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DOI
10.1016/j.agwat.2020.106174

Publication date
2020

Document Version
Final published version

Published in
Agricultural Water Management

Agricultural Water Management 236 (2020) 106174

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

A novel method to quantify consumed fractions and non-consumptive use of irrigation water: Application to the indus Basin irrigation system of Pakistan

G.W.H. Simons[a,b,*], W.G.M. Bastiaanssen[a], M.J.M. Cheema[c], B. Ahmad[d], W.W. Immerzeel[e]

[a] Faculty of Civil Engineering and Geosciences, Department of Water Management, Delft University of Technology, Stevinweg 1, Delft 2628 CN, the Netherlands
[b] FutureWater, Costerweg 1V, Wageningen 6702 AA, the Netherlands
[c] PMAS Arid Agriculture University, Rawalpindi, Pakistan
[d] Pakistan Agricultural Research Council (PARC), Plot No. 20, Sector G-5/1, Islamabad, Pakistan
[e] Faculty of Geosciences, Department of Physical Geography, Utrecht University, Princetonlaan 8A, 3584 CB Utrecht, the Netherlands

ARTICLE INFO

Keywords:
Consumed fraction
Non-Consumptive use
Water reuse
Budyko
Remote sensing

ABSTRACT

Increasing irrigation efficiencies remains the focus of numerous efforts to mitigate water scarcity. In reality, higher local efficiencies do often not reduce water scarcity, but instead cause a redistribution of water flows when the entire irrigation scheme or river basin is considered. Insufficient understanding of consumed fractions and non-consumptive use (i.e. return flows) have led to ineffective, or even harmful, water conservation measures. In this paper, we demonstrate a novel method for spatial quantification of the Consumed Fraction (*CF*) of withdrawn irrigation water based on satellite remote sensing and the Budyko Hypothesis. This method was applied to evaluate consumption of irrigation water (ET_{blue}), total water supply, and non-consumptive use across the Indus Basin Irrigation System (IBIS) of Pakistan. An average ET_{blue} of 707 mm/yr from irrigated cropland was found for 2004–2012, with values per Canal Command Area (CCA) varying from 421 mm/yr to 1011 mm/yr. Although canal supply (662 mm/yr on average) in most CCAs was largely sufficient to sustain ET_{blue}, a similar volume of additional pumping (690 mm/yr) was required to comply with hydro-climatological principles prescribed by Budyko theory. *CF* values between 0.38 and 0.66 were computed at CCA level, with an average value of 0.52. Co-occurrence of relatively low *CF* values, high additional water supply, and long-term canal diversions similar to ET_{blue}, implies that the IBIS is characterized by extensive reuse of non-consumed flows *within* CCAs. In addition, the notably higher *CF* of $0.71-0.93$ of the full IBIS indicates that return flow reuse *between* CCAs cannot be neglected. These conclusions imply that the IBIS network of irrigators is adapted to extensively recover and reuse drainage flows on different spatial scales. Water saving and efficiency enhancement measures should therefore be implemented with great caution. By relying on globally available satellite products and limited additional data, this novel method to determine Consumed Fractions and non-consumed flows can support policy makers worldwide to make irrigation systems more efficient without detriment to downstream users.

1. Introduction

Pressure on water resources is expected to increase in many of the world's river basins due to population growth and the associated increase in demand for food, fiber and biofuels. Changing precipitation, evapotranspiration and carbon fluxes are projected to further exacerbate water shortages. Recent policy reports and development programs supported by global institutions, as well as scientific and popular articles, promote irrigation efficiency improvements as a solution to water scarcity (e.g. World Bank, 2016; Siyal et al., 2016; Sultana et al., 2016; USAID, 2016). This perspective contradicts, however, with the growing body of work conveying the notion that aiming for more efficient water use in agriculture will not solve the water crisis (FAO, 2017; Grafton et al., 2018; Lankford, 2012; Perry, 2011).

The latter studies address the paradoxical effect of intended water savings having adverse effects, by in fact boosting water consumption (Scott et al., 2014). This efficiency paradox occurs when farmers find new use for the "freed up" water, by expanding irrigated areas, introducing new crops with higher water requirements, or switching from deficit to full irrigation (Berbel et al., 2015; Gómez and Pérez-Blanco,

* Corresponding author at: Faculty of Civil Engineering and Geosciences, Department of Water Management, Delft University of Technology, Stevinweg 1, Delft 2628 CN, the Netherlands.

E-mail addresses: g.w.h.simons@tudelft.nl (G.W.H. Simons), w.g.m.bastiaanssen@tudelft.nl (W.G.M. Bastiaanssen), mjm.cheema@gmail.com (M.J.M. Cheema), dr.bashir70@gmail.com (B. Ahmad), w.w.immerzeel@uu.nl (W.W. Immerzeel).

https://doi.org/10.1016/j.agwat.2020.106174
Received 11 October 2019; Received in revised form 10 February 2020; Accepted 25 March 2020

2014; Sanchis-Ibor et al., 2017). By now, the occurrence of this phenomenon, its preconditions, and implications, have been well-described in a large number of case studies (e.g. Pfeiffer and Lin, 2014; Contor and Taylor, 2013; Lecina et al., 2010; Rodriguez Díaz et al., 2012; Ward and Pulido-Velazquez, 2008). When no policy mechanisms are in place that incentivize farmers to reduce withdrawals or restrict either irrigated area or consumptive water use, there is a high risk of efficiency-enhancing measures leading to reduced non-consumed flows (i.e. return flows).

For effective planning of irrigation technology improvements and policies, it is therefore essential to understand the dependencies between water users (anthropogenic as well as natural) across a river basin. Reuse of non-consumed flows within and between sectors is facilitated by both natural pathways and human interventions, and results in a complex interplay between surface water and groundwater flows (Grogan et al., 2017). Intensity and complexity of reuse networks typically increase with scale (Simons et al., 2015; Wu et al., 2019). Environmental flow requirements of downstream ecosystems are often neglected, while their vulnerability to changes in agricultural non-consumed flows is potentially very high (Carrillo-Guerrero et al., 2013; Pastor et al., 2014).

As the conclusion of a literature review on impacts of drip irrigation introduction, Van der Kooij et al. (2013) called for an increased awareness of the scale-dependency of efficiencies and unintended reallocations of water flows. To achieve this objective and to account for spatial tradeoffs in policies and regulations, quantitative data on consumed and non-consumed portions of withdrawals are required. Quantifying consumed fractions on different scales would support assessments of the likely scope for water saving by irrigation modernization or policy alterations (Berbel and Mateos, 2014). In addition, it would support implementation of evapotranspiration caps in water rights systems, a key policy instrument to ensure water availability to downstream users (e.g. Dagnino and Ward, 2012; Bastiaanssen et al., 2008).

Data availability is currently a major limiting factor in the uptake of existing water reuse frameworks and indicators (Simons et al., 2015). Wiener et al. (2016) demonstrated how water reuse can be well-characterized for a watershed where extensive records of withdrawals, consumptive use and non-consumed flows are available. This is, however, not the case for most river basins. Governmental line agencies are struggling with the quantitative assessment of consumed fractions. Estimates of consumed fractions are therefore commonly limited to static literature values assumed at country level based on prevailing irrigation types, despite spatially varying biophysical factors having significant effects (Jägermeyr et al., 2015). Plot-level efficiency measurements in an experimental setting remain the main source of quantitative information (Bos et al., 2005; Bos and Nugteren, 1990), with simple extrapolation of these values to larger spatial scales increasing chances of misunderstandings and mismanagement (Merks, 2018; Molden and Sakthivadivel, 1999).

By definition, an assessment of consumed fractions in an irrigation context requires estimates of (i) the volume of water that is withdrawn for irrigation, and (ii) the fraction of this water that evaporates. To quantify the latter, over the past years the scientific community has turned to satellite remote sensing. Global satellite-derived data products can provide spatiotemporal insight in key hydrological parameters such as precipitation, actual evapotranspiration, soil moisture changes, runoff and storage change (Bastiaanssen and Harshadeep, 2005; Poortinga et al., 2017; Simons et al., 2016). Local estimates of consumed irrigation water can for example be obtained by analyzing evapotranspiration of nearby sites with similar land use, but known to be solely rainfed (van Eekelen et al., 2015). As satellites cannot measure water withdrawals, coupling remote sensing with simulation models has been explored for evaluating irrigation dynamics (Droogers et al., 2010; Peña-Arancibia et al., 2016; Santos et al., 2008). Promising results were achieved, but site-specific calibration remains necessary, prohibiting an easily scalable monitoring approach. In addition, some global-scale hydrological models compute consumed fractions by partitioning irrigation water into consumed and non-consumed flows (e.g. Jägermeyr et al., 2015). Although this enables scenario studies at the global scale, their applicability for monitoring purposes at the basin level remains limited.

Application of the Budyko Hypothesis (Budyko, 1974) is an approach that has not yet been pursued by the scientific community for quantifying consumptive use of irrigation water. The Budyko curve prescribes the theoretical partitioning of precipitation into streamflow and evapotranspiration based on water and energy climatologies. It has frequently been applied successfully for purposes of developing, constraining and validating water balance models (e.g. Zhang et al., 2008; Gentine et al., 2012; Chen et al., 2013; Poortinga et al., 2017). Although initially developed for natural river basins in dynamic equilibrium and with precipitation as the sole source of water supply, extensions and reformulations of the original Budyko approach have recently been proposed to evaluate the water balance of systems with anthropogenic supply or storage of water (Chen et al., 2020; Greve et al., 2016; Wang et al., 2016). These formulations have previously been tested favorably in irrigated, arid environments, such as the Tarim Basin (Han et al., 2011), Heihe River Basin (Du et al., 2016), and the Lower Jordan (Gunkel and Lange, 2017).

In this paper, we present a novel method for quantifying consumed fractions of irrigation systems based on Budyko theory and satellite-derived data products of evapotranspiration and precipitation. The approach is demonstrated by describing its application to the Indus Basin Irrigation System, which is the largest continuous irrigation system in the world. Consumptive use, irrigation water supply and non-consumed flows are presented and findings are discussed in the context of water reuse and water saving potential.

2. Materials and methods

2.1. Study area

This study focuses on the Pakistani part of the Indus Basin Irrigation System (IBIS), excluding the Canal Command Areas (CCAs) upstream of Jinnah Barrage (Fig. 1). IBIS receives its water mainly from snow melt and glacial waters in the upstream high-mountain areas of the Himalayas, Karakoram and Hindu Kush (Immerzeel et al., 2010), as well as from extraordinary rainfall falling on the windward slopes of the Himalayan mountains. The major part of IBIS surface area has an arid climate and rainfall in catchment areas is a secondary source of water. The monsoonal regime causes rainfall during the dry *rabi* season, in the months November to April, to be only 30 % of that in the rainy *kharif* season, from May to October (Habib, 2004). Surface water flow is concentrated in the Indus River and its tributaries Jhelum, Chenab, Ravi, Sutlej and Kabul. Water is buffered and distributed by a system comprising 3 major reservoirs, 18 barrages and headworks, 2 major siphons, and 12 inter-river link canals, serving a gross irrigable command area of over 16 million hectares in total (Qureshi, 2011). After extensive consumptive use for irrigation and, to a far lesser extent, municipal and industrial purposes, remaining streamflow downstream of the IBIS supports the rich diversity of vegetation and wildlife of the Indus Delta, where the Indus River eventually drains into the Arabian Sea. Annual environmental flow requirements are in place to combat inundation, sea water intrusion and coastal erosion (Kalhoro et al., 2016). Drainage flows, largely of poor quality, are also transported out of the system to evaporation ponds, or directly to the sea through the Left Bank Outflow Drainage (LBOD) canal (Basharat and Rizvi, 2016).

Cropping intensities in the IBIS have increased over the past decades and crop water requirements are, at the system scale, not fulfilled by the sum of surface water withdrawals and rainfall (Ullah et al., 2001). This discrepancy between water supply and demand is especially experienced by tail-end farmers, who typically have 32 % less water

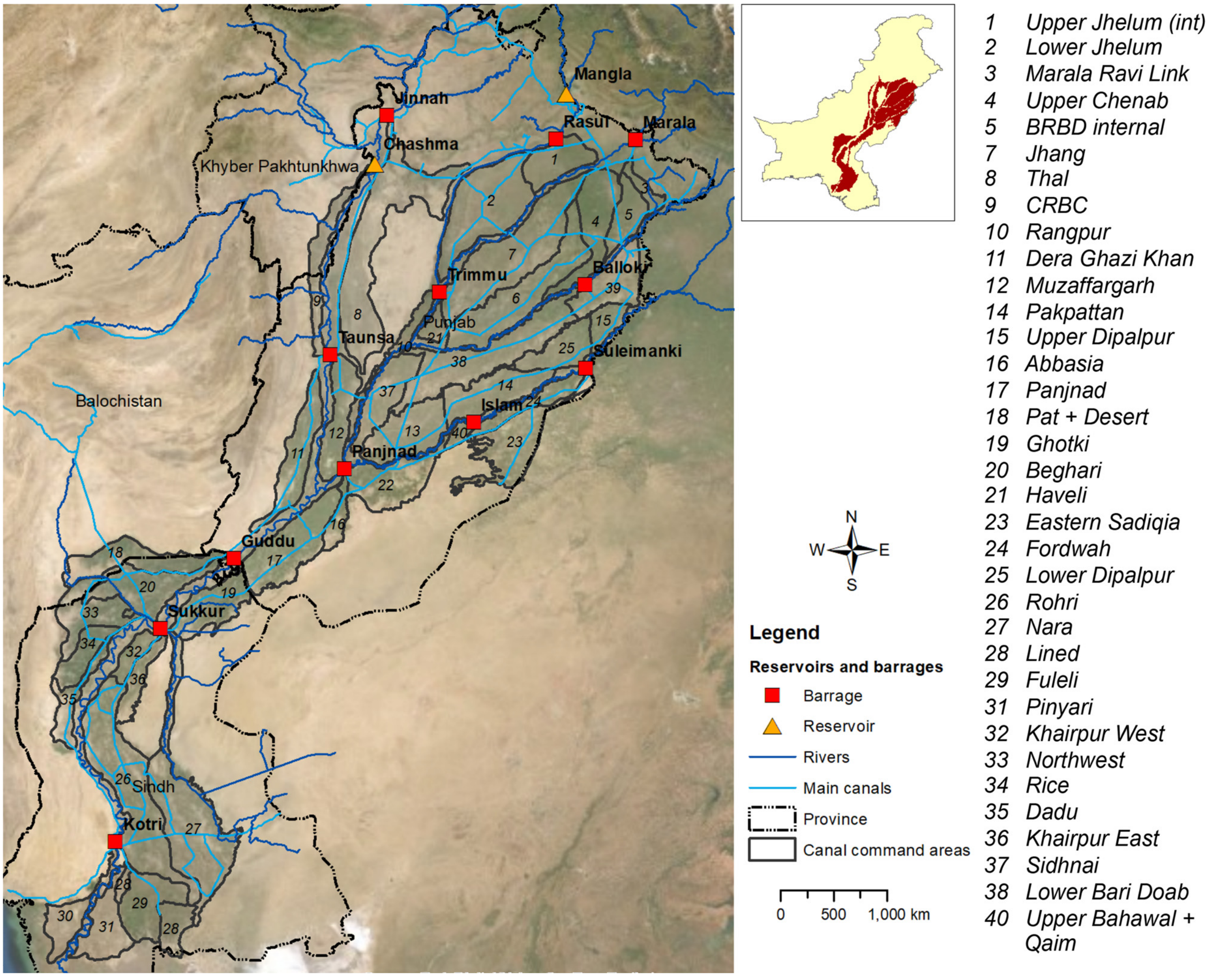

Fig. 1. The Indus Basin Irrigation System in Pakistan and its canal command areas.

available than head-end farmers (Qureshi et al., 2010). Inadequacy and unreliability of surface water supply has driven farmers to augment water shortages by pumping groundwater resources. Reported amounts vary from 52 to 61 km^3/yr, approaching the volume of annually replenished groundwater of 55 - 63 km^3/yr (Laghari et al., 2012; PBS, 2014; Watto and Mugera, 2016). Falling groundwater tables are observed in areas with fresh groundwater, most notably in the north-eastern part of the province of Punjab (Mekonnen et al., 2015). Particularly Eastern Punjab is a hotspot of groundwater depletion, with water table decline possibly exacerbated by transboundary impacts from extensive groundwater pumping across the Indian border (Cheema et al., 2014; Iqbal et al., 2017; Watto and Mugera, 2016). The situation is different in Sindh Province, where groundwater quality is generally marginal to hazardous and groundwater abstractions only constitute 4–8 % of total water use (Qureshi et al., 2008; van Steenbergen et al., 2015; Young et al., 2019). Structural waterlogging is a serious problem here, with over half of all CCA surface area increasingly affected by shallow water tables due to high surface water supplies and a low level of groundwater pumping, as well as poorly functioning drainage facilities and salinization (Basharat and Rizvi, 2016; van Steenbergen et al., 2015).

2.2. Analytical framework and calculation steps

The conceptual framework proposed by Simons et al. (2015) is followed in this study, thus defining the Consumed Fraction (*CF*) as the ratio between consumptive use of irrigation water and total water withdrawal. Following the common definitions of *green* and *blue* water (Falkenmark and Rockström, 2006), the component of actual evapotranspiration (ET_{act}) from surface or groundwater resource is denoted as ET_{blue}, and rain-dependent ET_{act} is termed ET_{green}:

$$ET_{act} = ET_{green} + ET_{blue} \quad (1)$$

Note that ET_{blue} is also referred to as incremental evapotranspiration (Hoogeveen et al., 2015), or secondary evaporation (Van Dijk et al., 2018). ET_{green} is referred to as net precipitation in classical formulations of irrigation water requirements (Jensen and Allen, 2016). The equation for computing *CF* then becomes:

$$CF = \frac{ET_{blue}}{Q_w} \quad (2)$$

where Q_w comprises withdrawals from surface water and/or groundwater for irrigation. In the context of an IBIS CCA, it is relevant to distinguish two types of inflow:

$$Q_w = Q_{div} + Q_{add} \quad (3)$$

where Q_{div} represents the volume of surface water diverted at the main canal head. Q_{add} comprises additional sources of water, such as local non-consumed flows that are pumped up, fossil groundwater abstraction, or drainage water from upstream CCAs entering through surface or sub-surface pathways other than the main canal.

The non-consumed portion of applied irrigation water is then calculated as the difference between total blue water supply and consumptive use of irrigation water:

$$Q_{nc} = Q_w - ET_{blue} \tag{4}$$

The proposed procedure for partitioning ET_{act} into ET_{green} and ET_{blue} is based on the Budyko Hypothesis (BH), which describes an empirical relation between ET_{act}, reference evapotranspiration (ET_0) and precipitation (P) for areas in dynamic equilibrium and with negligible storage changes (Sposito, 2017). The original Budyko equation has been reformulated several times in order to account for systematic differences between watersheds. This study applies the commonly used Budyko reformulation derived by Fu (1981):

$$\frac{ET_{green}}{P} = 1 + \frac{ET_0}{P} - \left(1 + \left(\frac{ET_0}{P}\right)^{\omega}\right)^{\frac{1}{\omega}} \tag{5}$$

where ω is a free parameter that describes the shape of the Budyko curve. ω can be viewed as an integrated catchment characteristic, determined by catchment-specific properties such as climate, land cover, vegetation and soil hydraulics (Condon and Maxwell, 2017; Li et al., 2013). Higher ω values indicate a higher ET_{green} under the same ET_0 / P ratio (the aridity index), and are thus related to a greater capacity of a basin to retain water for evapotranspiration.

In many river basins, the original BH assumptions are nowadays violated by extensive human influence on the water balance. This is in particular the case under irrigated conditions, when precipitation can no longer be assumed to be the only source of water available for evapotranspiration (Chen et al., 2020). However, various studies have demonstrated that accounting for alternative water sources in addition to P, such as canal water supply and storage changes, allow for successful application of Fu-type Budyko models in arid, irrigated regions (Du et al., 2016; Gunkel and Lange, 2017; Han et al., 2011). The ω parameter is then considered "the indicator to reflect the synthetical influence of basin characteristics on ET" (Chen et al., 2020). This includes, for example, the effect of deeper rooting of irrigated crops which enhances access to water from the soil profile (Zhang et al., 2004), as well as the artificial supply of surface water and/or groundwater to the crop. Multi-parameter Budyko models have been developed to examine these processes under unsteady-state conditions, such as on monthly or seasonal scales. However, these extended Budyko formulations do not provide additional explanatory power on a multi-annual time scale, as impacts of short-term rainfall and irrigation events are averaged out (Du et al., 2016; Greve et al., 2016).

For the irrigated IBIS, on a multi-annual time scale under the assumption of zero storage changes, alternative sources of water are included as follows:

$$\frac{ET_{act}}{P_{adj}} = 1 + \frac{ET_{ref}}{P_{adj}} - \left(1 + \left(\frac{ET_{ref}}{P_{adj}}\right)^{\omega}\right)^{\frac{1}{\omega}} \tag{6}$$

where:

$$P_{adj} = P + Q_w \tag{7}$$

Based on spatially distributed P, ET_0 and ω data (see Section 2.3), Eq. 5 can be solved for ET_{green}. By subtracting computed ET_{green} from satellite-derived ET_{act}, ET_{blue} can be calculated as the portion of consumptive water use that cannot be accounted for by rainfall according to the BH (Fig. 2, left panel). Under the assumption that Eq. 4 is valid at the pixel scale (Viola et al., 2017), this step yields spatial data of both rainfall- and irrigation-dependent ET. Subsequently, in order to estimate the supply side of CF, Eq. 6 is applied to find the value of P_{adj} for which ET_{act} / P_{adj} equals the theoretical value of this ratio prescribed by Budyko theory, as illustrated in the right panel of Fig. 2. In this case, 1 - ET_{act} / P_{adj} equals the runoff fraction R_f. Subtracting P from the comprehensive supply term P_{adj}, then, yields the estimate of Q_w required for quantifying CF (Eq. 2). If records of Q_{div} are available, Q_{add} can be computed by applying Eq. 3 to explore reuse of water and (unsustainable) groundwater pumping. An overview of the full approach is presented in Fig. 3.

2.3. Datasets

This study uses ET_{act} data for 2004–2012 from the Operational Simplified Surface Energy Balance (SSEBop) v4 model, which is one of several global-scale satellite-derived ET_{act} products available in the public domain (Senay, 2018; Senay et al., 2013). SSEBop is a surface energy balance model that calculates the latent heat flux from land surface temperature measured by the satellite-based MODIS sensor. It is based on pixel-specific pre-defined temperature differences between cold (wet) and hot (dry) conditions, where air temperature from climate models is used as an indicator for the coldest land surface temperature. The performance of SSEBop relative to other global ET_{act} products and field measurements has been evaluated in multiple studies, and has been generally found favorable (e.g. Simons et al., 2016; FAO, 2019). Another reason for using SSEBop in this study is the availability of a corresponding ET_0 product in the public domain, which ensures consistency between ET_0 and ET_{act} as required for BH application. The spatial resolution of the SSEBop ET_{act} and ET_0 products is 1 km^2 and 1 degree respectively.

Although SSEBop performance in terms of spatial and temporal dynamics has previously been found satisfactory, systematic biases can occur depending on the region of interest and the algorithm should be calibrated based on auxiliary data (Senay, 2018). This relates to the use of a "maximum ET scaling factor" (K) in the SSEBop algorithm, which depends on the aerodynamic roughness, the degree of advection and prevailing weather conditions, among others. Based on independent estimates of ET_{act}, e.g. from field experiments or the conservation of water mass at the river basin scale, a potential bias correction of the global SSEBop product in a river basin of interest is recommended.

In this study, we take the approach of inventorying previous efforts to quantify ET_{act} in the IBIS, and correcting long-term SSEBop ET_{act} for these values. Several previous studies have been performed in the Indus Basin, applying locally calibrated models to assess water consumption of irrigated crops. Table 1 presents the identified studies quantifying annual ET_{act} for at least a part of the IBIS. Based on the values presented in these studies and SSEBop values for the corresponding years and areas, a correction factor of 0.78 was applied to the original global SSEBop data to correct for overestimation. This linear bias correction is justified due to the linear relation of K to ET_{act} in the SSEBop formulation.

Next to ET_{act} and ET_0, data on rainfall and the Budyko ω parameter are required for application of the BH. Monthly rainfall data at ~5 km resolution were obtained from the quasi-global satellite-derived Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) v2.0 dataset (Funk et al., 2015). For Pakistan in 2004–2012, data from approximately 35 rainfall stations are incorporated in the CHIRPS algorithm to enhance satellite rainfall estimates. Data on ω were acquired from the study by Xu et al. (2013), who produced spatially discrete data on ω using a Neural Network model fed by ET_{act}, ET_0, P and streamflow data for 256 river basins. Their model was trained including NDVI as an explicit input, based on 23 years of P, ET_0, and Q data. The ω values can therefore be seen as representative for this period, including impacts of irrigation on vegetation and water. Depending on surface area, the number of unique ω values per CCA varies between 1 and 14. Finally, monthly data on canal diversions and reservoir releases, required for partitioning calculated withdrawals into Q_{div} and Q_{add}, were made available by the Water And Power Development Agency of Pakistan (WAPDA) for the years 2004–2012.

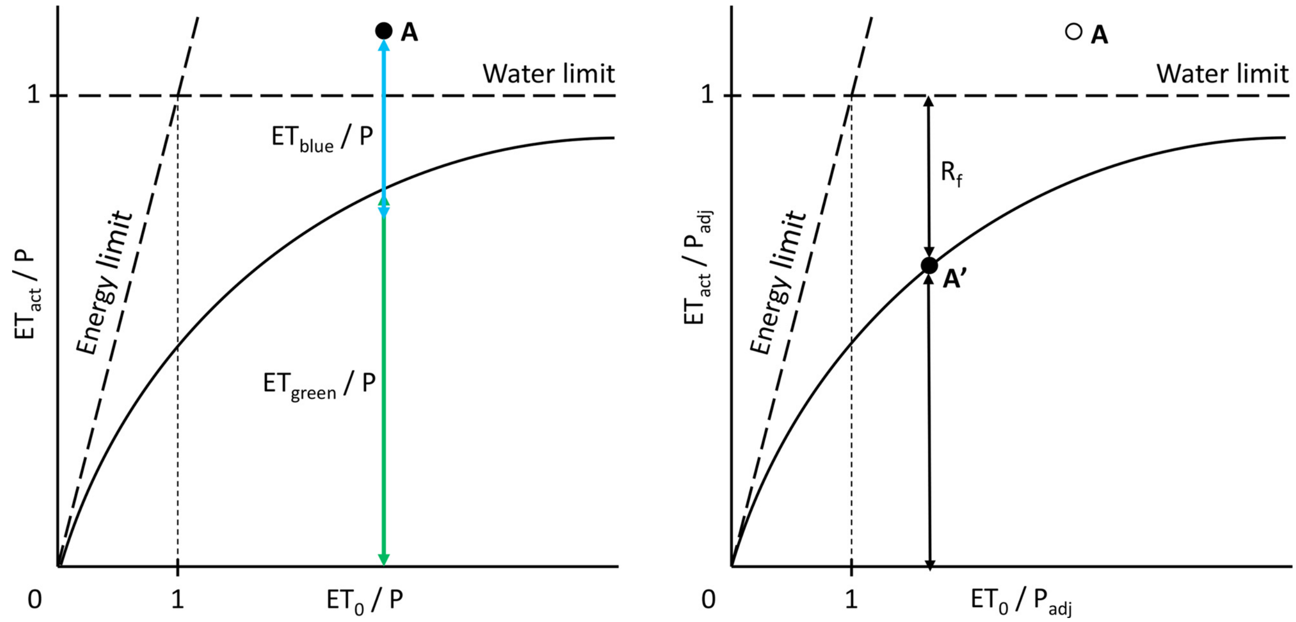

Fig. 2. Location of an irrigated basin (A) in the Budyko framework when considering rainfall (P) as the sole term on the supply side (left) and its new location A' on the Budyko curve when considering all sources of water (P_{adj}, right). ET_{act} and ET_0 refer to actual and reference evapotranspiration, respectively.

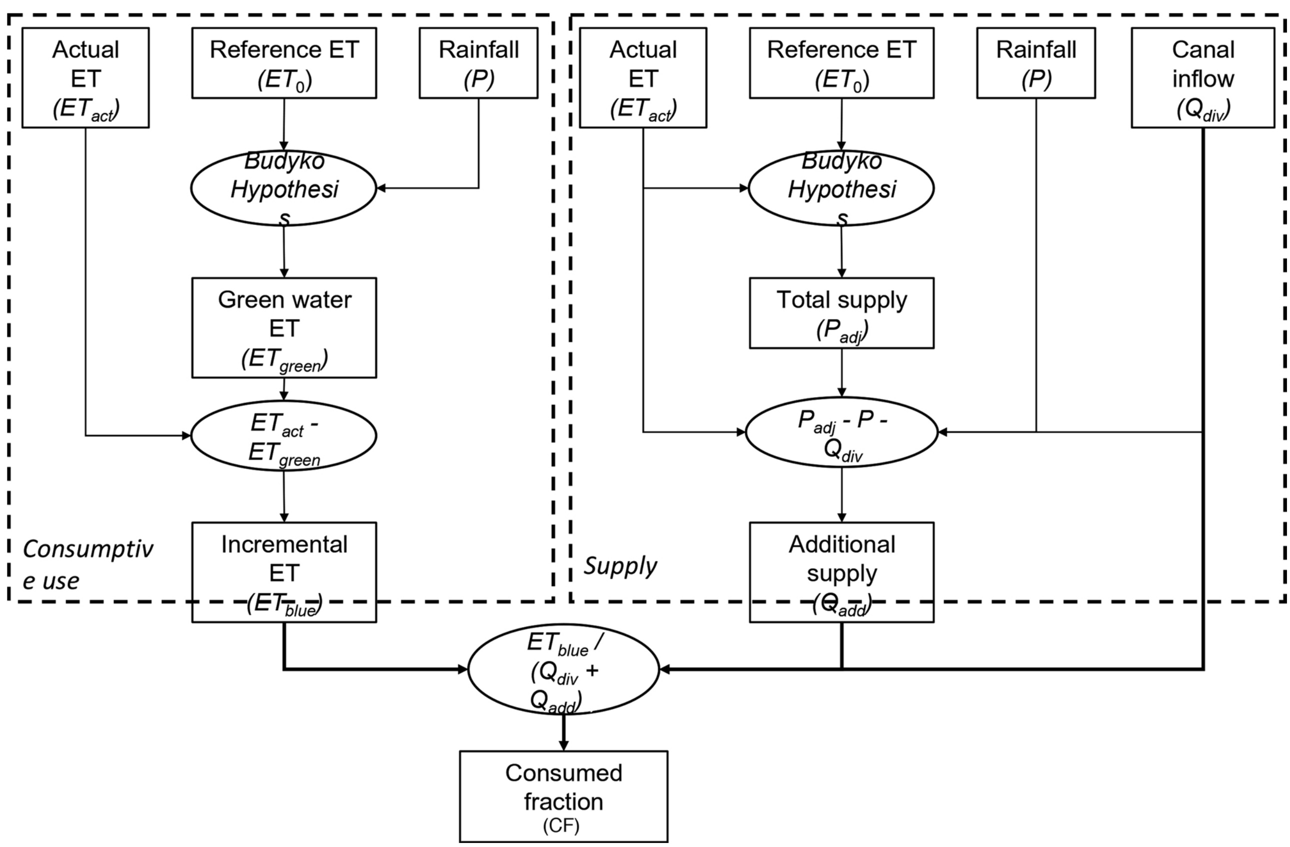

Fig. 3. Analytical framework and calculation steps, where ET refers to evapotranspiration.

3. Results and discussion

3.1. Evapotranspiration of irrigation water

Fig. 4 shows the position of the 40 IBIS CCAs in Budyko space, based on area-averaged values of mean annual ET_{act}, ET_0 and P over the period May 2004 - April 2012 (eight full hydrological years). Each of the CCAs has a unique theoretical Budyko curve depending on ω. For reference, Fig. 4 presents the curves corresponding with minimum and maximum ω at the CCA level, as well as one for the average ω value for entire IBIS. All CCAs are located well above the Budyko curves, where it should be noted that the y-axis is plotted on a logarithmic scale (base 2) to account for the relatively large distances to the theoretical curves. The arid climate in the IBIS is demonstrated by the high aridity indices

Table 1
Overview of different actual evapotranspiration (ET_{act}) studies and SSEBop values for corresponding areas and periods. The SSEBop_cor column presents ET_{act} values after correction with a factor of 0.78.

Area	Period	Literature ET_{act} *mm/yr*	Source	SSEBop *mm/yr*	SSEBop_cor *mm/yr*
Lower Chenab	2005–2012	793	Usman et al. 2015	1145	893
	2005–2011	853	Awan and Ismaeel 2014	1150	897
Hakra	2008–2014	963	Liaqat et al. 2016	1112	868
All CCAs	2009–2010	854 – 1208*	Liaqat et al., 2015	656 – 1257	512 - 980
Entire IBIS - irrigated fields (incl India)	2007	974	Bastiaanssen et al. 2012	1198	934
Pakistani IBIS	1993–1994	970	Bastiaanssen et al. 2002, 2003	–	–
	2001–2002	850	Ahmad et al. 2009	–	–
	2004–2012	–	–	1187	926

* This study only provides annual ET_{act} averages at the CCA level. Listed values are minimum and maximum.

plotted on the x-axis, with CCAs located in Punjab generally coinciding with lower ET_{act}/P and ET_0/P values than those in Sindh[1]. This is representative of the northeast-southwest rainfall gradient occurring in IBIS. Overall, given Budyko theory, Fig. 4 matches expectations with regards to an irrigated system, as for none of the CCAs the rate of water consumption can be explained by natural water supply through rainfall. The theoretical lines in Fig. 4 can be used to infer the ET_{act} value associated with P, i.e. ET_{green} in Eq. 5.

According to the theoretical concept illustrated in Fig. 2, ET_{act} can now be partitioned into ET_{blue} and ET_{green} for each CCA, based on the distance to the CCA-specific theoretical Budyko curves. Fig. 5 shows the resulting maps of annual ET_{blue} and ET_{green}, averaged for 2004–2012. Whereas annual ET_{green} follows a relatively smooth spatial pattern corresponding with the rainfall gradient, ET_{blue} is much more heterogeneous and depends on e.g. crop type, canal operations, groundwater pumping behavior, soil salinity and groundwater quality. High values for ET_{blue} are particularly observed in the central part of IBIS and in southern Sindh, particularly in areas close to the main river. Locally, values of over 1200 mm of annual ET_{blue} occur in Rohri, Lined, and Khaipur West CCAs. Low ET_{blue} values approaching zero are found at the edges of many CCAs where irrigation is absent, and further from the main canal inlets. It is striking that a major part of Thal CCA surface area has negligible ET_{blue}, which corresponds with the large extent of rainfed agriculture in this CCA reported by the land use / land cover map of Cheema and Bastiaanssen (2010).

Fig. 6 presents CCA-level averages for annual ET_{blue}, ET_{green}, and shows that ET_{green} generally follows the variability of CCA-averaged rainfall amounts precipitation, as is to be expected. Several CCAs in Punjab depend on rainfall for a substantial portion of their water consumption, with ET_{green} in four CCAs (Marala Ravi Link, Thal, Upper Jhelum, BRBD internal) accounting for over half of total ET_{act}. This is very different in Sindh Province, with annual ET_{green} for all CCAs at 25 % of total ET_{act} or less. Here, arid conditions require supply of high volumes of irrigation water to satisfy crop water requirements. In Punjab Province, annual ET_{blue} values vary between 268 mm/yr (Thal) and 937 mm/yr (Upper Bahawal + Qaim). In Sindh, minimum and maximum annual ET_{blue} is 588 mm/yr (K.B. Feeder) and 1011 mm/yr (Khaipur West), respectively.

In Table 2, ET_{blue} and ET_{green} results are aggregated for provinces, as well as for the agro-climatic zones distinguished by Ullah et al. (2001). Relatively low ET_{act} values in the mixed cropping zone can be explained by cultivation of (fruit) crops that are less water-demanding and by high seepage due to presence of sandy soils (Liaqat et al., 2015; Ullah et al., 2001). The table shows how, despite similar overall ET_{act} values at the provincial level, the relative attribution of this consumed water to rainfall and additional irrigation water differs substantially between the provinces. The ratio of ET_{green} over P presented in the far right column of Table 2 can be viewed as the percentage of effective rainfall, which on the annual scale for the entire IBIS amounts to 85 %. It should be noted that presented values do not include "unofficial" irrigation outside CCA boundaries, and that a thorough review of CCA boundaries is beyond the scope of the current research.

3.2. Canal diversions and additional water supply

The distance of the CCAs to the theoretical Budyko curves in Fig. 4 is indicative of water sources other than precipitation. Fig. 7 presents the CCAs in Budyko space once again, now with measured Q_{div} added to the supply side of both ratios. By adding Q_{div} as a supply of water, the ET ratio (vertical axis) and aridity index (horizontal axis) decrease, reflecting a situation with wetter land surface climatology. As a consequence, all CCA points have moved substantially towards the Budyko

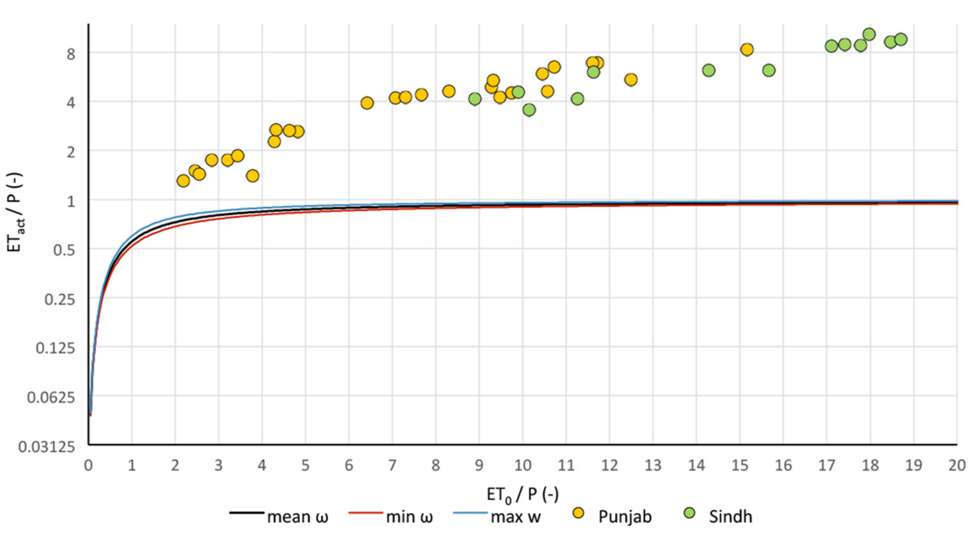

Fig. 4. Ratios between actual evapotranspiration (ET_{act}) and precipitation (P), and between reference evapotranspiration (ET_0) and P, of canal command areas in the Indus Basin Irrigation System for the 2004 – 2012 period. The presented Budyko curves are calculated with ω values of 1.88, 1.76, and 2.05, corresponding with command area-level mean, minimum, and maximum values, respectively.

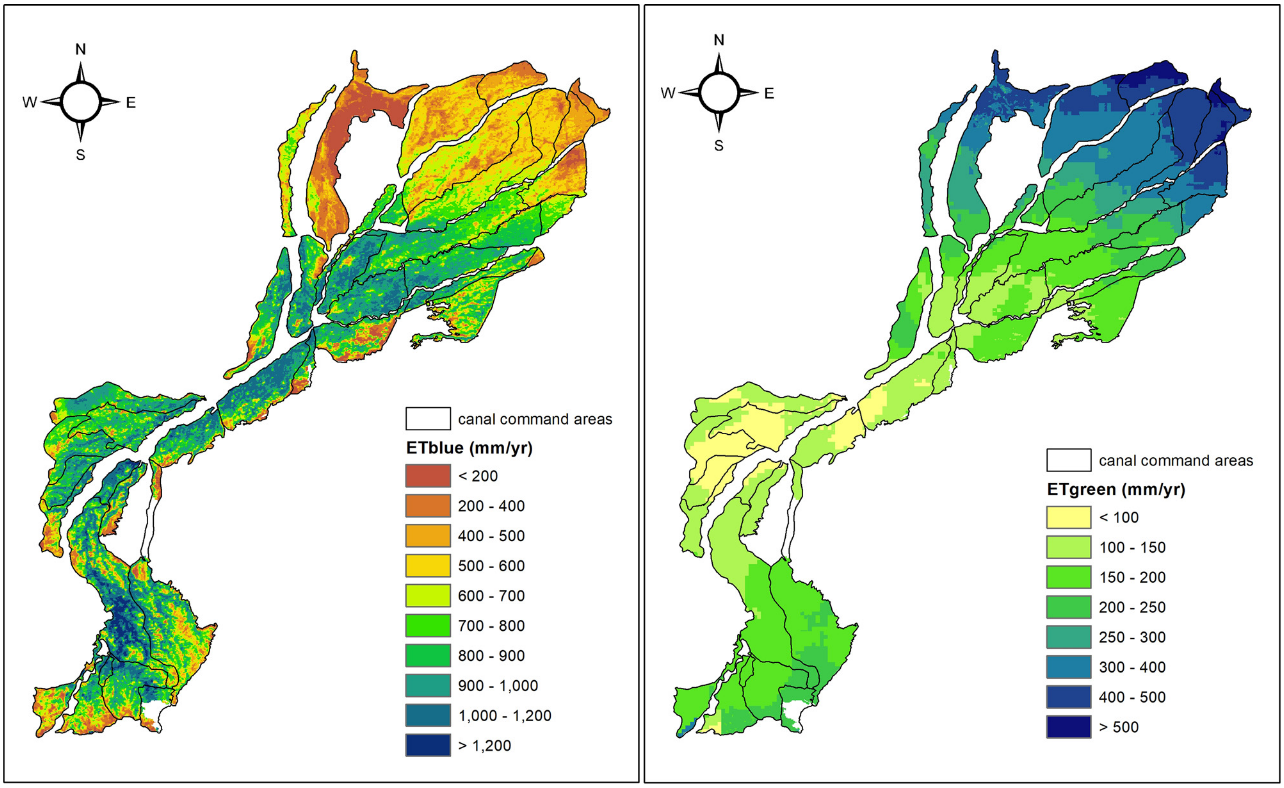

Fig. 5. Annual blue water evapotranspiration (ET_{blue}, left) and green water evapotranspiration (ET_{green}, right) across the Indus Basin Irrigation System, averaged for 2004 – 2012. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

lines. It should be noted that values are annual averages for the 2004–2012 period, and only CCAs are shown for which at least one full hydrological year of Q_{div} data is available during this period (see Table 3 for the years included per CCA) (Table 4).

The majority of the points are still above the theoretical Budyko lines, suggesting that the sum of precipitation and canal water diversions is unable to explain all water supplied to the crops. Strikingly, as opposed to what was observed in Fig. 4, Sindh CCAs are now generally closer to the Budyko curve than those in Punjab. This can be explained by relatively high surface irrigation allocations in Sindh. As described by van Steenbergen et al. (2015), excessive canal supplies in several of Sindh CCAs have been observed to lead to extensive water logging. A well-known example of this is Rice canal (no. 34), which fits the observation that it approaches the theoretical Budyko value in Fig. 7. K.B. Feeder (no. 30) is located below the Budyko curves, which can be explained by the fact that a substantial part of diverted water is transported for domestic use to the megacity of Karachi, adjacent to the CCA (Phul et al., 2010). This CCA is therefore excluded from further analyses. Most Punjab CCAs are still far from the theoretical Budyko curves, indicating that a relatively large portion of their water supply comes from sources other than main canal headwaters.

What follows from Fig. 7 is that ET_{act} in most CCAs is attributable to sources of water in addition to rainfall and canal diversions, as most CCA points plot well above the curve. Total Q_w can now be computed from the distance between the actual data points in Budyko space and the theoretical Budyko curve as prescribed by the CCA-specific ω

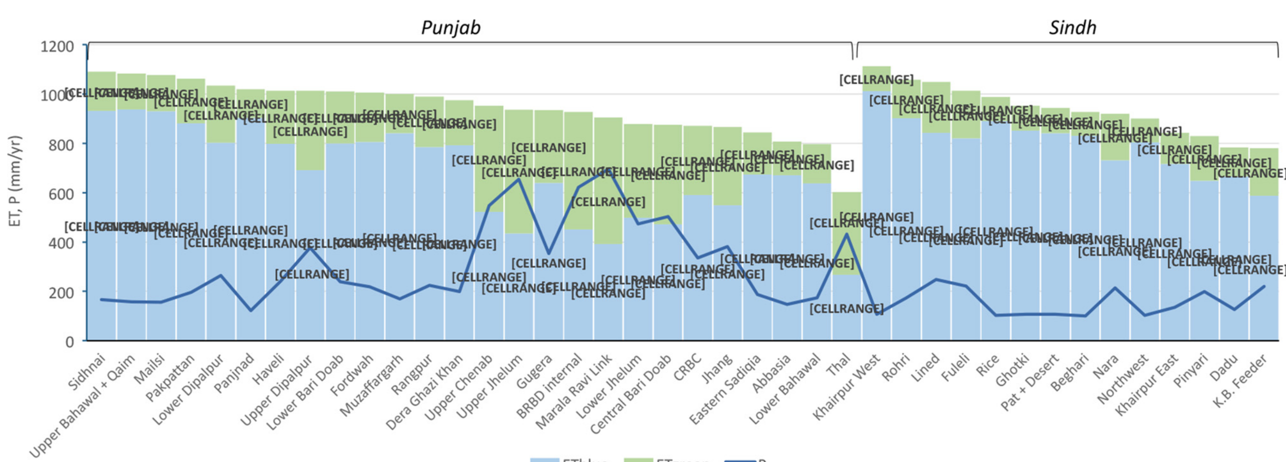

Fig. 6. Annual average blue water evapotranspiration (ET_{blue}), green water evapotranspiration (ET_{green}), and precipitation (P) for each canal command area. Percentages represent ET_{blue} and ET_{green} amounts with respect to total actual evapotranspiration. (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

Table 2
Precipitation (P), actual evapotranspiration (ET_{act}), blue water evapotranspiration (ET_{blue}), and green water evapotranspiration (ET_{green}) for the agro-climatic zones and provinces of the Indus Basin Irrigation System.

Province	Agro-climatic zone	Area (km^2)	*P*		ET_{act}		ET_{blue}			ET_{green}			
			mm	*BCM*	*mm*	*BCM*	*mm*	*BCM*	*% of* ET_{act}	*mm*	*BCM*	*% of* ET_{act}	*% of P*
Punjab	Mixed cropping	10,494	435	4.6	602	6.3	268	2.8	45%	334	3.5	55%	77 %
	Rice wheat	12,527	541	6.8	929	11.6	505	6.3	54%	423	5.3	46%	78 %
	Cotton wheat	55,840	189	10.6	986	55.1	814	45.4	83 %	172	9.6	17%	91 %
	Sugarcane wheat	26,524	425	11.3	899	23.8	555	14.7	62%	344	9.1	38 %	81 %
	Total	105,385	321	33.2	915	96.9	649	69.3	71%	266	27.5	29%	83 %
Sindh	Cotton wheat	29,472	174	5.1	984	29.0	828	24.4	84 %	156	4.6	16%	90 %
	Rice wheat	30,419	154	4.7	915	27.8	778	23.7	85 %	137	4.2	15 %	89 %
	Total	59,891	168	9.8	950	56.8	801	48.0	84 %	149	8.8	16%	89 %
IBIS total		165,276	263	43.0	927	153.7	707	117.3	76 %	220	36.3	24%	85 %

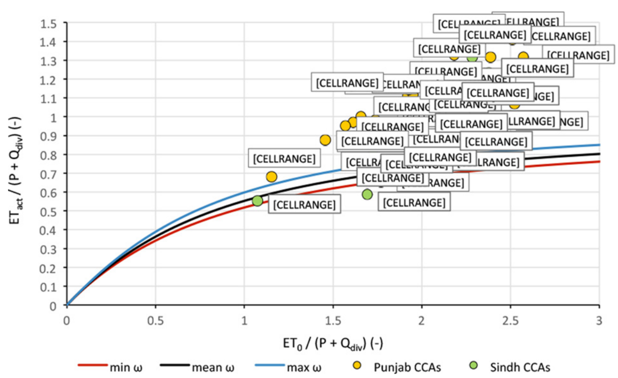

Fig. 7. Ratios between actual evapotranspiration (ET_{act}) and the sum of precipitation (P) and canal water supply (Q_{div}), and between reference evapotranspiration (ET_0) and (P + Q_{div}), of canal command areas in the Indus Basin Irrigation System for the 2004 – 2012 period. The presented Budyko curves are calculated with ω values of 1.876, 1.76, and 2.05, which correspond with CCA-level mean, minimum, and maximum values, respectively. Canal command area numbering is as listed in Fig. 1.

values, by solving Eq. 6 for the comprehensive supply term P_{adj} and subsequently applying Eq. 7. A full overview of all blue water fluxes per CCA, including additional supply Q_{add} as the difference between Q_w and Q_{div}, is provided in Table 3. It is clear that relatively large volumes of Q_{add} are computed for almost all CCAs. At the same time, a substantial amount of non-consumed water (Q_{nc}) is computed as, apparently, Q_w has to exceed ET_{blue} substantially to maintain the hydrological processes imbedded in the Budyko Hypothesis. This annual water balance looks as follows:

$$Q_{div} + Q_{add} = ET_{blue} + Q_{nc} \tag{8}$$

For the IBIS, filling in the terms in Eq. 8 with their average values yields:

662 + 690 = 707 + 645

with all values in mm per year.

As described in Section 2.2, Q_{add} can be a combination of different sources of water, both depending on hydrological processes *within* the respective CCA and *between* CCAs. It is interesting to explore the Q_{add} term further, as it provides insight into the nature of reuse of non-consumed flows in the IBIS and potentially also includes unsustainable groundwater pumping. Fig. 8 presents Q_{add} relative to other water supply components for all CCAs. Dependency on Q_{add} differs highly among the areas, with values ranging between 5 % (Rice) and 61 % (Khaipur West). At the provincial level, these values amount to 47 % and 38 % of total water supply including precipitation for Punjab and Sindh respectively. This difference could be explained for example by coarser soils with more percolation losses, the degree to which canal water allocation meet crop water requirements, and groundwater quality issues.

Evaluating multi-annual Q_{div} against ET_{blue} provides insight in the long-term blue water balance and the source of Q_{add}. In CCAs where ET_{blue} exceeds Q_{div}, Q_{add} must structurally depend on non-consumed flows from upstream CCAs, rainfall recharge outside of CCA (or total IBIS) boundaries, or unsustainable groundwater use. On the other hand, positive values for Q_{div} - ET_{blue} indicate a net positive contribution of blue water in the corresponding CCA to the aquifer system. Table 3 shows that, on average, Q_{div} (662 mm) on average is largely able to sustain ET_{blue} (707 mm, or 107 % of Q_{div}). However, Fig. 9 demonstrates that Q_{div} – ET_{blue} varies greatly per CCA and, in fact, per province. Clearly, Jhang, Panjnad, Lower Bari Doab, and Rohri are examples of CCAs requiring substantial volumes of water on the long-term in addition to Q_{div} to explain irrigation consumptive use. An example of the opposite phenomenal is Rice canal, which due to excessive canal supply has a blue water surplus of 1.8 BCM. Looking at the provincial level, substantial differences exist between Punjab and Sindh. Annual ET_{blue} in Punjab is approximately 7 BCM (15 %) higher than Q_{div}, whereas for Sindh a minor positive Q_{div} - ET_{blue} value is calculated.

The above analysis shows that consumptive use in Punjab CCAs is more dependent on return flows and aquifer recharge generated outside CCA boundaries, and / or fossil groundwater pumping. The latter has received elaborate attention in recent scientific literature and model assessments. Although local falling water tables due to unsustainable groundwater use are a well-known point of concern, especially in Punjab, they cannot be regarded as dominant in explaining Q_{add} volumes. Since long-term Q_{add} is substantially higher than Q_{div} - ET_{blue} in all CCAs, the main source of Q_{add} must lie within the CCA and must be replenished within the annual time frame. This finding is supported by previous analyses of GRACE water storage data, in which groundwater depletion over the Upper Indus Plain in 2003–2010 was estimated at 1.48 BCM/yr or 13.5 mm/yr (Iqbal et al., 2016). This corresponds to only 4% of annual Q_{add} computed for the relevant CCAs. The groundwater balance presented by Young et al. (2019), based on a comprehensive literature review, similarly suggests that the recharge and discharge components of the overall aquifer system are largely in balance.

Overall, the Budyko-based analysis paints a picture of a system where discrepancies between crop water demands and canal water supply during the irrigation season lead to pumping of a mixture of Q_{div} and Q_{add}. Based on the magnitude of Q_{add} volumes in both Punjab and Sindh compared to other blue water fluxes, it can be safely stated that this additional supply term mainly consists of local (within – CCA) non-consumed flows (Q_{nc}). In this regard, it is interesting to note the similar magnitude of Q_{add} and Q_{nc} presented in Table 3. Irrigation in IBIS CCAs is characterized by the pumping of considerable volumes of non-consumed flows generated within the same CCA, which for a major part drain back into the system and are withdrawn again in a next cycle.

Table 3
Annual blue water fluxes* for the IBIS canal command areas. Not presented due to insufficient availability of canal diversion data are Gugera, Mailsi, and Lower Bahawal. K.B. Feeder is also not shown, as a substantial portion of canal water is used for Karachi urban water supply (see main text).

ID	CCA	Area (km^2)	ET_{blue} (mm) (MCM)	Q_w (mm) (MCM)	Q_{div} (mm) (MCM)	Q_{add} (mm) (MCM)	Q_{nc} (mm) (MCM)	Period
1	Upper Jhelum (int)	2830	432 (1222)	1144 (3238)	401 (1134)	743 (2104)	712 (2016)	2004 – 2007
2	Lower Jhelum	7489	494 (3697)	1118 (8375)	445 (3332)	673 (5043)	625 (4679)	2004 – 2007, 2010 – 2012
3	Marala Ravi Link	855	421 (360)	923 (789)	270 (231)	653 (558)	502 (429)	2004 – 2007
4	Upper Chenab	4334	531 (2300)	1205 (5222)	465 (2015)	740 (3207)	674 (2923)	2004 – 2007
5	BRBD internal	2197	438 (963)	998 (2193)	288 (634)	710 (1559)	560 (1230)	2004 – 2007, 2010 – 2012
7	Jhang	9113	536 (4882)	1049 (9561)	259 (2356)	791 (7205)	513 (4680)	2006 – 2007
8	Thal	10,494	267 (2797)	489 (5133)	489 (5131)	0 (1)	223 (2336)	2004 – 2007, 2010 – 2012
9	CRBC	2745	574 (1575)	1265 (3473)	418 (1149)	847 (2325)	691 (1898)	2007
10	Rangpur	1606	764 (1227)	1512 (2429)	444 (714)	1068 (1715)	748 (1202)	2006 – 2007, 2010 – 2012
11	Dera Ghazi Khan	4188	788 (3299)	1573 (6588)	877 (3674)	696 (2914)	785 (3289)	2004 – 2007, 2010 – 2012
12	Muzaffargarh	3662	835 (3057)	1676 (6137)	847 (3100)	829 (3037)	841 (3080)	2004 – 2007, 2010 – 2012
14	Pakpattan	4278	857 (3667)	1640 (7016)	725 (3103)	915 (3913)	783 (3348)	2006 – 2007, 2010 – 2012
15	Upper Dipalpur	1438	685 (985)	1288 (1851)	497 (714)	791 (1137)	603 (867)	2006 – 2007
16	Abbasia	1199	659 (789)	997 (1195)	583 (699)	414 (497)	339 (406)	2004 – 2007
17	Panjnad	6017	910 (5474)	1686 (10,147)	653 (3929)	1033 (6218)	777 (4673)	2004 – 2007, 2010 – 2012
18	Pat + Desert	4410	841 (3711)	1537 (6780)	915 (4033)	623 (2747)	696 (3069)	2004–2012
19	Ghotki	3819	852 (3253)	1511 (5772)	933 (3565)	578 (2207)	660 (2519)	2004–2012
20	Beghari	4627	831 (3845)	1480 (6848)	671 (3107)	809 (3742)	649 (3003)	2004–2012
21	Haveli	816	802 (654)	1680 (1370)	646 (527)	1034 (843)	879 (717)	2004 – 2007
23	Eastern Sadiqia	5130	669 (3434)	1114 (5717)	768 (3938)	347 (1779)	445 (2283)	2006 – 2007, 2010 – 2012
24	Fordwah	2136	787 (1681)	1416 (3025)	554 (1184)	862 (1841)	630 (1345)	2004–2012
25	Lower Dipalpur	2890	776 (2242)	1603 (4632)	525 (1516)	1078 (3116)	827 (2391)	2006 – 2007, 2010 – 2012
26	Rohri	11,446	902 (10,321)	1671 (19,123)	682 (7811)	988 (11,312)	769 (8801)	2004–2012
27	Nara	10,996	731 (8041)	1378 (15,152)	802 (8817)	576 (6335)	647 (7111)	2004–2012
28	Lined	2402	843 (2025)	1568 (3767)	585 (1406)	983 (2361)	725 (1742)	2004–2012
29	Fuleli	4294	820 (3521)	1409 (6052)	1052 (4517)	357 (1535)	589 (2531)	2004–2012
31	Pinyari	3576	649 (2320)	1074 (3841)	722 (2581)	352 (1260)	425 (1521)	2004–2012
32	Khairpur West	1336	1011 (1351)	2046 (2733)	742 (992)	1304 (1742)	1035 (1382)	2004–2012
33	Northwest	3907	804 (3143)	1525 (5958)	808 (3159)	717 (2800)	721 (2816)	2004–2012
34	Rice	2261	891 (2014)	1779 (4022)	1687 (3813)	92 (209)	888 (2008)	2004–2012
35	Dadu	2211	667 (1474)	1100 (2432)	820 (1813)	280 (620)	433 (958)	2004–2012
36	Khairpur East	1876	717 (1345)	1131 (2123)	715 (1342)	416 (780)	415 (778)	2004–2012
37	Sidhnai	3508	927 (3253)	1854 (6505)	647 (2271)	1207 (4234)	927 (3252)	2004 – 2007, 2010 – 2012
38	Lower Bari Doab	7935	795 (6310)	1577 (12,515)	664 (5271)	913 (7244)	782 (6205)	2004 – 2007, 2010 – 2012
40	Upper Bahawal + Qaim	555	937 (520)	1899 (1054)	1418 (787)	481 (267)	962 (534)	2004 – 2007, 2010 – 2012
Area-weighted average (mm)			707	1352	662	690	645	Varying

Q_{add} = additional supply, Q_{nc} = non-consumed irrigation water.
* ET_{blue} = blue water evapotranspiration, Q_w = total irrigation water withdrawal, Q_{div} = canal water supply.

Table 4
Selected IBIS irrigation efficiency values from various literature sources. It should be noted that definitions vary and, therefore, not all values can be directly intercompared.

Data source	Area	Value	Definition as used in source
Khan et al. (2006)	Rechna Doab	0.32	Surface water irrigation efficiency
Hussain et al. (2011)	IBIS	0.35	Canal conveyance efficiency * watercourse conveyance efficiency * field channel efficiency * field application efficiency
Basharat and Tariq (2013)	Lower Bari Doab Canal	0.49	Conveyance efficiency * watercourse efficiency * field application efficiency
Yu et al. (2015)	Punjab and Sindh	0.35	Canal efficiency * watercourse efficiency * field efficiency
Qureshi et al. (2010)	Pakistan	0.3	Overall irrigation efficiency
Shakir et al. (2010)	IBIS	0.4	Irrigation efficiency “from canal head to the field level”
Jägermeyr et al. (2015)	IBIS	0.24	Beneficial irrigation efficiency (transpiration / withdrawals)
Rohwer et al. (2007)	Pakistan	0.32	Actual project efficiency

3.3. Consumed fractions and implications for agricultural water management

Thanks to the availability of ET_{blue} and Q_w data, Eq. 1 can now be applied to calculate consumed fractions of water withdrawals at the CCA level. Fig. 10 shows the resulting map of *CF* across IBIS. Although *CF* values differ between CCAs, *CF* values in Sindh are generally found to be higher than in Punjab. Overall, *CF* ranges between 0.38 (Upper Jhelum) and 0.66 (Abbasia) at the level of the IBIS main CCAs, with an average size of 4036 km^2. The average CF at CCA level for entire IBIS, weighted according to total Q_w, is 0.52.

To provide reference for the BH-based results, Error! Reference source not found. gives an overview of IBIS irrigation efficiency values found in scientific literature. Though efficiency definitions are not consistent among these studies, they typically incorporate “losses” of diverted water in the processes of conveyance through canals and application to the field crop. The Budyko-based analysis generally yields higher values than irrigation efficiencies previously assumed for Pakistan, which vary between 0.3 and 0.49. This suggests that irrigation in the IBIS is more “efficient” than previously reported, mostly based on local-scale measurements. In comparison to literature efficiency estimates separating beneficial and non-beneficial consumption, it should be noted that ET_{blue} does not discriminate between crop transpiration and soil evaporation, which logically yields somewhat higher *CF* values.

Evaluating *CF* values on different spatial scales leads to insight in the system-scale reuse of non-consumed flows. In this study, it is assumed that the CCA level is the minimum scale on which Budyko theory assumptions are valid. *CF* of the entire IBIS can be estimated by dividing Budyko-derived ET_{blue} by the total water supply to the system. As long-term net groundwater recharge is virtually zero, a conservative estimate of *CF* can be computed based on total releases of the main reservoirs at the IBIS head, which in 2004–2012 amounted to 163.6 km^3/yr or 990 mm/yr on average (PBS, 2014). CF of entire IBIS can then be estimated by the ratio between ET_{blue} (Table 3) and

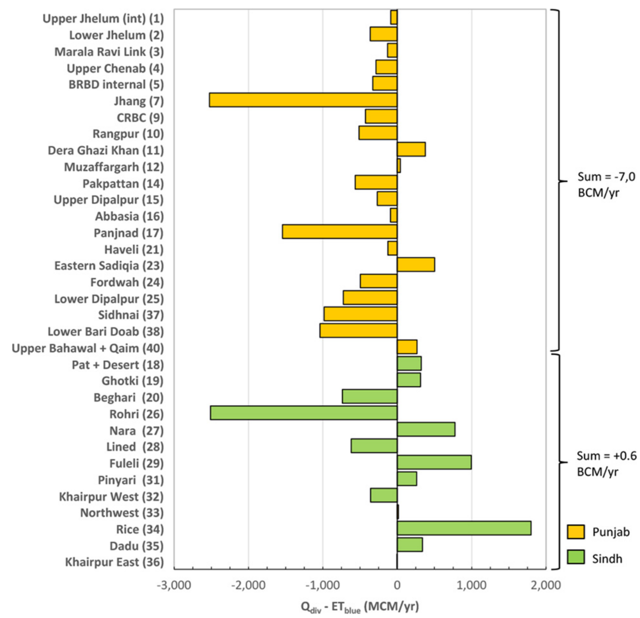

Fig. 9. Difference between canal water supply (Q_{div}) and blue water evapotranspiration (ET_{blue}) for each of the canal command areas. Not presented due to insufficient availability of Q_{div} data are Gugera, Mailsi, and Lower Bahawal. K.B. Feeder is also not shown, as a substantial portion of Q_{div} is used for Karachi urban water supply (see main text). (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

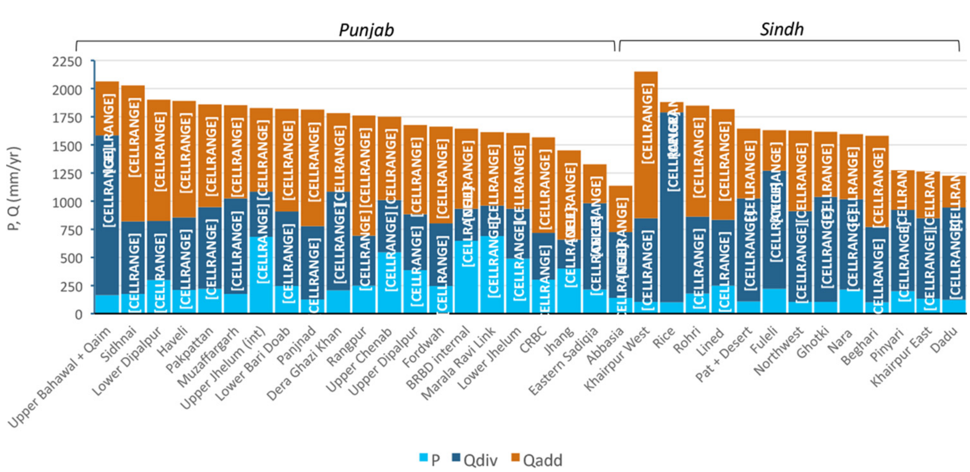

Fig. 8. Different sources of water for each canal command area: precipitation (P), canal water (Q_{div}), and additional supply (Q_{add}). Percentages indicate the extent to which water use in each command area depends on sources other than rainfall or water diverted to the main canal.

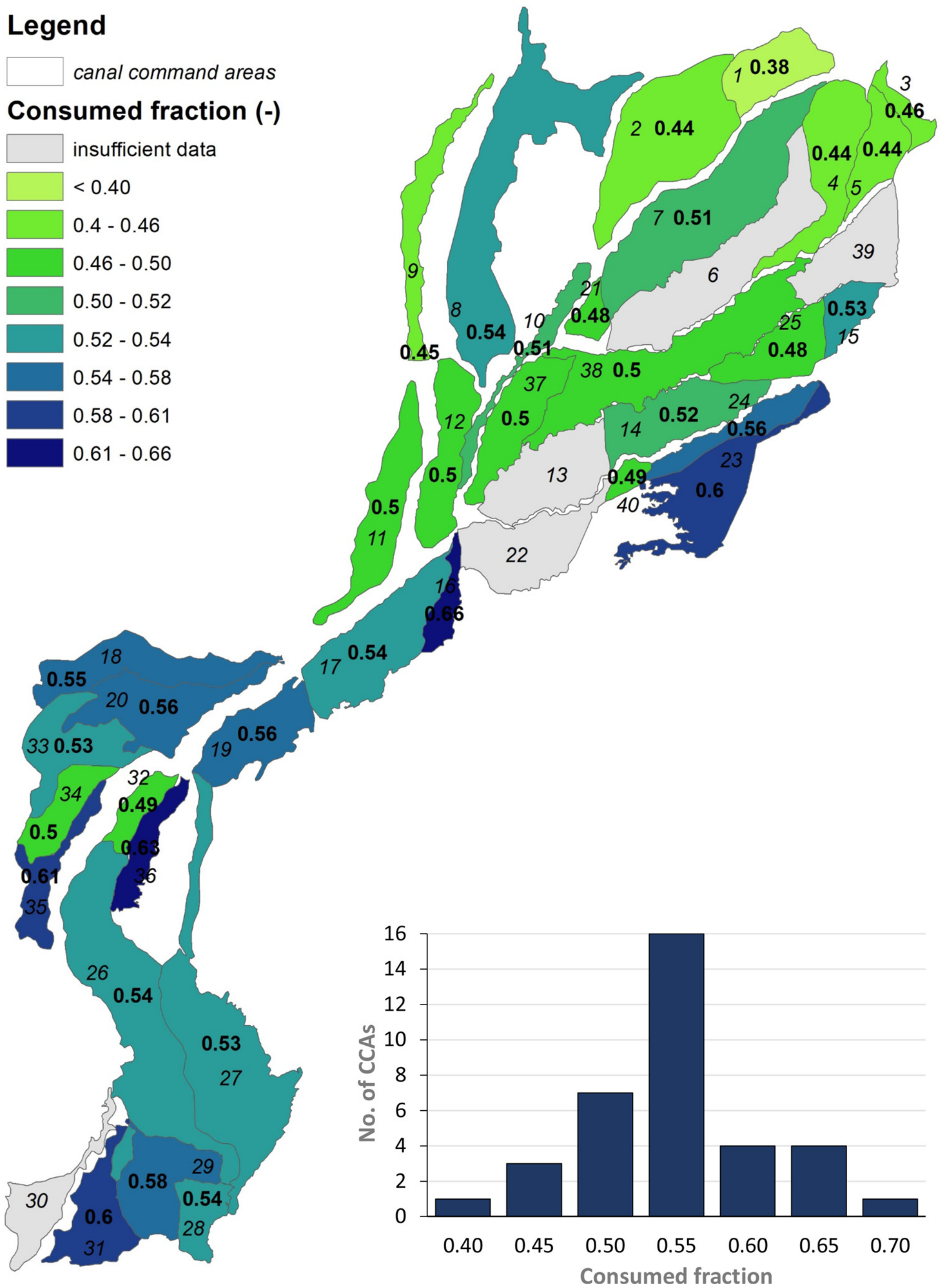

Fig. 10. Map and histogram of consumed fractions per canal command area.

reservoir releases, i.e. 707 / 990 = 0.71. However, as not all of the released water is used for irrigation purposes, a different estimate can be calculated based on total official surface water withdrawals of 125 BCM/yr (Young et al., 2019), or 756 mm/yr which leads to a total system *CF* of 0.93. Although the real supply volume arguably lies somewhere in between, both estimates are well above the CCA average of 0.52 and signify a relatively efficient system despite substantial water “losses” on smaller scales. This indicates that non-consumed flows to unconfined aquifers, drainage canals, and baseflow contribution to rivers cause water reuse processes to extend beyond CCA borders. In reality, informal irrigation outside official CCA boundaries leads to higher ET_{blue} and thus an even greater return flow reuse and system *CF*. When increasing the scope of the analysis to the full transboundary Indus Basin, *CF* may be further enhanced by lateral groundwater flows between India and Pakistan (Khan et al. 2017).

This study has successfully quantified total water supply and consumed fractions in the IBIS command areas, demonstrating the production of considerable volumes of non-consumed flows. As discussed above, this water is not only extensively reused within the CCAs, for example to mitigate differences in head vs. tail canal supplies, but also leave CCA boundaries for pumping downstream. This notion of a dense and complex network of water (re)use is supported by various studies. According to Van Steenbergen and Gohar (2005), an estimated 79 % of pumped groundwater in IBIS originates from canal seepage, percolation from the river, and non-consumed flows. Karimi et al. (2013) report a basin-scale “classical efficiency” of 84 % for the full Indus Basin, incorporating transboundary lateral flows. Grogan et al. (2017) showed that the Indus flow regime will significantly shift when consumed fractions are altered, due to extensive reuse of non-consumed flows. It is evident that further increases of system-scale *CF* will impact flow volumes and patterns downstream of Kotri Barrage and, therefore, hydrological and sedimentation regimes in the Indus Delta (Salik et al., 2016).

The results of this study exemplify the need to account for the system scale when considering efficiency improvement measures in the IBIS. In practice, increases in evapotranspiration in the IBIS are often achieved by a reduction in groundwater recharge, exacerbating the decline of the groundwater table and reducing water availability to downstream users (Ahmad et al., 2007). By providing spatially disaggregated *CF* values, the proposed approach facilitates a more effective and tailored development of water conservation measures in the different CCAs. It is found that in many CCAs, field-scale efficiency improvements may impact on an existing equilibrium of non-consumed flows and reuse of these flows by others as part of their Q_{add}. However, in areas where observations of rapidly falling groundwater tables coincide with a relatively low *CF*, such as on the Upper Indus Plain (Fig. 10), appropriate measures could result in a greater sustainability of the system. Similarly, occurrence of low *CF* values in areas with hazardous groundwater quality (particularly found in Sindh), may justify interventions to minimize recharge of saline groundwater bodies.

4. Conclusions and recommendations

A new method for spatially quantifying consumptive use of irrigation water based on the Budyko Hypothesis was successfully demonstrated for the IBIS in Pakistan. The innovation is twofold, as the approach (i) distinguishes green and blue water consumption using reference evapotranspiration and precipitation data, and (ii) computes total water supply to support Consumed Fraction estimates, which are essential for understanding system-scale water use and potential for water savings. It was found that out of the average annual ET_{act} of 927 mm/yr, 707 mm/yr (76 %) depends on irrigation water. ET_{blue} values vary greatly among CCAs with a range of 421 to 1011 mm/yr, as a consequence of differing canal headwater volumes, crop types, climate conditions, and groundwater quality, among others. By evaluating Budyko-based total blue water supply against long-term main canal diversions, it was concluded that most command areas rely substantially on water not diverted at the head of the primary canal, with additional supply Q_{add} (690 mm/yr) on average even slightly exceeding Q_{div} (662 mm/yr).

The average consumed fraction of the IBIS canal command areas was computed at 0.52, with CCA values ranging between 0.38 and 0.66. From the relatively low *CF* values, high additional water supplies, and long-term canal supplies largely sufficient to sustain ET_{blue}, the conclusion can be drawn that the IBIS is characterized by extensive reuse of non-consumed flows within CCAs. At the same time, a notably higher *CF* at the system scale indicates that reuse of non-consumed water facilitated by lateral connectivity between CCAs cannot be disregarded. These conclusions imply that, although the IBIS is generally not regarded as an efficient irrigation system, it is in fact tailored to recover and reuse drainage flows on different spatial scales. Water saving measures should therefore be implemented with caution. It is recommended to supplement the results of this study with ancillary information on groundwater quality and groundwater table time series, to identify locations where CF increases may be beneficial on the system scale. It should be noted that the accuracy of the CCA map used in this study is continuously under revision by government institutions, allowing for more refined CF assessments in the future, e.g. by accounting for irrigated area dynamics and city boundaries.

By providing quantitative estimates of previously unexposed parameters ET_{blue}, *CF* and Q_{nc} per CCA, the proposed approach contributes significantly to the understanding of water consumption and reuse in the IBIS. Results of the consecutive steps of the Budyko-based approach (climatology and ET partitioning, consumptive use, and assessments of water supply components) were shown to be in agreement with the existing knowledge base on the IBIS. A big advantage of the method over alternative approaches is that estimates of ET_{blue}, Q_{add} and Q_{nc} were produced without the need for complex hydrological models, data on soil parameters, or assumptions on curve numbers. Although diversion data were used for partitioning total withdrawals into canal water and additional supply, they are not required for the basic ET_{blue} and *CF* analyses, allowing for application of the method in ungauged irrigated basins. As the use of global satellite-derived data products allows worldwide replication, the proposed method holds great potential for more accurate evaluation of consumptive use, reuse, and dependencies among water users in river basins. This can facilitate targeted and more effective water allocation policies and water conservation measures, thus allowing accounting in practice for the scale dependency of efficiencies that has long been discussed in scientific literature.

This study fits in a recent body of work exploring the potential of the Budyko Hypothesis, in various reformulations, to function under differing conditions in terms of spatial and temporal scales, storage changes, and degree of anthropogenic impact on the natural water balance. CCAs, typically with areas of several thousands of km^2, were assumed appropriate units for BH-based analysis. Analyses were based on multi-annual input datasets to allow for assumption of zero storage change, and seasonal-scale results were deemed incongruous with BH preconditions and were therefore not presented. It is recommended for future studies to further explore opportunities and limitations of Budyko-based analyses in an irrigation context, with regards to appropriate spatiotemporal dimensions and, potentially, more complex BH formulations to account for non-steady states or incorporate physical catchment parameters in a more explicit way. Factors determining ω in irrigated basins could be further investigated, to acknowledge the importance of this parameter in a Fu-type Budyko application and allow further optimizing of methods for its estimation. By using pixel-based satellite data products on evapotranspiration and precipitation, the proposed method is highly flexible in terms of scale and can easily be applied to other basins and Budyko formulations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to Dr. Xianli Xu of the Institute of Subtropical Agriculture, Chinese Academy of Sciences, for kindly sharing their global ω dataset. In addition, the authors would like to thank Dr. Miriam Coenders-Gerrits (Delft University of Technology) and Dr. Johannes Hunink (FutureWater) for their feedback and suggestions based on earlier versions of the manuscript.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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