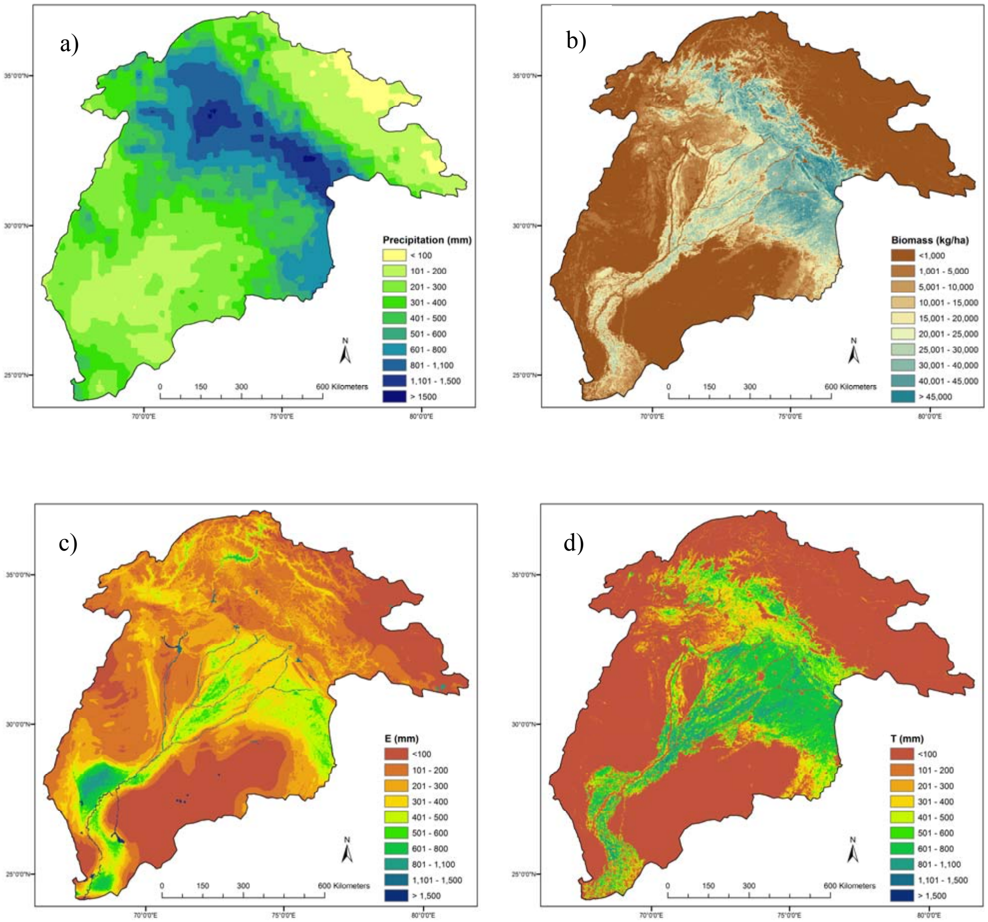

Fig. 2. (a) Precipitation (based on data from Cheema and Bastiaanssen, 2012) **(b)** biomass production **(c)** evaporation **(d)** transpiration (based on data from Bastiaanssen et al., 2012) in the Indus basin in 2007.

ΔS_{sw}, of 9.4 km^3 was calculated for 2007 with most water released from Pong reservoir. While not a topic for this paper, it is interesting to note that remote sensing techniques are increasingly being utilized to estimate water level fluctuations from radar and laser altimetry. Water volume changes in reservoirs can be assessed by combining these level measurements with areal estimates (e.g. Birkett and Beckley, 2010; Zhang et al., 2011).

3.4.2 Groundwater storage

Information on groundwater storage at basin scale is limited. Changes in storage can be obtained from gravitational satellites such as the Gravity Recovery and Climate Experiment (GRACE) (e.g. Frappart et al., 2011; Henry et al., 2011). While this new source of data is appealing, the accuracy of GRACE data is to be improved to make it reliable for monitoring groundwater changes at the basin scale (e.g. Tang et al., 2010). Hydrological models simulate vertical and horizontal groundwater movements with discretized cells (e.g. Siebert et al., 2010; Wada et al., 2010) which then provides estimates of storage change. But these numerical models use gross assumptions about local groundwater withdrawals and are thus not very reliable. Data on withdrawals are normally obtained from tubewell density, electricity bills, farm interviews and changes in groundwater levels (e.g. Ahmad et al., 2005). This unfortunately does not provide a reliable and reproducible data set either. Despite heavy utilization of groundwater in the Indus, direct measurements on groundwater change remain limited. The WA+ offers the possibility to estimate total bulk groundwater storage change through mass conservation of the water balance. This is only feasible if the ET data can be estimated independently from the other terms of the water balance. These conditions were met for this demonstration study. The measured basin outflow was 21.3 km^3, and this number was used to back-calculate total groundwater storage change by closing the water balance. It appears that groundwater storage depletion during 2007 was 29.8 km^3.

Table 1. Change in surface storage in the major reservoirs of Indus during 2007.

Reservoir	Reservoir capacity (km^3)	Reservoir area (10^9 m^2)	Water level change (m)	Change in surface Storage (km^3)
Tarbela	13.9	0.26	−10.3	−2.67
Mangla	7.3	0.25	−10.6	−2.65
Chashma	0.88	0.006	+3.9	+0.02
Bhakra	9.6	0.17	−6.4	−1.07
Pong	8.6	0.24	−12.8	−3.06
Total	40.28	0.92		−9.4

3.4.3 Glacier and snow storages

Glacier and snow melt are major contributors to river flow. The glacier area in the Indus basin is estimated at 22 127 km^2 (Immerzeel et al., 2010). Bolch et al. (2012) estimated the annual specific mass balance of Himalayan–Karakoram glacier to be around −0.5 m per year during the last decade. Based on findings of Fowler and Archer (2006), the Karakoram glacier, with an area of 18 000 km^2, is believed to be stable. Hence, the snow storage change in the Indus basin is confined to a limited area only. The change in glacier storage over an area of 4127 km^2 (22 127–18 000) will yield an annual stream flow of 2.1 km^3 ($4127 \times 0.5 \times 0.001 = 2.1$) (W. W. Immerzeel, personal communication, 2012). Information on glacier storage change in a specific year is scant. We therefore used an average annual estimate as representative for 2007 in this study. This is a gross estimate which points to the desirability of future research.

4 WA+ sheets for the Indus basin

4.1 Resource base sheet

The WA+ resource base sheet for 2007 is presented in Fig. 3. The net inflow was 523 km^3 of which 482 km^3 originated from precipitation. The remaining 41 km^3 was freshwater storage depletion. As described above, the major share of storage decline was ascribed to groundwater, 29.8 km^3, followed by 9.4 and 2.1 km^3 loss of storage from surface reservoirs and glaciers respectively.

Inter-basin transfer certainly occurs underground via the Quaternary upper tertiary deposits. The amounts are difficult to quantify however, and are assumed to be small in comparison to other water balance components. Due to the absence of documented estimates on groundwater outflow to the sea – or intrusion – exchanges with the Indian Ocean were ignored as well. All inter-basin transfers were set at zero.

The net inflow was divided into landscape ET (green water: the direct ET from rainfall) and exploitable water (blue water: water in streams, lakes, reservoirs, snow cover, glaciers and aquifers). The landscape ET accounted

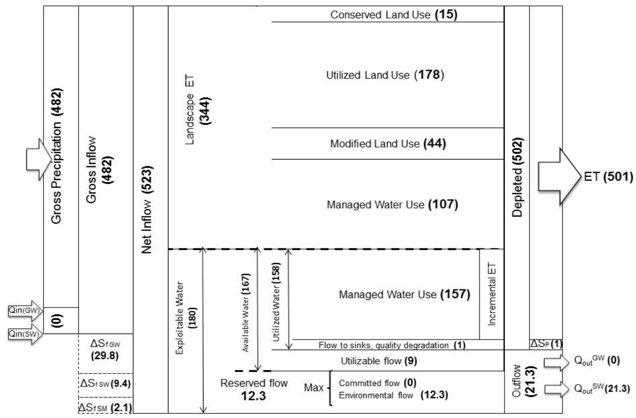

Fig. 3. WA+ resource base sheet for the Indus basin during 2007. All components are in km^3.

for 344 km^3 (66 % of the net inflow and 71 % of total gross precipitation). This is a substantial water volume that can be managed only by modifying the land use and soil treatments. The exploitable water was 180 km^3, at 34 % of the net inflow.

The major water-depleting land use category was the group MWU. The total water depletion by MWU accounted for 264 km^3, slightly over 50 % of the net inflow. Of 264 km^3, 107 km^3 (or 41 %) was directly from rainfall over the irrigated areas, urban areas, and reservoirs; this is an integral part of landscape ET. The remaining incremental ET (157 km^3) originated from utilized water flows.

The other components of the landscape ET include ET from CLU, ULU, and MLU. Within the landscape ET the group ULU used 178 km^3 of water. These are the savanna, forests, deserts, and natural lakes which all provide ecosystem services. The group MLU (essentially rainfed crops) depleted 44 km^3. The group CLU depleted only 15 km^3. Table 2 shows the breakdown of ET by LULC classes within these groups.

Based on the Inter-provincial Water Apportion Accord 1991, an amount of 12.3 km^3 of flow should be set aside annually to meet the environmental flow requirements to curb seawater intrusion in the Indus Delta (Ram, 2010). This water volume, based on water rights formulation, is treated as

Table 2. Water depletion by LULC class in the Indus basin in 2007.

Land use class	Land use group	E^* (mcm** yr^{-1})	T (mcm yr^{-1})	ET (mcm yr^{-1})
Snow and ice permanent	CLU	4376	157	4533
Conserved areas	CLU	7025	3092	10 117
Snow and ice temporary	ULU	7199	927	8127
Bare soil	ULU	7996	57	8053
Very sparse vegetation	ULU	2979	94	3073
Pastures deciduous	ULU	10 713	368	11 080
Pastures evergreen lowland	ULU	6520	874	7394
Pastures deciduous alpine	ULU	8125	234	8359
Savanna evergreen open	ULU	6712	1984	8696
Savanna evergreen closed	ULU	5757	7373	13 130
Savanna deciduous	ULU	23 462	2829	26 291
Forests evergreen needleleaf	ULU	10 627	18 305	28 932
Forests evergreen broadleaf	ULU	1380	3682	5062
Forests deciduous alpine	ULU	7,457	5550	13 007
Forests/cropland alpine	ULU	6497	15 457	21 955
Natural lakes, rivers	ULU	15 088	0	15 088
Rainfed crops wheat/grams	MLU	2641	857	3498
Rainfed crops mixed cotton, wheat rotation/fodder	MLU	4,648	2541	7189
Rainfed crops general	MLU	17 194	3382	20 576
Rainfed crops and woods	MLU	8660	3702	12 361
Irrigated mixed cotton, wheat rotation/orchards	MWU	14 973	31 781	46 754
Irrigated mixed cotton, wheat rotation/sugarcane	MWU	17 294	23 889	41 183
Irrigated rice, wheat rotation	MWU	39 161	67 489	106 649
Irrigated mixed rice, wheat rotation/cotton	MWU	8679	12 098	20 776
Irrigated wheat, fodder rotation	MWU	8,211	10 851	19 063
Irrigated rice, fodder rotation	MWU	9366	8054	17 420
Irrigated mixed rice, wheat rotation/sugarcane	MWU	674	1105	1779
Urban and industrial settlements	MWU	6731	2013	8744
Reservoirs	MWU	1914	0	1914

* E includes both evaporation and interception; ** mcm = million m^3.

reserve flow in WA+. The difference between the exploitable water and the reserved flows (167 km^3) is the available water of which 157 km^3 was consumed by MWU as a result of water diversions and 1 km^3 flowed to sinks (i.e. saline groundwater aquifers), rendering it unavailable for further use due to quality degradation. Given the non-existence of major flood events, non-utilizable flow which is mostly a consequence of major flood events, was assumed to be negligible in the accounting year. An amount of 21.3 km^3 water flowed into the Indian Ocean. This figure was derived from discharge measurements (PBS, 2008).

Utilizable flow, the difference between available water and utilized water, was estimated at 8 km^3 for 2007. Utilizable flow represents the amount that is available for further water resources development in an above-average rainfall year. To establish the amount reliably would need a multi-year assessment. The notable point is that, in the year assessed, the Indus basin has some surplus water leaving the basin, while it is losing its precious groundwater storage at a fast rate.

4.2 Evapotranspiration sheet

The WA+ evapotranspiration sheet (Fig. 4) divides the total ET into evaporation (E), transpiration (T) and interception (I) for each LULC (Table 2). The evapotranspiration sheet also expresses the benefits, and the WA+ user can insert a judgment value to estimate to what extent water is consumed beneficially. Figure 4 shows the WA+ evapotranspiration sheet for the Indus for 2007. For this example all the transpiration was assumed to be 100 % beneficial except for transpiration from floating vegetation in reservoirs, waste lands and weeds. All the interception was assumed non-beneficial, although interception has certain benefits for micro-meteorological conditions for crops. Except for evaporation from natural lakes, wetlands, rivers and industries (e.g. cooling towers, hydropower, etc.) all the evaporation was assumed 100 % non-beneficial. These proportions of beneficial and non-beneficial E and T can be modified by users based on their judgment.

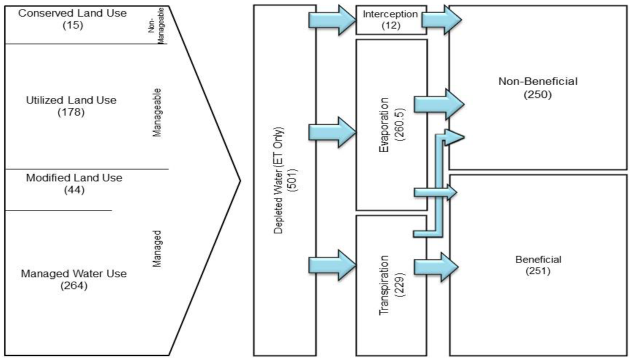

Fig. 4. WA+ evapotranspiration sheet for the Indus basin based on 2007. All components are in km^3.

In the accounting year, 261, 229, and 12 km^3 were depleted by E, T and I, respectively. This implies that bare soil E is the main process through which water is depleted, being a surprisingly large number. As a consequence, beneficial water depletion was limited to only 50 % of total water depletion. It comprises beneficial E (22.5 km^3) plus 228.5 km^3 beneficial T. Non-beneficial depletion accounted for 251 km^3, with non-beneficial E being the major contributor (238 km^3). As demonstrated in Fig. 2c, this occurred mainly in the downstream areas of the Sindh province. The total agricultural water depletion was 297 km^3, of which 165 km^3 (55 %) occurred via T and 132 km^3 through E and I. The average evaporation in irrigated areas, 380 $mm\,yr^{-1}$, is two times more than that in rainfed areas, 190 $mm\,yr^{-1}$. Given the fact that double cropping is the main practice in most of irrigated areas in the basin, the annual E from rainfall is expected to be lower in irrigated areas compared to rainfed areas where the land remains fallow after the main cropping season is over. This indicates that more than half of the total evaporation in irrigated areas is associated with irrigation. This is an unfavorable situation that requires corrective action. For typical situations in irrigation systems, T is 67 % of the total ET (Ahmad et al., 2002). However, it is highly dependent on the pattern of rainfall.

4.3 Productivity sheet

Biomass production by LULC class is an indication of profits in terms of food, feed and fiber production (see Fig. 5). The total biomass production in the accounting year was 1015 million tons (Mt). Results show that MWU was the major contributor to biomass production (596.7 Mt and 21.4 $t\,ha^{-1}$). MWU is followed by ULU that produced 356 Mt of biomass in the accounting year, equal to 5.8 $t\,ha^{-1}$. The remaining two classes, MLU and CLU, had minor shares in the total biomass production.

A total of 584 Mt of CO_2 was sequestered in the Indus basin through fresh biomass production. Further to the total biomass production, the annually sequestered carbon varies with land use class. For each land use class, the fraction of biomass that fixed carbon was specified. For instance, a large part of biomass of crops is removed from the field after harvest and does not contribute to carbon sequestration, except when crop residuals are ploughed and zero tillage is applied. For this study, we assumed the fraction to be 100 % for land uses where vegetation is not removed (such as forests) and 15 % for croplands where the crops are harvested and only a portion of biomass is left (mostly below ground biomass). These values can be defined by WA+ users based on their knowledge of the study area. Due to competition for space and light resources, each ecosystem has a certain maximum value of standing biomass. Part of the total standing biomass will be decayed by natural death and competition among species. This decay is not included in the production sheet.

The absorption of 390.8 Mt of carbon annually shows the important role of that ULU in carbon absorption and thus as an ecosystem services provider. The ULU figure translates to 6.4 $t\,ha^{-1}$, which is higher than the average 5.1 $t\,ha^{-1}$ of CO_2 in the basin. MWU is the second major land use group in terms of carbon sequestration. It fixed 160 Mt of atmospheric CO_2, equal to 5.7 $t\,ha^{-1}$, and created soil organic matter. CLU contributed to 23 Mt of CO_2 sequestration followed by MLU with 10.3 Mt CO_2. Note that this is gross sequestration and that net sequestration due to natural decay was not considered.

Land productivity was calculated for a hypothetical cereal reference crop with a harvest index of 0.35. The average annual land productivity in MWU was 7.8 $t\,ha^{-1}\,yr^{-1}$. This figure in most areas represents the harvest of two seasons. For a single crop it would be 3.9 $ton\,ha^{-1}$, a value that is realistic for cereal crops in the Indus basin. Land productivity for rainfed agriculture was estimated at 0.94 $t\,ha^{-1}$.

Water productivity (WP) is a fundamental indicator in performance assessment of river basins and it has immense food and water security implications (Molden, 2007). In the Indus basin, WP in terms of biomass production per hectare was close to 2 $kg\,m^{-3}$. MWU had the highest biomass WP among all the land use groups (2.3 $kg\,m^{-3}$). It is followed by 2.0, 1.1 and 1.1 $kg\,m^{-3}$ for ULU, CLU, and MLU respectively. The average crop water productivity was calculated based on the estimated reference yields and annual ET. Results show crop WP in irrigated agriculture to be 0.77 $kg\,m^{-3}$ and 0.35 $kg\,ha^{-1}$ for rainfed agriculture. This shows that WP in the basin is low compared to many other basins across the world (Cai et al., 2011). Zwart et al. (2010) reported 1.1 $kg\,m^{-3}$ as the world average crop water productivity for wheat. Although certain pockets in the Indus basin have a WP value of 1.2 $kg\,m^{-3}$ (Cai and Sharma, 2010), the average is 0.6 $kg\,m^{-3}$, which is among the low performing basins in terms of productive use of water. One of the main contributing factors to the low WP is excessive E from irrigated lands of which the majority is from irrigation.

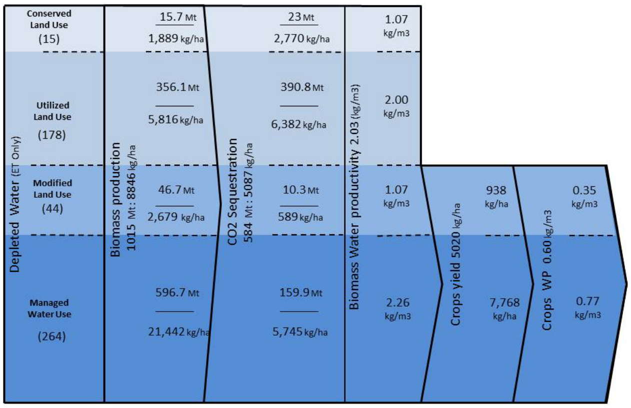

Fig. 5. WA+ productivity sheet for the Indus basin pertaining to the year 2007. Water use figures are in km^3.

4.4 Withdrawal sheet

The WA+ withdrawal sheet provides information on total withdrawal (surface water diversions and groundwater abstractions). Withdrawal data cannot be derived from satellite measurements. Other sources, such as secondary statistics and hydrological model outputs, need to be used if available. For the Indus basin, in addition to the remotely sensed data, FAO Aquastat database, canal water release information from the Line Agencies, and Soil and Water Assessment Tool (SWAT) model results were used to complete the WA+ withdrawal sheet.

The SWAT modeling results – after assimilating the remote sensing data - showed that an amount of 181 km^3 of water was diverted for use in agriculture in 2007 (Cheema et al., 2013). Of this, 68 km^3 originated from groundwater while surface water contributed 113 km^3. Of the 181 km^3 gross withdrawal for irrigation, 152 km^3 was depleted by ET and the remaining non-consumed water (30 km^3) was recovered in the system downstream of the point of application. Aquastat-estimated withdrawals for domestic and industrial uses as 12.2 and 1.8 km^3 a year respectively; a combined withdrawal of 14 km^3. The majority of the resource is groundwater, and we estimated that 10 km^3 was abstracted by wells. Out of the 14 km^3, an amount of 4.6 km^3 was lost through ET, which leaves the majority to be non-consumed (9.4 km^3). The total ET from the LULC class "urban and industrial settlements" was 8.7 km^3, which is larger than the 4.6 km^3 (see Table 2), but part of the ET was attributed to rainfall. The incremental ET from reservoir operation was 1 km^3. Figure 6 shows the WA+ withdrawal sheet for the Indus basin. Gross withdrawals in the accounting year was estimated at 196 km^3, out of which 118 km^3 ($113 + 4 + 1$ km^3) was diverted from surface water system and 78 km^3 ($68 + 10$ km^3) was extracted from aquifers.

After correction for non-recoverable flow to sinks, the recoverable flow will be 37.8 km^3. The total return flow was

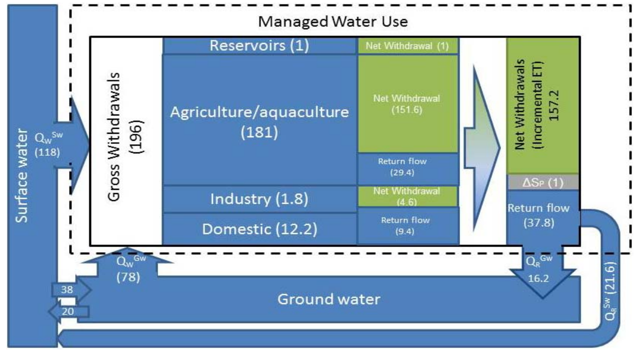

Fig. 6. WA+ withdrawal sheet for the Indus basin based on 2007 data. All components are in km^3.

partitioned into surface water (SW) and groundwater (GW) recharge. Spatial data from the SWAT model was used to partition the return flows to SW (21.6 km^3) and GW (16.2 km^3). There is also a direct interaction between SW and GW within MWU. Seepage from irrigation canals was responsible for 38 km^3 flowing from SW to GW. The flow from GW to SW was 20 km^3 (Fig. 6). Combining all the numbers gives the mass balance of the bulk aquifer which indicated that groundwater storage depletion in MWU alone was 43.3 km^3. The feeding of aquifers from the non-MWU classes (i.e. CLU, ULU, and MLU) was however not considered. Van Steenbergen and Gohar (2005) estimated this amount to be 14 km^3, leaving the ΔS_{gw} to be approximately 29.3 km^3. A similar value of 29.8 km^3 is presented in the resources base sheet.

5 WA+ performance indicators

The WA+ offers a range of standard indicators (see Table 3). Every sheet comes with its own indicators that are derived from information in the sheets (Karimi et al., 2013). Table A1 in Appendix A summarizes the WA+ indicators definitions.

The WA+ resource base sheet indicators include a storage change fraction, an exploitable water fraction, an available water fraction, a basin closure fraction, and a reserved flow fraction. The exploitable water fraction (EWF) represents the portion of exploitable water in the net inflow. The storage change fraction (SCF) defines the portion of storage change in exploitable water. EWF is closely related to the natural run-off coefficient in a basin when no infrastructure is present, and when storage changes can be neglected. The Indus basin showed a EWF of 0.34 and its SCF was −0.23. The available water fraction (AWF) indicates the proportion of the exploitable water that is actually available for withdrawals after corrections for reserved flows. The calculated AWF of the Indus basin was 0.93, which indicates that the basin's water commitments are not a constraining factor for allocations. Indeed, most of the available water is utilized.

Table 3. WA+ indicators for the Indus basin based on the situation in 2007.

Indicators	Value	Unit	Remarks
Resource base sheet			
Exploitable water fraction	0.34	–	Plenty of renewable water resources
Storage change fraction	−0.23	–	Highly unsustainable practices
Available water fraction	0.93	–	Low amount assigned to reserved flow
Basin closure fraction	0.95	–	Almost closed to new development
Reserved flow fraction	0.58	–	Downstream requirements are met
Evapotranspiration sheet			
T fraction	0.46	–	Low canopy water depletion
Beneficial fraction	0.50	–	Low benefits from water depletion
Managed fraction	0.61	–	Many ET processes can be regulated
Agri. ET fraction	0.59	–	Agriculture is a major water consumer
Irri. ET fraction	0.85	–	Agriculture relies on irrigation water
Productivity sheet			
Land productivity$_{\text{crops}}$	5020	kg ha^{-1} yr^{-1}	Very low crop yield
Land productivity $_{\text{pastures}}$	177.4	kg ha^{-1} yr^{-1}	Extremely low grass yield
Water productivity $_{\text{crops rainfed}}$	0.35	kg m^{-3}	Rainfed crops not efficient with water
Water productivity $_{\text{crops irrigated}}$	0.77	kg m^{-3}	Irrigated crops not efficient with water
Food Irri. Dependency	0.90	–	Food security relies on irrigation
Withdrawals sheet			
GW withdrawal fraction	0.40	–	Reliance on groundwater is significant
CE (Classical irrigation efficiency)	0.84	–	Basin as a whole is an efficient system
Recoverable fraction	0.20	–	Recycling situation is normal

Basin closure fraction (BCF) describes the extent to which available water is utilized in a basin. The Indus, for the single year investigated, had a BCF of 0.95 which shows utilized water is reaching its maximum in terms of volume. This leaves a limited window for further increases in withdrawals, especially during below-average rainfall years.

Reserved flow fraction (RFF) defines whether or not surface water outflow is meeting the required reserved flow. The RFF in the Indus basin was estimated at 0.58, which suggests that outflows from the basin were almost two times bigger than reserved flows. However, most of these outflows (17.1 km^3) took place during the wet season (Kharif); outflow during the dry season (Rabi) was only 4.2 km^3.

The WA+ evapotranspiration sheet has five indicators, namely a transpiration fraction, a beneficial fraction, a managed fraction, an agricultural ET fraction, and an irrigated ET fraction. The transpiration fraction gives an indication of which part of the ET is vaporized via plant leaves. For the Indus basin the ratio was 0.46, meaning the majority of water depleted in 2007 in the basin was through soil and water evaporation and interception for canopies and other wet surfaces; something that is remarkable but unfavorable.

The managed fraction represents the portion of ET that is related to any kind of human intervention (MLU, MWU), and can be used to help save water (Seckler, 1996). MWU includes both rainfed and irrigated systems, as well as industrial and domestic uses. The managed fraction for the Indus basin in the accounting period was 0.61, which implies that human activities in the basin dictate depletion of water to a large extent. The agricultural ET fraction in the basin was 0.59, which shows that agricultural activities are intense water consumers. The reason is the extremely large extent of agriculturally related LULC area, covering almost 40 % of the total area of the basin. The irrigated ET fraction for the basin was 0.85, which indicates that 85 % of agricultural ET was through irrigated systems.

The productivity sheet indicators are meant to reflect the basin's performance in productive use of land and water resources. Land productivity in cropped areas in the Indus basin was estimated at 5 t ha^{-1} yr^{-1} (rainfed: 0.94 t ha^{-1} yr^{-1}; irrigated: 7.77 t ha^{-1} yr^{-1}). Land productivity of pastures is essential for grazing. Pasture productivity can also be used to value pastures in terms of economic benefit. Land productivity of pastures was about 0.18 t ha^{-1} yr^{-1}. Food irrigation dependency deals with the level to which a basin relies on irrigated agriculture for food production. The ratio was 0.9 for the Indus basin, indicating that food security

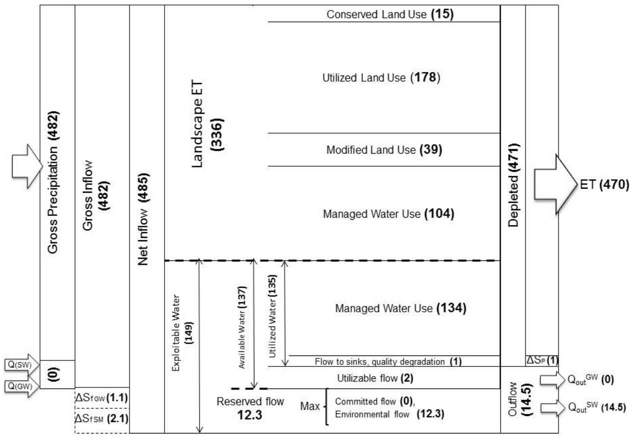

Fig. 7. Impact of scenario B on WA+ resource base sheet for the Indus. All components are in km^3.

is highly dependent on continued irrigated agriculture. This is in fact a high number.

The results show the basin enjoys a relatively high classical irrigation efficiency of 0.84 at basin level (Seckler et al., 2003) despite its low classical irrigation efficiency of 0.35 to 0.40 at field scale (Qureshi, 2011). This implies that water is recycled about 4 times in the Indus basin. Hence, in general, the system is efficient in capturing and reusing non-consumptive water use from farms and conveyance canals through the natural geographic setting. This WA+ performance indicator reveals that the irrigation efficiency for the basin is excellent, and will be difficult to improve. The recoverable fraction for the basin (0.2) indicates than 20 % of the gross water withdrawals were recovered into the hydrological system and reused through surface and groundwater systems.

6 Future scenario evaluation using WA+

As mentioned earlier, this paper does not provide recommendations for the management of the Indus basin. The intention is merely to demonstrate the contribution of WA+ for appraising basin scale water management options. The 2007 WA+ results for the Indus demonstrate that there is limited scope for more water withdrawals in the basin and almost no opportunity to allocate more water for agriculture. In the remarks column of Table 3 a number of problems that need more attention are listed. The main problems can be summarized as follows:

- severe over-exploitation
- large reliance on groundwater resources
- high volumes of non-beneficial soil evaporation
- low crop yield in rainfed and irrigated land
- low crop water productivity in rainfed and irrigated land
- basin closure is almost reached
- insufficient storage capacity
- waterlogging in downstream areas.

For demonstration purposes, solutions for (i) zero over-exploitation, and (ii) increasing land productivity has been worked out. Three different scenarios have been analyzed, aided by the WA+ framework (Table 4).

To meet the first goal of zero over-exploitation, storage depletion must be avoided. In 2007 the storage changes of groundwater and surface water were −29.8 and −9.4 km^3, respectively. Hence, for 2007 a real water saving of 39.3 km^3 needed to be achieved. In nearly 8.8 million ha of irrigated lands in the basin soil evaporation (E) accounted for more than 40 % of ET. Limiting E to 40 % of the total ET would result in a net saving of 7.7 km^3 of water. Water saving would increase significantly by 13.3 km^3 if $E/\mathrm{ET} < 0.36$ is introduced as a guideline in irrigated areas. There are several methods to reduce soil evaporation. Methods such as the use of drip systems and subsurface drip systems can significantly reduce soil evaporation losses of irrigated land (Wang et al., 2009). In rainfed systems, soil evaporation can be reduced by mechanical mulching (Prathapar and Qureshi, 1999) or by straw mulching (Zhang et al., 2003). E can also be reduced in shallow water table areas by means of installation of sub-surface drainage systems (Smedema, 2000).

It is not new to conclude that the crop water productivity in the Indus basin is low (Bastiaanssen et al., 2003; Cai and Sharma, 2010) and it is imperative to investigate options to improve yields if the increasing food demands are to be met. Crop yield is a function of biomass production and harvest index. The biomass production can be improved by better fertilization and the selection of good quality seeds. The uniformity, adequacy and reliability of irrigation systems contribute to the production of a healthy biomass (Murray-Rust et al., 1994). Uniform water distribution by means of drip systems and land leveling will ensure a low spatial variability of biomass. Adequate irrigation prevents moisture stress and reliable surface water supply will ensure that farmers invest more time and resources in their crop. With these measures a 5 % increase in biomass production is plausible. A consequence of more biomass production is that T will increase at the same time. Steduto et al. (2009) established an empirical relationship between biomass production and T which forms the basis of the AquaCrop model. Every increase of 1 mm in T – normalized against reference ET_0 – will increase biomass production by 13 kg ha^{-1}. So biomass production improvement will increase ET, unless E is reduced concomitantly. Thus ET reduction can be achieved only if the reduction of E exceeds the increase of T. The harvest index varies mainly with crop variety and the soil moisture situation during flowering and panicle stage. An adequate supply

Table 4. Impact of alternative future scenario's on WA+ indicators aiming at zero-over-exploitation (storage change fraction) and increase food security (land productivity).

Scenario	Action	Real water saving ($km^3 yr^{-1}$)	WA+ indicators
A Mixed actions	Reduce *E* rainfed land by 5 % Reduce *E* irrigated land by 15 % Reduce irrigated area by 0 % Biomass production increase 5 % Harvest index increase 5 % Reduce utilizable flow by 50 %	12.6	Storage change fr.: −0.17 Reserved flow fr.: 0.73 *T* fr.: 0.48 Beneficial fr.: 0.53 Land productivity $_{\text{irri}}$: 8,560 Land productivity $_{\text{rainfed}}$: 1,030 Water productivity $_{\text{irri}}$: 0.90 GW withdrawal fr.: 0.41
B Reduce *E*	Reduce *E* rainfed land by 15 % Reduce *E* irrigated land by 35 % Reduce irrigated area by 0 % Biomass production increase 5 % Harvest index increase 10 % Reduce utilizable flow by 75 %	37.8	Storage change fr.: −0.02 Reserved flow fr.: 0.85 *T* fr.: 0.50 Beneficial fr.: 0.55 Land productivity$_{\text{irri}}$: 9300 Land productivity$_{\text{rainfed}}$: 1130 Water productivity$_{\text{irri}}$:1.09 GW withdrawal fr.: 0.32
C Modify area	Reduce *E* rainfed land by 5 % Reduce *E* irrigated land by 15 % Reduce irrigated area by 15 % Biomass production increase 5 % Harvest index increase 10 % Reduce non-utilizable flow by 75 %	39.4	Storage change fr.: −0.01 Reserved flow fr.: 0.85 *T* fr.: 0.45 Beneficial fr.: 0.50 Land productivity$_{\text{irri}}$: 9300 Land productivity$_{\text{rainfed}}$: 1,130 Water productivity y_{irri}: 0.93 GW withdrawal fr.: 0.30

during this critical period can increase the harvest index by 5 to 10 % (Doorenbos and Pruitt, 1977).

Table 4 demonstrates the real water savings and the adjusted WA+ indicators under 3 scenarios, which are built around existing options to achieve water saving and better food security targets.

Scenario A involves some mixed interventions. Scenario B is based on reducing soil evaporation losses by mulching, drainage and micro-irrigation (drip and micro-sprinkler). Note that micro-irrigation will contribute to crop production and crop water productivity (Soman, 2012). Sub-surface irrigation is rapidly being adopted in India, and the same is feasible in Pakistan. Farmers will have a better future with improved livelihoods if scenario B is adopted by policy makers. Figure 7 shows the WA+ resource base sheet after implementing scenario B.

Scenario C is based on a land retirement plan. This is likely going to happen if other interventions are not implemented in a timely fashion.

WA+ demonstrates that with these interventions, the future of the Indus basin will be more progressive. It is important to note that the above analyses are only based on results of water accounting in one year (2007) and are merely to demonstrate how the WA+ functions in scenario development and assessment. Therefore results must be treated with caution, and future research through multiple year analysis is required to validate the outcomes. Only options on reduced groundwater abstraction and increased food production have been investigated in depth. A more integrated approach is needed to formulate proper policy recommendations.

7 Summary and conclusions

Sustainable production in the Indus Basin is threatened by a host of issues, such as water scarcity, rapid population growth, groundwater over-exploitation, water logging, soil salinization and low productivity of land and water resources. A clear understanding of current water resources is the cornerstone for informed water management strategies for the future. However, data availability and a standard way of presenting data are two main obstacles in providing comprehensive, yet easy to comprehend, information on water management. The complexity of water is exacerbated in transboundary basins such at the river Indus.

In this study we used the Indus basin as an example to demonstrate how the WA+ framework can be implemented

Appendix A

Table A1. WA+ indictors definitions.

Indicators	Definition
Exploitable water fraction	Exploitable water divided by the net inflow
Storage change fraction	Freshwater storage change divided by exploitable water
Available water fraction	Available water divided by exploitable water
Basin closure fraction	Utilized flow divided by available water
Reserved flow fraction	Reserved outflows divided by the total outflow
T fraction	Total T divided by the total ET
Beneficial fraction	Beneficial E and T divided by the total ET
Managed fraction	Managed ET divided by the total ET
Agri. ET fraction	Agricultural ET divided by the total ET
Irri. ET fraction	Irrigated agricultural ET divided by the agricultural ET
Land productivity$_{\text{crops}}$	Crop biomass times harvest index divided by cropped area
Land productivity$_{\text{pastures}}$	Pastures biomass times harvest index divided by pasture area
Water productivity$_{\text{crops rainfed}}$	Rainfed crops biomass times harvest index divided by rainfed crops ET
Water productivity$_{\text{crops irrigated}}$	Irrigated crops biomass times harvest index divided by Irrigated crops ET
Food Irri. Dependency	Irrigated food production divided by total food production
GW withdrawal fraction	Groundwater withdrawals divided by total withdrawals
Classical irrigation efficiency	Incremental ET of agriculture divided by withdrawals for agriculture
Recoverable fraction	Return flow divided by total withdrawals

to provide much-needed explicit information on the water resources situation, depletion, and productivity in a systematic way by using minimum ground-measured data and accounting results that can be used to identify weaknesses, strengths, and opportunities.

The results suggest that the Indus basin is nearly a closed basin in which more than 95 % of the available water is used. Almost all depleted water can be ascribed to ET. The managed water use group, chiefly dominated by irrigated agriculture, accounts for 52 % of ET. It is followed by the utilized land use group (36 %), modified land use group (9 %) and conserved land use group (3 %). Half of the water depletion is through processes that produce very little or no benefits, i.e. non-beneficial depletion. The majority of these non-beneficial depletion is through human-intended water use, particularly through irrigated agriculture in the form of excessive soil evaporation. Hence, large amounts of valuable groundwater resources are vaporized non-beneficially into the atmosphere.

On the supply side, precipitation falls short of meeting the water demand. This leads to significant reduction in storage, especially groundwater storage (29.8 km^3 in 2007). If the rapid decline in GW storage that occurred in 2007 is representative of other years, it may have major implications for the sustainability of the basin, considering the crucial role that GW plays in the basin's food security.

While agriculture accounts for 59 % of total water depletion it has a considerably low productivity, especially in terms of water use. Therefore, to improve the situation and reach sustainability in the water-food nexus, it is wise to provide attention to water and land productivity improvement. This will in turn result in increased production with reduced water consumption. The results suggest that of the main opportunities for reducing water depletion is through decreasing wasteful soil evaporation in agricultural areas, particularly in irrigated land. The results show – based on a single year analysis – that an amount of 37.8 km^3 can be saved. If interventions are not timely implemented, retirement of irrigated land seems unavoidable.

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