Water accounting through Remote Sensing (WA+) in Helmand River Basin

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Acknowledgements

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Acronyms and abbreviations

CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CRU	Climatic Research Unit (University of East Anglia)
HRBMP	Helmand River Basin Master Plan
EROS	Earth Resource Observation System
ET	Evapotranspiration
ET_0	Reference ET
FAO	Food and Agriculture Organization of the United Nations
GMIA	Global map of Irrigation Areas
GPP	Gross Primary Productivity
ha	hectare
LST	Land Surface Temperature
m^3	cubic meter
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Productivity
RS	Remote sensing
TRMM	Tropical Rainfall Measuring Mission
USGS	United States Geological Survey

1. Background

It has been recognized by several Governmental and Non-Governmental Organizations that access to good quality water resources is a limiting factor for developing economies and securing food, among others. Many river basins experience issues of water stress and populations live with an inadequate level of water security. Water stress affects food and energy production, the ecological status of the basin, and adversely impacts on the health and livelihoods of its populations. Climate change and the associated increases in climate variability, as well as other global and regional changes such as declining groundwater tables, are expected to exacerbate water issues.

There is an urgent need for independently gathered water resources-related data sets that can be commonly understood by hydrologists, economists, agronomists, environmentalists, social scientists, legal experts and political scientists, and that enable evidence-based decision support and policy making. Access to accurate and up to date information continues to be a serious constraint for actors in the fields of natural resources management, in particular for water resources. Considerable progress has been made in many countries in processing and storage of basic data; however, data dissemination is often constrained by ownership policies or lack of resources for proper data distribution. Moreover, the integration of data and information from across sectors that depend on access to water remains difficult and subject to case-by-case solutions.

A common system of water accounting has so far been missing as an important element in the emerging debate of global water governance. The concept of water accounting provides a coherent and consistent water resources reporting methodology that comprises hydrological processes, distribution of water to various competing sectors, the consumption of water and the ecosystem services that result from that consumption. A prerequisite for profiting from the availability of water accounts, is that all reports and linked data sets are public domain, something that is not straightforward in the current world of limited data democracies. Further to data sheets, tables and maps, the decision maker has to understand the band width of uncertainty.

As part of TCP/AFG/3402 project "Analysis on water availability and uses in Afghanistan river basins", the FAO Regional Office for Asia and the Pacific has requested technical assistance related to project Output 1: "Water Resources availability and uses in five major basins in Afghanistan are analysed". In particular, the technical assistance was requested in support of the following project activity:

- Activity 1.1 Assessment of water resources availability conducted through literature review, horizontal and vertical discussions and appropriate modelling as required.

- Activity 1.2 Assessment on water uses (irrigation, hydropower, domestic etc.) in different river basins in Afghanistan conducted.

A standardized approach for rapid water accounting through Remote Sensing is being developed by UNESCO-IHE (Delft) and IWMI (Colombo) in partnership with FAO (Rome). Such approach, named "Water Accounting +" (WA+), makes use of global public domain datasets to estimate water balance components and report on the results through a set of standardized indicators sheets. FAO has applied WA+ in the Okavango and in the Awash Rivers basins in SSA (GCP/INT/072/ITA) with methodologies and results described in the reports available at: http://www.fao.org/nr/water/projects_scarcity_phase2.html.

The main objective of technical support to TCP/AFG/3402 project is to carry out water balance analyses for one river basin in Afghanistan. The Helmand basin has been selected for this purpose, as explained in section 3.

2. Water Accounting through Remote Sensing

The lack of open access to water resources data in international basins is cause for great concern. Therefore, measurements by earth observation satellites are a great alternative to acquire a comprehensive data base on hydrological and land surface processes. Access to data implies that the water accounts for all major river basins in the world can be computed, an essential starting point to survey the planetary boundaries. The raw data from multiple satellite systems need to be integrated, organized and presented in a framework on water resources reporting that all professionals understand.

In view of the great water challenges that the world community is facing, UNESCO-IHE and its partners the International Water Management Institute (IWMI) and the United Nations Food and Agriculture Organization (FAO) joined forces to pro-actively create an operational water accounting system platform referred to as www.wateraccounting.org. A new Water Accounting system (WA+) has been developed. The comparative advantages of WA+ are:

- WA+ is essentially based on open-access satellite measurements, which avoids lengthy discussions on ownership and intellectual property rights of data sets collected by certain governmental agencies;
- The full spatial variability of river basin water and environmental processes are measured through the satellite systems;
- Flows, fluxes and storage are computed by land use class, enabling to define services, benefits, economics and livelihoods;
- The product consists of sheets, tables, maps and the original spatial data;
- Using remote sensing for water accounting has the advantage that it is applicable without the need for extensive field monitoring and data collection.

The technical procedures focus on the water consumption of the different types of land/water use, including protected areas, pastures, rainfed and irrigated agriculture. Consumptive use can be estimated from satellite measurements (e.g. Bastiaanssen et al., 2014 for the Nile Basin or van Eekelen et al. 2014 for the Incomati Basin). The approach makes a distinction between beneficial and non-beneficial parts by separating the total evapotranspiration (ET) into evaporation (E), transpiration (T) and interception (I) processes. The productivity per unit of land (kg/ha) and productivity per unit of water consumed (kg/m^3) can also be determined from satellite measurements. Examples of the determination of crop yield for wheat, rice, corn and cotton in Pakistan are for instance provided in Bastiaanssen and Ali (2003). Zwart et al. (2010) computed global water productivity values from remote sensing data to get a better understanding of the actual variabilities and what the scope for improvements of the crop water productivity are.

Since the approach is based on remotely sensed information, it has the advantage that a study can be implemented in a short time and that the source of information is neutral and does not depend on field data that might or might not have been collected already (FAO, 2012a). Satellite measurements are owned by space agencies that provide the raw data as an open access service to users through large data bases. Since the majority of the WA+ data is based on these open-access data sets, the water accounts do no longer belong to a particular basin organization or Ministerial Department; it is based on publicly available data and this has great advantages in a free dissemination to all stakeholders involved in the distribution of scarce water resources. The implication is that all national and international agencies involved in the water and environmental management of the Helmand basin has access to the same information, and it is likely that this positively influences the decision making process related to the management of water resources.

3. Helmand River Basin

Helmand River basin, as defined for the purpose of this study, lies between latitude 29^o N and 35^o N, and longitude 60^o E and 69^o E, mainly in Afghanistan, but with small portions in Iran and Pakistan. Although Helmand and Farah-Harut basins are often treated as one basin in Afghan hydrological studies, it was decided to focus on the Helmand basin as delineated using the Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) which is a global standard dataset that provides hydrographic information for regional and global-scale applications in a consistent format.. This approach furthermore allows taking greater advantage of the Land Cover Atlas recently developed by FAO for the Islamic Republic of Afghanistan (FAO, 2010), and apply one consistent land cover input data throughout the basin, with the very limited exceptions of two swaths of land in Iran and Pakistan.

Figure 1: Helmand basin delineation derived from HydroSHEDS

While national governments tend to focus on resources that are confined within their political boundaries, it is recommended that water accounting keep a basin approach and thus focus on topographically defined units of analysis (FAO, 2015). In order to respond to countries' request for national bound data and information, results can also be presented, when possible, at different aggregation levels: basin, land use, administrative units. The table available under Annex F, for example, reports on the distribution of land and water use classes and their relative ETa in the three countries. Afghanistan accounts for 90% of the area and 95% of the water consumed in the Helmand basin, and 99% of annually generated renewable water resources.

The elevation and precipitation gradient of the basin range from 4,000 m above sea level with average annual precipitation of about 300 mm in the north-eastern part, and an elevation of 500 m and about 50 mm of annual precipitation in the south-western part (HRBMP, 2013). The population of the Afghan part of the basin was estimated at around 6 million in 2013, of which 83% live in rural areas (FAO, CountrySTAT Afghanistan) and largely rely on irrigated agriculture.

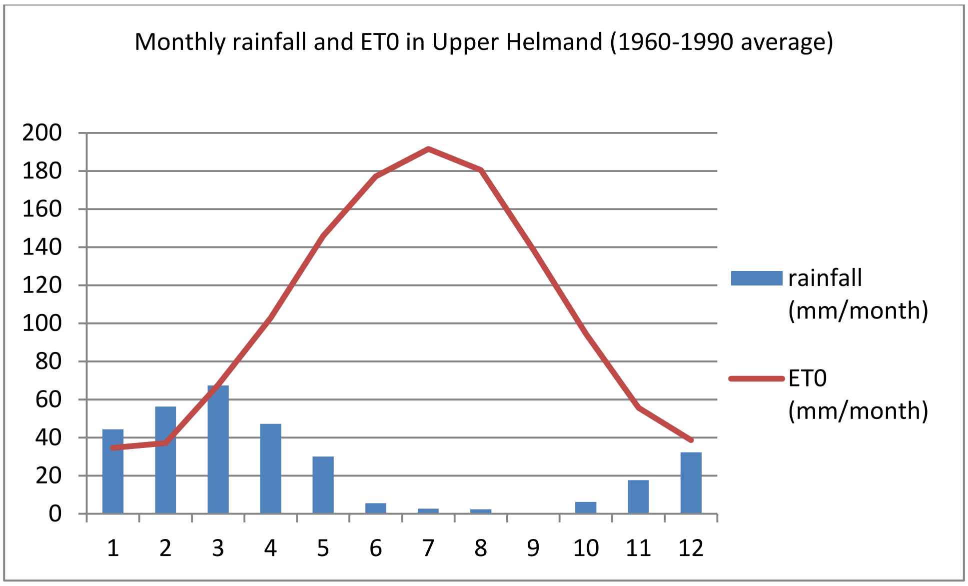

Figure 2: Monthly rainfall and ET0 in Upper Helmand

4. Input data

4.1. Land cover and use

The land and water use data is a key input data in remote sensing based water accounting, as it provides the basis for interpretation and reporting of the remote sensing derived information, as explained later in this section.

Several dataset have been combined to develop a land cover product consistent throughout the basin, and compliant to Water Accounting requirements.

1. Land Cover Atlas of the Islamic Republic of Afghanistan (FAO, 2012b).

This land cover database has been developed using FAO land cover classification system (LCCS) and distributed in its aggregated classification version (11 classes, first column in Table 1), with a spatial resolution of 1 km as a grid format, or as vector with equivalent scale of 1:50,000 (http://www.fao.org/geonetwork/srv/en/main.home?id=42510). Although not yet distributed due to ongoing validation process, the detailed classification version has been made available for this exercise, limited to the Helmand basin.

Vector shapefile of the land cover database has been rasterized at 250 m resolution. Polygons with a mixed classification, with the dominant one representing more than 60 percent of the total extent, have been classified according to the dominant class.

Table 1: Classification adopted in the Land Cover Atlas

AGGREGATED CLASS	AGG CODE	CLASS ELEMENT	LC CODE
		Built-up, urban	1A
Built-up	URB	Built-up, non-urban	1B
Fruit trees	AGT	Fruit trees	2A

Grapes	AGV	Grapes	2B
Irrigated agriculture	AGI	2 crops/y: graminoid followed by rice	3A
		2 crops/y: graminoid followed by non-aquatic crop	3A1
		1 crop every 2-3 years (marginal)	3B
		Active Karez system	3C
Rainfed agriculture	AGR	Flat lying areas	4A
		Mountainous areas	4B
Forest and shrubs	NFS	Dense needle-leaved	6A
		Open needle-leaved	6B
		Degenerate with shrubs	6C
		Open undifferentiated	6B1
		Pistachio	5
Rangeland	NHS	Undifferentiated	7
Barren land	BRS	Outcrops and bare soil	8A
Sand cover	BSD	Sand covered areas	8B
		Sand dunes	8C
Water and marshland	WAT	Water bodies, permanent	10A
		Water bodies, seasonal	10B
		Water bodies, flowing	11
		Marsh, permanent	9A
		Marsh, seasonal	9B
		River banks and floodways	12
Snow covered	SNW	Snow covered	13

In order to include the non-Afghani parts of the basin (Figure 1), the above mentioned land cover product has been combined with GLC2000 (see below) to cover the –limited- basin areas in Pakistan and Iran. The Helmand basin is part of Pakistan at two different locations.

2. Global Land Cover Share database (GLC-Share)

The FAO Global Land Cover Share database (GLC-Share) provides a set of major thematic land cover layers resulting by a combination of "best available" high resolution national, regional and/or sub-national land cover databases and is distributed at a spatial resolution of 30 arc-seconds[1]. It has been used to compile land cover information for the Iranian part of the basin. As GLC-Share does not differentiate between rainfed and irrigated cropland, it has been combined with GMIA data to derive a classification consistent with WA+ approach.

3. Global Land Cover 2000 Project (GLC 2000)

The South Asia regional dataset of GLC2000[2] has been used in substitution of the GLC-Share product in the Pakistani part of the basin, due to a boundary discrepancy between Afghanistan and Pakistan with regard to classification of rangeland and barren land.

[1] Available at: http://www.fao.org/geonetwork/srv/en/main.home?id=47948
[2] Available at: http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php

4. Global Map of Irrigation Areas (GMIA)

GMIA data for Afghanistan are largely based on a land cover product of 1993 jointly produced by FAO, UNDP and the government of Afghanistan[3] . Given the availability of a more recent and detailed product, irrigation areas for Afghanistan are taken from the 2010 FAO database.

On the contrary, GMIA data for Pakistan and Iran have been updated in the most recent version and were thus preferred to the above mentioned land cover products (GLC-Share and GLC2000) in capturing irrigated areas in those countries.

5. World Database on Protected Areas (WDPA)

Protected areas are used to identify the Protected Land Use class of the WA+ framework. The International Union for the Conservation of Nature (IUCN) classifies protected areas according to –among other variables- the level of restrictions applied: categories I and II indicate areas where agriculture is not allowed. The WDPA reports two protected areas within the Helmand basin, Ab-i-Estada and Hamun-i-Puzak. The first one is reported as a National Park with IUCN status "unknown", and the second one is a waterfowl sanctuary in IUCN category IV. They both cover wetlands systems and thus are included in the WA+ group PLU.

6. MODIS Normalized Difference Vegetation Index (NDVI)

MODIS product MOD13Q1 for the period 1/1/2007-31/12/2011has been downloaded and processed to better characterize water bodies regime and distinguish perennial from seasonal water bodies. First, monthly raster data have been derived by averaging 16-days composites, then the occurrence of monthly negative values has been assessed and areas in which negative Normalized Difference Vegetation Index (NDVI) are recorded for 11 months or more have been classified as perennial water bodies. The near-infrared reflectance of water is lower than the red reflectance, causing the NDVI to become negative. This characteristic applies to water bodies only, and can therefore be applied to create a monthly water map. The year 2007 has been chosen as reference for water bodies characterization.

7. Global Reservoirs and Dams Database (GRanD)

The GRanD database (Lehner B. et al., 2011) has been used to locate two dams in the basin, Kajaki and Dahla. The water bodies upstream of the dams have been classified as 'managed water bodies' in the category "Managed water use".

Data processing

The first phase of data processing aimed at producing a set of input data consistent in their coordinate system, spatial resolution and extent. In this case, it was decided to use

[3] Available at: http://www.fao.org/geonetwork/srv/en/main.home?uuid=c1b18130-88fd-11da-a88f-000d939bc5d8

the land cover data projection (WGS84 - UTM 42N) and rasterize the vector products to the spatial resolution of the final RS-derived evapotranspiration data, which is downscaled to 250 m using NDVI products.

The second phase aimed at combining the input data in order to have one consistent land cover / use dataset covering the whole basin. This was done giving priority to the most recent land cover product in Afghanistan and by combining the GLC-Share/GLC2000 with GMIA version 5 on irrigated areas in the Iranian and Pakistani parts of the basin.

Land and water use final product

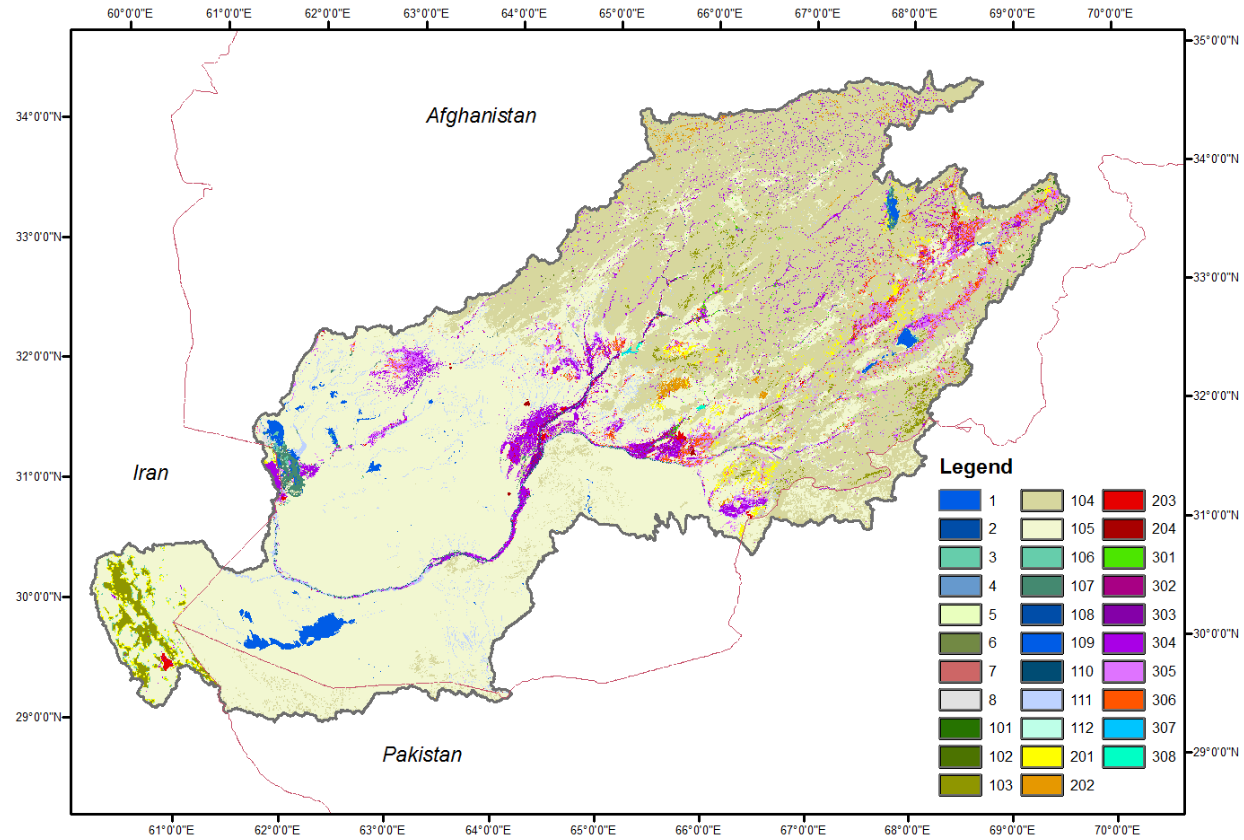

Figure 3: Land cover/use of the Helmand basin (see Table 1 for legend key)

Conversion to WA+ classification

Consumptive use expresses the consumption of water resources, which are no longer available for downstream users. The benefits, services and livelihoods associated to consumptive use are, particularly in arid zones, essential information, which are generated and enriched by coupling between land cover and land use with water consumption patterns. The land cover product presented in Figure 3 feeds the WA+ accounting framework through the identification of four main land and water uses groups which are relevant for evaluation and policy making in the context of water management (Karimi et al., 2013):

- Protected Land Use (PLU): areas where no changes in land and/or water management are possible/advisable. Typical examples include tropical rainforests, wetlands, and mountainous vegetation. They are often national parks
- Utilized Land Use (ULU): land where vegetation is not managed on a regular basis and the human influence is limited; typical examples include forests, natural pastures, savannas and deserts.
- Modified Land Use (MLU): areas where vegetation and/or soils are managed, but all water supply is natural (rainfall); typical examples include rainfed agriculture, and built-up areas,.
- Managed Water Use (MWU): all sectors that withdraw water from surface water and/or groundwater; typical examples include irrigated agriculture, urban water supply, industrial extractions and water withdrawals for ecological purposes.

Table 2: Land cover/use classes and WA+ classification

	Land and water use	Area (km²)	as %	Water Management Class		Area (km², and as % of total)
1	Protected: seasonal water bodies	453.1	0.2%	PLU1	Protected land use	709 (0.3%)
2	Protected: permanent water bodies	3.2	0.0%	PLU2		
3	Protected: seasonal marshes	60.7	0.0%	PLU3		
4	Protected: permanent marshes	3.8	0.0%	PLU4		
5	Protected: rangelands	40.8	0.0%	PLU5		
6	Protected: forest and shrubs	5.3	0.0%	PLU6		
7	Agriculture (irrigated) in protected areas	17.8	0.0%	PLU7		
8	Protected: bare soil	124.8	0.0%	PLU8		
101	Forest, needle-leaved	130.4	0.1%	ULU1	Utilized land use	230 527 (91.6%)
102	Forest, undifferentiated	26.2	0.0%	ULU2		
103	Forest, degraded with shrubs	3 293.4	1.3%	ULU3		
104	Rangelands	92 125.9	36.6%	ULU4		
105	Bare soil	126 253.0	50.2%	ULU5		
106	Permanent marshes	542.0	0.2%	ULU6		
107	Seasonal marshes	1 274.8	0.5%	ULU7		
108	Permanent water bodies	1.9	0.0%	ULU8		
109	Seasonal water bodies	1 915.3	0.8%	ULU9		
110	Water courses	389.4	0.2%	ULU10		
111	River banks and floodways	4 519.2	1.8%	ULU11		
112	Snow covered	55.8	0.0%	ULU12		

201	Rainfed: flat lying areas	2 416.0	1.0%	MLU1	Managed land use	4 607 (1.8%)
202	Rainfed: mountainous areas	1 116.6	0.4%	MLU2		
203	Built-up, urban	970.1	0.4%	MLU3		
204	Built-up, non-urban	104.7	0.0%	MLU4		
301	Fruit trees	496.6	0.2%	MWU1	Managed water use	15 785 (6.3 %)
302	Grapes	469.6	0.2%	MWU2		
303	Irrigated, double cropping (wheat and rice)	470.1	0.2%	MWU3		
304	Irrigated, double cropping (wheat and vegetables)	7 005.6	2.8%	MWU4		
305	Irrigated, 1 crop every 2-3 years	5 213.2	2.1%	MWU5		
306	Irrigated (karez system)	2 044.9	0.8%	MWU6		
307	Managed permanent water bodies	18.8	0.0%	MWU7		
308	Managed seasonal water bodies	66.3	0.0%	MWU8		

Distribution of the four land/water uses groups in the basin is summarized in Figure 4.

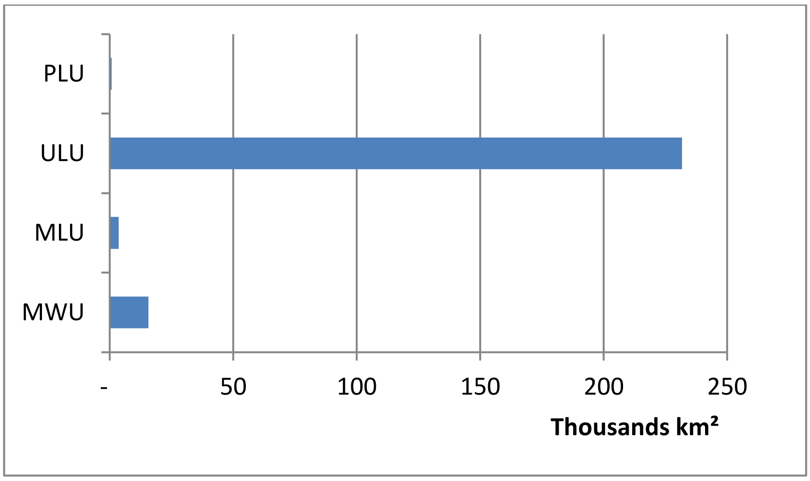

Figure 4: WA+ land/water uses in the Helmand basin

4.2. Actual Evapotranspiration

Actual evapotranspiration (ETa) data for this study has been kindly provided by the EROS Data Center of the USGS. The USGS has developed a prototype of a global ET product on the basis of the Operational Simplified Surface Energy Balance (SSEBop). This USGS product will be released during the next years , and the developers are testing the model performance on various locations. The current report is one of their testing experiments. Further to that, also other global ET products are under development such as MOD16 (Mu et al., 2007), ALEXI (Anderson et al., 2012), CMRSET (Guerschman et al., 2009) and GLEAM (Gonzales et al., 2011). It is expected that within a few years, several global scale ETa products will be available. Hofste et al. (2015) tested 7 of these models for the Nile basin, and concluded that an ensemble mean product is superior.

SSEBop is a method for calculating ETa using a specific solution of the surface energy balance equation (Senay et al., 2013). The idea behind the Simplified Surface Energy

Balance Operational (SSEBop) algorithm is to integrate reference ET0 with Land Surface Temperature (LST) data to account for soil moisture induced evaporative stress (ET_f). The reference ET_0 is determined using the Penman-Monteith equation (FAO, 1998) using the Earth Resource Observation System (EROS) and meteorological data from the National Oceanic and Atmospheric Administration (NOAA). The conversion from ET_0 to a potential value for ET is accomplished using a crop coefficient k_c:

$$Eta = ET_f \; k_c \; ET_0$$

where ET_0 is the grass reference ET for the location; *kc* is a coefficient that scales the ET_0 into the level of a maximum ET experienced by an aerodynamically rougher crop such as alfalfa. An ET fraction approach similar to S-SEBI from Roerink et al. (2000) using the prevailing LST in combination with a hot and cold pixel selection is then used to reduce the potential ET to actual ET. This ET fraction should not be confused with the trapezoid type of ET fractions. In this case, the ET_f fraction determines a linear combination of hot and cold pixel properties, where the hot pixel is geographically fixed or taken as certain percentile of frequency distribution of the surface temperature, and Th - Tc is approximated analytically:

$$ET_f = \frac{Th - Ts}{Th - Tc} = \frac{Th - Ts}{dT}$$

where Ts is the satellite-observed land surface temperature of the pixel whose ETf is being evaluated on a given image date. Th is the estimated Ts at the idealized reference “hot/dry” condition of the pixel for the same time period, Tc is the estimated Ts at the idealized “cold/wet” reference point. The difference between the extreme ends of the Ts frequency distribution, i.e. Th and Tc, is simply approximated by the dT function, assuming that the difference is caused by sensible heat flux only, which can be approximated instantaneously as being equal to Rn - G. If further the G-term is ignored, then physically feasible surface temperature range dT of a given pixel can be estimated as (Senay et al., 2013):

$$dT = \frac{R_n r_{ah}}{\rho_a C_p}$$

where *R*n (W/m^2) is clear-sky net radiation; *r*ah (s/m) is the aerodynamic resistance to heat flow from a hypothetical bare and dry surface, estimated at 110 s/m (Senay et al., 2013); ρ_a is the density of air (kgm−3) and *Cp* is the specific heat of air at constant pressure (1.013 kJkg−1 _C−1). dT is calculated under clear-sky assumption and does not change from year to year, but is unique for each day and location.The Tc data is based upon the 8-daily MODIS thermal product. The results are presented in Figure 5. This is the original data from USGS-Eros Data Center using MODIS-Terra spectral measurements. No calibration procedure has been applied to the ETa layers. The same data set was also the basis for Senay et al. (2007) who published the ETa values for irrigated crops in the Kabul and Helmand basins.

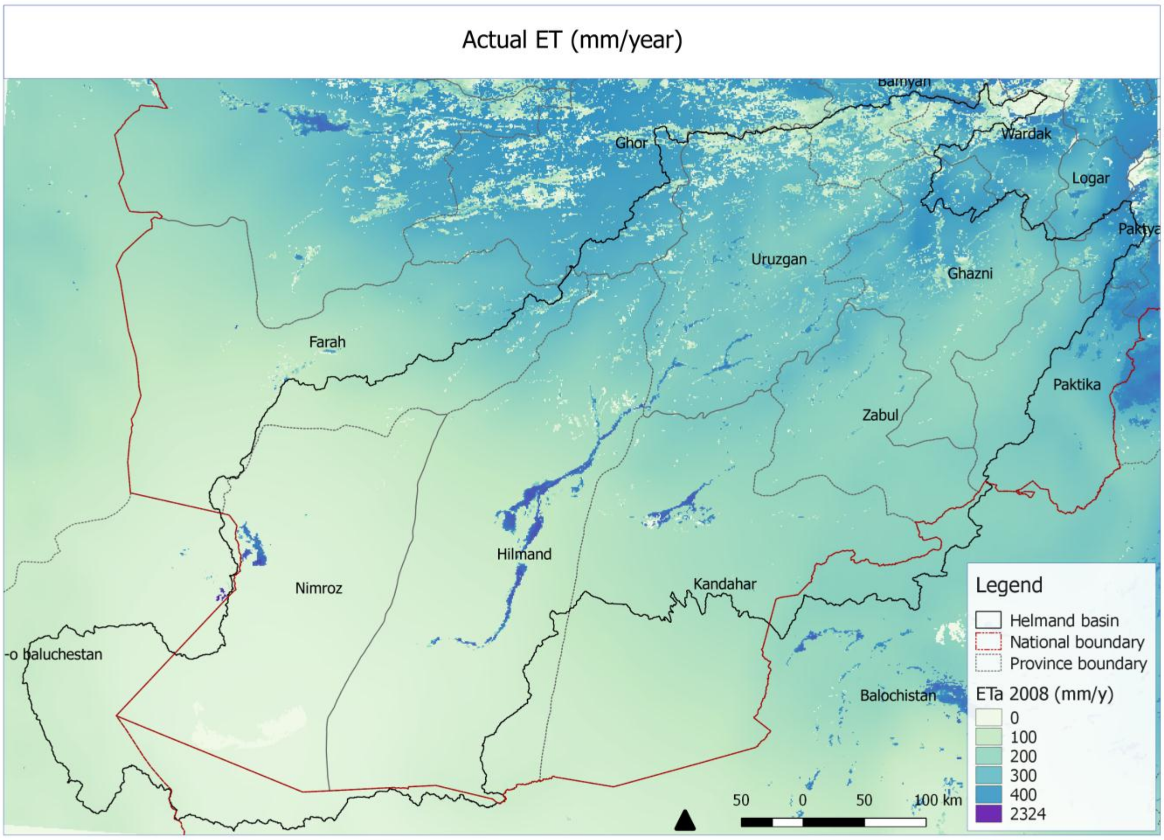

Figure 5: Map of annual ETa over Helmand basin, derived from SSEBop data. The data for the year 2008 is shown.

The original SSEBop data comes at 1 km spatial resolution and it has been downscaled at 250 m resolution using NDVI data. A weighing approach to dis-aggregate each 1 km pixel data of ET into a grid of 4x4 pixels has been applied. It is assumed that the relative NDVI value for each 250 m pixel relative to the 1000 m pixel can be used as an indicator of the relative ET value for the same 1000 m pixel, hence the proportional differences in NDVI are assumed to be similar to the proportional differences in ET.

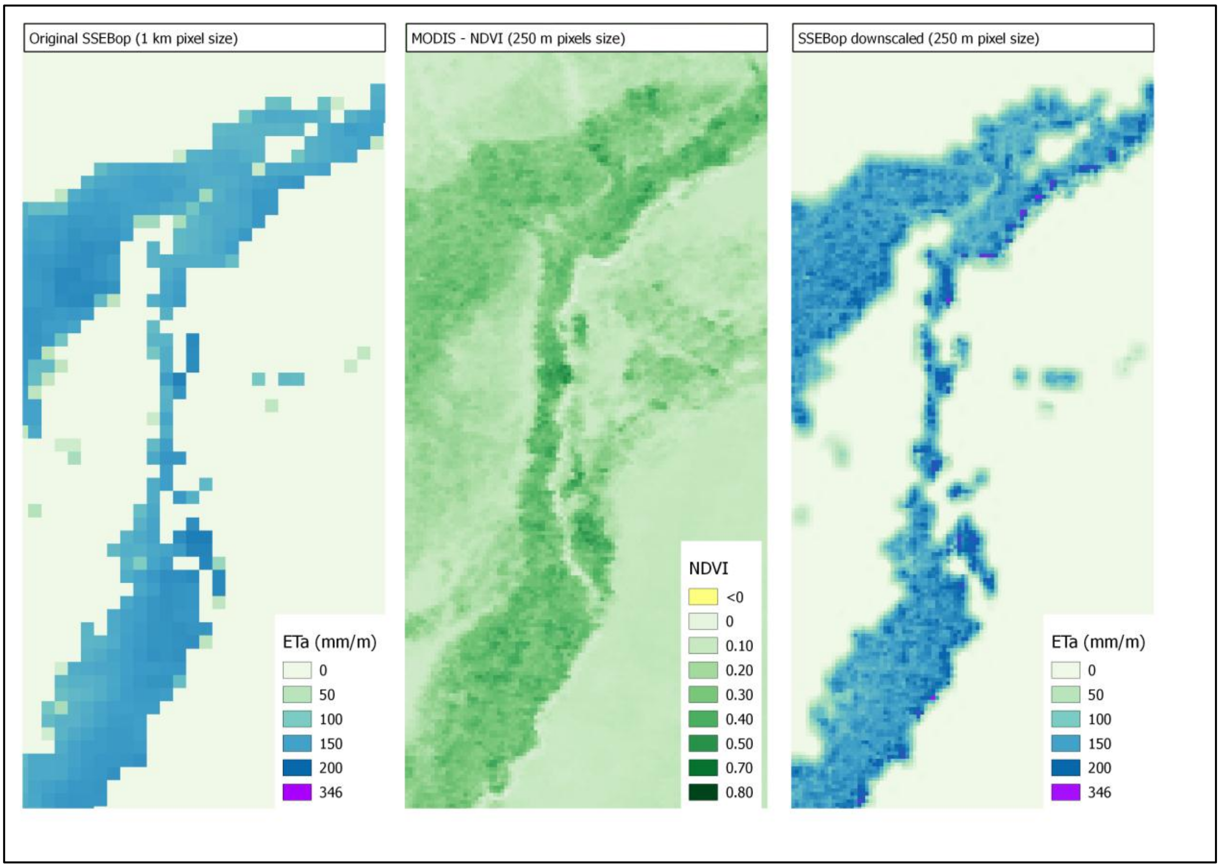

Figure 6: Illustration of ETa downscaling procedure. From left to right: original SSEBop,MODIS NDVI, downscaled ETa product for June 2007, over an irrigated area in Hilmand province

While the spatial variability of the ET product is in agreement with land cover and NDVI products, the inter-annual variability is smaller than expected when compared to rainfall or to commonly observed inter-annual variations in ETa. Figure 7 compares annual rainfall from different sources (CHIRPS, TRMM and the one adopted for this study, TRMM_CRUcal, further described in section 4.5) with the SSEBop product used, and the table provided in Annex E shows ET by land cover class and by year. One likely explanation is the tradeoff between higher reference ET during drier years, and the lower soil moisture during these same years that induce more crop water stress.

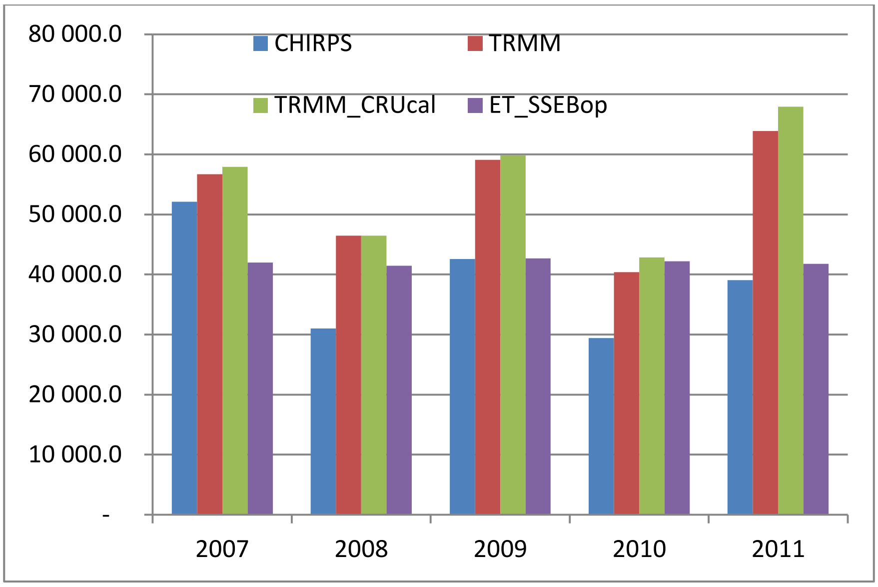

Figure 7: Comparison of annual ET and rainfall from different sources

4.3. Net and Gross Primary Productivity

Net Primary Productivity (NPP) takes into account how much carbon dioxide ($CO2$) is taken in by vegetation during photosynthesis and how much $CO2$ is given off during respiration, which is the process by which organisms use sugars to produce energy[4]. The net amount of carbon dioxide taken in by vegetation can be converted into dry matter or biomass information. Net and Gross Primary Productivity (GPP) are NASA MODIS products distributed by the Land Processes Distributed Active Archive Center (LP DAAC) with a spatial resolution of 1 km and temporal granularity of 8 days for GPP and annual for NPP (i.e. NPPy). A monthly synthesis product taking into account maintenance and growth respiration of vegetation over the year has been created from this data sets according to the monthly values of GPP (i.e. GPPm) and the sum of all monthly GPPm values (i.e. GPPy):

$$NPPm = GPPm/GPPy \times NPPy.$$

The accumulated NPP map from $\sum$NPPm is presented in Figure 8 and shows a strong spatial agreements with the independently gather ETa values displayed in Figure 5. This is in line with the general expectations.

[4] http://modis.gsfc.nasa.gov/data/dataprod/nontech/MOD17.php

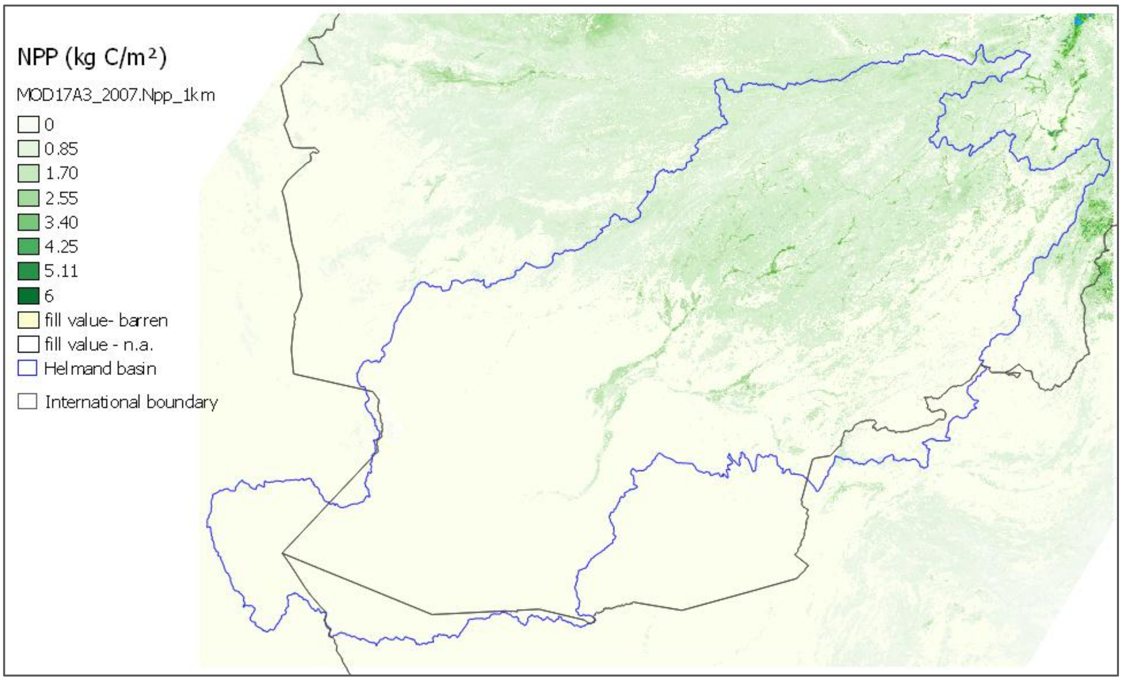

Figure 8: MOD17A3 Annual NPP (2007) in Helmand basin

4.4. Canopy Cover

Canopy cover information is used to compute the intercepted rainfall and in the partition of ET into evaporation and transpiration. Interception can be calculated from two different MODIS products: Leaf Area Index (LAI), at 1 km resolution, or NDVI at 250 m resolution. This study adopted the NDVI derived canopy cover because of i) its higher spatial resolution of 250 m (vs. 1 km for the default LAI values of MOD15) and, ii) the pre-classification of MODIS LAI according to land cover classes, whereby large areas of the basin are classified under pre-assigned fill values, often not coinciding with the new FAO land cover adopted in this study.

The formula adopted to transform NDVI to CC is the following (Kustas et al., 2001)

Cc = 1-((NDVImax-NDVI)/(NDVImax-NDVmin))^c

Where the maximum value of NDVI = 0.8 is obtained at full canopy cover, and the minimum value of NDVImin = 0.125 applies to bare soil conditions. The power coefficient c = 0.7 is based on field data, and is sometimes also taken as c=1.0.

4.5. Rainfall

The networks of rain gauge measurements were insufficient for preparing an acceptable estimate of the total rainfall for Helmand basin. It was decided to use two well-known rainfall data sets, namely the Tropical Rainfall Measurement Mission (TRMM) and Climatic Research Unit (CRU) data. TRMM is a dedicated rainfall satellite with several different instruments onboard that all compute different aspects of rainfall as an atmospheric process. The core product is a C-band radar that measures the size and density of rainfall droplets. This spaceborne rain radar is used to internally calibrate the other sensors such as the microwave brightness temperature and optical instruments. The TRMM data has been downscaled from its original value of 0.25° to 1 km rainfall products using a regression analysis between TRMM rainfall, NDVI and terrain elevation:

$$TRMM25km = a25km * NDVI25km + b25km * DEM25km + c25km + residual25km$$

The set coefficients a, b, c and residual at 25 km resolution was interpolated to 1 km resolution using Spline tension method. The coefficients so obtained were then applied to NDVI1km and DEM1km to generate the downscaled 1 km precipitation map, labelled as P1km:

$$P1km = a1km * NDVI1km + b1km * DEM1km + c1km + residual1km$$

This map yielded in very sharp spatial contrasts of rainfall that were too tightly coupled to land use and manmade water management activities. A filtering was applied to blur away the sharp contrasts.

CRU refers to the Climate and Research Unit of the University of East Anglia, and they have developed a rainfall product solely on the basis of gauge measurements. The CRU product is known to be good in the presence of many rain gauges. For Helmand basin, it is not certain that they have used any rain gauge, and hence the rainfall maps are likely based on rain gauges from the adjacent basins.

The TRMM and CRU products have been averaged, and the resulting uncalibrated rainfall map was the basis for a local comparison against rain gauges. The measured annual rainfall rates from the year 2011 appeared to be the best (see Table 3). There is more information available for the longer term average rainfall, but that could not be used for the calibration of one particular year.

Table 3: Measured rainfall during 2011 in the Helmand basin

STATION_NA	Elevation (m AMSL)	Measured (mm/yr)
Near Kandahar	971	162.9
Ghazni Bridge	2 181	433.2
Gardandewal	2 739	152.4
Adraskan	1 339	145.1
Farah	651	100.2

This rainfall information, together with the maps of uncalibrated P minus ET, have been used to derive one calibration curve for the entire basin. The rainfall at annual basis should namely exceed the ET values, and the confidence of the standard USGS-based ET product was good. The resulting map of rainfall is displayed in Figure 9. The Northern and higher elevation areas have more rainfall. The annual rainfall reduces to 50 mm in the downstream part of the basin, although more rainfall is received at the wetlands at the end of the river system.

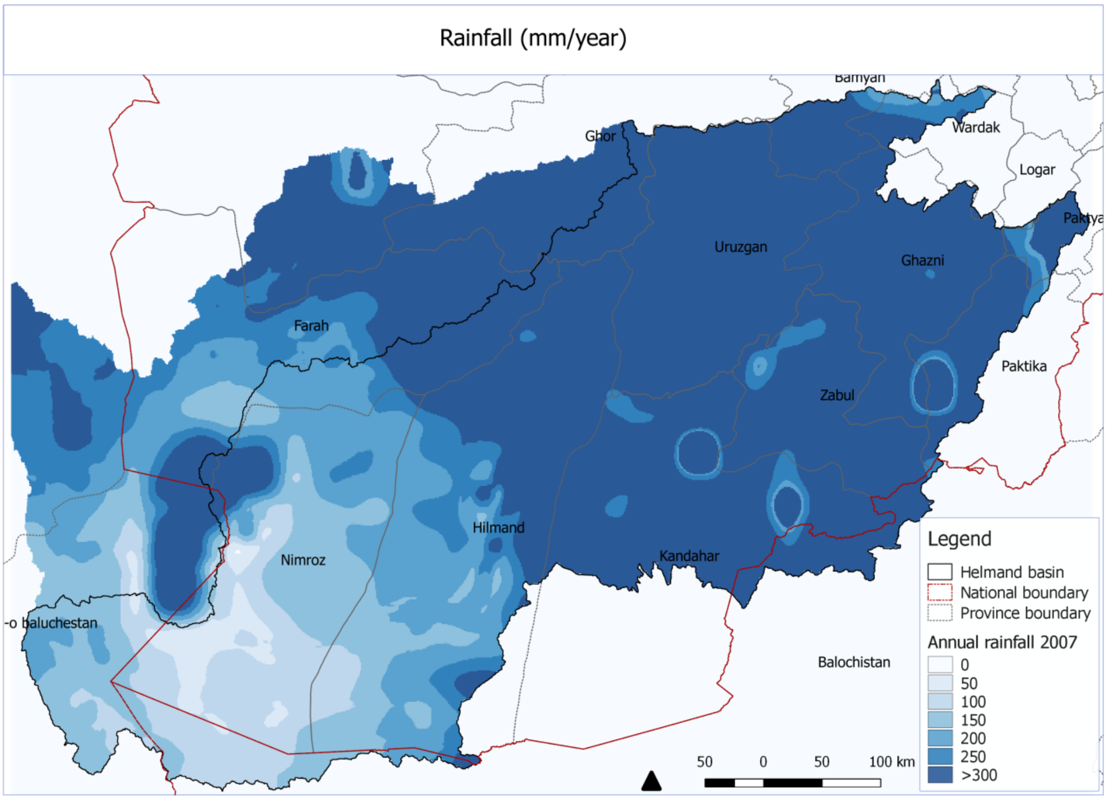

Figure 9: Map of annual precipitation in the year 2007

Time didn't allow for integrating other rainfall products, but it is recommended to explore options for averaging TRMM with the Climate Hazards Group InfraRed Precipitation with Station CHIRPS data in future studies (Funk et al., 2014), whose annual values are shown in Figure 7.

4.6. Interception

Intercepted rainfall occurs when leaves are large enough to catch raindrops and prevent rainfall from falling on the ground. The water intercepted on the leaves will evaporate back into the atmosphere immediately. It is a component of the total evaporation, and this process takes energy that affects the soil evaporation and canopy transpiration. This process is therefore taken into account during this study. An empirical function based on the days with rainfall, the LAI and canopy cover originally proposed by von Hoyningen-Hunen (1983) and Braden (1985) has been applied.

4.7 Global models and data on irrigation water use

Information on the share of irrigated area service by groundwater in the basin was extracted from the Global Map of Irrigation Area developed by FAO and Rheinische Friedrich-Wilhelms-Universität in Bonn (Siebert et al., 2013).

Input data, in particular ETa, and study results were also compared with global models of consumptive water use in irrigation, and namely with GlobWat, FAO global water balance model to assess water use in irrigated agriculture (Hoogeveen et al., 2015).

A summary table of input data used and the website accessed is provided below, and more resources for public domain data sources are available at http://www.wateraccounting.org/html/31_public_domain_data_sources.html.

Table 4: Summary table with input data

Input data	Source	Accessed through
Land cover	FAO	http://www.fao.org/geonetwork/srv/en/main.home?id=42510 and personal communication
ETa	SSEBop EROS USGS	Personal communication
NPP	NASA MODIS MOD17A3	http://www.ntsg.umt.edu/project/mod17 or https://lpdaac.usgs.gov/
GPP	NASA MODIS MOD17A2	http://www.ntsg.umt.edu/project/mod17 or https://lpdaac.usgs.gov/
NDVI	NASA MODIS MOD13Q1	https://lpdaac.usgs.gov/
Rainfall	TRMM and CRU	http://trmm.gsfc.nasa.gov and http://www.cru.uea.ac.uk/cru/data/hrg/
Withdrawals	GMIA (FAO and others)	http://www.fao.org/nr/water/aquamaps/ or http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm
Reference water balance	FAO GlobWat	http://www.fao.org/nr/water/aquamaps/

5. Methodology

5.1. Biomass production and crop yield

This section describes the conversion from annual NPP (carbon kg/m^2) to biomass expressed in dry matter weight (kg/ha). The Net Primary Production is offered as an operational MODIS product (MOD17). NPP describes the net amount of carbon C absorbed by vegetation as a result of assimilation (in) and respiration (out). The amount of C is expressed in a weight per unit area (kg/m2). The CO2 flux is the source of carbon in plants and the general photosynthesis equation determines that carbon is converted to carbohydrates (CH2O) being a crucial element of the vegetation dry matter. Considering the molecular weights, the weight of C can be converted into dry matter production (CH2O) or "biomass production" by:

Biomass = NPP*30/12

Because the MOD17 product is strongly coupled to land cover data - and its resolution is rather course - an improved version at 250 m spatial resolution was created by a simple regression analysis between biomass production derived from MOD17 and NDVI. The NDVI data layers are more consistent in space and time than what was observed for the biomass production. The regression analysis plotted in Figure 10 allowed for direct use of 250 m resolution NDVI data in biomass calculations. This is a stronger basis for assessing the agricultural performance, and also for assessing the ecological production in wetlands and other types of vegetation. The maximum NDVI value for every pixel has been selected as the peak in greenness, which has a strong association with the accumulated biomass production for the year.

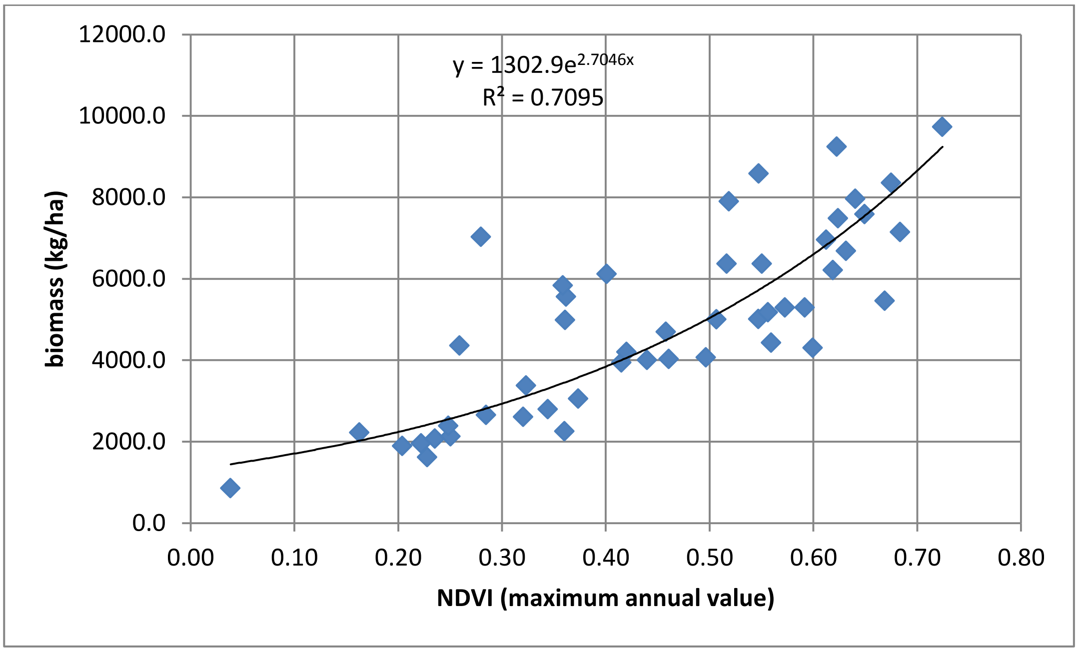

Figure 10: Regression between biomass and NDVI

In order to redistribute annual biomass (B_y) to monthly time steps, monthly gross primary productivity (GPP_m) has been downloaded. The breakdown of annual biomass production into monthly values (Bm) was achieved from the total annual GPP (GPP_y) and its monthly values:

$B_m = (GPP_m/GPP_y)\ B_y$

The monthly biomass production has been summarized into crop specific seasonal accumulated biomass production values, elapsing from sowing to harvest as shown in Table 5). Fresh crop yield information can be acquired from applying a harvest index and moisture content in harvested product parameters available from literature and adapted to the specificity of the study area (e.g. Bastiaanssen and Ali, 2003). The harvest index and moisture content are kept constant for a given crop, although in reality this can vary due to breeding practices and varieties. We believe that more agricultural background information is needed before advancing certain input parameters. For a quick scan it is sufficient to deal with constant values.

Table 5: Parameters used to derive crop yields from seasonally accumulated biomass production data

Crop	Month – sowing	Month-harvest	Harvest Index	Moisture content in harvested product
Wheat (irrigated)	January	May	0.45	0.15
Rice (irrigated)	June	October	0.45	0.15

Vegetables (irrigated)	June	October	0.70	0.85
Fruit (irrigated)	annual		0.30	0.85
Grapes (irrigated)	annual		0.25	0.85
Rainfed wheat	single cropping		0.30	0.15

5.2. Incremental ET over irrigated areas, open water and wetlands

This section describes the analysis of rainfall dependent evapotranspiration (ET over rainfed and natural vegetation), and the calculation of incremental ET over irrigated areas, wetlands and open water.

Additional ET due to irrigation and additional ET over wetlands and water bodies has been calculated by subtracting rainfall dependent ET from total ET. Rainfall dependent ET (ET_P) has been calculated by taking monthly ET over rainfed areas (excluding water bodies, wetlands and irrigated areas) and spatially extrapolating it to land cover classes where incremental ET occurs. The incremental ET over irrigated areas, water bodies and wetlands (ET_Q) can then be estimated from the total ET map provided by USGS Eros Data Center:

$$ET_Q = ET - ET_P$$

Irrigation withdrawals (Q_{irr}) have been assessed by applying crop specific irrigation efficiency (Q_{eff}) reported in Table 6 to the seasonal incremental ET due to irrigation. These efficiencies are mainly based on the type of irrigation system involved. Hence, irrigation withdrawals are estimated in this study on the basis of ET_Q and Q_{eff}, and this makes it feasible to get realistic estimates of water withdrawals without flow meters (van Eekelen et al., 2014; Hoogeveen et al., 2015):

$$Q = ET_Q / Q_{eff}$$

The impact of fixing a constant value for the efficiency within a certain crop class is that the gross withdrawals become a reasonable estimate only. This has impact on the gross withdrawals, but not on the net withdrawals, which are more relevant for the consumptive use.

Table 6: Irrigation efficiency (Q_{eff}) adopted for selected crops

Crops	Efficiency
Wheat	0.45
Rice, paddy	0.45
Vegetables, fresh nes	0.45
Pulses, nes	0.5
Grapes	0.7
Fruit, fresh nes	0.7

5.3. Irrigation water productivity

This section describes the identification of the explicit role of irrigation processes on the increments in the crop biomass production and crop yields by computing water productivity related to irrigated crops. Irrigation Water Productivity (IWP) is considered as an essential indicator for the returns (kg, calories, $) per unit of water consumed due to irrigation supply. This is the part of the agricultural water cycle that can be influenced by management, and it is good to isolate IWP from CWP. The basic idea is that cropping systems consume water that is no longer available for downstream users. From the context a river basin, consumed water is a sink and need therefore to be profited from to the maximum extent possible. Seasonal totals of ET due to irrigation (ET_Q) have been used together with incremental crop yields due to irrigation (Y_Q) to calculate a water productivity that is explicitly related to the irrigation process, and excludes all effects arising from rainfall (e.g. Jensen, 1969; Feddes, 1985; Menenti et al., 1989):

$$IWP = Y_Q / ET_Q$$

The crop yields calculated according to section 5.1 refer to total seasonal yield or, in other words, to crop development fed by both rainfall and irrigation water. In order to understand the productivity of irrigation water, the need comes to differentiate between rainfall dependent and irrigated yield. The methodology adopted in this study takes randomly selected points in rainfed and irrigated land cover and retrieves cumulated seasonal biomass production during the growing period. The biomass is then plotted against effective rainfall (rainfall which is available for vegetation ET, net of the precipitation which infiltrates or goes into runoff) which allows identifying a threshold line, or a cluster of points, above which additional biomass is only possible if irrigation water is supplied (Figure 11). The selection of pixels that reflect the actual response to a certain rainfall regime prevents that IWP is becoming too much a theoretical indicator with crop production becoming a function of assumed rainfall distributions.

In this case the threshold for rainfall dependent biomass was set at 900 kg/ha for the first cropping season and to 0 for the second crop, when the rainfall doesn’t contribute to biomass development. This is based on real conditions encountered in the field following certain rainfall regimes. The threshold value needs to be modified for years with a different rainfall regime and sowing calendars. The data reveals that the biomass production variability is not much explained by rainfall (100 mm or 250 mm will provide the same minimum production), but more by other factors such as irrigation and agronomical practices.

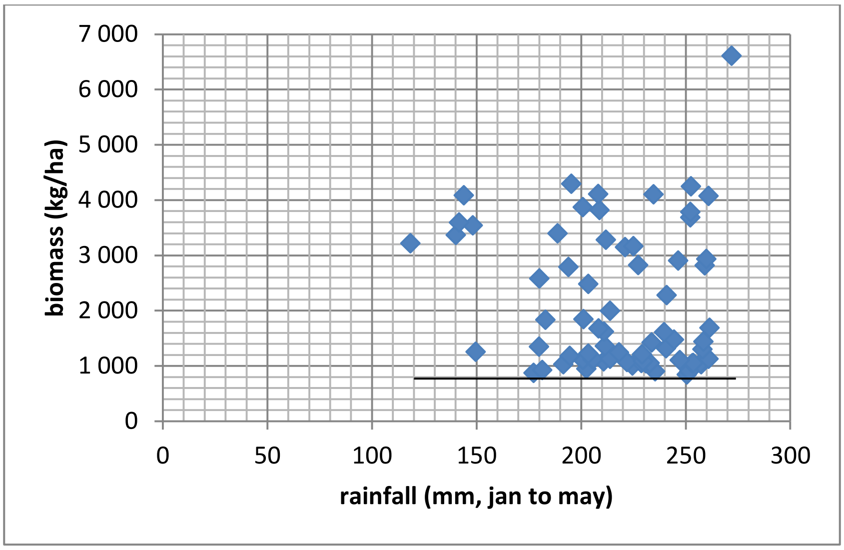

Figure 11: Chart used for the estimation of rainfall dependent biomass

Once the rainfed component is subtracted from total yield, the resulting irrigated yield is divided by the amount of irrigation water consumed (incremental ET due to irrigation) in the growing season to calculate irrigation water productivity:

WP_{irr} = irrigated yield/irrigation water consumed

Rainfed crop water productivity was also calculated for one reference crop (wheat) taking the total seasonal yield and dividing it by the total actual ET (see Table 7 in the result section).

5.4. Evaporation and Transpiration

Partitioning actual evapotranspiration into evaporation (E) and transpiration (T) is instrumental to assess the beneficial and non-beneficial components of water consumption in the basin. The methodology adopted builds on the equations explained in FAO AquaCrop model manual (FAO, 2011a) and in FAO I&D paper 56 (FAO, 1998) to derive a simplified equation which relates transpiration to canopy cover, taking into account the comparatively lower weight of evaporation from bare soil (which is limited to water content in the topsoil):

$E = ETa(1\text{-}cc^*)\ (K_e\ /\ (Kc_{TR} + K_e))$, and

$T = ETa - E$

where cc* is the canopy cover[5], K_e is the soil evaporation coefficient and Kc_{TR} is the crop transpiration coefficient. In this study, it has been assumed that K_e is on average 0.5 of Kc_{TR} (FAO, 1998). The fixed values for K_e and Kc_{TR} demonstrate that this approximation is applicable to the average field in Helmand Basin, and that locally some deviations with dryer and wetter soil and subsequent impact on K_e occurs.

[5] corrected to account for interrow microadvection

6. Results: Water Accounting sheets

Results are provided through the standardized reporting methodology of WA+, which makes use of a selection of sheets to summarize key findings organized around different indicators: the resource base sheet, the utilized flows sheet, the evapotranspiration sheet and the agricultural services sheet. Additional reporting sheet have been applied to other rivers basins, and examples are available on the dedicated website www.wateraccounting.org.

6.1. Resource base

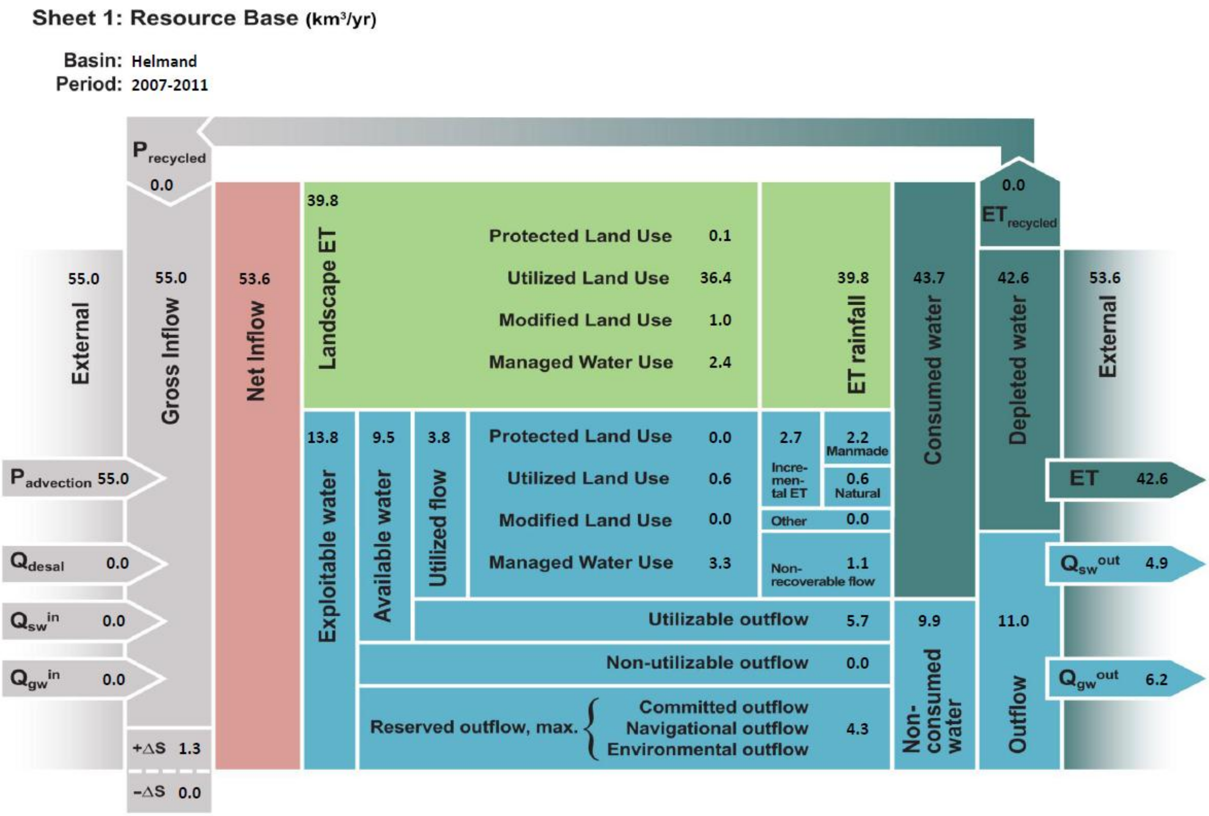

Figure 12: Resource Base sheet

The Resource Base Sheet provides a quick overview of incoming and outgoing flows for the basin and the four Land and Water Use categories. The delineation of the basin adopted in this study (Figure 1) covers only partially the Sistan depression and terminal lakes (*hamoun*) in Iran, and, in particular, it excludes those fed by the Farah and Harut rivers, whose basins are outside this study area of interest. That is why, while the Helmand with Farah-Harut is classified as a closed basin (HRBMP, 2013), the water balance presented here only covers the Helmand basin part and shows an annual surface outflow of nearly 5 km^3 which represents the Helmand river flow to Iran (downstream of the 'fork') plus other minor streams along the border. Many uncertainties remain with regard to groundwater in the basin and in particular to groundwater outflow, and the values adopted here (6.2 km^3/year) make reference to available historic surface flow data at Khwabgah (Williams-Sether, 2008), assuming the rest goes to groundwater.

Reserved outflow are those pertaining to the Helmand Treaty with Iran (HRBMP, 2013) being 0.8 km^3/yr, plus an estimated 25% of the mean annual runoff to maintain environmental flow (Smakhtin et al., 2004).

The Resource sheet shows that, over the five years period, Managed Water Use (incremental ET due to irrigation and non-recoverable flow, plus evaporation from managed water bodies, is 3.3 km^3/ year) accounts for the depletion of about 35% of available flow, while the details of water use components are described in the Utilized flow sheet. The contrast between water consumed in the category Managed Water Use (3.3 km^3/year) with the Utilized Land Use total water consumption of 36.4 km^3/year (see resource base sheet) remains an intriguing. Water is largely evaporated with a very low utilization. It is recommended to examine dry-land agricultural farming possibilities.

On average for the period 2007 to 2011, the utilizable outflow is, with 5.7 km^3/ year, more than the incremental ET. In dry years, however, the utilizable outflow reduces to virtually nothing, as shown in Table of annual values provided in Annex C.

6.2. Utilized flows sheet

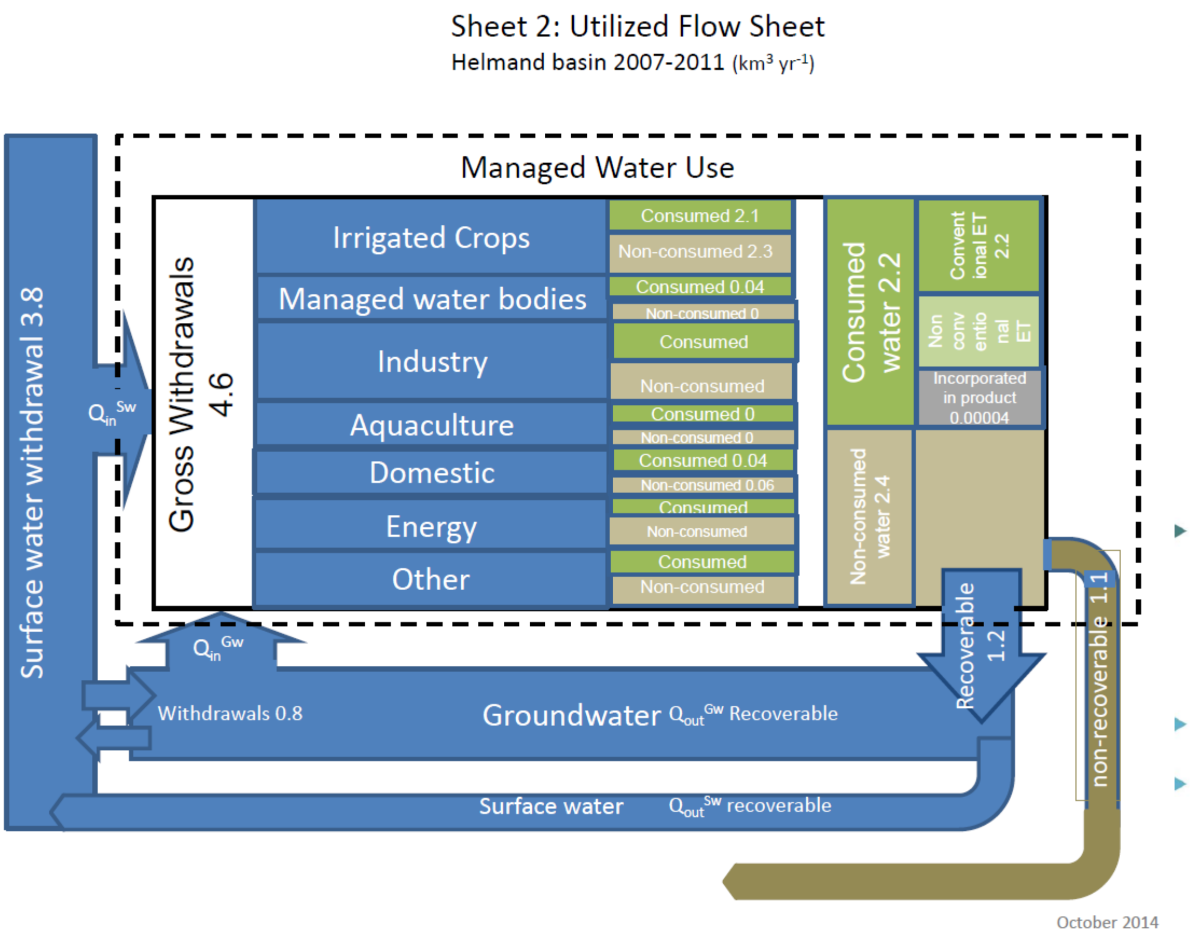

Figure 13: Utilized Flow Flow sheet

The Utilized Flow Sheet provides a summary of consumptive and non-consumptive water uses in the basin within the category of Managed Water Use, including the amount recovered through return flow. This sheet reflects the manmade decisions on allocating and re-distributing surface and groundwater flows. Infrastructure must be in place to displace these water volumes. While the incremental ET from rural areas is the basis for withdrawals in the classes irrigated crops, managed water bodies and aquaculture, the consumptive use of industry, domestic sector and energy has to be estimated from literature or statistical data. This study estimates that about half (2.2 km^3/year) of total gross withdrawals (4.6 km^3/year) are consumed, mainly by irrigated crops and, of the remaining non-consumed part, half goes back to the system both through groundwater and surface water (recoverable flow) while another half is non-recoverable as it infiltrates to salt sinks, or to inaccessible groundwater. This is a direct consequence of the irrigation efficiencies defined in Table 6. The sum of consumed water (2.2) and non-recoverable flow (1.1) corresponds to the Managed Water Use of renewable water resources generated in the basin, as seen in the Resource Base sheet.

6.3. Evapotranspiration sheet

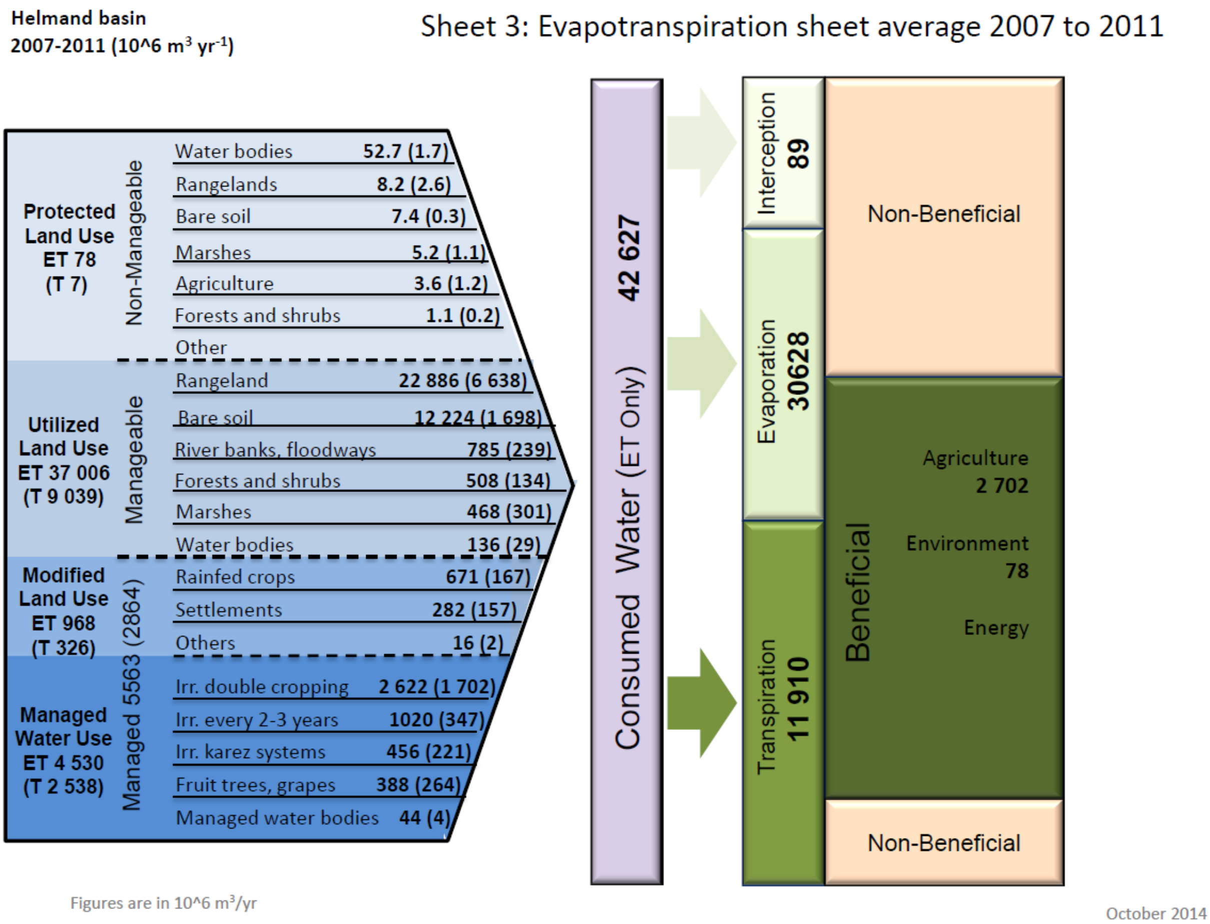

Figure 14: Evapotranspiration sheet

The Evapotranspiration sheet provides a summary of water consumed by the different Water Use/Land Use classes in the basin, including an indication of the more beneficial transpiration component (in brackets). The Helmand basin is characterized by a significant evaporation component (soil and water evaporation: 30.6 km^3/year), representing about 71 % of total ET. The transpiration from crops and other types of vegetation totals 11.9 km^3/year or 28%, while interception is only 0.1 km^3/year. This large amount of evaporation originates mainly from bare soils due to sparse vegetation cover.

The Evapotranspiration Sheet provides also information on whether water is consumed beneficially or non-beneficially. Although this value assessment is subjective to opinions and visions, a straightforward approach with default table with values can be used. A substantial amount of water is used non-beneficially by interception or soil evaporation, although evaporation is also considered as beneficial to the environment in Protected Land Use. The highest share of beneficial consumption in the basin comes from the agricultural sector, accounting for about 95% of total beneficial water consumption.

Table A in Annex provides details of Precipitation and ET in mm per water use / land use.

6.4. Agricultural services sheet

Sheet 8: Agricultural services
Part 1: Agricultural water consumption (km³/yr)

Basin: Helmand
Period: 2007-2011

Crop													Agricultural water consumption	4.1
Cereals	Non-cereals				Fruit & vegetables			Oil-seeds	Feed crops	Beverage crops	Other crops			
	Root / tuber crops	Leguminous crops	Sugar crops	Merged	Vegetables & melons	Fruits & nuts	Merged							
0.67									-			ET	rainfed	0.7
1.09					0.04	0.15						ET from rainfall	irrigated	1.3
1.04		0.07			0.74	0.23						Incremental ET	irrigated	2.1
2.14		0.09			0.78	0.39						Total ET	irrigated	3.4

Sheet 8: Agricultural services
Part 2: Land productivity (kg/ha/yr) and water productivity (kg/m³)

Basin: Helmand
Period: 2007-2011

	Crop													
	Cereals	Non-cereals				Fruit & vegetables			Oil-seeds	Feed crops	Beverage crops	Other crops		
		Root / tuber crops	Leguminous crops	Sugar crops	Merged	Vegetables & melons	Fruits & nuts	Merged						
Land productivity	906	-	-	-	-	-	-	-	-	-	-	-	Yield	rainfed
	320	-	600	-	-	47	2,200	-	-	-	-	-	Yield from rainfall	irrigated
	1,286	-	139	-	-	8,636	5,649	-	-	-	-	-	Incremental yield	irrigated
	1,606	-	739	-	-	8,683	7,849	-	-	-	-	-	Total yield	irrigated
Water productivity	0.45	-	-	-	-	-	-	-	-	-	-	-	WP	rainfed
	0.32	-	0.67	-	-	0.44	1.43	-	-	-	-	-	WP from rainfall	irrigated
	0.65	-	1.23	-	-	8.19	2.37	-	-	-	-	-	Incremental WP	irrigated
	0.52	-	0.73	-	-	7.48	1.98	-	-	-	-	-	Total WP	irrigated

Figure 15: Agricultural Services sheet

The total amount of water consumed for crop production is 4.1 km^3/year. Most of the water is consumed in cereals (2.8 km^3/year), followed by vegetables (0.8 km^3/year) and fruits (0.4 km^3/year). The majority of the water resources for agriculture are consumed for irrigation systems (3.3 km^3/year or 83 %). Irrigation systems benefit from rainfall with an amount of 1.3 km^3/year, which is more than the water consumption of rainfed crops (0.7 km^3/year). Hence, the total ET from rainfall is, with 2.0 km^3/year, very similar to the 2.1 km^3/year that originates from irrigation. The green and blue water consumption of the agricultural sector in the Helmand basin is thus similar.

The Agricultural Services sheet provides a summary of agricultural water use and its productivity (Part 2), both under rainfed and irrigated conditions. The harvest indices and moisture contents of the reference crops specified in Table 5 are used.

The analysis shows that land productivity of rainfed cereals (906 kg/ha) is significantly lower than the irrigated cereals who reach a total yield of 1606 kg/ha. Irrigation thus almost doubles the land productivity of cereals. Vegetables are cultivated as second crop in the dry season, when the rainfall contribution is almost negligible, which explains the zero yield from rainfall. Leguminous crops are assumed to be cultivated as second crop in traditional karez systems, which are apparently irrigated only when water availability allows, and thus present a limited incremental ET when averaged over a five years period. Their productivity is 8683 kg/ha, and it is a bit more than for irrigated fruit trees with 7849 kg/ha. Because fruit trees are perennial, they have a larger contribution from production in the rainy season.

When crop yields are represented on a map (Figure 16), the spatial variability in yield performance becomes evident, and explanations can be sought on how this variability is linked to management practices and agro-climatic conditions. These kinds of maps, beyond providing support to analyses, are powerful communication tools and can solicit actors' involvement at different levels. The wheat yields in Hilmand province are systematically higher (i.e. many fields exceed 3000 kg/ha) than being observed for other places. The wheat yield decreases towards the upstream part of the basin, which is related to the rainfed nature of these fields. The crop yields derived through this study are in satisfactory agreement with those reported in FAOSTAT database (Appendix D).

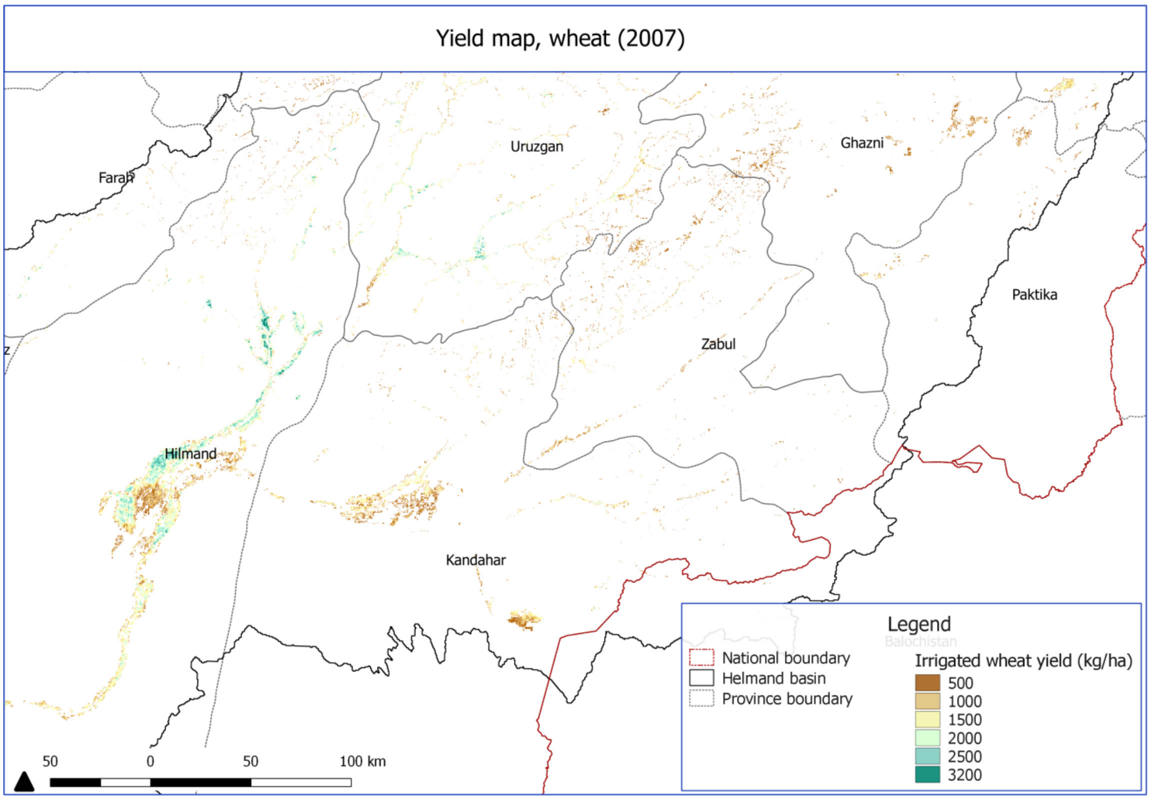

Figure 16: Yield map of irrigated wheat in 2007

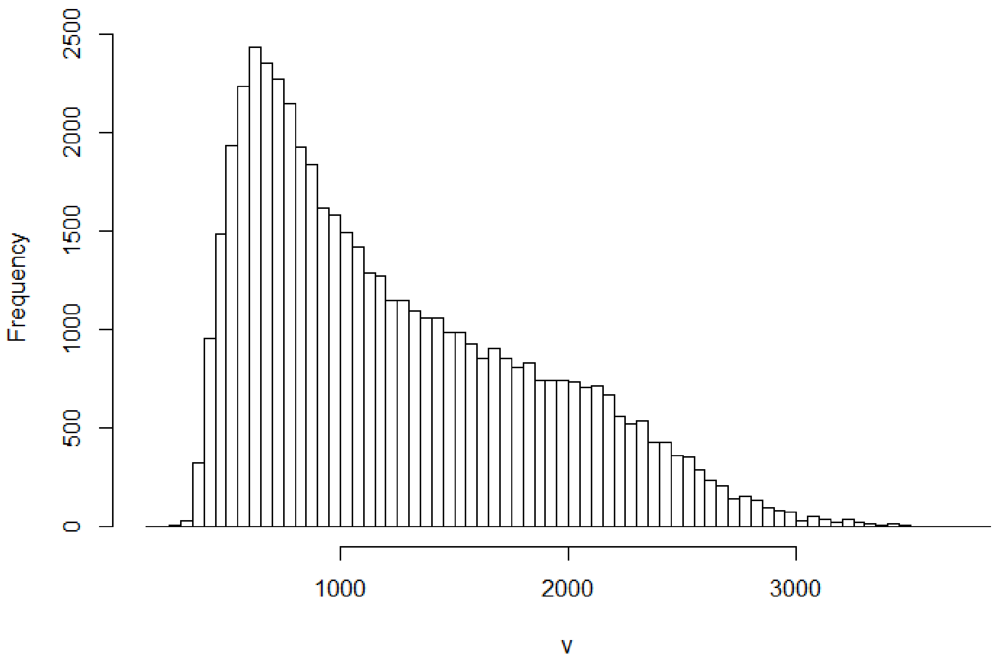

Figure 17: Frequency distribution of wheat yields in 2007

Such spatial variations in land productivity are linked primarily to the different cropping systems. The values of yield and crop water productivity shown in Figure 15

(Agriculture service sheet) are averaged for crop groups but they can also be looked at in their specific cropping system, as in Table 7. By doing this, one can observe that, on average, wheat cultivated in the land use class "Irrigated, double cropping: wheat and rice" tends to have comparatively higher yields. It should be noted that irrigated yield and, by consequence, crop water productivity for traditional (karez) systems and areas irrigated every two-three years, are averaged over a five years period in this table and thus hide the natural inter-annual variations of these systems. The IWP of wheat in the historic karez irrigation systems is with 1.68 kg/m^3 far better than the 0.71 kg/m^3 for the surface irrigation systems. While their yields are not very impressive, the farmers probably have very well developed procedures for sharing the water because their source is defined and known to them. This could be a possible reason for the high Irrigation Water Productivity (Perry, personal communications, 2015).

The concept of water productivity is to reduce the water consumption while conserving the yield. Overall the water productivity numbers are lower than what is achieved in other countries with similar climates. The world average value for wheat is 1.09 kg/m^3 (Zwart and Bastiaanssen, 2004). Further analysis, coupled with local knowledge and field data would be needed to account for the variations in cropping calendar and practices occurring under different water availability conditions. It is recommended to detect the fields in each province with the maximum water productivity for irrigated fields, as well as for rainfed fields.

Table 7: Yield and water productivity of major crops in the basin (average 2007-2011)

Crop/land use class	Total yield	Irrigated yield	WP - irrigated	WP - rainfed	WP - TOT
	(kg/ha)	(kg/ha)	(kg/m^3)	(kg/m^3)	(kg/m^3)
wheat (in "Irrigated, double cropping: wheat and rice")	2,096	1,620	0.71	0.51	0.65
wheat (in "Irrigated, double cropping: wheat and vegetables")	1,149	672	0.97	0.45	0.65
rice (in "Irrigated, double cropping: wheat and rice")	1,572	1,566	0.27	0.02	0.25
vegetables (in "Irrigated, double cropping: wheat and vegetables")	8,683	8,636	8.19	0.44	7.48
fruits	9,440	7,040	2.99	1.38	2.31
grapes	6,259	4,259	1.75	1.48	1.65
traditional irrigation/irrigation every 2-3 years					
wheat (in "Irrigated, 1 crop every 2-3 years")	869	392	2.07	0.33	0.53
pulses (in "Irrigated, 1 crop every 2-3 years")	692	92	1.26	0.67	0.71
karez wheat (in "Irrigated, karez systems")	1,078	602	1.68	0.33	0.60
karez pulses (in "Irrigated, karez					

systems")	786	186	1.21	0.67	0.75
Rainfed					
wheat (in "Rainfed: flat lying areas")	836	-	-	0.52	
wheat (in "Rainfed: mountainous areas")	975	-	-	0.39	

An example of local variability is demonstrated in Figure 17, which shows a map combining Irrigation Water Productivity and Yields, where dark green are fields characterized by yields higher than 1000 kg/ha and irrigated water productivity higher than the basin average (0.84). Apparently certain farmers are able to reach a much higher IWP for the same crop yield class than colleague farmers. This can only be explained by a reduction in consumptive use, and that is exactly what needs to be achieved under arid climatic conditions. Irrigation advisors and agricultural extension officers should inspect the best practices of these farmers with lower consumptive use and copy them to other farmer communities in the same region.

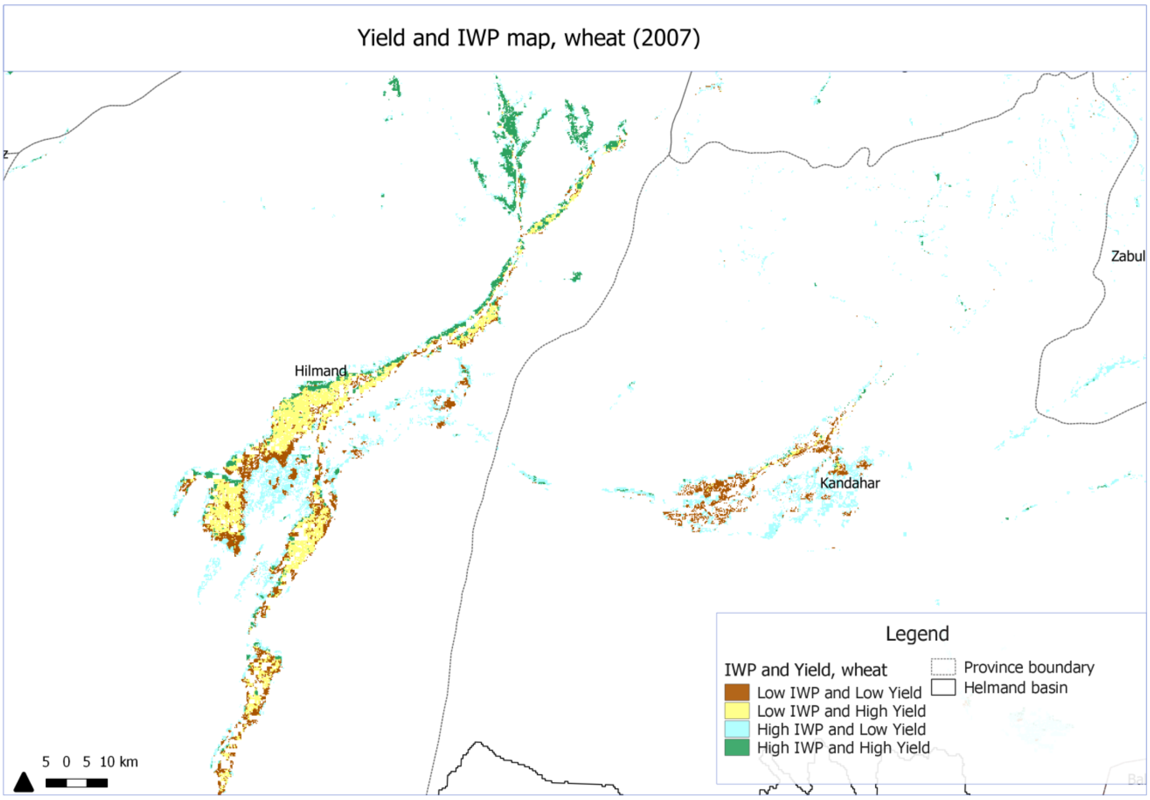

Figure 18: Irrigation water productivity and yield in wheat, 2007

The possibility to achieve comparatively higher water productivity values, regardless of the achieved yield, is also illustrated in Figure 19, where histograms of water productivity are plotted for different intervals of wheat yields (from less than 1t/ha, left side, to above 3 t/ha, on the right). Each yield class shows significant variability with regard to CWP, thus supporting the case for developing more efficient use of resources and achieving higher CWP, even in limited yield conditions.

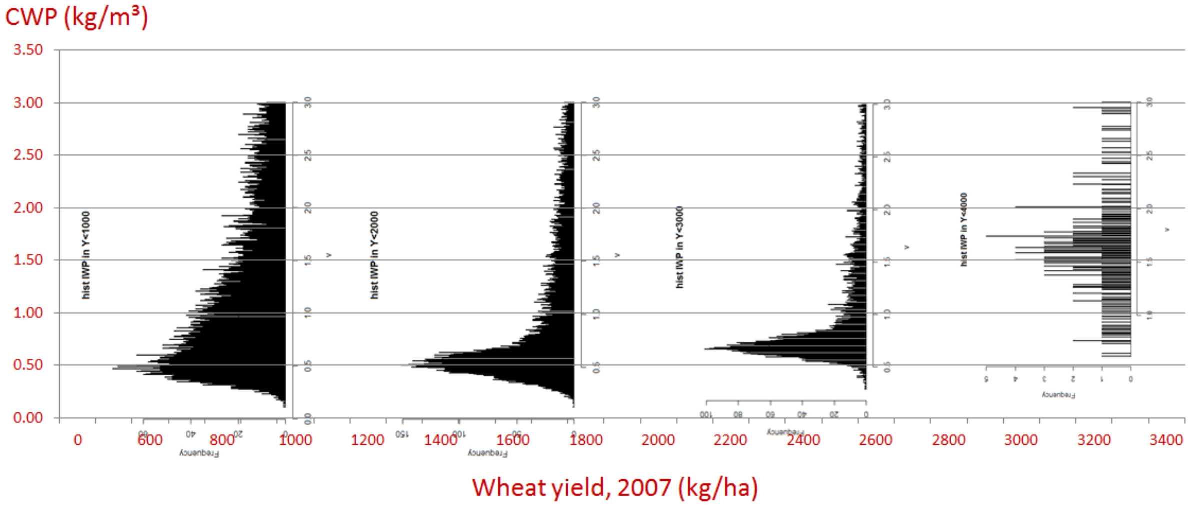

Figure 19: Frequency distribution of crop water productivity (CWP), after climatic normalization, under various yield intervals.

7. Conclusion

7.1. Uncertainties

Remote sensing based water accounting takes advantage of continuous improvements in RS data and algorithm quality but is, at the same time, challenged by this evolving context and needs to keep pace by testing and validating data and understanding uncertainties (Karimi and Bastiaanssen, 2013).

Main uncertainties related to input data include:

- Actual ET inter-annual variability. We have used in this study a novel ET product (Section 4.2) which proved to be spatially accurate when compared to land cover (see Annex B for monthly spatial distribution), but appears to show limitations with regard to inter-annual variability, due to the unexpected temporal constancy;
- Rainfall product is a single-calibration average of TRMM and CRU but uncertainties remain with regard to both quantity and spatial distribution, especially when compared to other publicly available rainfall data, such as CHIRPS (Funk et al, 2014), Figure 7. It is likely that total annual rainfall in the period 2007-2011 has been overestimated in this study, due to insufficient time and data availability for more accurate calibration, leading to overestimation of basin outflow. In a next study, more time should be dedicated to spatial variability of rainfall. Any small change in rainfall will have a signifcant impact on the exploitable and available water resources;

- Irrigated area: difference in irrigated extent between this study and the HRBMP are not negligible. The data source used in this study has been developed on high resolution satellite images and aerial photos (FAO,2012) but further investigations would be needed to clarify sources of inconsistencies between the datasets.

7.2. Conclusions and recommendations

On the use of Remote Sensing based Water Accounting as monitoring tool.

This study demonstrates that the approach we used is well suited for monitoring selected water accounting components and, more specifically, biomass, water productivity, evaporation and transpiration. The main added values are:

- it requires lower resources in terms of costs and time, when compared to traditional field based water accounts, particularly in data-poor conditions;
- it is an approach based on input data which are objective and replicable over time, thereby supporting sound time-series analysis for detecting changes and impact of policy;
- it provides spatially explicit information products, in this case with a spatial resolution of 250 m, which allow for improved geographic targeting;
- it monitors directly consumptive water use, or net withdrawals avoiding assumptions related to non-consumptive use (such as irrigation efficiency, return flows, etc.)
- it is particularly useful in security–constrained locations where field surveys are difficult or too expensive to implement.

Constraints and areas of improvement of this approach include:

- it requires a baseline calibration of input data, particularly rainfall and surface flows, which can be time and data intensive. However, once the baseline calibration is performed, monitoring can be highly automated;
- withdrawals can't be measured through Remote Sensing and need to be estimated by applying efficiency factors between withdrawals and incremental ET;
- although water accounting should pursue stakeholder engagement throughout the process, RS water accounting tends to be performed in isolation due to its technology and knowledge intensive nature. On the other hand, the quality of such studies can be largely improved through better inclusion of ground knowledge at different levels, and processes integrating local with RS information need to be enhanced.

On Helmand River Basin water accounting.

The study shows that water consumption due to irrigation (3.3 km^3/year, corresponding to 2.2 km^3 of ET directly due to irrigation, plus 1.1 non-recoverable flow) represents 24% of the exploitable water (13.8 km^3/year) and 35 % of the available water resources (9.5 km^3/year), net of reserved flows, annually generated in the basin. This result is in line with FAO global analysis of water scarcity by river basin which calculates this ratio at 20% for the Helmand Basin (Hoogeveen et al., 2015). Based on the fact that ET due to irrigation on average represents half of irrigation withdrawals, the study derives that agricultural water withdrawals account for about 45% of renewable water resources in this basin which, according to FAO global water scarcity classification (FAO, 2011b), characterizes the Helmand as a severely water scarce basin.

The mapping of rainfall with virtually no real time rainfall measurements on the ground has a serious implication on the assessment of the river flow. We believe that our rainfall is a bit at the higher side in certain parts of the basin, which causes non-utilized outflow that could provide a wrong picture on the basin average surface outflow of 4.9 km^3/year. As mentioned in section 6.2, a different delineation of the basin makes it difficult to directly compare the outflows with those of the Master Plan (HRBMP, 2013), which are estimated at 5.5 km^3/yr for the period 1952-2012, and 1.8 km^3/year for the period 1999-2012, but even considering different delineations, it seems likely that our study overestimates rainfall in certain years.

The study also shows that significant variations of crop water productivity both spatially and by farming systems are found in the basin. This, in the above mentioned settings of severe water scarcity, makes the efficient use of resources –water in this case- a priority issue in the Helmand. A national scale Crop Water Program could be developed using the good practices gathered from the farmers with the highest water productivity scores in every yield zone interval, as illustrated in Figure 19, thus identifying different target farmers in every crop class.

Several options are available for coping with water scarcity by managing water demand and supply at field, irrigation scheme, and basin level (FAO, 2012a). Some options, more directly linked to this study's findings, are below summarized.

Reducing non-beneficial water consumption appears to be relevant both in rainfed and in irrigated agriculture in the Helmand Basin. Rainfed systems have an annual average 75% of soil evaporation on their total ET (Figure 14): management practices aiming at improving infiltration (as in-situ rainwater harvesting), soil moisture retention (through increased soil organic content) and reducing soil evaporation (mulching, agroforestry) could be identified and tailored to local cropping systems. While reducing evaporation from rainfed agriculture would not have a significant impact on the basin water balance because of the limited extent, it could probably support the sustainability of rainfed farming systems. Non-beneficial consumption in irrigated systems accounts for 40% of total irrigation ET, but it could be further reduced by improving irrigation management. Most water resources are utilized in non-productive land. It is recommended to look for options to plant more trees and shrubs that deliver agricultural services. The distance between individual plants can be enlarged for coping with annual rainfall rates of 300 mm or less.

The water productivity analysis shows areas that need improvements in the irrigation scheduling. This could be addressed through modernization of irrigation schemes, and particularly by improving the flexibility of water supply to meet farmers 'needs, but more field verifications are needed for understanding the background (why certain canal command areas and irrigation units have a lower irrigation performance). This study provide spatial maps where irrigation water productivity is standardized by crop yield class, and farmer communities can be detected from the images that are highly efficient with water. The best practices of these farmers need to be copied and transferred to other farmers in the same region. This could vary from soil treatment, sowing date, crop variety, crop water stress, irrigation scheduling to functioning of the sub-surface drainage system and maintenance of structures and canals.

The analysis would also suggest that crops cultivated in *karez* systems tend to have higher water productivity. While these results need to be backed up with more information on those cropping systems and on the amount of water supplied in the growing season, they might support the case for looking further at the use of deficit irrigation, which tends to achieve higher yield per unit of evapotranspiration. Through this strategy, farmers apply less water than that needed to meet full crop water requirements, thereby accepting some yield losses but reaching and economic optimum between water use and crop yields.

Limitations and areas of improvements of this study include:

- No specific analysis of groundwater resources and use was performed: despite it being a concern because of reported decrease of the level of groundwater table and increased abstractions, a thorough assessment of groundwater resources was beyond this study's scope and duration.
- Linkage with HRBMP: tight timing and resources didn't allow for a better integration of this study with the master plan but, on one hand, results of this study could be further improved by comparing and making use of data collected through the master plan and, on the other hand, RS based water accounting could be a valid opportunity for monitoring the implementation of

the master plan through time series collection of selected indicators. A summary table comparing main discrepancies/agreements is provided in Annex G. Although direct comparisons are difficult to make due to different basin delineation adopted, it is clear that the major disagreement is in the extent of irrigated area which, in the Master Plan, is nearly half of the extent assessed in the land cover adopted for this study. As previously mentioned, the comparison would also suggest that rainfall is overestimated in our study, leading to comparatively higher generated runoff and outflow.

- There are quite a few “fixed” parameters in WA+ (harvest index, irrigation efficiency) that in future studies could be made variable. The harvest index is in certain studies made a non-linear function of the biomass production because better seeds are often related to more favorable grain/straw ratio. A fixed or distributed efficiency will not affect the conclusions that return flow is key process in arid basins such as Helmand.

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ANNEXES

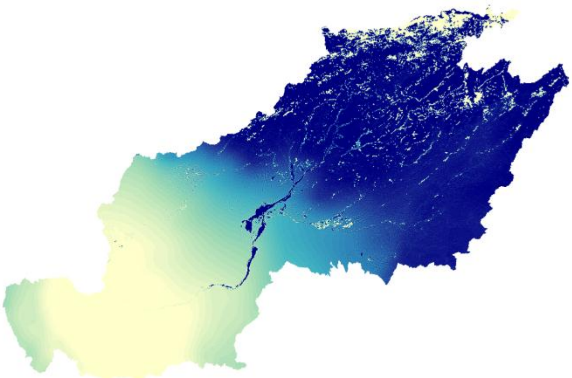
Annex A: Annual precipitation and actual evapotranspiration by water use / land use over the 5 years period 2007-2011

WULULC	Type	P(mm/y)	ET(mm/y)	km²	P-ET
Protected: seasonal water bodies	PLU	495	115	453	380
Protected: permanent water bodies	PLU	429	126	3	303
Protected: seasonal marshes	PLU	516	83	61	433
Protected: permanent marshes	PLU	438	52	4	386
Protected: rangelands	PLU	424	201	41	223
Protected: forest and shrubs	PLU	595	206	5	389
Protected: agriculture (irrigated)	PLU	356	191	18	165
Protected: bare soil	PLU	529	59	125	470
Forest, needle-leaved	ULU	448	387	130	61
Forest, undifferentiated	ULU	232	239	26	-6
Forest, degraded with shrubs	ULU	170	137	3,293	33
Rangelands	ULU	296	248	92,126	47
Bare soil	ULU	157	97	126,253	60
Permanent marshes	ULU	128	136	542	-7
Seasonal marshes	ULU	206	307	1,275	-101
Permanent water bodies	ULU	316	193	2	123
Seasonal water bodies	ULU	127	70	1,915	57
Water courses	ULU	202	283	389	-81
River banks and floodways	ULU	210	143	4,519	67
Snow covered	ULU	319	474	56	-155
Rainfed: flat lying areas	MLU	214	161	2,416	53
Rainfed: mountainous areas	MLU	292	252	1,117	39
Built-up, urban	MLU	243	287	970	-44
Built-up, non-urban	MLU	223	155	105	68
Fruit trees	MWU	293	408	497	-114
Grapes	MWU	269	381	470	-112
Irrigated, double cropping (wheat and rice)	MWU	221	922	470	-701
Irrigated, double cropping (wheat and vegetables)	MWU	240	307	7,006	-67
Irrigated, 1 crop every 2-3 years	MWU	292	195	5,213	96
Irrigated (karez system)	MWU	296	222	2,045	75
Managed permanent water bodies	MWU	288	759	19	-471
Managed seasonal water bodies	MWU	340	449	66	-109

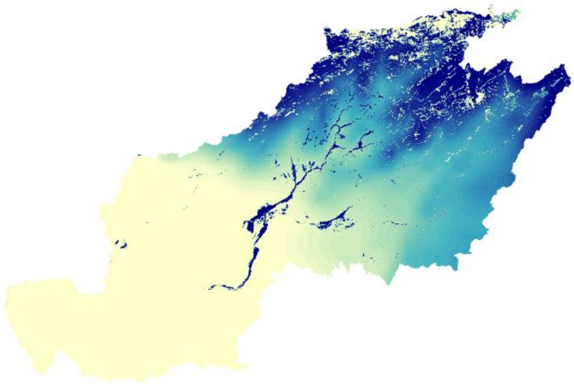
Annex B: Maps of monthly ETa (2007)

January

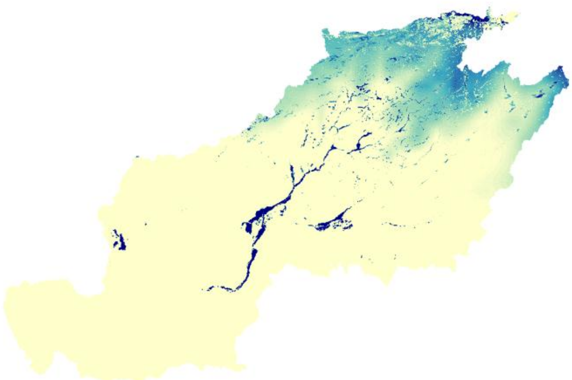
February



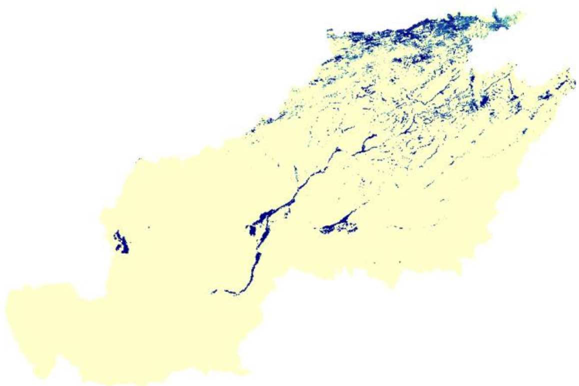
March



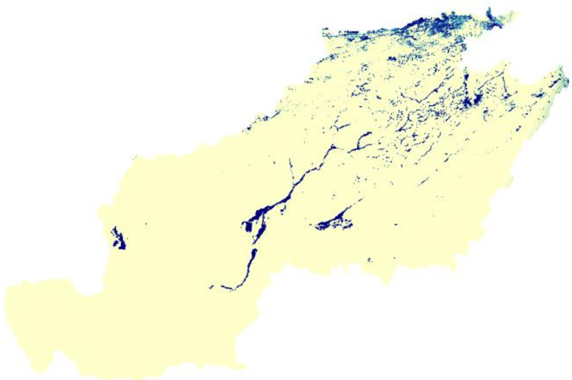
April



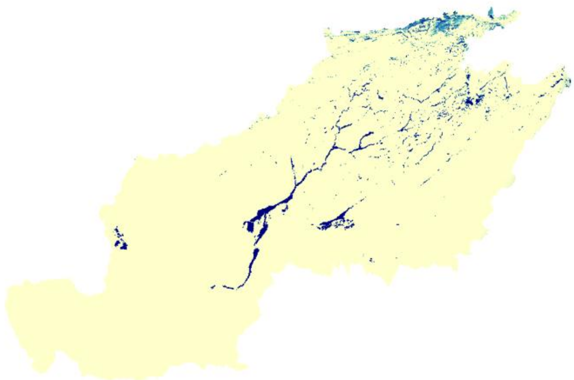
May



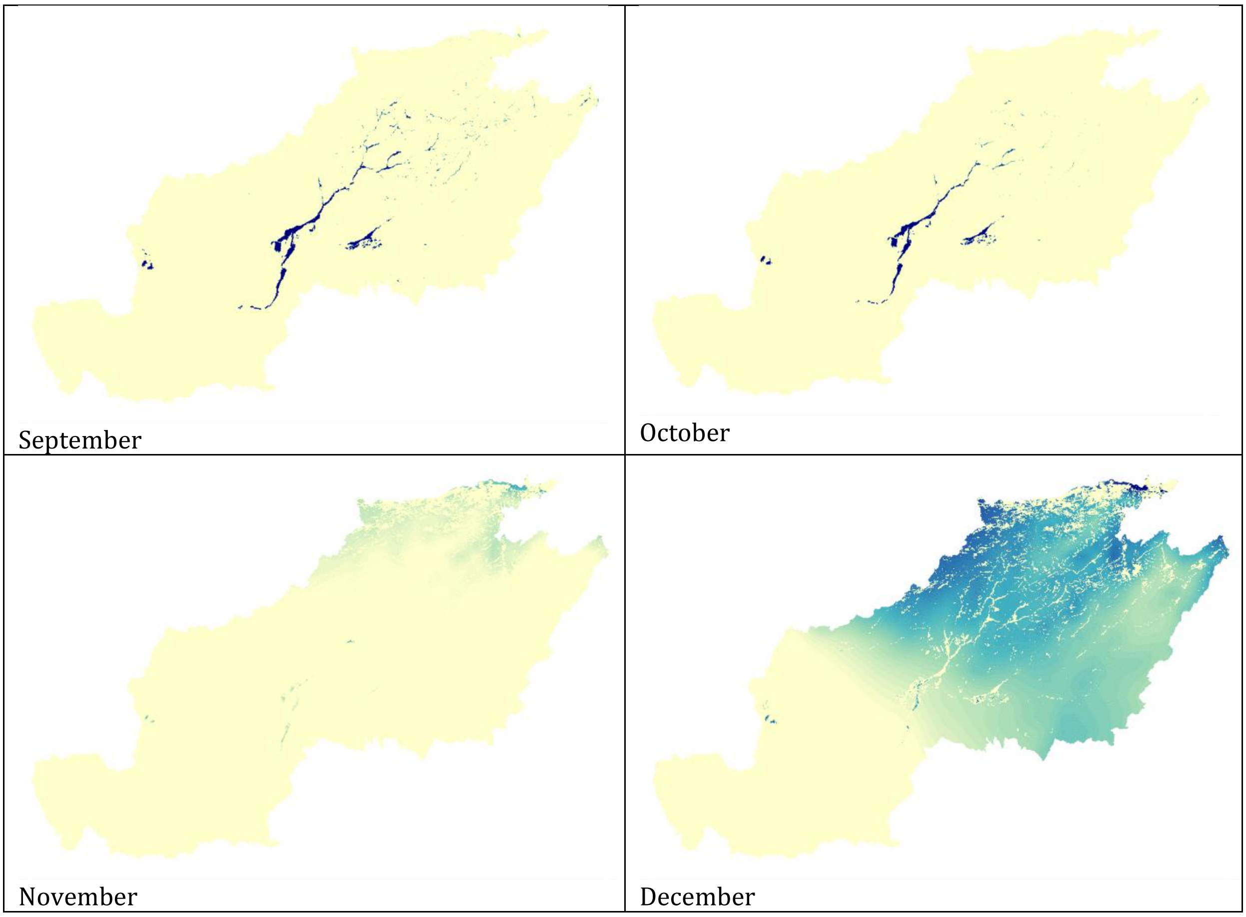
June



July



August


September
October
November
December

Annex C: Annual values of the Resource Base sheet (km^3/year)

Component	2007	2008	2009	2010	2011	5y-avg
Gross inflow	57.9	46.4	59.8	42.8	67.9	55.0
Delta storage	-1.5	-0.2	-2.0	1.00	-4.0	-1.3
Net Inflow	56.4	46.2	57.8	43.8	63.9	53.6
Landscape ET	39.8	39.4	40.37	39.92	39.6	39.8
PLU ET	0.08	0.08	0.08	0.08	0.08	0.1
ULU ET	36.4	36.0	36.91	36.56	36.2	36.4
MLU ET	1.0	0.9	0.99	0.97	1.0	1.0
MWU ET	2.4	2.3	2.39	2.32	2.4	2.3
Exploitable w	16.6	6.8	17.4	3.9	24.2	13.8
Available w	11.6	4.3	12.2	2.1	17.4	9.5
Utilized flow	3.9	3.6	4.2	3.8	3.8	3.9
MWU utilized flow	3.9	3.6	4.2	3.8	3.8	3.9
ULU incremental ET	0.60	0.53	0.60	0.57	0.52	0.6
MWU incremental ET	2.2	2.0	2.3	2.1	2.2	2.2
MWU non-rec. flow	1.2	1.1	1.2	1.1	1.2	1.1
Utilizable outflow	7.7	0.7	8.1	-1.7	13.5	5.7
Non-util. outflow	-	-	-	-	-	-
Reserved outflow	5.0	2.5	5.2	1.8	6.9	4.3
Consumed water	43.7	43.0	44.5	43.8	43.4	43.7
Non-cons water	12.7	3.2	13.3	0.1	20.4	9.9
Depleted	42.6	41.9	43.3	42.6	42.3	42.6
Outflow	13.8	4.3	14.5	1.2	21.6	11
ET external	42.6	41.9	43.3	42.6	42.3	42.5
ET recycled	-	-	-	-	-	-

Annex D: Crop yields reported in FAOSTAT for Afghanistan (kg/ha)

	2007	2008	2009	2010	2011
Wheat	1818	1226	1967	1925	1518
Rice, paddy	3247	3221	3225	3231	3200
Vegetables	9559	9500	9501	9545	8936
Pulses	999	1020	943	743	827
Grapes	6546	6319	6214	6494	8000
Fruit	9033	12000	15000	12000	7000

Annex E: Actual evapotranspiration (ETa) in mm/year

	ETa (mm/year)				
Land and water use class	2007	2008	2009	2010	2011
Protected: seasonal water bodies	115.0	115.0	114.6	114.6	114.8
Protected: permanent water bodies	125.3	125.5	125.5	125.5	126.3
Protected: seasonal marshes	81.3	81.5	83.5	83.5	82.8
Protected: permanent marshes	52.1	52.9	51.2	51.7	51.1
Protected: rangelands	200.0	200.7	201.9	202.3	201.1
Protected: forest and shrubs	205.5	205.7	207.4	204.9	203.9
Protected: agriculture (irrigated)	190.7	190.2	191.4	192.2	190.7
Protected: bare soil	59.1	59.5	59.3	59.2	59.2
Forest, needle-leaved	381.9	381.3	389.7	392.2	388.3
Forest, undifferentiated	237.1	238.3	238.5	239.4	239.7
Forest, degraded with shrubs	136.7	136.3	137.4	136.9	136.6
Rangelands	247.7	244.1	253.1	249.8	245.8
Bare soil	96.8	96.8	97.0	96.6	96.8
Permanent marshes	140.5	130.1	142.4	138.5	126.3
Seasonal marshes	327.0	296.6	322.9	306.6	280.2
Permanent water bodies	191.7	189.3	191.3	199.9	191.5
Seasonal water bodies	70.7	69.5	71.3	71.1	69.8
Water courses	286.9	270.4	292.2	277.8	288.0
River banks and floodways	142.6	141.4	144.7	142.4	143.7
Snow covered	471.7	475.9	472.8	476.0	474.2
Rainfed: flat lying areas	160.8	160.8	161.5	160.8	161.0
Rainfed: mountainous areas	251.4	243.9	260.4	257.0	247.8
Built-up, urban	288.9	277.5	296.6	282.3	289.7
Built-up, non-urban	154.7	154.5	156.2	153.1	154.3
Fruit trees	401.9	386.2	430.4	412.9	407.0
Grapes	375.9	360.9	400.4	381.5	385.3
Irrigated, double cropping (wheat and rice)	954.9	881.3	952.2	877.4	943.0
Irrigated, double cropping (wheat and vegetables)	307.7	294.3	321.7	305.1	307.2
Irrigated, 1 crop every 2-3 years	194.8	193.0	199.7	194.9	194.8
Irrigated (karez system)	217.3	213.7	234.9	223.4	218.6
Managed permanent water bodies	773.4	749.8	778.3	719.1	774.0
Managed seasonal water bodies	456.2	438.0	467.8	427.9	454.4

Annex F: Distribution of land & water use area and ETa in the three basin countries

	Area (km²)			ETa 2007 (10^6m³/year)		
Land & Water Use	**Afghanistan**	**Iran**	**Pakistan**	**Afghanistan**	**Iran**	**Pakistan**
Protected: seasonal water bodies	453	-	-	52	-	-
Protected: permanent water bodies	3	-	-	0	-	-

Protected: seasonal marshes	61	-	-	5	-	-
Protected: permanent marshes	4	-	-	0	-	-
Protected: rangelands	41	-	-	8	-	-
Protected: forest and shrubs	5	-	-	1	-	-
Protected: agriculture (irrigated)	18	-	-	3	-	-
Protected: bare soil	125	-	-	7	-	-
Forest, needle-leaved	130	-	-	50	-	-
Forest, undifferentiated	22	2	2	6	0.1	0.1
Forest, degraded with shrubs	1 355	1 925	13	321	129	1
Rangelands	88 960	12	3 154	22 251	1	571
Bare soil	108 758	8 004	9 491	10 961	472	787
Permanent marshes	139	403	0	52	25	0
Seasonal marshes	1 272	3	0	417	0	0
Permanent water bodies	2	-	-	0	-	-
Seasonal water bodies	1 913	2	0	136	0	0
Water courses	388	2	-	111	0	-
River banks and floodways	4 516	3	1	644	0	0
Snow covered	56	-	-	26	-	-
Rainfed: flat lying areas	1 470	942	5	328	61	1
Rainfed: mountainous areas	1 107	-	10	279	-	2
Built-up, urban	874	95	1	278	6	0
Built-up, non-urban	105	-	-	17	-	-
Fruit trees	497	-	-	199	-	-
Grapes	470	-	-	176	-	-
Irrigated, double cropping (wheat and rice)	470	-	-	447	-	-
Irrigated, double cropping (wheat and vegetables)	6 712	276	17	2 134	12	4
Irrigated, 1 crop every 2-3 years	5 213	0	0	1 019	0	0
Irrigated (karez system)	2 045	-	-	444	-	-
Managed permanent water bodies	19	-	-	14	-	-
Managed seasonal water bodies	66	-	-	30	-	-
Totals	*227 266*	*11 669*	*12 694*	*40 417*	*706*	*1 366*

Annex G: Comparison of selected data between this study and the Helmand River Basin Master Plan (HRBMP).

	this study	HRBMP
Basin area	25 162 900	40 175 900
Irrigated area (ha)	1 019 400	519 018
Irrigation water demand (10^6 m³/year)	4 569	3 805
Generated annual runoff - long term average	13 300	9 517
Generated annual runoff - recent period		5 844
Outflow /"balance remaining" - long term average	9 500	5 486
Outflow /"balance remaining" - recent period		1 813