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Water Accounting Plus (WA+) – a water accounting procedure for complex river basins based on satellite measurements

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Abstract

Coping with the issue of water scarcity and growing competition for water among different sectors requires proper water management strategies and decision processes. A pre-requisite is a clear understanding of the basin hydrological processes, manageable and unmanageable water flows, the interaction with land use and opportunities to mitigate the negative effects and increase the benefits of water depletion on society. Currently, water professionals do not have a common framework that links hydrological flows to user groups of water and their benefits. The absence of a standard hydrological and water management summary is causing confusion and wrong decisions. The non-availability of water flow data is one of the underpinning reasons for not having operational water accounting systems for river basins in place. In this paper we introduce Water Accounting Plus (WA+), which is a new framework designed to provide explicit spatial information on water depletion and net withdrawal processes in complex river basins. The influence of land use on the water cycle is described explicitly by defining land use groups with common characteristics. Analogous to financial accounting, WA+ presents four *sheets* including (i) a *resource base sheet*, (ii) a *consumption sheet*, (iii) a *productivity sheet*, and (iv) a *withdrawal sheet*. Every sheet encompasses a set of indicators that summarize the overall water resources situation. The impact of external (e.g. climate change) and internal influences (e.g. infrastructure building) can be estimated by studying the changes in these WA+ indicators. Satellite measurements can be used for 3 out of the 4 sheets, but is not a precondition for implementing WA+ framework. Data from hydrological models and water allocation models can also be used as inputs to WA+.

1 Introduction

Over the last 50 yr the world has changed from a situation of an abundance of water to a situation of water scarcity. Over 1.2 billion people live in basins where

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water demand is reaching, or has exceeded limits of sustainable use (Gleick, 2000; Molden, 2007; Rockström et al., 2009; World Health Organization, http://www.who.int/water_sanitation_health/hygiene/en/). Population growth, changing diets, and economic growth, are some of the main causes of increased water use, which has resulted in competition for water, closed basins (a basin where all available water is depleted), over-exploited groundwater resources, degraded land, reduced ecosystem services, and anthropologically induced droughts. People have been quite proficient in changing land and water management practices and in modifying river flows to exploit water, also from aquifers. However, the era has now arrived that we need to communicate multi-sectorally for developing joint visions and targets for sustainable water and environmental management.

Our water institutions have been less effective in managing water in this relatively new era of scarcity, and this leads to a decline in the per capita water availability in various water stressed river basins that are often located in arid climates (UN-Water, 2007; Molden, 2007; Alcamo et al., 2007; Wallace, 2000; Vorosmarty et al., 2000). While the emphasis in the 20th century was on water resources development, there need to be a shift to improved water management practices to meet the demands of a changing world in the 21st century. Clearly one obstacle for improved water management is the lack of standard data collection processes. Interpretation of water resources data and communication to a diverging group of water professionals is generally also inadequate. Management of complex river basins involves hydrologists, climatologists, water managers, engineers, policy decision makers, economists, environmentalists, agronomists, anthropologists and lawyers among others; all from different backgrounds, cultures, and education levels. Obviously, this leads to misconceptions and misinterpretations (Perry, 2007), not very favorable for improving management of the scarce water resources. Terms such as “irrigation efficiency” and “water productivity” are often used interchangeably. The term “water use” is not unambiguous and can for instance be interpreted as being a “withdrawal” from a water system, “site specific flow” or “consumptive use”. Reduction of “water supply” is often confused with

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"reduction of consumptive use". This confusion in terminology can have severe consequence for downstream water availability. Because it can lead to wrong interpretations and wrong water management decisions (e.g. de Vries et al., 2010). For this reason, Seckler (1996) remarked that it is better to refer to actual water savings. Groundwater abstraction, groundwater depletion and groundwater draft is also classically terms which are confused and leading to underestimation of the over-exploitation of aquifers.

Investment in water resources management can be more effective with good and appropriate data being available and if the management options are commonly understood, accessible, and acceptable by various stakeholders. The data source underpinning the presentation of water resources conditions and management should be described, and the error sources should be understood. This calls for an appropriate framework for planning, operation, monitoring and evaluation of water resources in river basins. Very often the existing frameworks consider one water use sector only (i.e. drinking water supply sector), focus on one aspect of water management (i.e. gross withdrawals), or are based on one particular hydrological processes (i.e. rainfall and surface runoff relationships) without any attempt to link these processes by a common analytical framework.

Water accounting integrates the fields of hydrology, water and environmental management, water allocations, reporting and communication, and policy decisions. It facilitates identification of central problems in river basins, constraints, and opportunities for improved climate resilience; it assists with decisions regarding carbon sequestration and safeguarding sufficient water resources for a good quality life, also during periods of prolonged drought. Water accounting is described in this context below.

This paper introduces a simple, understandable, and standardized way of describing the overall land and water management situation in complex river basins. Ideally, complex conditions should be summarized on a few pages with tables and graphs. It is a challenge to present integrated water resources management issues in both a simplistic and sufficiently comprehensive way. For some it will always be over-simplified, while other water professionals prefer a simplified version. The benefit of having a standard analytical framework and associated terminology has been demonstrated by FAO in the field of evapotranspiration. The FAO standardization of reference evapotranspiration ET (Allen et al., 1998) has for instance been widely adopted by the international community of agricultural and irrigation engineers to describe ET processes and get global uniformity in crop and irrigation water requirement computations. Similarly, a standard water accounting procedure can facilitate the description of the state conditions of river basins and the opportunities to exploit manageable water flows more effectively, efficiently, productively and sustainably.

The objective of this paper is to introduce a significantly revised water accounting framework that is called *Water Accounting Plus* (WA+) and can be executed with satellite data that are available in Data Active Archives. WA+ is based on the early definitions introduced by the International Water Management Institute (Molden, 1997). The objective of this update is to make water accounting easier to use in terms of available input data, and to help improve strategic decisions in water resources management. The companion paper (Karimi et al., 2012b) describes the application of the WA+ in the Indus basin.

2 Brief review of water accounting frameworks

The importance of accounting for water has motivated several national and international organizations like the UN, FAO, IWMI, and the Australian government to develop standard water accounting frameworks. Food and Agriculture Organization‘s (FAO) global information system on water and agriculture, Aquastat, remains an important source of data, and has the advantage of consistency and standard terminology. However, Aquastat falls short of giving enough detail about the interaction between land use and water use. One major point pertinent to water scarce basins is that Aquastat focuses on water withdrawals, and does not include recycling or consumption by evapotranspiration (ET). The United Nations Statistics Division has proposed a water accounting framework called System of Environmental Economic Accounting for Water

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(SEEAW). SEEAW describes hydrological and economic information through a set of standard tables and has also some supplementary tables to cover social aspects (UN, 2007). The SEEAW accounting includes precipitation, soil water, and reports on natural evapotranspiration as one cause of decreasing water stocks. The SEEAW accounts separately for withdrawals and consumption and thus allows for a wider range of water resources and uses to be included. However, the focus is more on domestic and industrial use and in general SEEAW is not structured to accommodate natural vegetation water use and agricultural water use, which are typically the major water users in river basins. The SEEAW for example describes water input from precipitation, and total evapotranspiration, but does not describe rainfall dispersal through the different water uses and evapotranspiration pathways characterized by different land use classes. The essential difference in green and blue water resources (Falkenmark and Rockström, 2006; Rockström and Gordon, 2001) is not recognized in the SEEAW framework. Soil water use in agriculture, also, is vague in the framework in both irrigated and rainfed land use systems. Despite mentioning rainfed agriculture, the framework fails to properly accommodate it.

The Australian water accounting system is based on SEEAW guidelines (ABS, 2004, 2006) with run-off as the first descriptor. Compared to rainfall and evapotranspiration, flow in streams and rivers represent only a small fraction of the total water movement in basins (Molle and Wester, 2009; Sivapalan et al., 2003). The framework accounts for water withdrawals rather than consumption. It ignores the essence of consumed water being a sink of the water in the land hydrological system. In the case of agriculture, forests, and natural vegetation cover the Australian method only considers irrigated agriculture and does not provide any information on rainfed systems. The impact of rainfed ecosystems on volumes of water available for irrigation is ignored.

Perry (2007) proposed a framework for water accounting which divides withdrawals into consumable and non-consumable fractions of water. The consumable fraction is ET and like in the IWMI water accounting framework published by Molden (1997), it is divided into beneficial and non-beneficial consumption. The non-consumed fraction is

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considered as return flows which could be recoverable or non-recoverable. The latter being the water that is not available for further use like flows to saline groundwater aquifers. Foster and Perry (2010) suggested refinement of soil-water accounting in this way in order to account for the effects of changes in irrigation practices on groundwater. Perry and Bucknall (2009) proposed that basin water balances can be structured on the same approach by including rainfall and inflows as sources and classify uses as beneficial/non-beneficial, recoverable/non-recoverable flows and by dividing water accounts into different end-use classes. However, considering the origin of this water accounting method, it is more applicable to irrigation systems where distinction between beneficial and non-beneficial is clear, rather than in river basins where multiple uses of water make it difficult to distinguish between beneficial and non-beneficial use.

The International Water Management Institute (IWMI) developed a Water Accounting (WA) procedure with the aim of tracking water depletion rather than withdrawals to avoid errors when neglecting recycling, and to account for evapotranspiration. The method provides a means to determine the output per unit of water effectively depleted (Molden, 1997; Molden and Sakthivadivel, 1999; Molden et al., 2003). The depletion of water resources renders water unavailable for further use. Water depletions are divided into beneficial and non-beneficial water according to the type of use. The IWMI WA framework has been applied by IWMI in many irrigation system studies (e.g. Bhakra system in India: Molden, 1997; Zhanghe Irrigation System in China: Loeve et al., 2004; Dong et al., 2004; Nile Delta: Molden et al., 1998). It has also been applied at river basin scale (e.g. Krishna: Biggs et al., 2007; Karkheh: Karimi et al., 2012a; Indrawatti: Bhattarai et al., 2002) and at the national scale (e.g. India: Amerasinghe et al., 2007; Sri Lanka: Bastiaanssen and Chandrapala, 2003).

The IWMI WA framework was originally designed for irrigation schemes within a basin, but was later used for basin analysis. Some of the components of the IWMI WA are, therefore, too generic for basin level studies For instance, consumption at irrigation service scale represent only crop evapotranspiration while at basin scale it includes irrigated lands, municipalities and industries, fisheries, forestry, dedicated wetlands and

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all other uses. As a result, parts of the information that are important in a basin context are not covered in the original IWMI framework.

3 Water accounting plus (WA+)

3.1 Withdrawals, consumption and return flow

Water Accounting Plus (WA+) is a new framework that uses the IWMI WA principles of tracking water depletions rather than withdrawals. Data sets on withdrawals, consumption and return flows are scarce and incomplete, both at the river basin scale, as well as locally by certain water use sectors. Advances in earth observations have however demonstrated that consumptive use can be acquired from satellite measurements (e.g. Anderson et al., 2012). By exploring the spatial data on consumptive use, WA+ provides explicit information on water depletion processes for every land use class. WA+ is based on a mass water balance approach. The basis of this water balance approach is that outflows from a certain river basin are explicitly related to the inflow from rainfall and depletion through a measurable evapotranspiration processes. By doing so, the return flow can be assessed. This cycle of withdrawals – consumption – return flow can be described for catchment and river basins and also be described for a particular water use sector, which allows to make an estimation of the depletion of water that otherwise would have been present in a river or aquifer. The advantage is that inflows and return flows are no longer necessary to be measured because the depletion can be obtained directly. The difference between gross withdrawals and return flow – via percolation and runoff – is the incremental ET or net withdrawal (see Fig. 1). The symbol for incremental ET is ET_Q.

The incremental ET is the depletion related to withdrawals only. Incremental ET is expressed as ET_Q, and ET_Q is part of the total ET:

$$ET = ET_{prec} + ET_Q. \tag{1}$$

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ET from natural processes (ET_{prec}) can be approximated as:

$$ET_{prec} = P - R \tag{2}$$

where P is the gross precipitation, R is the return flow, and ET_{prec} is the ET quantity that originates from precipitation only. The return flow R is composed of surface runoff, lateral sub-surface drainage and deep percolation:

$$R = R_0 + P_{deep}. \tag{3}$$

P_{deep} is the percolation that feeds the groundwater and R_0 is the surface runoff. The key point is that ET_Q can be determined from ET and ET_{prec}, without any flow measurement (not further demonstrated in this paper). Spatially distributed data on ET_Q is useful in ungauged (sub-) basins where withdrawals occur. Water depletion from natural flows and withdrawals can be tracked via spatial ET information for every discrete area, and for every land use class. This concept has been adopted by the WA+ framework to estimate water consumption in different land use management categories and to report on net withdrawals in a basin without the use of in situ gauging stations that require substantial effort and cost to collect and interpret the data. The net withdrawal is equal to ET_Q.

WA+ adopts the same definition for water depletion as the IWMI WA, but considers more details in the processes and essential mechanisms. According to the definition water depletion is the removal of water from a water basin that renders it unavailable for further use (Molden, 1997). A common view on irrigation is that water delivered to the land that is not evaporated by crops is lost to surface runoff or percolation. But in fact that "loss" is often an important water source for downstream users. For example on-farm water losses can recharge shallow water tables and deep aquifer systems and be re-used during periods of prevailing droughts. Groundwater re-enters the river system naturally, and the interactions between rivers and groundwater systems is often ignored.

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WA+ contains four sheets that summarize the water management situation in complex river basins in an understandable manner. The purpose of each sheet is summarized in Table 1.

The main differences between the IWMI WA from 1997 and the WA+ are the following:

- The link between land use and water depletion is made explicit in order to understand the impact of land use changes on water resources availability.
- Manageable and non-manageable depletions are defined and the processes are quantified, which will show that large volumes of water are controlled by geographical and atmospheric processes that cannot be managed.
- Surface and groundwater systems are differentiated as they have different management options and legal regulations.
- Net withdrawals (ET_Q) are computed for different land use categories and water user groups to assign benefits from manageable water flows.
- Partitioning of consumed water (ET) into transpiration, evaporation and interception to appraise beneficial depletion for food and ecosystem services vs. non-beneficial losses.
- Input data for WA+ can be guaranteed by using satellite measurements so that dependence on local agencies does no longer hold, and data collection systems become standard and transparent. It opens the door for applying WA+ at international basins level, also in conflict areas.

3.2 Role of land use categories in WA+

The total water resources consist of rainfall, inflow across water divides and storage changes in surface water, ground water (including soil moisture), and snow water. Only

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a fraction of the total inflow into basins can be controlled and regulated by means of barrier dams, infiltration dams, diversion weirs, inlet points and water harvesting facilities, to create ET_Q that otherwise would not occur. Land use change (e.g. urban expansion, land reclamation, deforestation) and land cultivation practices (land preparation, crop sowing date, zero tillage) have a regulating role on ET_{prec}. Hence land use, cultivation practices and water resources development are controlling factors of ET at the basin scale. Regulation of ET in areas with a high degree of natural land cover such as savannah and mountains is very limited and largely dependent on natural ecosystem processes. Consequently, not all land use classes and their associated water flows can be controlled.

Water management practices are commonly focused on optimizing water resources that can be controlled. Water flow regulation through managing land use practices is less common, but essential to address the growing water scarcity of the future. Analogous to the common accounting procedures, the WA+ framework encompasses four sheets that each reveals specific insights in the attainment of objectives. For the sake of simplicity, the hydrological summary can be portrayed on a single page "resource base sheet". The second objective is to describe the water depletion (presented on a "consumption sheet"), and the third objective is to estimate the biomass services and benefits (presented on a "productivity sheet"). The fourth objective of WA+ is the quantification of the (net) withdrawals via the "withdrawals sheet". Hence, WA+ provides concise water information that reflects the real situation in complex river basins in a standardized manner (four one page sheets). Presented information in every sheet is linked to a set of standard indicators that help to improve understanding of the basin water resources and conditions, and water management achievements.

To address the role of land use changes and land use planning in the water accounting scheme, we propose to present four different categories of land use groups, based on the potential to manage the land and water resources. These categories include *managed water use*, *modified land use*, *utilized land use*, and *conserved land use*.

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The group "managed water use" represents the land use classes in which the natural water cycle is manipulated by physical infrastructure; water is intentionally retained, withdrawn, pumped, diverted and spilled by pumping stations, valves, pipes, dams, weirs, gates, canals, sluices, culverts and drains for certain objectives. Examples are drinking water supply schemes, irrigation systems, storage for hydropower, maintaining water levels for navigation, flood storage in wetlands, etc. The group "managed water use" includes domestic water use in urban areas and villages, irrigated agriculture, expanding industries for economic development, and golf courses.

The group "modified land use" refers to land that is significantly modified by human activity for the sake of food, fodder, fiber, and fish production. It also includes improved road networks to connect growing populations, dump sites, and increasing space for leisure and for socio-economic growth in the most general terms. Water diversions and abstractions do not take place in the "modified land use" group, but by modifying vegetation density, hydrological processes such as ET, drainage, percolation, and recharge are affected. Changes in ET in the "modified land use" class can have significant impact on groundwater levels, streamflow, and downstream water availability. Rainfed cropping systems, deforestation, creation of plantation forests, establishment of lanes and parks, home gardens and wind shelters typically fall in the "modified land use" class.

The group "utilized land use" represents a land use that provides a range of ecosystem services and which has had little interference by man. However, people often use such land for the services it provides, like food production or fuelwood and nomads on natural pastures. Examples include grassland or savanna (for grazing or wood) and forest land (for timber). This group is typically eligible for green water credits, and carbon credits. Returns from "utilized land use" are often expressed in terms of livestock, wildlife, aquatic birds, fuelwood, oil, and minerals. Groundwater dependent ecosystems are also part of this group. Alien invasive species are also part of this group because invasion is unintentional by humans.

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The group “conserved land use” represents areas set aside for minimal disturbance by humans. It includes natural ecosystems or biomes earmarked for conservation as a heritage for the future. Examples are national parks, coastal protection areas, game reserves, glaciers and Ramsar sites.

Table 2 shows the association between land use classes and the four land use groups identified for water accounting. A distinction between land use and land cover is essential in this context. Global land cover databases are available (e.g. GLC2000 by Loveland et al., 2000; Globcover by Bicheron et al., 2008) but do not provide information on usage. Land use databases with particular functions have been produced locally (e.g. Indus Basin: Cheema and Bastiaanssen, 2010), but do not yet provide systematic cover for river basins. Ideally, the land use classes specified in Table 2 should, for water accounting purposes, be created from satellite databases.

4 The WA+ analytical framework

4.1 WA+ Resource base sheet

The WA+ resource base sheet (Fig. 2) provides information on water volumes. Inflows are shown on the left of the resource base sheet diagram, the middle part provides information on how and through what processes the water is depleted within a domain, and information on water use and reports on blue water depletion and outflows are summarized on the right.

Precipitation plus any surface or groundwater that flows to the domain from outside its boundaries is *Gross inflow*. *Net inflow* includes water storage changes over the period of accounting. The fresh water storage changes are (i) surface water ($\Delta S_{\mathrm{f,SW}}$), (ii) groundwater including soil moisture storage change ($\Delta S_{\mathrm{f,GW}}$) in the vadose zone and (iii) snow and glacier melt ($\Delta S_{\mathrm{f,SM}}$). The net inflow is partitioned into *landscape* ET and *blue water* present in streams, soils and aquifers. The *landscape* ET is a consequence of a certain rainfall distribution across a composite terrain with mixed land use,

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geological formations, soil types, slopes, elevations and natural drainage to streams. This vaporized water is consumed and not available for downstream withdrawals and water resources development, unless moisture recycling through the atmosphere occurs (Savenije, 1995; Van der Ent and Savenije, 2011). Mohamed (2005) showed that atmospheric recycling can be a common phenomenon in highly elevated areas with upwind plains covered by green and moist vegetation, but it does not occur everywhere.

The difference between rainfall (P) and landscape (ET across sufficiently long periods – and at the scale of the river basin – is equal to total surface runoff, and groundwater recharge and the subsequent drainage of groundwater systems into the surface water network . The difference between rainfall (P) and ET is used as a proxy for total runoff (surface water and groundwater runoff), see also Bastiaanssen and Chandrapala (2003). This is the "blue water" which is thus estimated as P – ET. The rate P – ET ($\mathrm{L\,T^{-1}}$) from a discrete area ($\mathrm{L^2}$) represents a flow ($\mathrm{L^3\,T^{-1}}$). On these principles, the net inflow minus landscape ET can be referred to as *blue water*. It represents the portion of the net inflow that is not evaporated and is a renewable water resource available for downstream use and withdrawals. For the sake of simplicity, the resource base sheet does not distinguish between surface and groundwater in the blue water. The latter will be taken care of by the withdrawal sheet.

The landscape ET is further divided into the four land use categories "conserved land use", "utilized land use", "modified land use", and "managed water use". The portion of the categories managed water use that falls under landscape ET represents evapotranspiration that originates from precipitation over this particular land use category ($\mathrm{ET_{prec}}$ in Fig. 1). Irrigated land for instance do receive rainfall, but insufficient for crop production. The difference between crop water requirement and rainfall is incremental ET due to utilized flow.

Not all of the blue water is available for use as part of it has to be reserved to meet downstream water right requirements (committed flows, navigational flow, and environmental flow). Guidelines for environmental flow are provided by for instance (Smakhtin et al., 2004a, b). This water is called *reserved flow*. The reserved flow is equal to the

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maximum of committed flows, navigational flow, and environmental flow. It is because none of these actually deplete water; the same water that serves navigational needs can serve environmental flow demand and then flow out to meet any downstream water commitment. Non-utilizable flow arises during and after flood events when excess water threatens to inundate large areas which then need to be evacuated. It could partially be committed to outflow, but the volume and timing will most likely not match the reserved flow requirements, and is therefore presented separately.

Blue water less reserved flow is *available water.* It is the available water that can be allocated to various water use sectors. Part of the available water is depleted. This depleted water is called *utilized flow* and mainly takes place through *incremental* ET, but it also includes the water that flows to sinks (e.g. flows to saline groundwater aquifers or other locations where the water is no more recovered) or becomes unavailable for further use due to contamination, pollution, and any quality degradation because of a lack of treatment plants or beds. The available water less the utilized water is *utilizable water* representing the amount of additional water that could be utilized. It represents the water that is not depleted, nor reserved, and is thus available for use within the basin or for export and intra basin water transfers. WA+ can be applied at different time scales and for the planning of additional water resources, it is necessary to consider the WA+ version with longer term focus.

Depleted water (lastly) is total ET plus flows to sink (ΔS_p) which is the water that flows to sinks or become unfit for use quality wise; for instance deep percolated irrigation water that ends up in saline groundwater aquifers. *Outflows* refer to the amount of water that physically leaves the basin through surface water system (surface outflow) and through subsurface system (groundwater outflow). Appendix A summarizes the WA+ definitions.

Performance indicators for resource base sheet

The resource base sheet in WA+ has a set of minimum performance indicators that are presented as fractions. These indicators are to help basin planners to understand the

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key information on water management in a basin, or any domain that water accounts are provided for. Time series of these indicators reveal trends in satisfying water management threats. Target values for these indicators are defined.

Blue water fraction is that part of the net inflow that is not lost to the natural ET processes. The fraction relates to total run-off generated in a river basin and also exploited water from fresh water storage.

$$\text{Blue water}_{\text{fraction}} = \frac{\text{Blue water}}{\text{Net inflow}} \tag{4}$$

Storage change fraction defines the degree of water withdrawals dependent on fresh storage change (ΔS_{fw}). The fresh water resources are surface water storage, groundwater storage, and total water storage. The negative values indicate storage depletion while positive values indicate that in the accounting period water storage has been increased in the domain.

$$\text{Storage change}_{\text{fraction}} = \frac{\Delta S_{\text{fw}}}{\text{Blue water}} \tag{5}$$

Available water fraction relates available water to blue water. It describes the portion of blue water that is actually available for withdrawals within a basin.

$$\text{Available water}_{\text{fraction}} = \frac{\text{Available water}}{\text{Blue water}} \tag{6}$$

Basin closure fraction describes to what extent available water is already depleted in a basin or domain. A closed basin is one where all available water is depleted. In such circumstances the Basin closure fraction is equal to 1.

$$\text{Basin closure}_{\text{fraction}} = \frac{\text{Utilized flow}}{\text{Available water}} \tag{7}$$

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Reserved flow fraction relates the reserved flow to the surface water outflow. It indicates whether the committed flows are being met.

$$\text{Reserved flow}_{\text{fraction}} = \frac{\text{Reserved flow}}{Q_{\text{out}}^{\text{SW}}} \tag{8}$$

4.2 WA+ Consumptive use sheet

The consumptive use sheet describes which parts of the depletion processes are managed, manageable or non-manageable. The term manageable implies that it is not actively managed yet, and that a light form of utilization is accepted under the current situation. Knowing the physical volumes of water depletion by different users, the next step is to evaluate the benefits derived from the use of water. It requires a value judgment to define beneficial and non-beneficial use. Generally "beneficial use" refers to use of water for agriculture, aquaculture, domestic and industrial use, hydropower, recreational use, navigation, and all other activities that generate direct or indirect socio-economic and/or environmental benefits. The definition of "beneficial" and "non-beneficial" use can be adjusted in specific cases. The user of the water consumption sheet should have the possibility to modify the default setting and adjust it to local value assessment.

Non-beneficial consumption occurs through certain physical processes: evaporation (from soil, water, buildings), and interception evaporation from wet leaves and canopies (Rutter et al., 1971; Savenije, 2004). Transpiration (T), is the transfer of water by the plant to the atmosphere through stomata in the leaves. Water vapor transfer via transpiration and CO_2 inhalation are biophysically linked (e.g. Monteith, 1988). While T is generally considered as beneficial, it can be considered non-beneficial in some cases such as weed infestations in cropland or in degraded landscapes, or when there are non-desirable plants. Alien invasive species are considered as highly undesirable and distorting sensitive balances between rainfall and ET. Countries such as South Africa and Australia have active programs to clear large areas of alien invasive. This exemplifies that definition of "beneficial" or "non-beneficial" depends on a value assessment.

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E is usually considered as non-beneficial because the vast majority of E originates from wet soils that are fallow or covered partially (Choudhury et al., 1998). However, the E from water surfaces is often beneficial, for example in cases where water bodies serve the purpose of fishing, aquatic birds, storage of water for droughts, buffering floods, water sports, leisure, etc. The WA+ consumptive water use sheet is shown in Fig. 3. It reports on the breakdown of ET into E, T and interception and defines which portion of ET is beneficial and which non-beneficial.

Performance indicators for the consumptive use sheet

Performance indicators for the WA+ consumptive use sheet provide key information on the magnitude of beneficial use of water depletion in a basin. Water used by key water users in a basin is expressed in terms of fractions.

Transpiration fraction is the part of ET that is transpired by plants and it reflects an impact on bio-physical process in water scarce basins.

$$\text{Transpiration}_{\text{fraction}} = \frac{T}{\text{ET}} \tag{9}$$

Beneficial ET *fraction basin* relates beneficial E and T to the total ET in a basin.

$$\text{Beneficial}_{\text{fraction}} = \frac{E_{\text{beneficial}} + T_{\text{beneficial}}}{\text{ET}} \tag{10}$$

Managed ET *fraction* indicates the ET processes in a basin that could be manipulated by land use, cultivation practices and water withdrawals.

$$\text{Managed}_{\text{fraction}} = \frac{\text{ET}_{\text{managed}}}{\text{ET}} \tag{11}$$

Agricultural ET *fraction* is the part of ET attributable to agricultural activities.

$$\text{Agricultural ET}_{\text{fraction}} = \frac{\text{Agricultural ET}}{\text{ET}} \tag{12}$$

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Irrigated ET fraction describes the portion of agricultural ET that is related to irrigated agriculture.

$$\text{Irrigated ET}_{\text{fraction}} = \frac{\text{irrigated agricultural ET}}{\text{Agricultural ET}} \tag{13}$$

4.3 WA+ Productivity sheet

The WA+ productivity sheet is meant to describe the organic production and is illustrated in Fig. 4. The sheet reports on the bio-physical land productivity (kg/ha) and water productivity (kg m^{-3}) in the WA+'s four land categories. Economic dimensions such as proposed by Hellegers et al. (2012) are for the sake of simplicity excluded. Productivity measurement in WA+ is based on biomass production. Biomass production is a consequence of plant photosynthesis and is the primary foundation for food, fodder, fiber, shelter, biodiversity, carbon storage, and overall a regulator of the near-surface climatic conditions. Biomass production results in terrestrial carbon sequestration which is the process through which CO_2 from the atmosphere is absorbed through photosynthesis, and stored as carbon in biomass, both above ground and below ground. Carbon sequestration is gaining more attention as an opportunity to stabilize CO_2 levels in the atmosphere and to mitigate climate change impacts (Gibbs and Herold, 2007). Several studies provide spatial databases that estimate global vegetation carbon stocks (Olson et al., 1985; Gibbs, 2006). Ruesch and Gibbs (2008) have produced a global biomass carbon map for 2000 based on the GLC2000 land use map.

The WA+ productivity, given the importance of the subject, encompasses figures for CO_2 sequestration by different land uses alongside biomass production. Crop and pasture biomass production can be translated to equivalent yields by using harvest indexes and then to the water productivity by using ET figures. In the diagram for the productivity sheet, values will be presented in kilogram per hectare of land for biomass production, CO_2 sequestration, and yield equivalent and in kilogram per cubic meter for biomass water productivity and yield equivalent water productivity.

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Performance indicators for the productivity sheet

The WA+ productivity sheet's performance indicators have been formulated to indicate the state of a basin in terms of land productivity and water productivity. This is translated into food security conditions and carbon sequestration.

Land productivity indicators relate biomass production and yield equivalent of crops to unit of land in the period of accounting in terms of kg per ha.

$$\text{Land productivity}_{\text{crops}} = \frac{\text{Crops biomass production} * \text{harvest Index}}{\text{Cropped area}} \tag{14}$$

$$\text{Land productivity}_{\text{pasture}} = \frac{\text{Pature biomass production\#harvest Index}}{\text{Pasture area}} \tag{15}$$

Water productivity indicators report on the physical mass of production per unit volume of water consumed in terms of kg m^{-3}.

$$\text{Water productivity}_{\text{crops rainfed}} = \frac{\text{Rainfed crops biomass production} * \text{Harvest index}}{\text{Rainfed crops ET}} \tag{16}$$

$$\text{Water productivity}_{\text{crops irrigated}} = \frac{\text{Irrigated crops biomass production} * \text{Harvest index}}{\text{Irrigated crops ET}} \tag{17}$$

Overall land and water productivity of crops and pasture can be further broken down into rainfed and irrigated land systems. This will provide productivity figures for rainfed and irrigated land separately.

$$\text{Food-irrigation dependency} = \frac{\text{Irrigated food production}}{\text{Total food production}} \tag{18}$$

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4.4 WA+ Withdrawal sheet

The WA+ withdrawal sheet, which can also be used as a stand-alone water accounting framework for managed water flows, tracks water withdrawals, depletions (i.e. incremental ET) and returns with separated surface water and groundwater systems. In fact, the withdrawal sheet has several common elements with the existing UN water accounting procedure that is merely based on allocations and withdrawals. Despite the fact that the resource base sheet avoids complex hydrological processes that requires groundwater and surface water use to be quantified specifically, it is of utmost relevance to discern between surface and groundwater systems. The main reason is that their management options are quite different; surface water can be used for example for hydropower, while groundwater is more suited for domestic drinking water, and is a choice of preference for many farmers. Most excess water flows to surface water systems, and this water is easier to regulate and manage than groundwater systems. Streams and rivers can be seasonal and this has significant consequences for certain water use sectors.

As opposed to surface water systems, groundwater resources are accessible rather instantly without passing through conveyance networks and contain water throughout the entire year. As a result this flexibility has enhanced the extraction of groundwater for irrigated crops (Qureshi et al., 2010) and other purposes. Thus considering the importance of groundwater, and the different management opportunities as compared to surface water systems, it is imperative to separate surface and groundwater systems in WA+. An example of an accounting system for groundwater is given by Foster et al. (2009) and Foster and Perry (2010).

The aim of the WA+ withdrawals sheet is to provide an explicit picture of managed flows, from withdrawals and consumption to returns, for managed water use. The water users are reservoirs, irrigated agriculture, aquaculture, domestic use, and industries. The withdrawal sheet provides information for reservoirs as they are part of managed water use. The reservoirs have incremental ET and it mostly takes place

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through evaporation from free water surface. The withdrawal sheet diagram is displayed in Fig. 5. Fresh water is drawn from surface and groundwater resources, Q_w^{SW} and Q_w^{GW}, for different uses. Part of the withdrawn water is consumed as an incremental ET (ET_Q) and the rest returns to the surface and groundwater sources, Q_R^{SW} and Q_R^{GW}. Groundwater withdrawals for drinking water supply can after water treatment be discharged into rivers, hence surface water and groundwater can interact in the withdrawal sheet.

Performance indicators for the withdrawal sheet

Information on water withdrawals from surface and groundwater resources, net withdrawals and return flows presented in the WA+ withdrawal sheet can be essential for estimating the impact of some widely supported solutions in water scarce environments, including efficiencies, artificial recharge, rules for conjunctive use, and groundwater quota. Given the importance of these concepts the performance indicators defined for this sheet include the following:

Groundwater withdrawal indicators provide much needed information related to the groundwater resources stability.

$$\text{Groundwater withdrawal fraction} = \frac{Q_w^{GW}}{Q_w^{SW} + Q_w^{GW}} \tag{19}$$

Classical irrigation efficiency (CE) follows the concept of Israelsen (1932) and Jensen (1967) as presented by Seckler et al. (2003). It is defined as the net evapotranspiration (incremental ET in our terminology) divided by the amount of water withdrawals.

$$\text{CE} = \frac{\text{incremental ET irrigated agriculture}(\text{ET}_Q)}{\text{QW(Irrigated agriculture)}} \tag{20}$$

Recycling factor indicates the proportion of abstracted water that is not consumed and, thus, returns to surface and groundwater system

$$\text{Recycling factor} = \frac{\text{Return flows}}{\text{Gross withdrawals}} \tag{21}$$

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WA+ indictors have been formulated to serve various policy objectives. They cover a broad spectrum of indices related to water resource management, water-ecosystem sustainability, and food security. WA+ users (e.g. policy makers) can, therefore, pick and focus on the indictors that they perceive to be relevant to their purpose of the accounting exercise.

5 Satellite data measurements

Collection of data from various sources and institutes to feed WA+ is a rather challenging task and is currently the largest obstacle for using WA in an operational conflict. While rainfall can be measured relatively simply with gauges (not being free from errors), ET can be measured with advanced instruments only (Twine et al., 2000; Teixeira and Bastiaanssen, 2010). It is a generally misconception that ET can be measured by routine weather stations. Hydro-meteorological observatories are available, but only at selected locations in river basins. Maintenance of the hydro-meteorological observation is not straightforward – certainly in developing countries. So large components of the basin water flows are not measured and are at best difficult to measure in situ. The input data into WA+ therefore has to be based upon satellite measurements, and alternatively from hydrological models.

Except for the withdrawal sheet that is more related to the classical water accounting processes, the input data for the other WA+ sheets can be estimated through satellite measurements. Remote sensing techniques ensure access to spatial data, and make it possible to apply the framework to all ungauged or poorly gauged basins. Another benefit of using remote sensing is the low cost of acquiring data and the immediate availability of data. Measuring ground data and collecting data through surveys often requires significant manpower to collect and interpret the data. Remote sensing analysis can also be done relatively quickly and cheap.

Given this difficulty, the WA+ framework is amenable to satellite measurements that are becoming more easily available. The number of earth observation satellites is

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growing fast, and the data bases emerging from these spatial measurements show the same evolving trend. Land use, rainfall, ET, soil moisture, biomass production, separation into E and T, interception, water levels changes, and changes of total water storage can all be retrieved from raw satellite measurements, provided that the proper interpretation algorithms are used. The accuracy of determining important hydrological processes and water management aspects is acceptable, and it becomes an attractive alternative for conventional data sources (Schultz and Engman, 2000; Schmugge et al., 2002). It goes beyond the scope of the current paper to discuss in detail the recent advances in earth observations.

Despite the fact that the WA+ is primarily designed to allow use of remote sensing data, remote sensing is not essential to set the framework up. The WA+ is a framework to present water accounting information regardless of how the data is obtained. For instance a hydrological model's generated data can be used as input to the WA+ to produce water accounts at any domain of interest.

6 Limitations/cautions

The WA+ is a comprehensive tool for assessing water depletion, net withdrawals and productivity in a basin in relation to land use, but it has its own limitations. The main limitation is that the WA+ cannot replace hydrological models in their function to provide detailed information on water flows in a basin. WA+ summarizes complicated water flows in basin, rather than analyzing flow from one location to another. The total mass water balance of rainfall and ET is used as a yardstick to determine lateral movement of water between land use classes. All rivers and tributaries are regarded as being one single bulk river and all the aquifers as one single bulk aquifer. WA+ can be envisaged as a display of hydrological modeling results, in a standardized manner that can be understood by a large society of water professionals.

All satellite data parameters have some level of uncertainty and error that needs to be taken into account. The errors in large water volumes (i.e. rainfall and ET) may result

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in large errors in river and aquifer flows. More research is required to understand the impact of these uncertainties in the WA+ outputs.

The accounting period for WA+ is normally one year. However, seasonal and annual variations have impacts on basin water flows. For instance, water deficits in dry season if followed by a wet season, might be overlooked when compiling annual bulk figures. The WA+ framework is applicable to shorter periods if detailed data on storage changes (i.e. surface and groundwater storage and soil moisture) are available for the beginning and the end of each accounting period.

WA+ only provides tentative guidelines for beneficial and non-beneficial depletion, and the user needs to define them based on a personal value assessment. One example of the complexity of the issue is the presence of floodplains. While flood plains and green corridors along rivers can be considered for contributing to ecosystem services, the incremental ET due to flooding could reduce the river flow to downstream countries beyond the committed minimum flow. These are disputes where both groups are right. Value assessment is needed to make good use of the WA+ analytical framework, and this can be achieved by prescribing beneficial and non-beneficial depletion by land use type. Agricultural, economic, and environmental benefits also need to be specified, and solutions with fractions are feasible.

Surface and groundwater systems are fundamental for development of water resources and basin management plans. The partitioning of surface/groundwater recharge and their successive gross withdrawals are considered in the WA+ withdrawal sheet. Although we have no operational system in place to quantify these flows, it is essential to recognize this in the WA+ framework. While net withdrawals (i.e. incremental ET) can be assessed in the resource base and withdrawal sheets, the gross withdrawals and return flows need to be assessed specifically and cannot be derived from satellite measurements. More methods are needed to develop quantitative analyses based on infiltration properties, vegetation cover and presences of aquifers.

7 Summary and conclusions

WA+ provides an analytical framework that summarizes water resources conditions and management in complex river basins. The WA+ framework goes beyond accounting of surface water flows and their withdrawals as in most reporting systems to basin authorities and national governments. The innovative character of WA+ is the incorporation of comprehensive watershed processes, the role of land use, explicit recognition of manageable flows, description of utilized flow, difference between gross and net withdrawals, reserved flows and the benefits resulting from water depletion processes in terms of biomass production, food security, carbon sequestration, among others. The availability of a standard set of indicators based on transparent data collection procedures is beneficial for discussions on water resources management solutions.

Water accounting starts with precipitation and changes in storage of surface water, groundwater and snow packs to arrive at net inflow. WA+ reports on water depletion in a basin using spatially distributed evapotranspiration rates, and assesses which part is depleted in the landscape after rainfall and which part is depleted due to diversions. The available water for diversions is further subdivided into utilized and utilizable flows. Utilized flow is expressed as a net withdrawal: a large portion of the gross withdrawals – that are difficult to measure – are recycled and re-used in downstream areas, thus being even more difficult to measure. This makes gross withdrawals of less interest as compared to net withdrawals. Net withdrawals, or incremental ET, are expressed separately for groundwater and surface water systems, because these water systems have their own conditions, regulations and laws. The outflow from the basin is compared to reserved flows. Within WA+, knowledge of production outputs such as biomass production, food production, carbon sequestration, hydropower, leisure, industrial economies, and ecosystem services in various land use categories is related to water depletion. This is the key to benchmarking and increasing the productivity of water.

WA+ uses accessible satellite measurements as its main input data source, instead of detailed hydro-meteorological measurements. This independence makes it feasible

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to apply WA+ basically everywhere, and by doing so, can get a clearer understanding of the national, continental and global scale status of water resources.

The WA+ framework provides strategic insights in the possibilities to secure water resources availability and resilience to droughts and climate change, while maintaining biodiversity, preventing land degradation and conserving water for committed flows. The WA+ framework evaluates the impact of interventions such as (i) water re-allocations, (ii) reduced groundwater abstractions, (iii) deficit irrigation, (iv) modernization of irrigation, (v) artificial recharge, (vi) water retention and storage, (vii) waste water treatment, (viii) water productivity improvement, (ix) urban expansion, (x) deforestation, (xi) introduction of biofuel crops, (xii) cropping pattern change, (xiii) altered cultivation practices, etc. The framework has a simple presentation by means of four sheets, and is easy to implement and understand. Communications and decision making has the potential to improve, provided that the framework is supported by larger international academic and donor organizations. Dissemination of the WA+ principles to the responsible water professionals is also an elementary prerequisite for making the framework commonly known.

The renewed WA+ framework is, for all above mentioned reasons, a valuable tool for water resource planning and development, particularly, in ungauged basins and internationally disputed water flows with millions of people where the per capita water resources availability has started to decline at an alarming rate.

Appendix A

Definitions WA+

Gross inflow is the total amount of water that flows into the domain, including precipitation plus any inflow from surface or ground water sources.

Net inflow is the gross inflow after correction of storage change (ΔS) and represents water available for landscape ET, utilized flow and utilizable flow.

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Landscape ET is the water that evapotranspires directly from the natural water cycle without artificial supply.

Blue water represents water being present in reservoirs, rivers, lakes and groundwater that is used for utilized, utilizable and reserved flow.

Reserved flow is the water that has to be reserved to meet the committed flows, navigational flows, and environmental flow.

Available water is the blue water minus reserved flows. It represent the water that is available for use at the domain *Utilized flow* is the part of available water that is depleted for uses.

Utilizable flow is the available water for resources development.

Conserved land use relates to the environmentally sensitive land uses and natural ecosystem that is set aside for protection.

Utilized land use represents a low to moderate resource utilization, such as savannah, woodland and mixed pastures.

Modified land use relates to the replacement of the original vegetation for increased utilization of land resources.

Managed water use represents landscape elements that receive withdrawals from utilized flows.

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Table 1. The purpose of WA+ sheets.

Water sheets	Purpose	Bookkeeping sheets
Resource Base	Hydrological, manageable, utilizable flows, water security, sustainability	Understanding assets, liabilities
Consumptive Use	Beneficial & non-beneficial flows	Profit and loss
Productivity	Biomass returns, carbon sequestration, food security	
Withdrawal	Management, regulations, allocations	

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Table 2. Categories of land use classes with similarity in ecosystem services, provisioning services, human interaction and interventions in the hydrological cycle. These classes form the basis for management options in WA+.

Conserved land use	Utilized land use	Modified land use	Managed water use
Reserves or national parks	Closed natural forests	Plantation trees	Irrigated pastures
Areas set aside for conservation	Tropical rain forest	Rainfed pastures	Irrigated crops
Glaciers	Open natural forest	Rainfed crops	Irrigated fruits
	Woody savanna	Rainfed fruit	Irrigated biofuels
	Open savanna	Rainfed biofuels	Reservoirs & canals
	Sparse savanna	Rainfed recreational parks	Greenhouses
	Shrub land	Fallow land	Aquaculture
	Natural pastures	Dump sites	Residential areas & homesteads
	Deserts	Oasis & wadis	Industrial areas
	Mountains	Roads and lanes	Irrigated recreational parks
	Rocks	Peri-urban areas	Managed wetlands & swamps
	Flood plains		Inundation areas
	Tidal flats		Mining
	Bare land		Evaporation ponds
	Waste land		Waste water treatment beds
	Moore fields		Power plants
	Wetlands & swamps		
	Alien invasive species		
	Permafrost areas		

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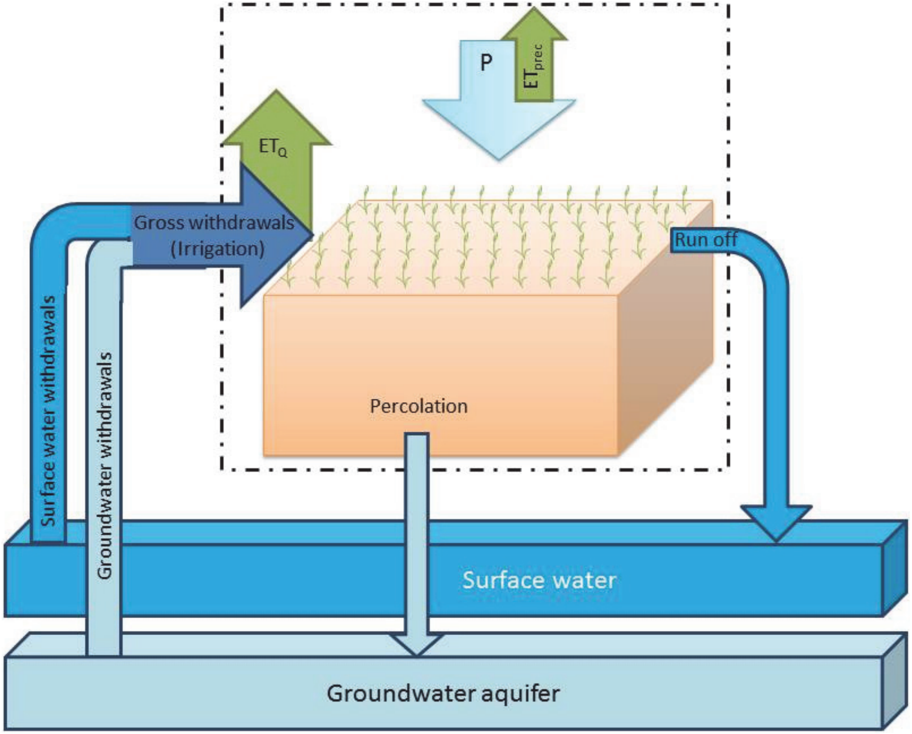

Fig. 1. Basic diagram explaining fundamental differences between gross and net withdrawals in relation to incremental ET.

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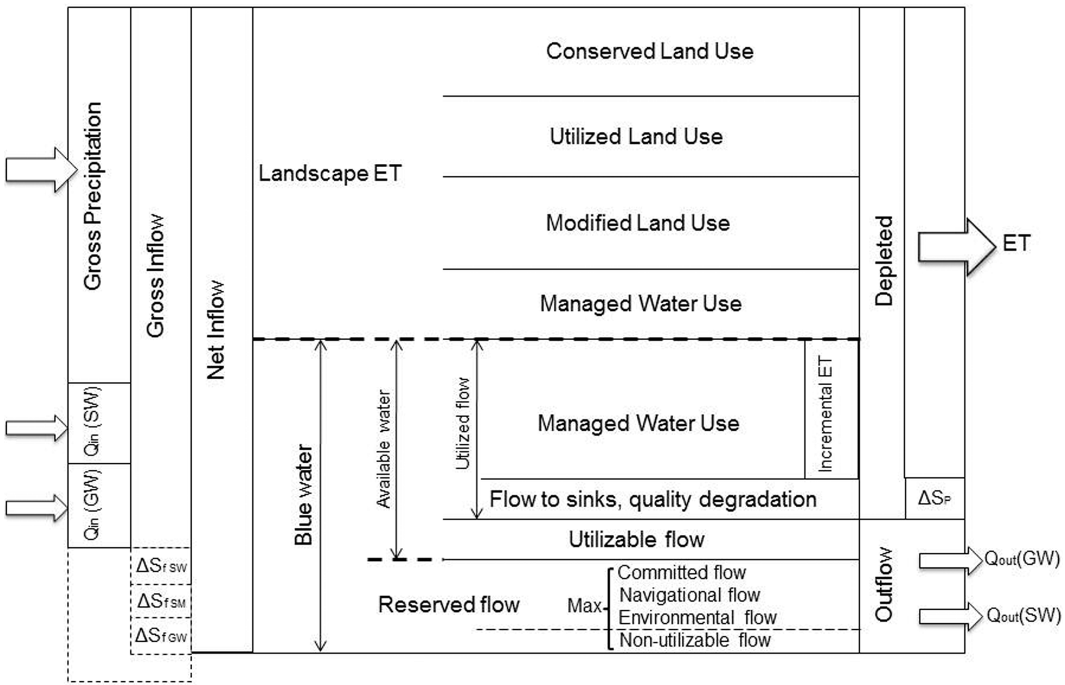

Fig. 2. Schematic presentation of the resource base sheet.

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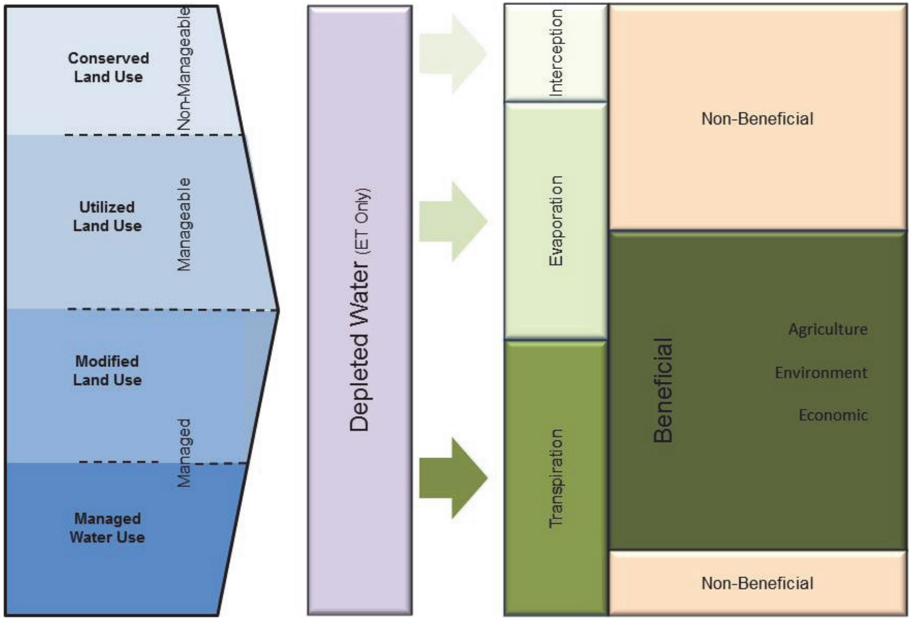

Fig. 3. Schematic presentation of the consumptive use sheet.

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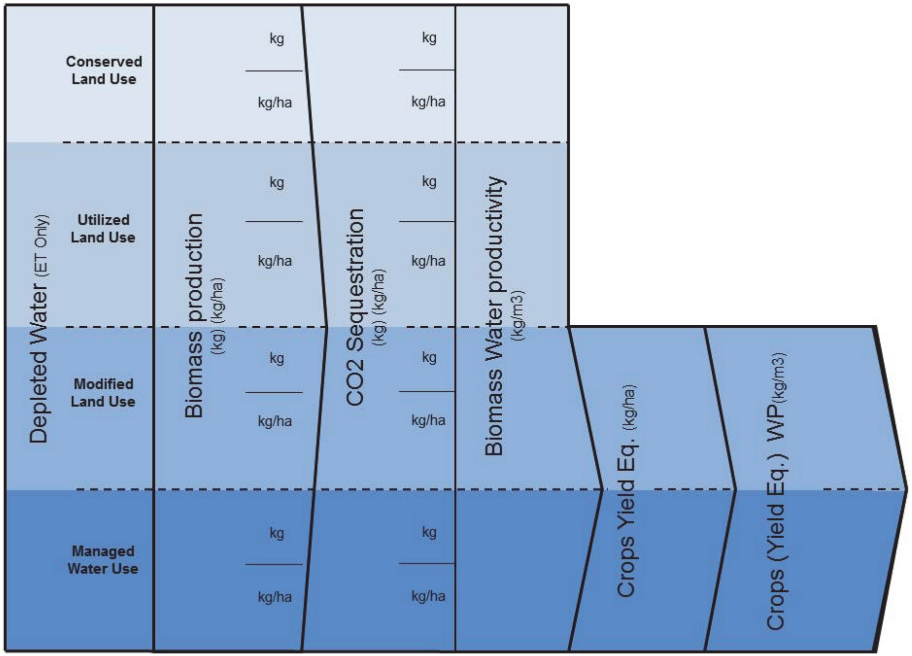

Fig. 4. The WA+ productivity sheet.

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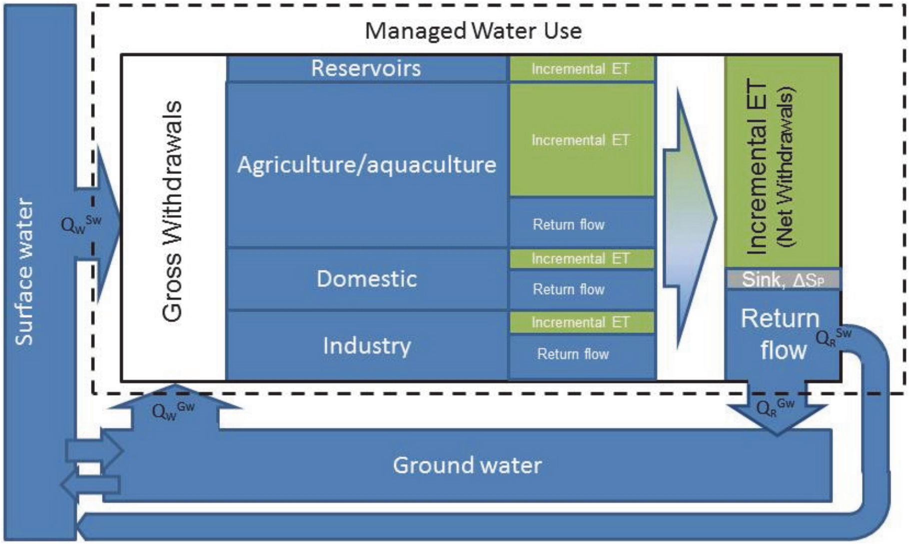

Fig. 5. Schematic presentation of withdrawal sheet.

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