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India: Water Accounting in Tungabhadra River Basin

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For Asian Development Bank

Asian Development Bank

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Water Accounting in Selected Asian River Basins: Pilot study in Tungabhadra basin (Karnataka, India)

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Executive Summary

1. Karnataka is facing challenges in satisfying the growing water demand. Conflicts arise because of competing water demands: agriculture and drinking water a clear priority but also industry and fishery demand for their fare share. Sustainable water management strategies are fundamental to support a year-round clean and affordable water supply. These strategies needs to be based on reliable water resources data which is often not available. The concept of conducting country water assessments as a means to plan for improved national water security was suggested in the ADB Water Operational Plan 2011-2020. Essential to the concept of the ADB country water assessments is the element of water demand forecasting, per economic sector (agriculture, industry, energy and municipal), vs. the surface water and groundwater resources for each (major) river basin. Note that environmental water demands are usually excluded while natural land also consumes a large amount of water. At the core of the activity now proposed is a complementary "Water Accounting" procedure.

2. Water accounting can provide a coherent and consistent methodology for quantifying hydrological processes and the distribution of water over various competing sectors. It also considers the consumption of water and the benefits and services - including ecosystem services - that result from that consumption, including the return flow of non-consumed water. The Water Accounting Plus system (WA+) is based on open access remote sensing data - in conjunction with open access GIS data and hydrological model output. WA+ communicates information on water storage, flows and fluxes for a variety of land use systems using a number of intuitive resource sheets, tables and maps that are designed to be understood by people with technical and non-technical backgrounds alike. The WA+ framework is developed by IHE-Delft in partnership with the International Water Management Institute, the Food and Agriculture Organization, and the World Water Assessment Program.

3. The main objective of this project was to support the local recipient organizations and ADB activities in Karnataka in defining sustainable water management strategies by: (a) applying the WA+ procedure to estimate, on a monthly scale, available, exploitable, utilized and utilizable water resources for the Tungabhadra. Monthly and yearly accounts are produced, with a spatial resolution of 250 m, for selected historic years for the period 2000-2014, (b) providing inputs into the Country Water Assessment plan should it be undertaken in the future, (c) providing inputs for the Asia Water Development Outlook, and (d) providing training and capacity building on the WA+ system, including but not limited to: basic hydrology, GIS, remote sensing data, WA concepts, interpretation of WA+ results.

4. The conditions of the selected river basin were analyzed in the period 2009-2014 and three historical years were selected for detailed study: 2010 (wet year), 2011 (dry year), and 2014

(average year). In this report, we describe (1) the activity performed (data collection and analysis, training), (2) the major outputs obtained from the piloting of the Water Accounting + framework, and (3) we provide recommendations for water management options and possible water savings. The main observations are:

- The South-West part of the basin receives the most rainfall (up to 4,000 mm/yr).
- The Tungabhadra basin has a monsoonal climate and most of the runoff is generated within a few months per year.
- Actual Evapotranspiration (ET) is high close to the coast (where rainfall is also high) reaching up to 2,000 mm/yr.
- ET is relatively high also along the main river and close and above reservoirs. The average value of ET in the basin in 2010 was 1,250 mm/yr.
- On a yearly scale the water yield (difference between rainfall P and actual evapotranspiration ET) is generally positive. As expected, most of the runoff is generated close to the coastal areas with an excess of more than 2,000 mm/yr.
- In 2010, some areas close to the outlet have negative water yields (up to -200 to -1,000 mm/yr). The additional water consumed in these areas must come from runoff generated in other areas (upstream) of the basin or from groundwater (blue water).
- Large variations of water yield exist among land use groups. In protected areas two to four times more runoff is generated.
- Natural areas have limited spatial extent as the Tungabhadra basin is heavily modified by anthropogenic activities (mainly rainfed agriculture). More than 78% of the basin surface is covered by agriculture and urban areas.
- On a yearly scale the Tugabhadra basin utilizes 50% - 80% of the available water leading to and average of 6.55 km^3/yr of water that flows unutilized downstream. Large fluctuations of utilizable outflow (U_O) exists (the U_O of the dry year is only 27% of the U_O of a wet year).
- During dry months, the utilizable outflow is reduced to nearly 0 km^3/yr even when water is taken from storage. In addition, during these months the basin is not able to meet its environmental flow requirements, and has high rates of non-recoverable flow (polluted water).
- During a dry years, precipitation can decrease of 10 km^2/yr while ET only decreases of 2-3 km^3/yr.
- Both surface and groundwater should be carefully monitored to avoid potential over-expoitation of water resources.

- Solutions for local storage of water should be investigated to carry over water from the wet season for both basins
- Rainfed crops are responsible for most of the water consumed in the basin (71%) while natural protected areas only consume 7% of the total ET.
- Non-beneficial consumption, or water consumed without producing for purposes other than the intended, is around 25-30% of the total ET.
- Most of the beneficial ET generates benefits to the agriculture sector (60% of the beneficial consumption). Benefits for the environment reaches 25% of the beneficial ET.
- Values of agriculture production, and water productivity, are generally low if compared with the world average are in line the India average.
- As expected irrigated areas have higher yield than rainfed systems. Water Productivity ranges from 0.3 to 1.0 kg/m^3, meaning than certain areas within the basin are able to produce three times the amount of yield with the same amount of water.
- Water stress, estimated as the volumetric difference between demand and suppy, was estimated for natural ecosystems. Natural ecosystems in the Tugabhadra basin are under water stress. More surface water should therefore be allocated to natural water bodies, and more groundwater is needed for forests.

5. Please note that this report describes the major results only, all accounting sheets and spatial maps will be made available on our website (www.wateraccounting.org).

1 Introduction

6. Asia is the world's most dynamic region with fastest economic growth. Due to economic and demographic development pressures, water is becoming an increasingly scarce resource. If left unmanaged, this poses a real threat to continued growth and prosperity of the Asia region. The latest analysis by the International Institute for Applied Systems Analysis indicates that 80% of the population in Asia will be water insecure by the year 2050. Global water demand is projected to increase by about 55%, (from 4,500 billion cubic meters in 2010 to 6,350 by 2030) – growing demand from manufacturing, thermal electricity generation and domestic use. The role of wetlands, riparian corridors and shallow water table ecosystems remain undescribed.

7. In the monsoonal climate system of India there are urgent problems with water management due to an excess of water in the wet season, causing flooding and water pollution. In the dry season there is a lack of clean water to meet all agricultural, domestic and industrial needs. Sustainable water management strategies are fundamental to support a year-round clean and affordable water supply.

8. Various national water resources assessments and plans are underway or have been completed recently to reflect to this alarming situation. The quality of these water resources plans depends on adequate input data. This is not self-evident in the water sector because generally the intensity of hydro-meteorological stations is declining, and databases are not shared. A review of investments in water resource measurements in the international community reveals that fewer hydro-meteorological stations are functional, despite the era of modern sensor technology, information technology (IT) and crowd sourcing.

9. Considerable progress has been made in many countries in processing and storing of basic geographic information systems (GIS) data. Yet routine access to this information contained in servers is often restricted to the host organization and the agency that "owns" the data. This limits the benefits that could be obtained by wider use and sharing with other agencies. Information on water resources has to be coherent and synchronized in order to provide an integrated picture useful for the assessment of the problems and possible solutions. The current democracy on hydrological data does not provide the required data necessary to all stakeholders. This hampers the development of good water stewardship. Dissimilar sources of information and terminologies jeopardize the transparency necessary for joint decisions on water, land and ecosystems. Hence, there is a need for independently gathered water resources related data sets that can be commonly understood by all parties.

10. Water Accounting + can meet this requirement. It provides a coherent and consistent methodology that quantifies hydrological processes, water storage, base flow, and the distribution of water to various competing sectors. It also considers the consumption of water and the benefits and services - including ecosystem services - that results from that consumption, including the return flow of non-consumed water and the gap between water demand and water supply. A water accounting system based on open access earth observation satellite

data for complete river basins - including transboundary basins - is therefore proposed: The Water Accounting Plus system (WA+). It goes beyond the classical water budgets, and describes all hydrological and physical water management processes in a river basin.

11. The concept of conducting country water assessments as a means to plan for improved national water security was suggested in the ADB Water Operational Plan 2011-2020. Subsequently, the Asia Water Development Outlook 2013 made a first attempt to quantify national water security, using five key dimensions: (i) household water security, (ii) economic water security, (iii) urban water security, (iv) environmental water security and (v) resilience to water related disasters. In 2013, according to the Asian Water Development Outlook, India was one of the eight country having a National Water Security Index (NWSI) of 1, meaning that the national water situation was hazardous with a large gap between current state and acceptable level of water security. The water security situation in India is improving but at a slow pace. In 2016, the NWSI remains at 1. The Water Accounting + activity and the associated training might support and help improving the overall water conditions in the region.

12. The key water issues in Karnataka are irrigation (expansion), industry, domestic supply and sanitation, groundwater, hydro-power, fishery, droughts and floods and the environment (vulnerable ecosystems). The central issues in water management in Karnataka is securing water for sustainable growth, food security, poverty reduction, and minimizing the impact of natural disasters. The climate change situation will exacerbate this situation.

13. Essential to the concept of the ADB country water assessments is the element of water demand forecasting, per economic sector (agriculture, industry, energy and municipal), vs. the surface water and groundwater resources for each (major) river basin. This report follows an action plan (November 2015), an Inception Report (April 2016), and reflects an approved proposal from IHE-Delft to assist ADB with Water Accounting +. This study was initially intended for Viet Nam only. ADB subsequently requested to include Karnataka in this study. The inception phase report describes the planned steps to implement WA+ in the Tugabhadra river basin. The current report describes the major outcomes of the activity performed.

14. The Officer-in-Charge from ADB-HQ was the Principal Water Resources Specialist Ms. Yasmin Siddiqi. Mr. Lance Gore, ADB Senior Water Resources Specialist, was the point of contact for Karnataka together withDr. P.S. Rao, Director (Technical) of the Advanced Center for Integrated Water Resources Management (ACIWRM), Mr. Madhava, Superintending Engineer and Registrator (ACIWRM, WRD, GOK), and Mr. Clive Lyle, Chief Technical Advisor (ACIWRM). The Principal Investigator from IHE-Delft is Dr. Wim Bastiaanssen. Dr. Elga Salvadore, Water Accounting Expert of IHE-Delft, is responsible for the implementation of WA+ in the selected river basin in Karnataka and for the training and capacity building component with the support of Dr. Claire Michailovsky. Potential recipient organizations in Karnataka are the Water Resources Department (WRD) and ACIWRM.

2 Methodology

15. The Water Accounting Plus (WA+) framework is developed by IHE-Delft in partnership with the International Water Management Institute (IWMI), the Food and Agriculture Organization (FAO), and the World Water Assessment Program (WWAP). It is a multi-institutional effort that aims to provide a valuable and reliable source of information regarding presence and utilization of water resources. The WA+ framework communicates information on water storage, flows and fluxes for a variety of land use systems using a number of intuitive resource sheets that are designed to be understood by people with technical and non-technical backgrounds alike.

16. The WA+ framework focuses on the use of public access remote sensing data in an effort to maintain a high level of transparency. Remote sensing is a reliable and objective source of data. Data products from the National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) are provided free of charge for all users regardless of nationality or intended application. Datasets of precipitation, evapotranspiration, soil moisture, net primary production, land use, water surface areas and water level datasets can be downloaded or determined from the raw satellite data. An overview of open access data that can be downloaded or computed with WA+ tools is given in Tables 1.

17. The Water Accounting + reporting is based on sheets, tables and maps. Maps created from remote sensing, GIS and hydrological models form the basis of distributed computations on flows, fluxes and storage changes. This data is then compiled by Land Use - Land Cover (LULC) class. Class average values form the skeleton for presenting the results in tables. The results are also presented by means of tributaries and rivers; the monthly discharge at any point in the basin with a spatial resolution of 250 m can be computed. This practically means, that every 250 m of a river bed, the actual flow in that river can be estimated. The flow is changing continuously due to runoff, baseflow, withdrawals and return flows, apart from storage changes in lake and reservoirs. Tabular data are summarized by means of sheets, to ease the interpretation and overview of the key processes.

18. Computer software has been developed to read data from various open access data sources and convert the input data into added value hydrological and water management information. All scripts are programmed in Python language that is freeware and highly suitable for processing of spatial data sets. Supporting scripts are made for converting the information into the standard WA+ fact sheets. More background information can be found at www.wateraccounting.org. The software to perform computation and produce the accounting sheets is available free and open source on GitHub: https://github.com/wateraccounting.

Table 1: Input data consulted for WA+

RS data directly downloadable	More modelling needed indirectly available	GIS data	Hydrological data
Land Use Land Cover (LULC) - GlobCover	Actual Transpiration (T)	Protected Areas (A)	Ratio Fast/Slow Runoff
Precipitation (P) - CHIRPS, TRMM	Actual Soil Evaporation (E)	Bathymetry	Surface Runoff
Actual Evapotranspiration (ET) - ETEns	ET green water consumption (ET_green)	Weather data (meteo)	Baseflow
Soil Moisture (SM) - ASCAT	ET blue water consumption (ET_blue)	Terrain elevation (DEM)	Storage changes
Surface temperature (LST) - MODIS	Water withdrawals (Q)	Soil Physical data	Outflow from basins
Surface albedo (alpha) - MODIS	Beneficial/non-beneficial water consumption	Population density	Ratio SW/GW withdrawals
Water levels (l) - Jason	Reference Evapotranspiration (ET0)	Livestock density	Lateral GW flow
Change in gravity (delta S) - GRACE	Interception (I)	Grey Water consumption	Groundwater Recharge
Snow cover (cl) - MSG	Soil erosion (Ero)	Environmental flow requirements	
Cloud cover (sn) - MODIS	Dry matter production (Bio)	Depth of root zone	
Leaf Area Index (LAI) - MODIS	Crop Yield (Y)		
Vegetation Cover (Vc) - MODIS	Crop Yield due to rainfall (Y_P)		
Net Primary Production (NPP) - MODIS	Crop Yield due to irrigation (Y_IRR)		
Total Dissolved Solids	Crop water productivity (WP)		
Chlorophyll	Water Productivity due to rainfall (WP_P)		
Water body area	Water Productivity due to irrigation (WP_IRR)		
	Carbon sequestration (C)		
	Lifestock feed production (LiveS)		
	Fuelwood production (Fuel)		

3 Project Objectives

19. The main objective of this project was to support the Karnataka Water Resources Department, ACIWRM and ADB India in the development/update of the future National Water Resources Development Plan of Karnataka by:

a. applying the WA+ procedure to estimate, on a monthly scale, available and exploitable water resources for the selected river basin in Karnataka. Monthly and yearly accounts are produced for selected historic years for the period 2009-2014 (2010, 2011, and 2014),

b. input into the future Country Water Assessment plan and complement the National Water Status Report 2014 by providing additional recommendations based on water security diagnosis,

c. providing inputs for the Asia Water Development Outlook, and

d. training and capacity building on the WA+ system, including but not limited to: basic hydrology, GIS, remote sensing data, WA concepts, interpretation of WA+ results.

20. As part of this project several training session were provided. However because of the limited time, we believe additional support is needed to ensure that recipient organizations will be able to autonomously preform a full water accounting analysis for other river basins in Karnataka. Software and tools used are opens source and are transferred to the main recipient organizations at the end of the project.

21. The WA+ project for Karnataka had a total duration of 2.5 years. The number of working days from IHE-Delft staff, allocated for this project, was 80, which also includes 20 days for training and capacity building. A very steep learning process had to be introduced for transferring basic skills related to accounting procedure to Indian entities. Such period is insufficient for solving all water resources related questions, but can be regarded as a first step to show the latest technologies and get hands on experiences that can facilitate to the preparation of the National Water Resources Plan.

22. The work started in May 2016 and ended in May 2018. In this project we applied the Water Accounting + procedure to the Tugabhadra river basin in Karnataka (Figure 1) on a monthly scale with a spatial resolution of 250 m. The Work Plan and Milestones were described in the Inception phase report; below we summarize the Key Deliverables.

23. In addition to the agreed deliverables, during the course of this project additional requests were made: Sheet 7: ecosystem services analysis. The current project serves as a pilot for the new Water Accounting + methodology, therefore part of the work plan also takes into account a development and testing phase.

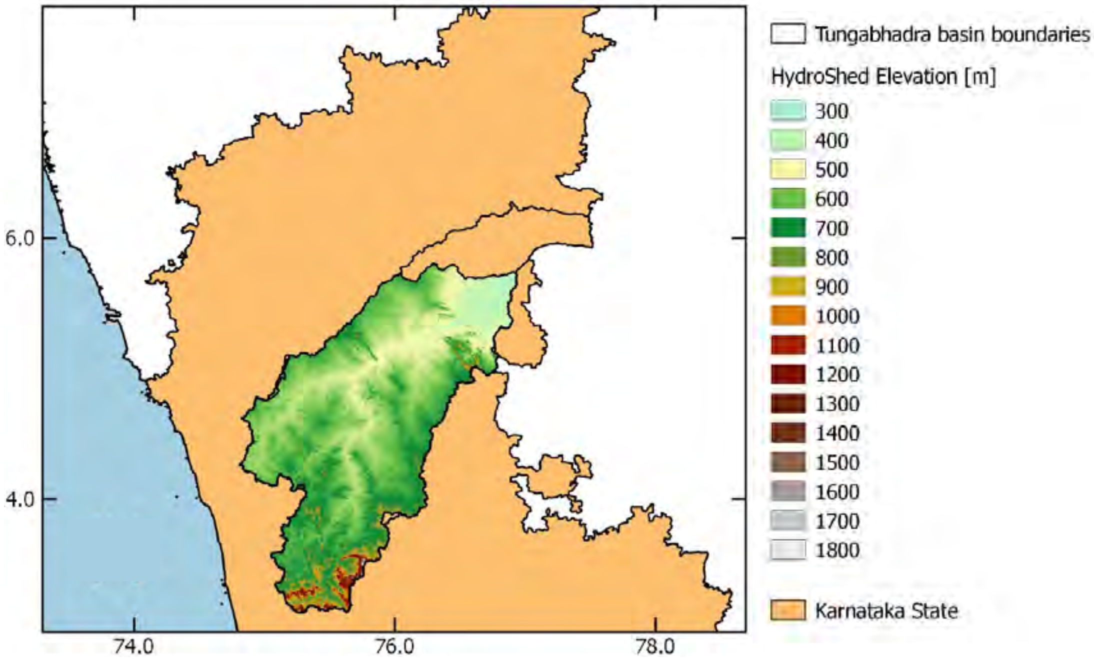


Figure 1: WA+ was implemented in the Tugabhadra river basin in Karnataka, India.

3.1 Key Deliverables

- Standardized WA+ sheets 1-6, tables and maps uploaded on the www.wateraccounting.org data repository with open access, for three selected years in the period 2000-2014 (wet, dry and average year) with a monthly time-scale, for the Tungabhadra river basin in Karnataka.
- In a second stage, it has been agreed to also generate sheet 7 (Ecosystem services) as part of the WA+ analysis of Karnataka basin
- Water Security Diagnosis (i.e. interpretation of the produced sheets)
- Review report of national and international experts
- Input into Country Water Assessment should it be undertaken in the future
- Input into Asian Water Development Outlook
- Training and capacity building in the WA+ system
- Scripts and tools transferred to the main recipient organizations
- Inception and final reports.

4 Training and Workshops

24. The following training schedule was devised after consultations with the ADB project leader and the local contact point in the Ministry of Water Resources:

- Inception mission (Bangalore): 18-23 May 2016
  - Introduction to WA+;
  - Discussion action plan
- Inception WA+ workshop for government officials (Bangalore): 23 January 2017 (80+ participants)
  - Introduction to WA+ framework;
  - Progress report on WA+ activity
- First training session (Bangalore): 24-28 January 2017
  - Training for technical staff (35 participants). Topics: WA+ fact sheets, Fundamentals of Water Accounting, how to download RS data and use the WA+ Python tools, Water consumption (E, T, I), beneficial and non-beneficial consumption, theory of green and blue water, fact sheets 1 and 2.
- Second Training session (Bangalore): 9-12 July 2018
  - Training for technical staff (40 participants). Topics: refresher WA+ basic concepts, WA+ results interpretation, Remote Sensing, RS evapotranspiration, computation of WA+ sheets for the Tungabhadra basin, RS crop yield estimation, water productivity and sheet 3.

5 Input Data and Data Validation

25. The WA+ procedure is strongly based on the use of Remote Sensing and open-access datasets. It is however important to validate (and possibly improve or correct) these data with locally obtained data for ensuring reliable results.

5.1 Land Use Land Cover Map

26. Of particular importance is to obtain or produce a high-resolution, reliable and thematically-detailed land use land cover map of the Tugabhadra basin in Karnataka. An initial land use map was provided by ACIWRM (Figure 2).

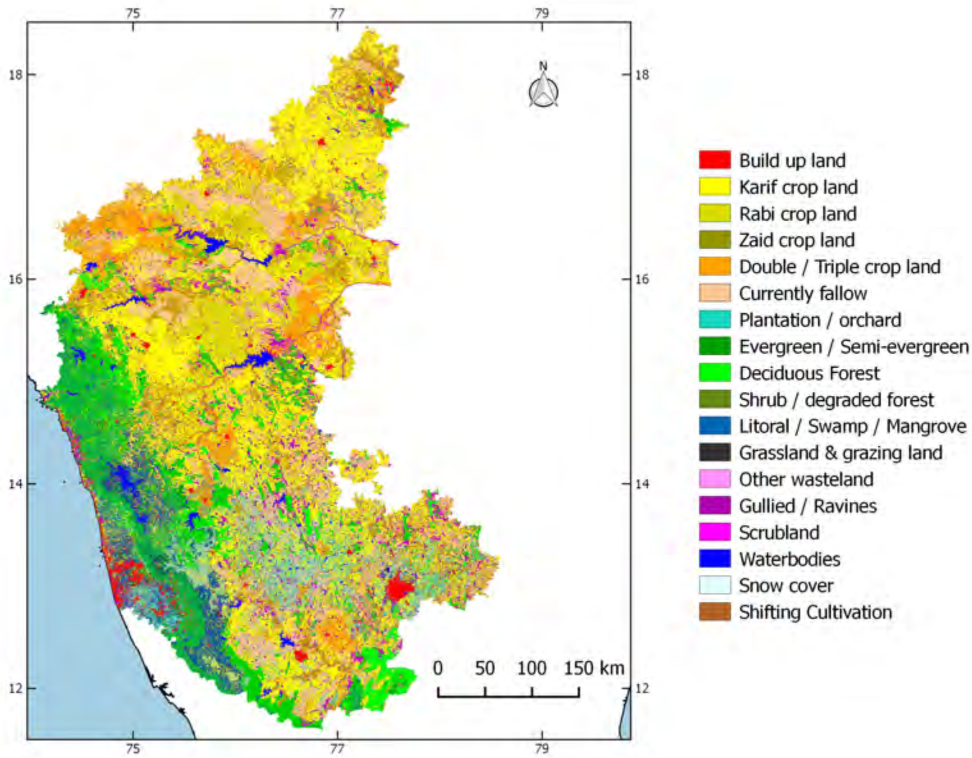


Figure 2: Land Use Land Cover map of Karnataka for the year 2006 provided by ACIWRM for the Water Accounting study.

27. To produce the final Land Use Land Cover (LULC) map according to the standard Water Accounting + classification (80 classes), we combine the information from the previous map with other open access data. The reader can find the list of datasets used and the description of the procedure in the Inception report. The final result was used to compute the Water Accounting + sheets for the Tungabhadra basin (Figure 3).

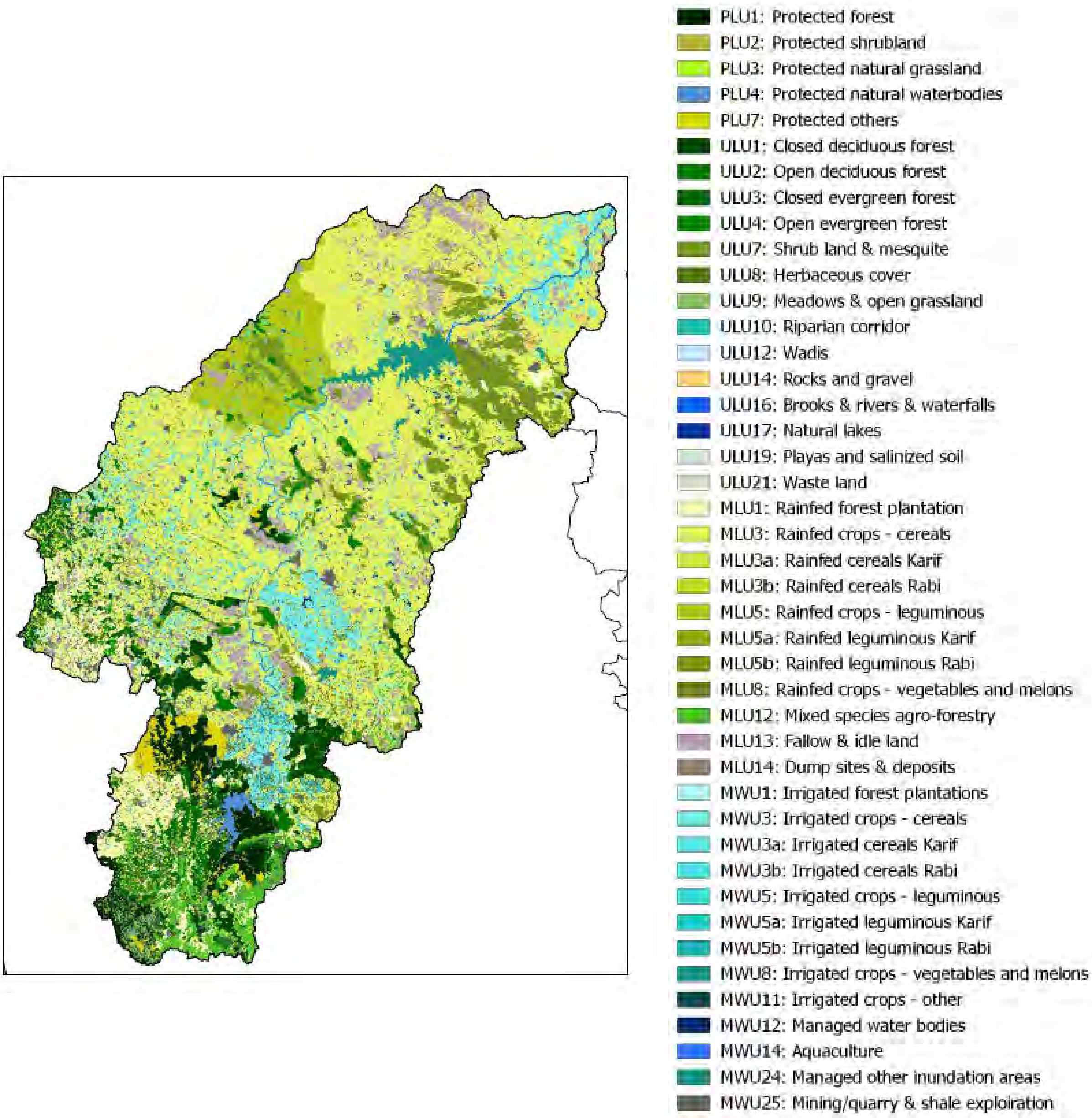


Figure 3: Final Land Use Land cover map, produced for this study according to the WA+ standard classification scheme.

28. Detailed crop maps covering the entire basins were not available and field survey, necessary for producing a new crop map of the area, was not part of the activities. Crop classification was performed by using open access data and statistics per districts. We have considered only two types of crop in this study (separated into irrigated and rainfed): rice

(cereals) and leguminous.

29. The Water Accounting + system takes into account both land and water management. For this reason, the land use land cover classes (80) are grouped into four major categories:

- *Protected Land Use*: Environmentally sensitive land uses and natural ecosystem that cannot be modified due to protective measures;
- *Utilized Land Use*: Represents land use classes with a low to moderate utilization of natural resources, such as savannah, woodland and mixed pastures;
- *Modified Land Use*: Represents land use elements where vegetation is replaced with the intention to increase the utilization of land resources. Examples are plantation forests, pastures and rainfed crops, among others;
- *Managed Water Use*: Represents land use elements with anthropogenic regulation of withdrawals and water supplies. It includes water withdrawals for irrigation, aquaculture, domestic use and industries, among others

30. An overview of these categories for the Tugabhadra basin is presented in Figure 4. A summary of the different land cover types and respective areas is displayed in Table 2.

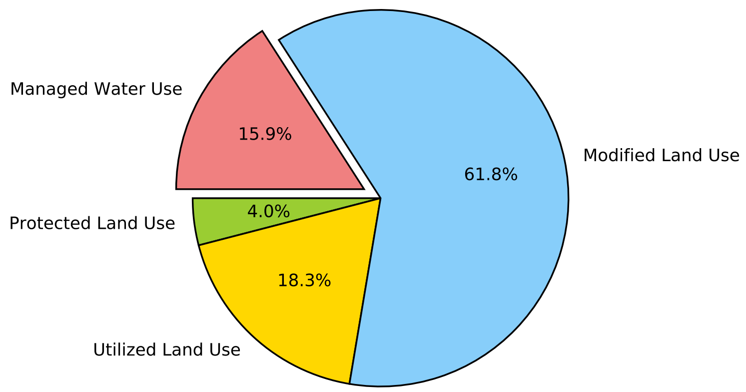


Figure 4: Distribution of the four major WA+ land use land cover category in the Tugabhadra basin in Karnataka.

Table 2: Distribution of land use land cover types in the Tungabhadra basin.

LULC	type	Area [km2]
PLU1	Protected forest	983.8
PLU2	Protected shrubland	40.1
PLU3	Protected natural grassland	0.3
PLU2	Protected natural water bodies	131.4
PLU3	Protected other	426.2
ULU1	Closed deciduous forest	1,266.0
ULU2	Open deciduous forest	689.5
ULU3	Closed evergreen forest	663.2
ULU4	Open evergreen forest	179.8
ULU7	Shrubland & mesquite	2,759.0
ULU8	Herbaceous cover	0.2
ULU9	Meadows & open grass	153.9
ULU10	Riparian corridor	1.3
ULU12	Wadis	74.9
ULU14	Rocks & gravel & stones & boulders	211.7
ULU16	Brooks & rivers & waterfalls	238.9
ULU17	Natural lakes	271.5
ULU19	Saline sinks & playas & salinized soil	165.4
ULU21	Waste land	18.47
MLU1	Rainfed forest plantation	1,311.4
MLU3	Rainfed crops - cereals	14,360.4
MLU5	Rainfed crops - leguminous	1,453.5
MLU8	Rainfed crops - vegetables and melons	517.2
MLU12	Mixed species agro-forestry	748.2
MLU13	Fallow & idle land	2,015.2
MLU14	Dump sites & deposits	9.6
MWU1	Irrigated forest plantation	77.9
MWU3	Irrigated crops - cereals	2,878.0
MWU5	Irrigated crops - leguminous	90.7
MWU8	Irrigated crops - vegetables and melons	151.8
MWU11	Irrigated crops - other	9.6
MWU12	Managed water bodies	39.4
MWU14	Aquaculture	0.5
MWU24	Managed other inundation areas	484.2
MWU25	Mining/quarry & shale exploration	1,219.7

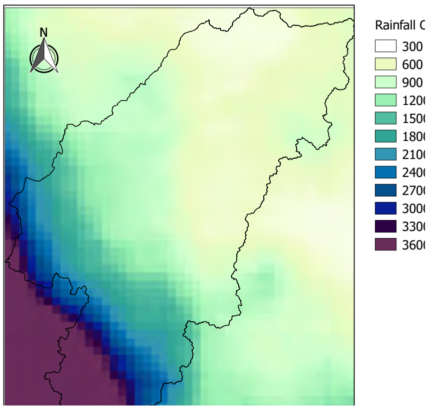
5.2 Elevation

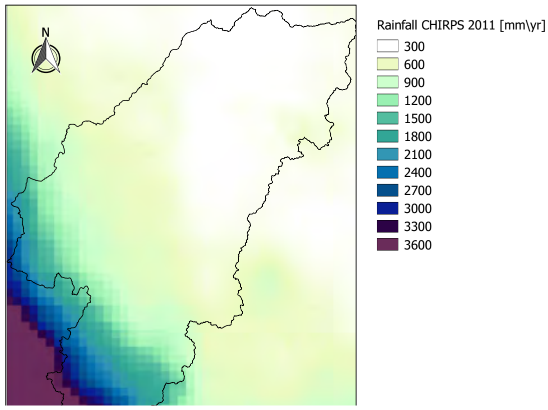
31. The elevation of the Tungabhadra basin ranges from about 1800 m in the South to 300 m in the North area downstream, and the average elevation is around 600 m (Figure 1).

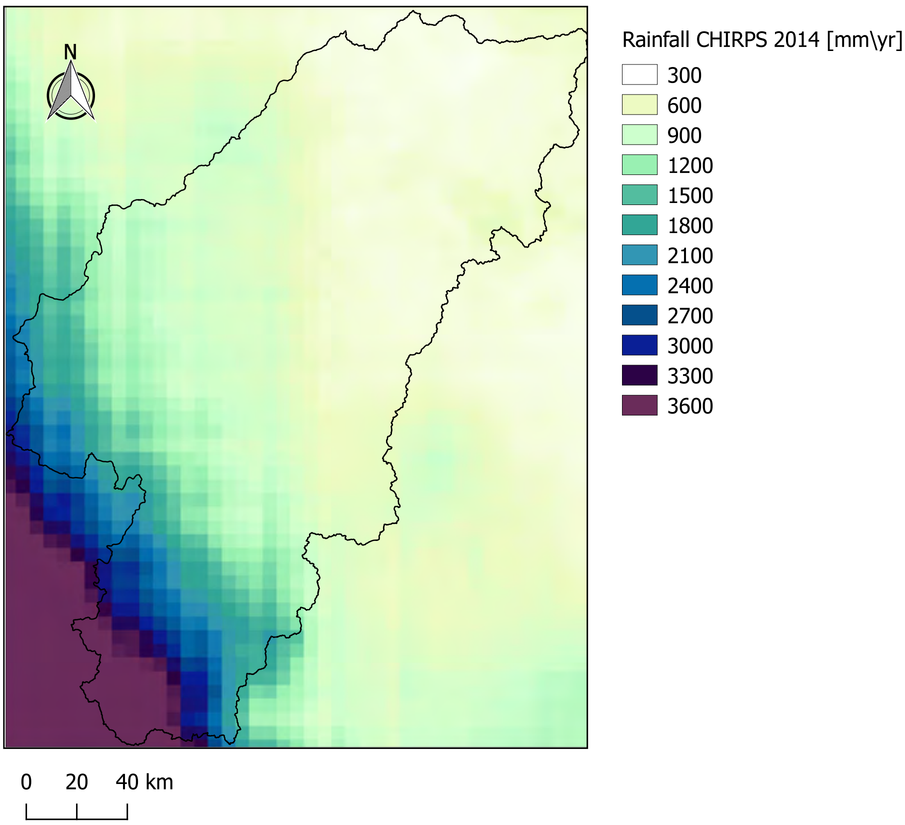
5.3 Rainfall Data

32. We collected monthly RS precipitation for the entire Karnataka for the period 2000-2015. In the Inception report we presented the comparison of two remote sensing products, TRMM and CHIRPS, and we selected CHIRPS for the subsequent analysis. We also selected three recent years for the creation of Accounting sheets: 2010 (wet rain: 1,409 mm/yr), 2011 (average rain: 881 mm/yr), and 2014 (average rain: 1,094 mm/yr) . Spatially distributed maps for the selected years are displayed in Figure 5. Most of the rainfall falls in the mountainous areas in the South-West part of the basin with peaks of 4,500 mm/yr during 2010 (wet year) and 4,000 mm/yr in the other years. The downstream part of the basin receives the least rainfall, as low as 250 mm/yr for all analysed years. Rainfall has a strong temporal dynamics due to the monsoon climate. The Tungabhadra basin has two main seasons: wet season (approximately June - October) and dry season (approximately November - May).

33. The ACIWRM has provided rainfall records from 221 rain gauge stations. Results of the comparison between RS-based rainfall and ground measurements are presented in the inception report. Water Accounting sheets, presented in this report, are computed using CHIRPS data. No correction was made using rain gauge measurements as no clear bias was noted.







(c) Rainfall distribution during the average year in the Tungabhadra basin

Figure 5: Spatially distributed Remote Sensing yearly rainfall data for the selected years (CHIRPS).

5.4 Other Open Access (Remote Sensing) Data

Actual Evapotranspiration

34. Several Actual Evapotranspiration remote sensing products exist. Most of the RS products presents similar spatial variability but a wide range of absolute values. To increase the reliability of actual ET estimates, we have developed monthly maps Actual Evapotranspiration (250 m resolution) for entire Karnataka for the period 2003-2012. This Actual ET dataset is the ensemble of seven global RS-based surface energy balance models (ETMonitor, GLEAM, CMRS-ET, SSEBop, ALEXI, SEBS, and MOD16). As an example in Figure 6, we show the yearly total Actual ET for Karnataka in 2010. The highest values, around 2000 mm/yr, are localized close to the coast, where precipitation is also the highest. Relatively high values are also visible along the river and reservoirs. The average Actual ET for the Tungabhadra basin for the year 2010 was around 1250 mm/yr.

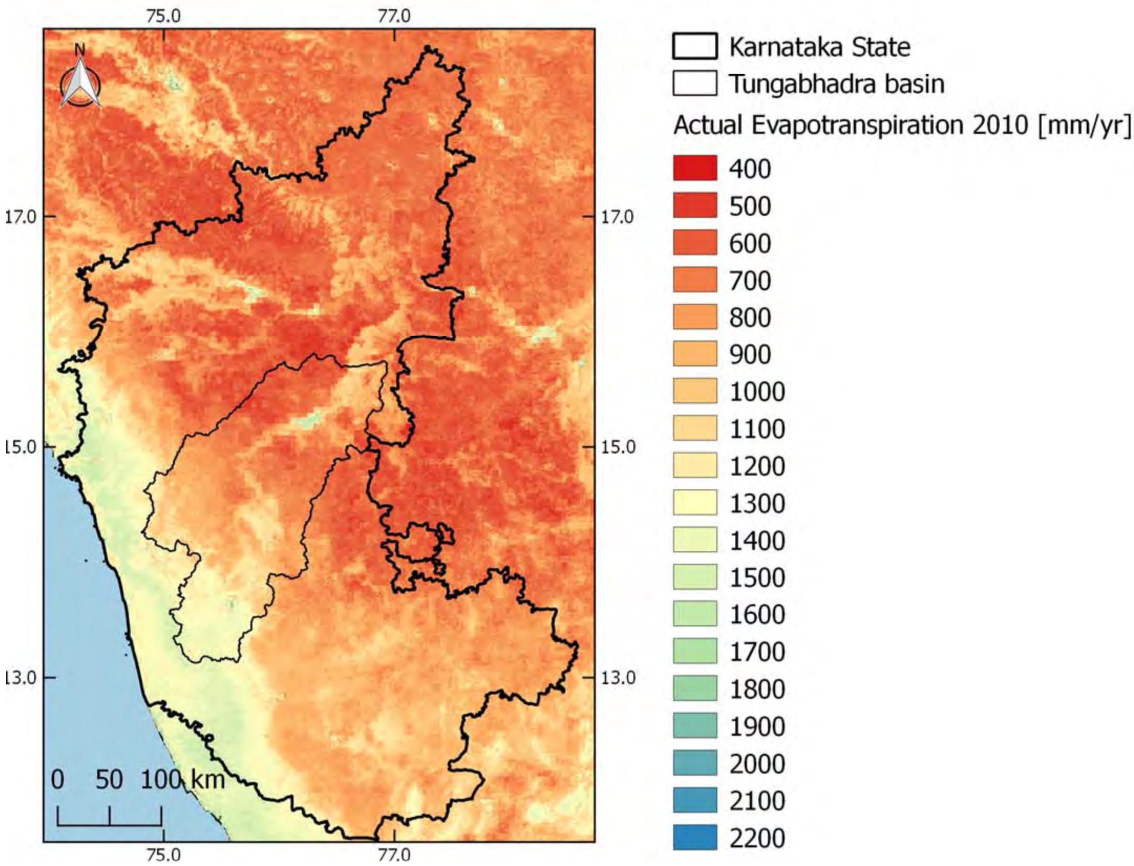


Figure 6: Total yearly Actual Evapotranspiration data for the wet year 2010 (Ensemble ET developed by IHE-Delft on bases of seven different RS-based ET products).

35. We compared Actual ET with RS-based rainfall data and created maps of Water Yield, both monthly and yearly, by subtracting ET from P. This simple calculation provides relevant information on water consumption, water scarcity and water excess.

36. As expected, most of the runoff is generated at the coast where rainfall is the highest. The excess of more than 2,000 mm/yr forms a substantial contribution to the available and utilizable water in the Tungabhadra and surrounding basins. In 2010 negative water yield values are found in the central part of the basin and at the outlet, which means that, on a yearly scale, ET is higher than P. The water evaporating from those regions must therefore have a different source, i.e. groundwater or surface water (blue water). This behaviour is typical of irrigated crops, water bodies, and downstream parts of catchments where floods occur.

37. In Table 3, we provide a summary of Precipitation (P), Actual Evapotranspiration (ET) and Water Yield (P-ET) with a break down to the four water management land use categories. As expected the Water Yield is generally highest during the wet year and lowest during the dry year where for certain land use types it becomes negative. Large variations exists between land use types. In natural areas (protected and non-protected) double to four times higher runoff is generated. This is due to the combined effect of the land use types and their geographical location. Forested areas are localized mainly upstream in mountainous areas where rainfall is the highest. Modified Land Use and Managed Water Use categories have the lowest water yield and are net consumers of water during the dry year.

Table 3: Yearly average Precipitation (P), Actual Evapotranspiration (ET), and Water Yield (P-ET) for the two analyzed basins. Units are expressed in [mm/yr]. Land Use Land Cover (LULC) groups analyzed are: PLU = Protected Land Use, ULU = Utilized Land Use, MLU = Modified Land Use, and MWU = Managed Water Use.

Kali Sindh	2010 -wet-			2011 -dry-			2014 -average-		
LULC	P	ET	P-ET	P	ET	P-ET	P	ET	P-ET
PLU	3077	1262	1820	2057	1247	814	2362	1196	1178
ULU	1668	955	714	1072	896	177	1291	909	383
MLU	1225	848	378	756	766	-10	965	785	181
MWU	1297	964	360	770	904	-121	965	873	111

Other (RS) data collected and processed

38. We have collected two Remote Sensing based vegetation index: LAI (2000-2015) from MOD15, NDVI (2001-2015) from MOD13 ($https://modis.gsfc.nasa.gov/data/dataprod/$) being standard MODIS products available for free usage. We have derived monthly 250 m resolution Net Primary Productivity (NPP) based on yearly NPP (MOD17), monthly Gross Primary Productivity (MOD17) and on the spatial resolution of NDVI. These monthly NPP are used to separate ET into evaporation (E) and transpiration (T). We have computed also spatially distributed reference ET based on FAO56 and climatic data from the global GLDAS model for the period 2000-2015 for the purpose of estimating ET that is related to rainfall ("ETgreen") and other water sources ("ETblue"). Statistical data on livestock and fish production were collected from FAOSTAT ($http://www.fao.org/faostat/en/$).

Global Hydrological simulation results

39. For certain accounting sheets we make use of the results of the global hydrological model PCR-GLOBWB (spatially distributed 10 km resolution, daily, developed by the University of Utrecht). For every grid cell of 10 km X 10 km, the water balance is simulated as described in Figure 7. Results of PCR-GLOBWB are used for estimating the fast-slow runoff ratio. River flow is computed directly by the Remote Sensing vertical water balance tool or WA+ (Water-Pix).

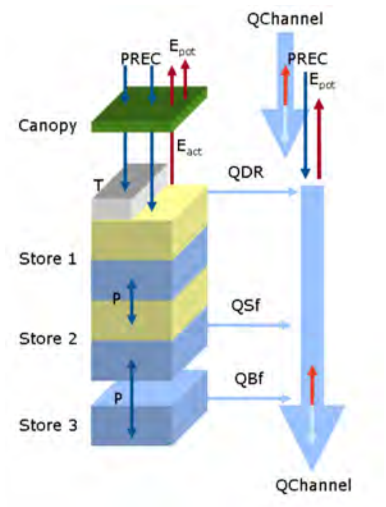


Figure 7: Schematic representation of the water balance computed by the global scale model PCR-GLOBWB.

40. As part of the development of automated tools for Water Accounting Plus computations, we have implemented a new water balance software which calculates, at a monthly time step, the major water balance components at pixel level (Water-Pix). Water-Pix inputs are fully based on Remote Sensing measurements. Surface water results of the Water-Pix tool are then used to calculate the river flow every 250 m using a newly developed tool specifically designed

for Water Accounting computations (Surf-Wat). Both tools are in testing phase and available on our GitHub repository: GitHub: https://github.com/wateraccounting. ACIWRM has kindly provided data for ten stations within the Tungabhadra basin (Figure 8). We used this data to validate the results of an uncalibrated Water-Pix Surf-Wat model. It is remarkable that the uncalibrated results of Water-Pix and Surf-Wat, in some locations in the Tugabhadra basin, seem to match well with ground measurement, peaks are however overestimated by the model in some locations downstream (Figure 9, Figure 10, and Figure 11). These river flow simulations, together with PCRGLOB-WB, are used to compute Fact Sheets 1 (Resource Base) and 5 (Surface Water).

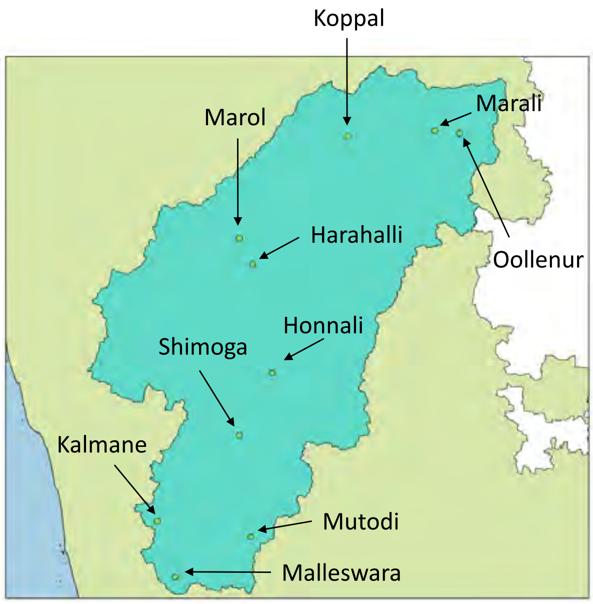


Figure 8: Location of river flow measurements stations provided by ACIWRM for the WA+ study of the Tungabhadra basin.

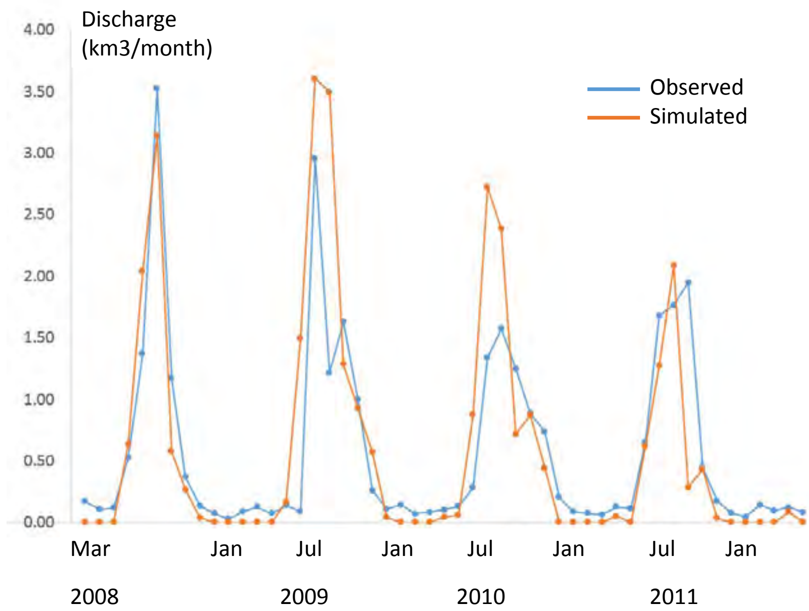


Figure 9: Comparison of WaterPix-SurfWat simulated flow with river flow measurements at the Honnalui river flow station (Nash-Sutcliffe efficiency = 0.50).

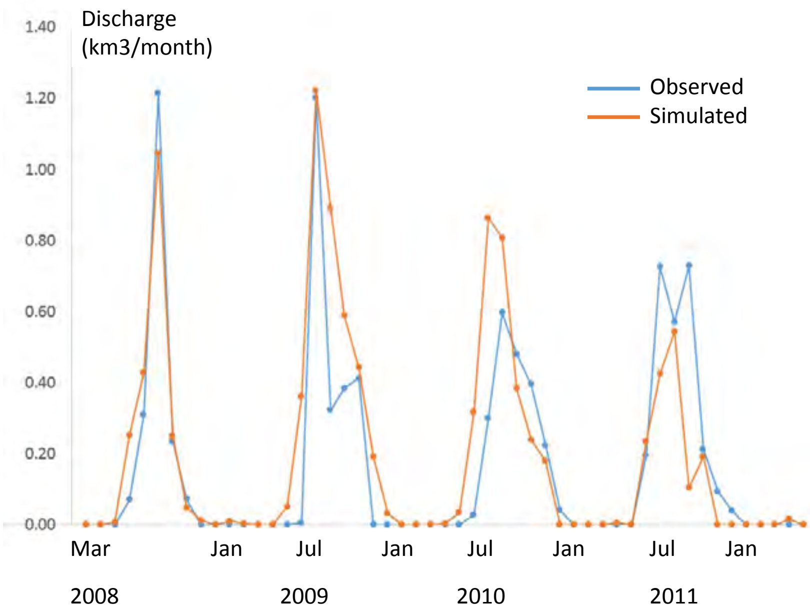


Figure 10: Comparison of WaterPix-SurfWat simulated flow with river flow measurements at the Marol river flow station (Nash-Sutcliffe efficiency = 0.63).

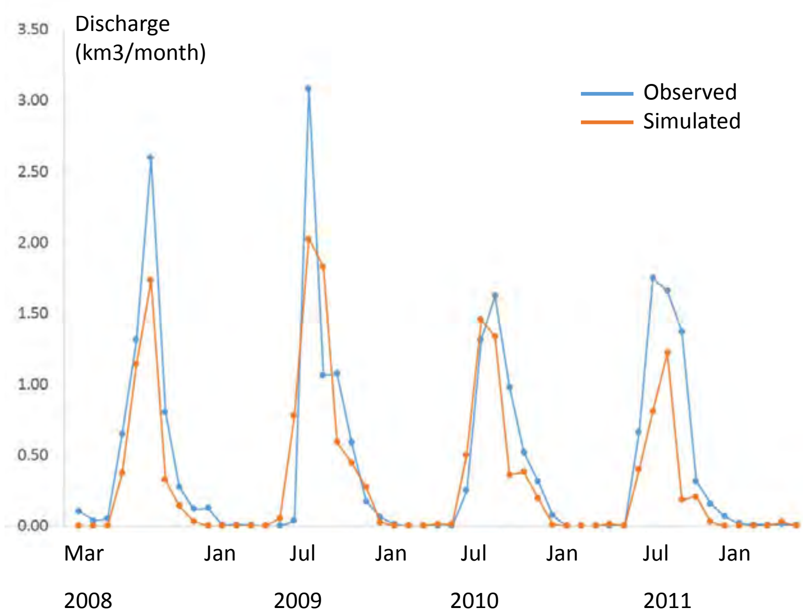


Figure 11: Comparison of WaterPix-SurfWat simulated flow with river flow measurements at the Shimoga river flow station (Nash-Sutcliffe efficiency = 0.73).

6 Water Accounts for the Tungabhadra basin in Karnataka, India

41. In this section, we will describe the major results of the Water Accounts for the Tugabhadra basin in Karnataka, which include accounting sheets and spatial maps. All the monthly and yearly Accounting sheets for the selected years are available for download from the Water Accounting + website: $http://wateraccounting.org/projects.html$.

42. The analysed river basin is heavily modified by human activity, mainly rainfed agriculture (Table 4). Natural areas (PLU: Protected Land Uses and ULU: Utilized Land Uses) only account for 24.6% of the total area of the basin.

Table 4: Partitioning of land use categories for Tugabhadra basin in Karnataka. PLU = Protected Land Use, ULU = Utilized Land Use, MLU = Modified Land Use, and MWU = managed Water Use

PLU [%]	ULU [%]	MLU [%]	MWU [%]
4.7	19.9	60.7	14.7

6.1 Sheet 1: Resource Base

43. Sheet 1 or Resource Base Sheet gives a general overview on over-exploitation, unmanageable, manageable, exploitable, reserved, utilized and utilizable flows at river basin scale. In this sheet we can discern between landscape ET (by rainfall) and incremental ET (by natural and man-made withdrawals). It can also be used to assessing commitments to environment and legal agreements and to understand water scarcity during dry years.

44. An example of Sheet 1 is presented in Figure 12 and Figure 13 for the years 2010 and 2011 respectively. The utilizable outflow during the dry year (2011) is roughly 25% of the utilizable outflow of the wet year (2010) going from 7.0 km^3/yr to only 2.8 km^3/yr. The reserved outflow (minimum environmental flow) is set at 1.6 km^3/yr. During the dry year, the basin consumes 27.4 km^3/yr as ET and 2.1 km^3/yr as non-recoverable flow (polluted water). At this rate of consumption there is no sufficient water to fulfil the minimum flow requirement (only 1.2 km^3/yr) even if the water storage (surface and groundwater) is depleted by 4.4 km^3/yr (Figure 13).

45. The utilizable outflow during the wet year (7.0 km^3/yr) is a small fraction of the net inflow (42.6 km^3/yr) but a considerable volume that flows unutilized downstream which, if stored, could be utilized during drought years. Non-recoverable flow (or polluted water) is computed using global maps of graywater footprint. Values of non-recoverable flows are high in the Tungabhadra basin and reach 6.3 km^3/yr in 2009. The rate of moisture recycling (ET recycled and P recycled on top of Figure 12) is low but non-negligible (0.6 km^3/yr). Low

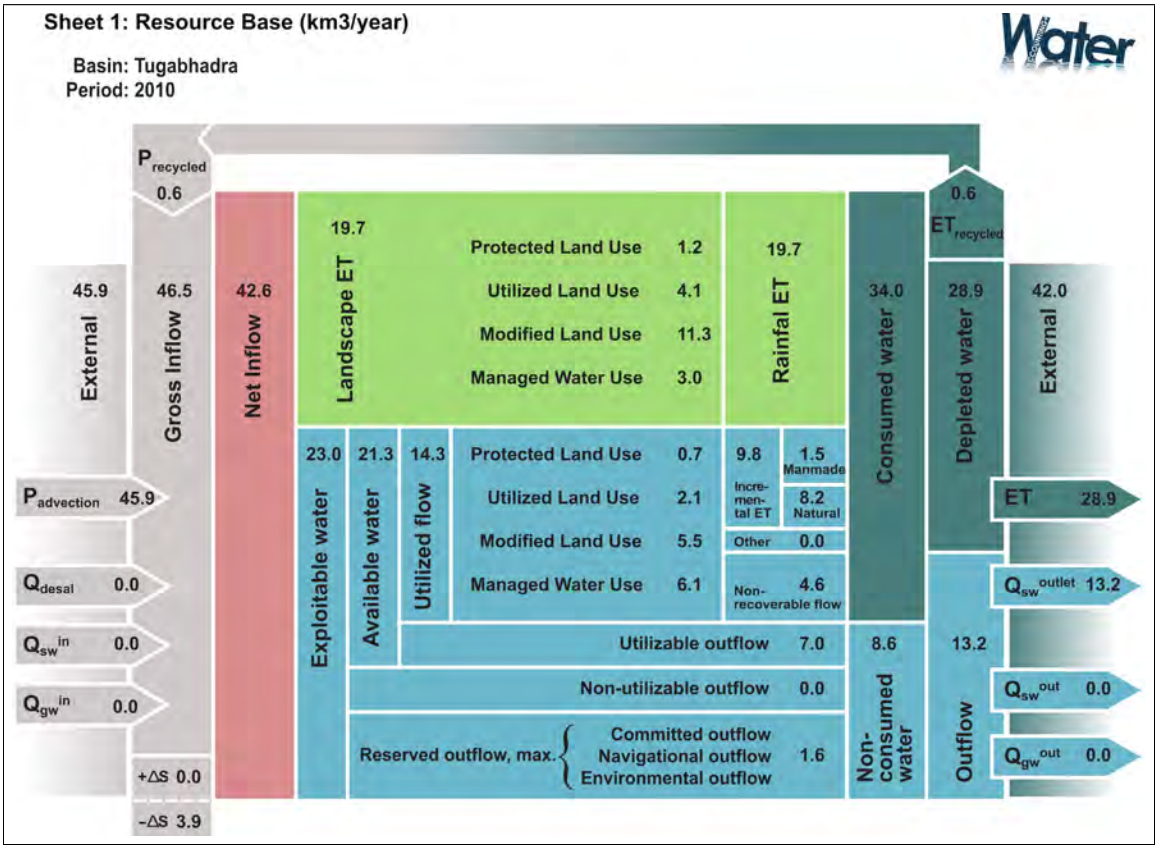


Figure 12: Resource Base sheet for the Tungabhadra basin during the year 2010.

values of ET recycled are however normal for river basins of the size of the Tungabhadra basin. ET green (or Landscape ET) is more than double than ET blue (or incremental ET) and most of the blue water consumption happen in areas modified by anthropogenic activities (Mandmade ET is at least 70% of the total blue ET).

46. During the wet year, groundwater and reservoirs are filled (3.9 km^3/yr in Figure 12), while during the dry year water is taken from storage (4.4 km^3/yr in Figure 13). Storage change needs to be monitored to assess if this is a systematic situation that can lead to overexploitation of surface and groundwater resources or if it is a natural fluctuation. Yearly analysis does not provide sufficient information, additional insights can be derived from the monthly analysis of water resources conditions, specifically in dry months. Figure 14 presents an example of such monthly information for the Tungabhadra basin in December 2011. During this month both utilizable and reserved outflow are 0 km^3/yr. To compensate for this water shortage, more local storage might be needed in the Tungabhadra basin.

47. In Table 5, we present a summary parameters that can be directly extracted from Sheet 1 for the period 2009-2014. We focus on two particular elements of Sheet 1, being the Utilizable Outflow and the Exploitable Water Resources. Exploitable water resources is the

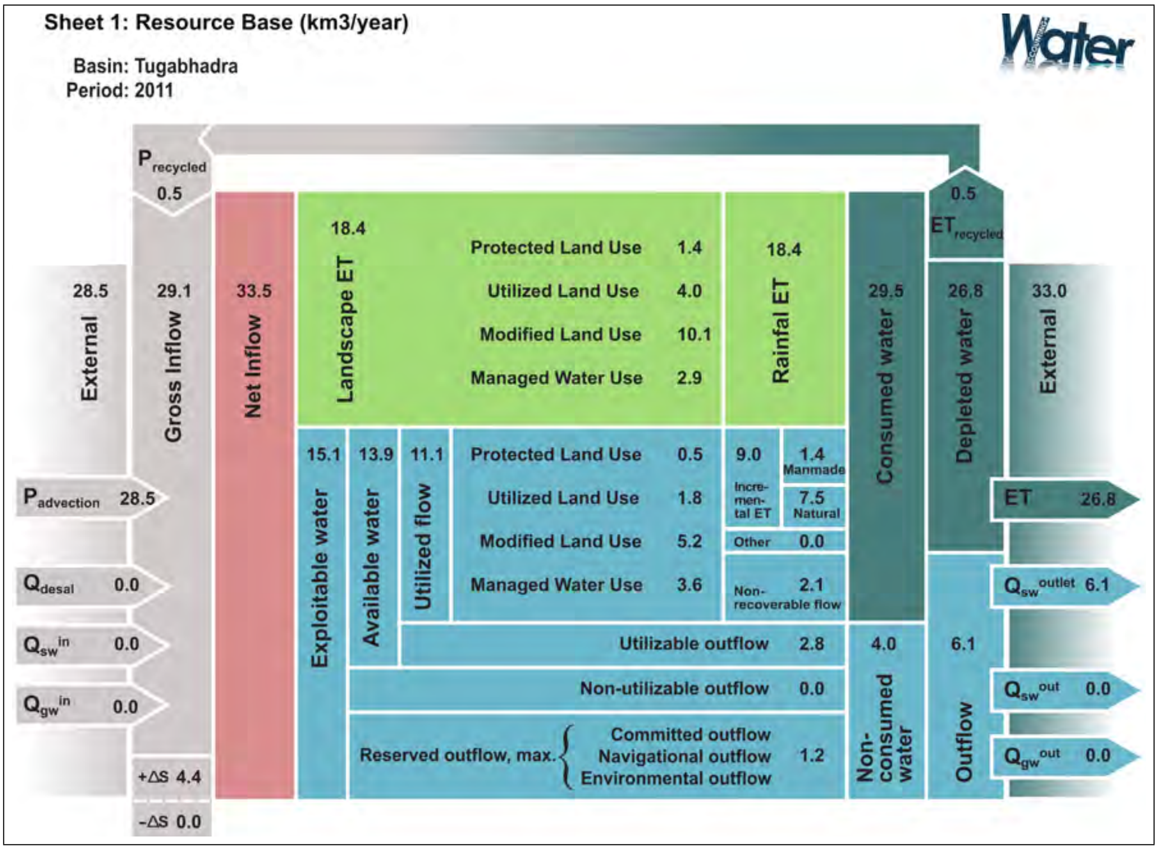


Figure 13: Resource Base sheet for the Tugabhadra basin during the year 2011.

difference between net inflow (rainfall, inflows from outside the basin, and change in storage) and landscape ET from soil moisture infiltrated after rainfall events. It is the maximum available amount of blue water resources in lakes, reservoirs, rivers, streams and aquifers. Not all this water is available, as certain volumes have to be set aside for environmental purposes or might not be utilizable (i.e., floods). The Available Water is therefore a better basis for assessing the extra withdrawals and abstractions. The Utilizable outflow represents water that is not used and could be considered for future allocation. Note that the data in Table 5 depicts the annual situation, and that monthly conditions may vary greatly.

48. The more recent years (2011-2013) are relatively dry with rainfall ranging from 29.0 to 33.1 km^3/yr, which is 10 km^3/yr less than during the first years. Water consumption also decreases during dry years but only buy 2-3 km^3/yr. The fifth column in Table 5 is the ratio between Utilizable Outflow and the Available Water. This parameter gives indications on the space for water development of the basin. The Tungabhadra basin utilizes in average 68% the available water but during dry years more than 80%.

49. Sheet 1 describes the water balance at the river basin scale. We can therefore look at

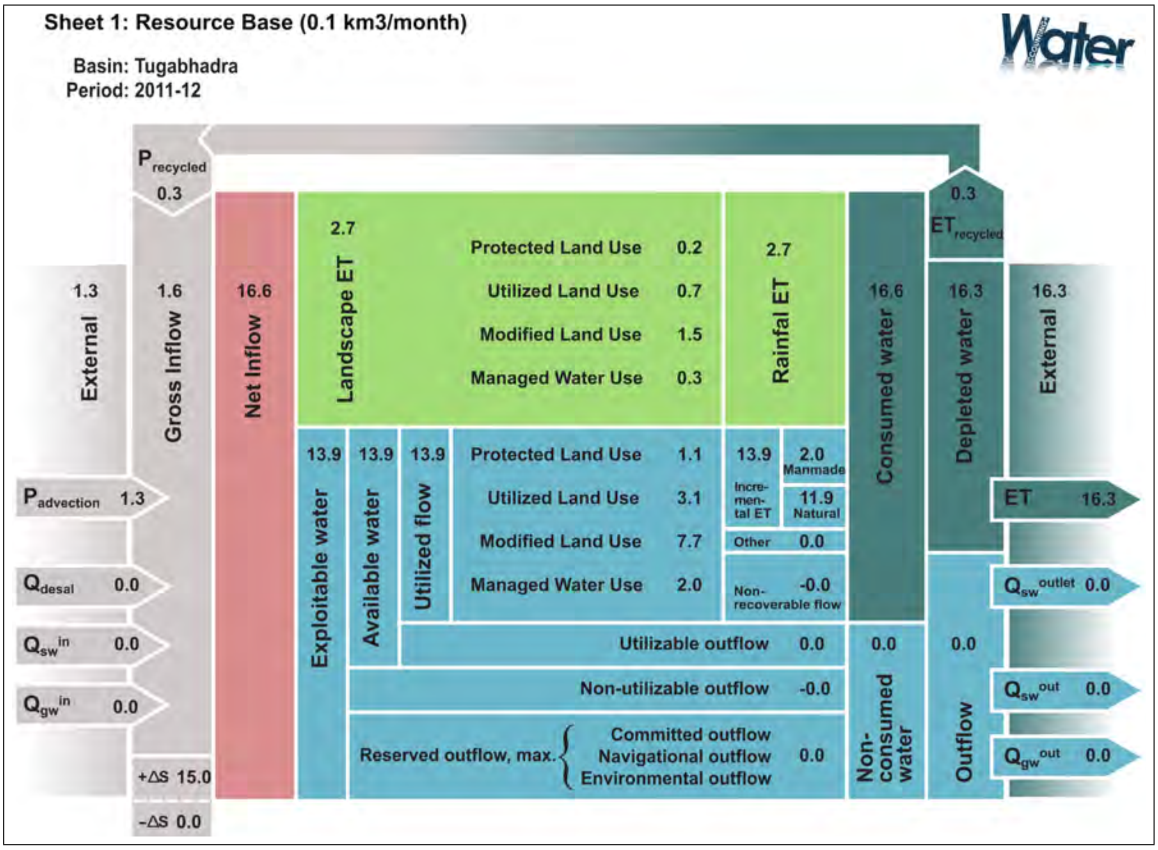


Figure 14: Resource Base sheet for the Tungabhadra basin during the month of December 2011.

Table 5: Summary of some components of the Resource Base sheet (U_O = Utilizable Outflow, A_W = Available Water).

Year	P $[km^3/yr]$	ET $[km^3/yr]$	U_O $[km^3/yr]$	U_O/ A_W [%]
2009	44.1	26.7	10.3	48
2010 -wet-	46.5	29.5	7.0	33
2011 -dry-	29.0	27.4	2.8	20
2012	31.3	24.9	4.7	33
2013	33.1	29.5	3.0	21
2014 -avg-	36.2	27.6	5.9	35
Average	36.7	27.6	5.6	32

the temporal variation of the water balance and analyse seasonal variability. In Figure 15, we present the major components of the water balance for the Tugabhadra basin. As expected, water stored during the wet season is then depleted in the dry season.

50. Overexploitation of surface and groundwater can be identified by analysing the evolution

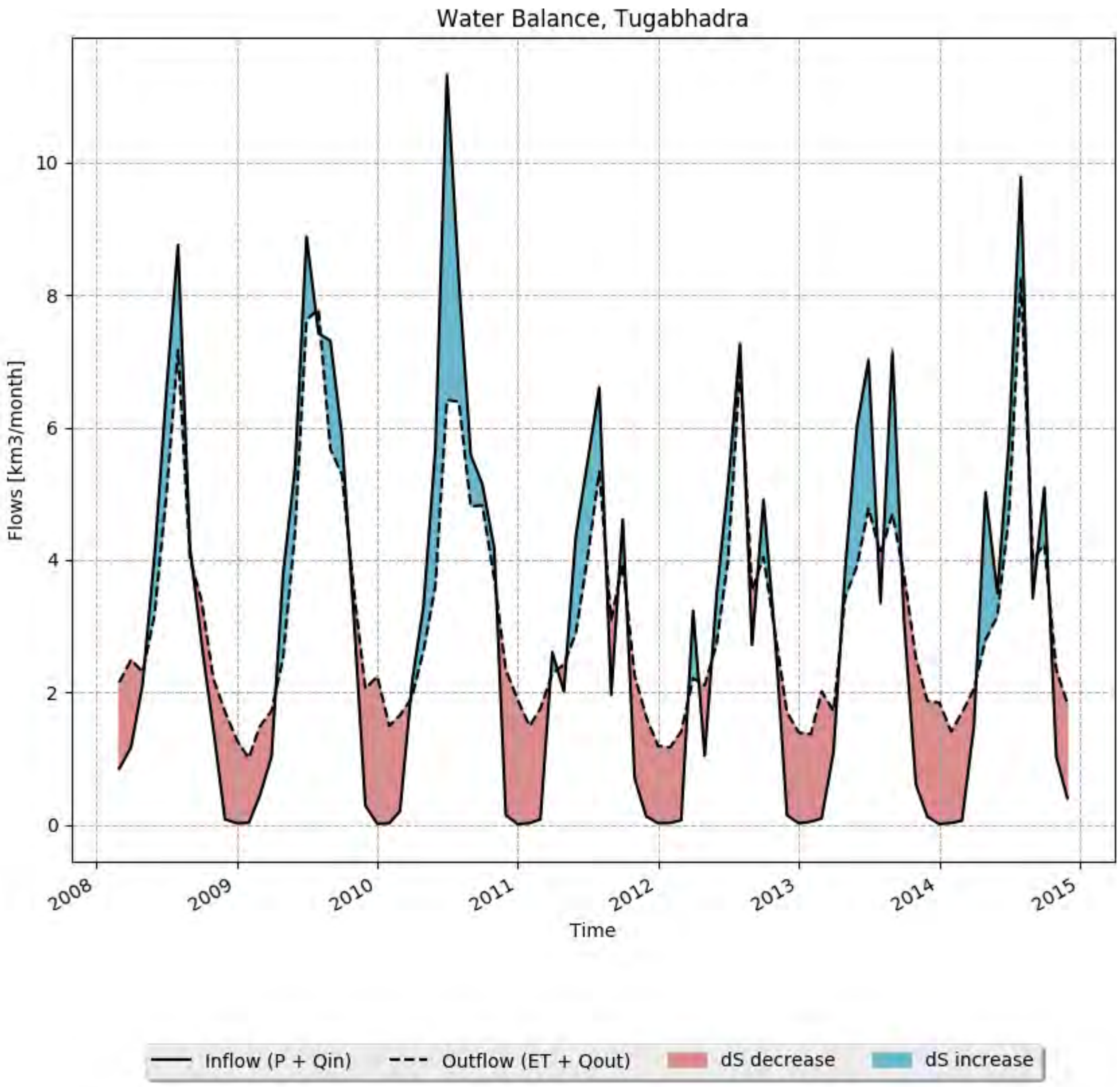


Figure 15: Temporal evolution of the water balance in the Tungabhadra basin for the analysed years (2009-2014).

of the storage change in Sheet 1 or the cumulative storage change over time (Figure 16). Because of the monsoonal climate, water storage in the Tungabhadra basin steadily increases and can reach an intensity of $+5$ km^3/month. At a total basin area of about 33,600 km^2, this is an equivalent depth of 150 mm/month. Delta S decreases again during the dry season, and seems not to recover completely in the most recent years. This is the consequence of several dry years and should be carefully monitored. From November to April, the consumptive use depends almost entirely on water released from storage (lakes, reservoirs and groundwater). Hence, storage is the main source of water during 6 months per year and this is mainly feasible due to the considerable decrease in water levels in reservoirs and increased pumping rates of groundwater. Any solution in enhancing the storage capacity would be worth considering and evaluate. Likely a combination of local storage mechanism and some larger scale interventions might lead to the best results. Enhancing groundwater recharge could also help mitigating the impacts of the erratic rainfall.

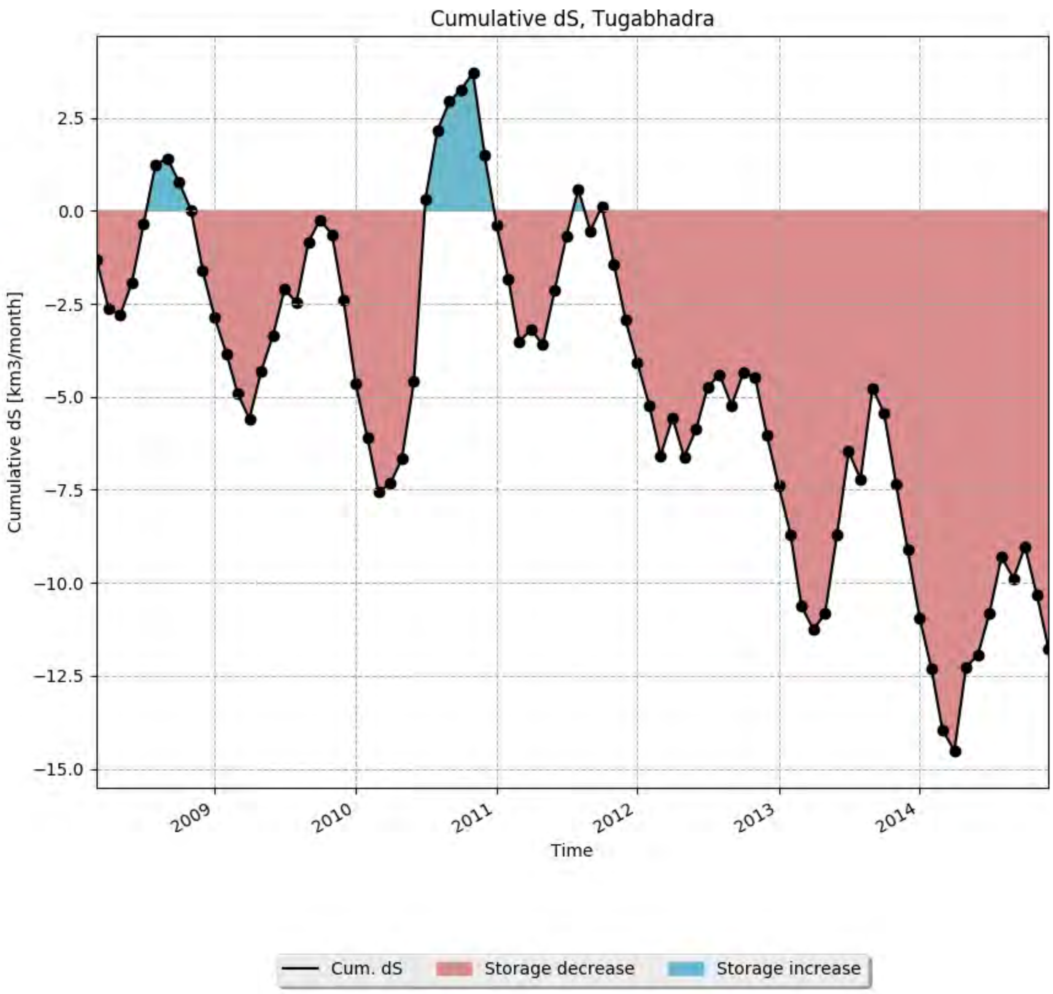


Figure 16: Temporal evolution of the storage change in the Tungabhadra basin during the analysed years (2009-2014).

6.2 Sheet 2: Evapotranspiration

51. The Evapotranspiration Sheet quantifies water consumption for all land use classes throughout the basin. It describes the anthropogenic impact on ET and concepts of ET management to reduce total water consumption from withdrawals and inundations. This sheet can be used to understand impact of land use planning on consumptive use and to relate water consumption to intended processes (beneficial vs. non-beneficial ET). Since ET is computed from an energy balance, it does not need information on the soil-physical growing conditions, and complex hydrological processes such as interflows, seepage zones etc. An example of Sheet 2 is presented in Figure 17 where we show the situation in 2011.

52. In 2011 the total ET consumption in the Tungabhadra basin was 27.3 km^3/yr. Rainfed and irrigated crops are the responsible of most of the water consumption (71% of the total water consumption in the basin is already managed). A non-negligible part of ET in the Tungabhadra basin is consumed by natural vegetation in protected areas, 7% of the total ET is therefore non-manageable.

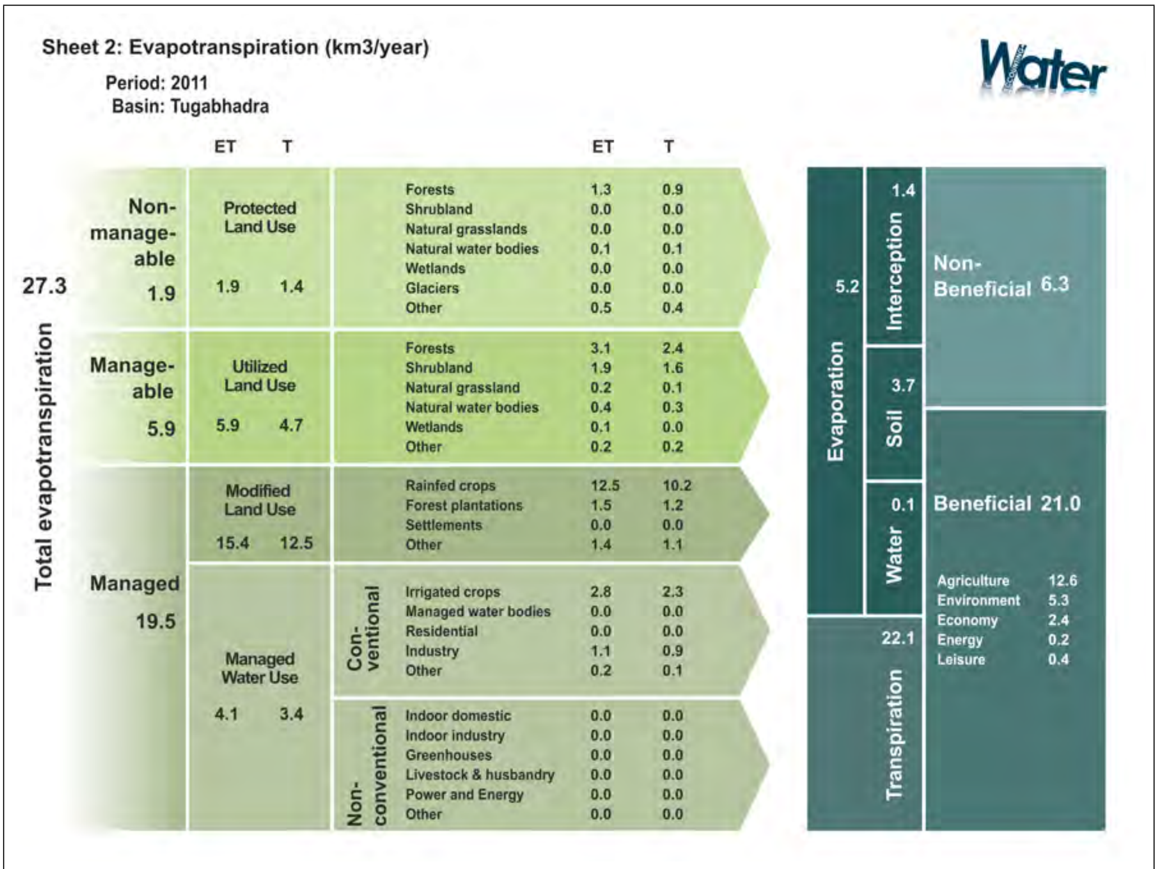


Figure 17: Evapotranspiration sheet for the Tungabhadra basin during the year 2011.

53. Non-Beneficial water consumption is high in the analysed catchment, between 24% to 31% of the total ET which correspond to 6.3 to 8.1 km^3/yr. A large fraction of the exploitable water is therefore not consumed for an intended purpose, meaning that the consumption of these large volumes of water does not produce any service. This is related to the large amount of partially flooded soils that after the monsoon remain wet for a very long time or that are flooded for irrigation. The reader should note that in this analysis pure evaporation from large reservoirs was not take into account. This additional evaporation will certainly increase the percentage of non-beneficial water consumption in the basin. Areas most suitable for water savings interventions could be identified based on results of Sheet 2 (fact sheet and maps).

54. Beneficial and Non-Beneficial consumption is a subjective matter. In the WA+ work flow we have developed standardized tables that relate ET and its components (Evaporation E, Transpiration T, and Interception I) to every land use land cover type to estimate which percentage is beneficial. ET is therefore separated into E, T and I using Remote Sensing data (Leaf Area Index LAI and biomass). An example of such a separation for the Tungabhadra basin is presented in Figure 18 as average for the entire basin. Interception (dark blue color) is the lowest component of ET and its temporal variation strongly follows the rainfall dynamics. Interception is generally considered to be non-beneficial. Evaporation (green color) can be considered beneficial when it occurs in natural areas (helping cooling down the atmosphere) or on fish ponds and reservoirs. It however does not provide any benefit when it occurs on wet soils (irrigated areas). Transpiration (light blue color) is generally beneficial both in natural and non-natural areas, an exception could be represented by riparian vegetation. Transpiration seems to be the highest component, which is surprising given the fact that the basin has large agricultural areas (as transpiration is higher in forested areas). We suspect a slight over estimation of transpiration and an underestimation of evaporation. More attention should therefore be given to the separation of ET into its three components.

55. Finally, it is also interesting to analyze the benefits that water consumption produces. In the Water Accounting + framework we divide the Beneficial Consumption into five categories: Environment, Agriculture, Leisure, Economy, and Energy. In Figure 19, the reader can see the break down of the Beneficial Consumption in these categories for the Tungabhadra basin. Water Consumption is primary beneficial for Agriculture (60% of the beneficial consumption in average in the period 2005-2014), while only a very limited fraction is consumed providing leisure benefits, producing energy or economical value (the total of these three components is 14.5%). The Tungabhadra basin has also natural protected and non-protected area. These areas consume water but provide environmental benefits, in average 25.5% of the total consumption is environmentally beneficial.

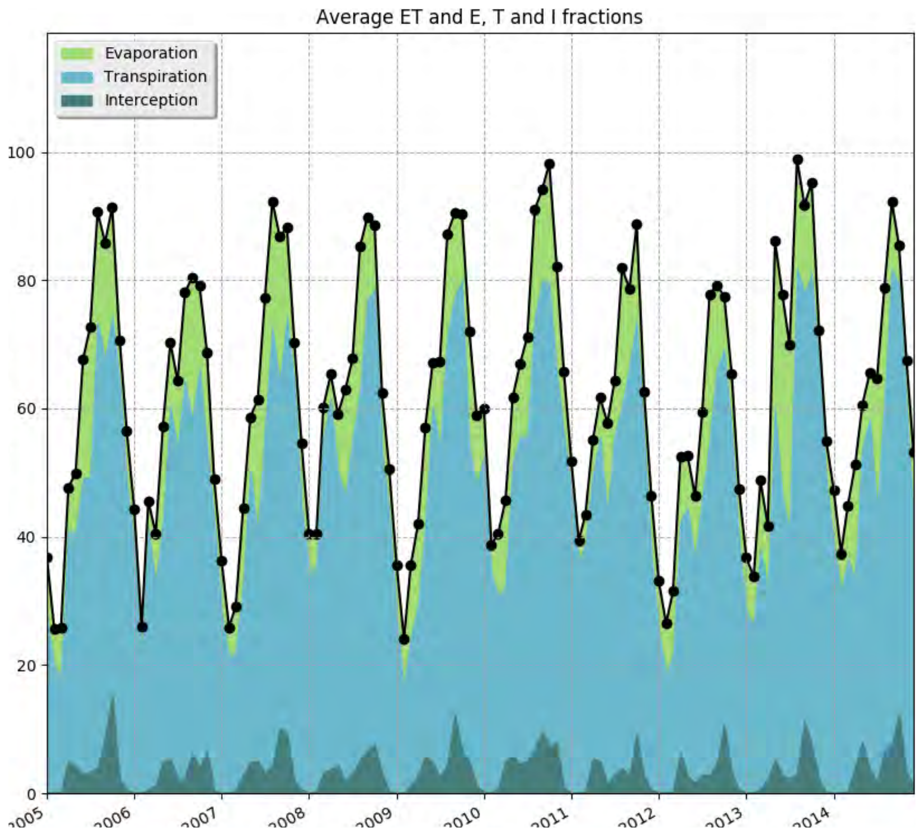


Figure 18: Temporal variation of ET components (evaporation, transpiration and interception) in the Tungabhadra basin.

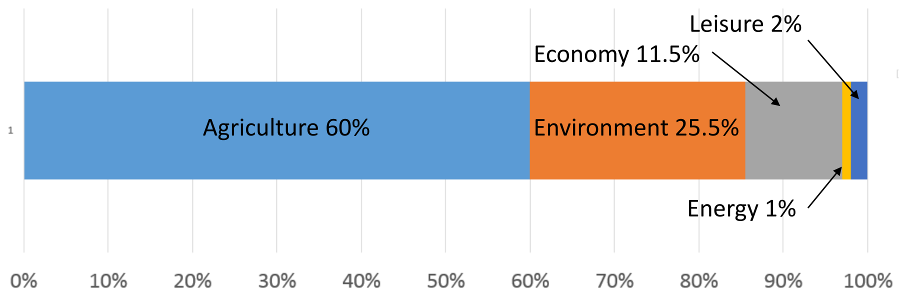


Figure 19: The beneficial consumption is further subdivided into five groups that refer to the services produced: Environment, Agriculture, Leisure, Economy, and Energy.

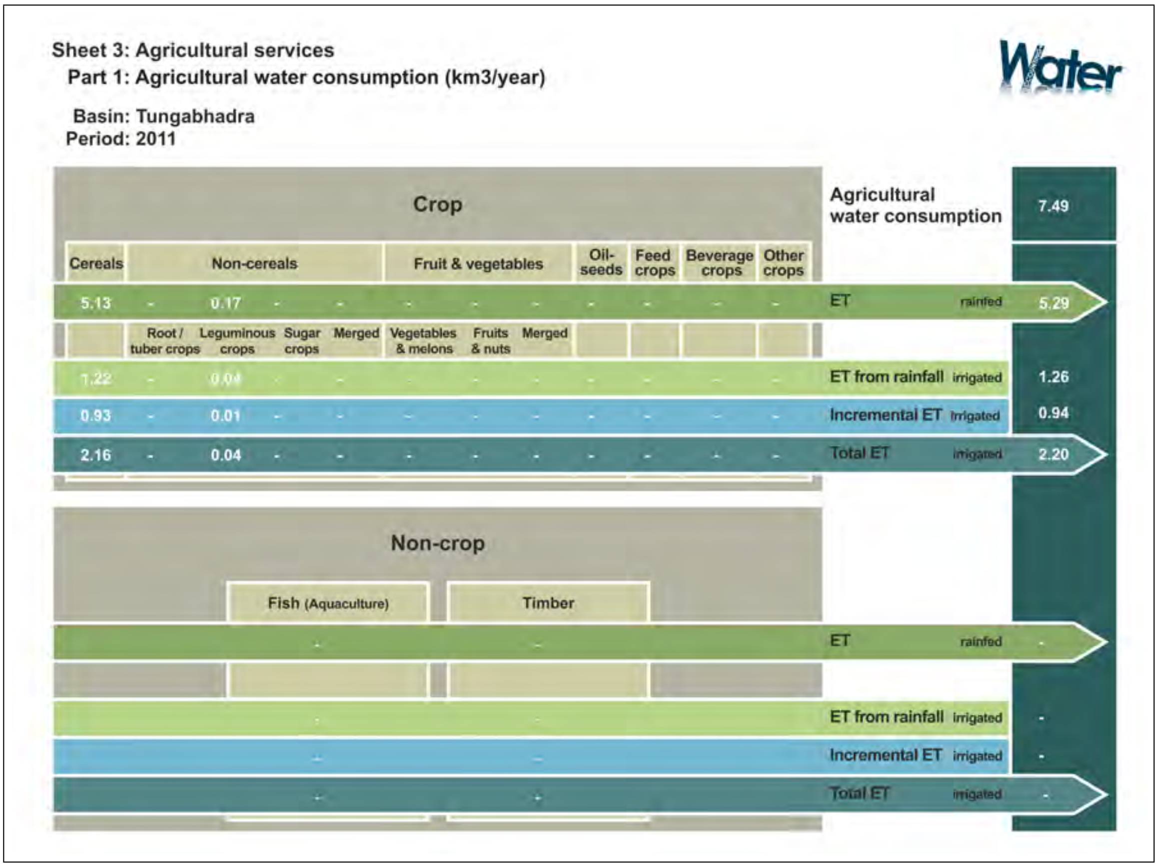
6.3 Sheet 3: Agricultural Services

56. Sheet 3 is mainly used to assess the agricultural production (kg/ha) in terms of food, feed, timber and fish products, to compute the related water productivity (kg/m^3) and the gap to demonstrate loss of returns (kg, $) and showing which geographical areas can become more efficient with water use. It can help in providing extra attention to certain rainfed and irrigated cropping systems and it indicates possibilities for saving water in agriculture, with an emphasis on non-beneficial water consumption and shifts from irrigated to rainfed crops and agroforestry systems. Sheet 3 is divided in two parts: part 1 presents water consumption in agricultural areas (Figure 20a) and part 2 the land and water productivity (Figure 20b).

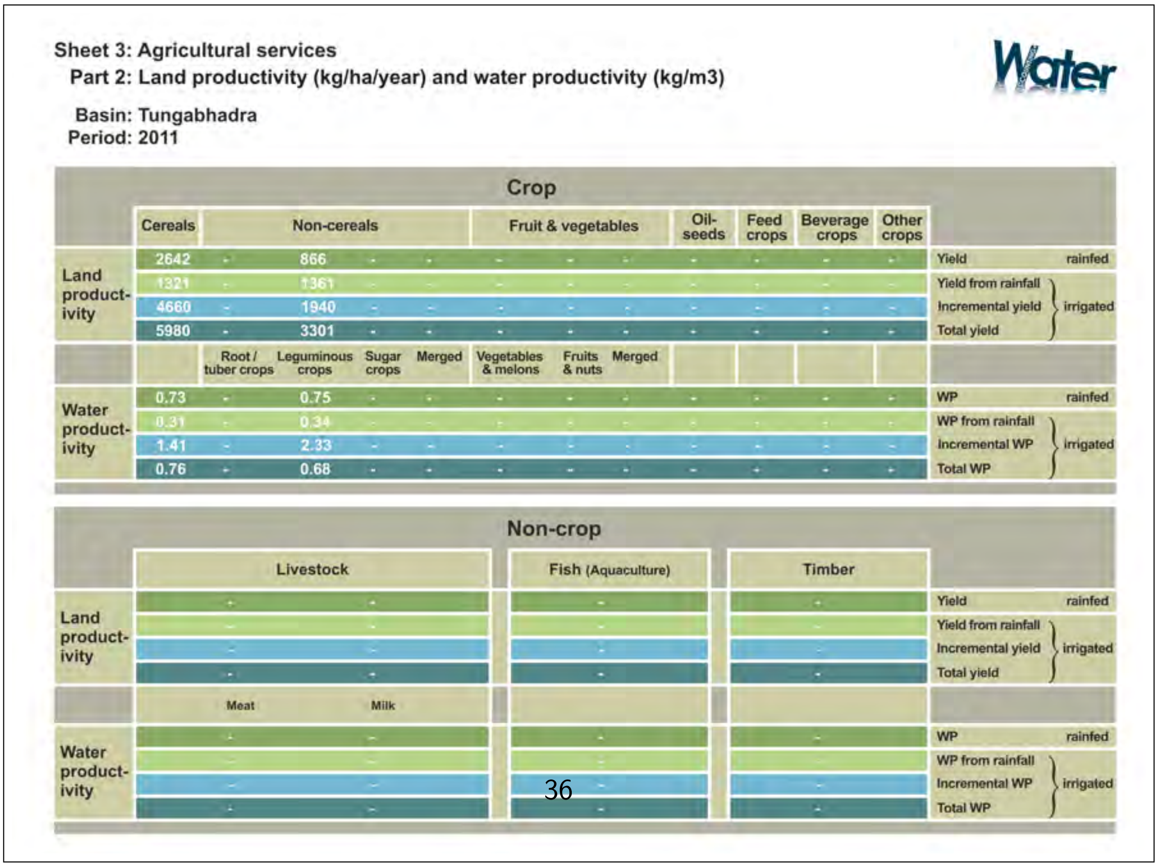
57. We have estimated Crop Yield and Water Productivity (ratio between crop yield -production- and Actual ET -consumption-) solely using Remote Sensing data. The major crops analysed and the crop seasons considered are summarized in Table 6. The results of the yearly Sheets 3 are summarized in Table 7 where the values for cereals are computed using parameters for rice. The values of rainfed agricultural production and water productivity of cereals are generally low if compared with world average (world average: 6000 kg/ha) but in line with the average production in India average (3000 kg/ha). Irrigated area have generally higher yield and higher water productivity as compared to the rainfed systems, partially because we consider more than one season per year, while the rainfed systems have one rotation per year.

Table 6: Major crops a crop seasons analysed for the Tungabhadra basin.

Crop Type WA+	Specific Crop Type	Start season	End Season
Cereals Rainfed	Rice	1 August	31 December
Non-Cereals Rainfed	Pulses	1 February	1 June
Cereals Irrigated	Rice	1 May	1 April
Non-Cereals Irrigated	Pulses	1 January	1 November



(a) Sheet 3 part 1: Agricultural water consumption for the Tungabhadra basin (2011).



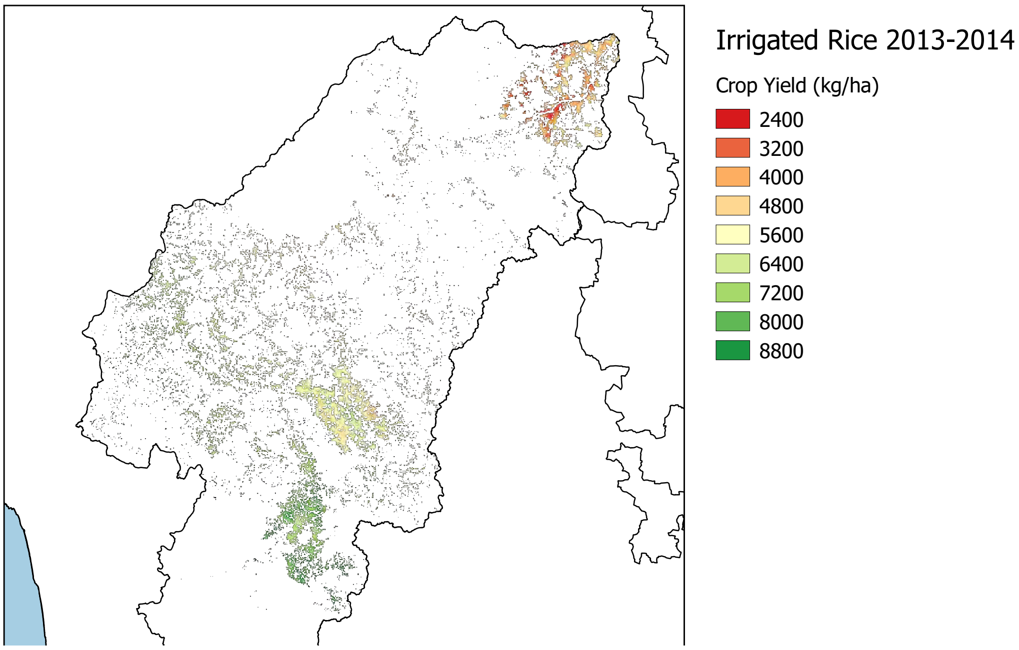
(b) Sheet 3 part 2: Land Productivity and Water Productivity for the Tungabhadra basin (2011).

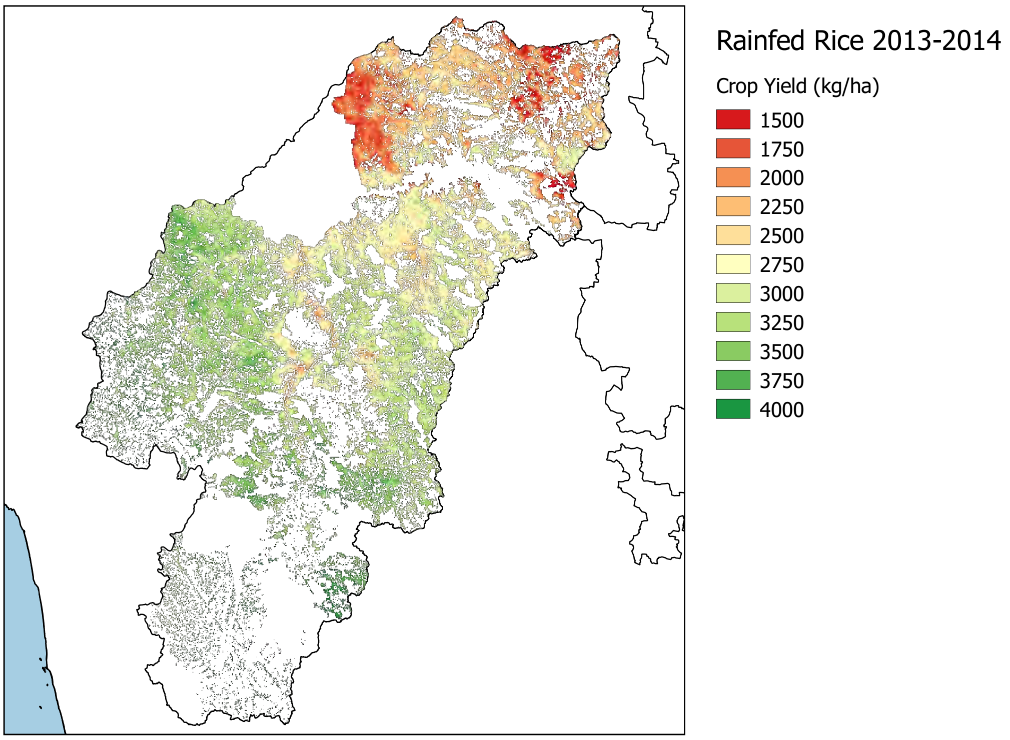
Figure 20: Agricultural services sheets for the analysed basin in 2011

Table 7: Summary of the results of Sheet 3 for the Tungabhadra basin. Values are yearly averages for the entire basin.

Tungabhadra	Crop Type	Area	Yield	Food Prod.	ET	WP
2010		[km2]	[kg/ha]	[Mt/season]	[km3/season]	[kg/m3]
	Rainfed Cereals	14,360	2,633	3.78	6.22	0.60
	Rainfed Leguminous	1,454	718	0.10	0.15	0.67
	Irrigated Cereals	2,878	5,966	1.72	2.45	0.68
	Irrigated Leguminous	91	3,037	0.03	0.05	0.54
2011						
	Rainfed Cereals	14,360	2,642	3.79	5.13	0.73
	Rainfed Leguminous	1,454	866	0.13	0.17	0.75
	Irrigated Cereals	2,878	5,980	1.72	2.16	0.76
	Irrigated Leguminous	91	3,301	0.03	0.04	0.68
2014						
	Rainfed Cereals	14,360	2,881	4.14	5.42	0.75
	Rainfed Leguminous	1,454	656	0.10	0.16	0.59
	Irrigated Cereals	2,878	5,942	1.71	2.48	0.67
	Irrigated Leguminous	91	3,284	0.03	0.05	

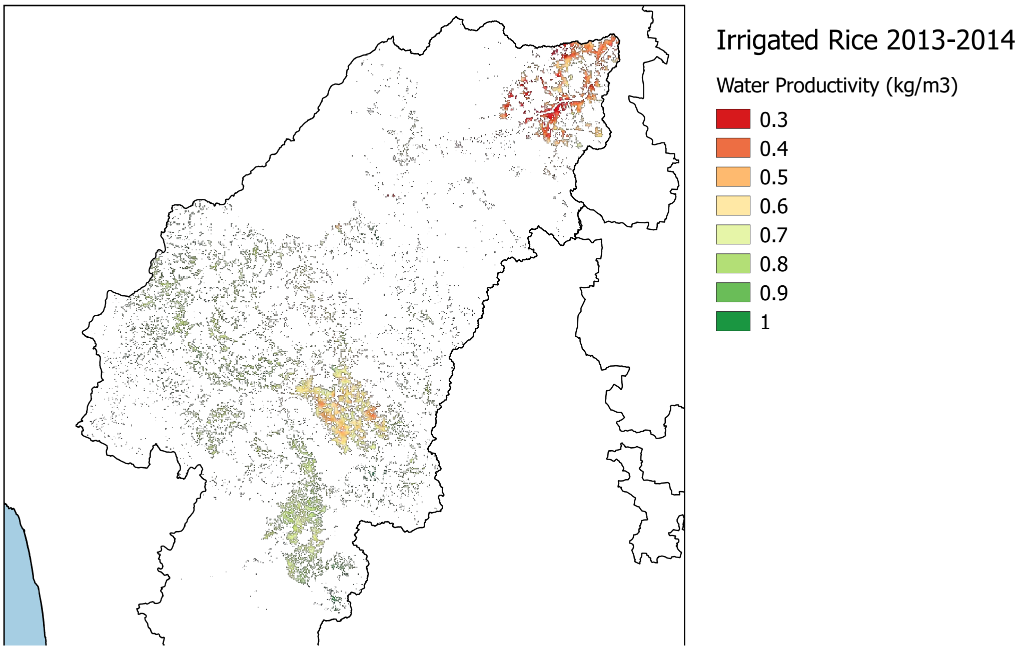
58. The upstream part of the basin (Shimoga, Davanagere and Haveri districts) seems to have the most productive areas for rice (Figure 21). The most productive areas for rice also have the highest values of Water Productivity which reaches 0.90-1.0 kg/m^3 (close to world average values). Large variations in Water Productivity exists in the Tungabhadra basin, specially for rice. In 2013-2014 values ranges from less than 0.3 kg/m^3 in red and 1.0 kg/m^3 in green (Figure 22). Agricultural area in green produce three times the amount of crop with the same amount of water than areas in red. These areas are localized at the central part of the basin and in the upstream areas.

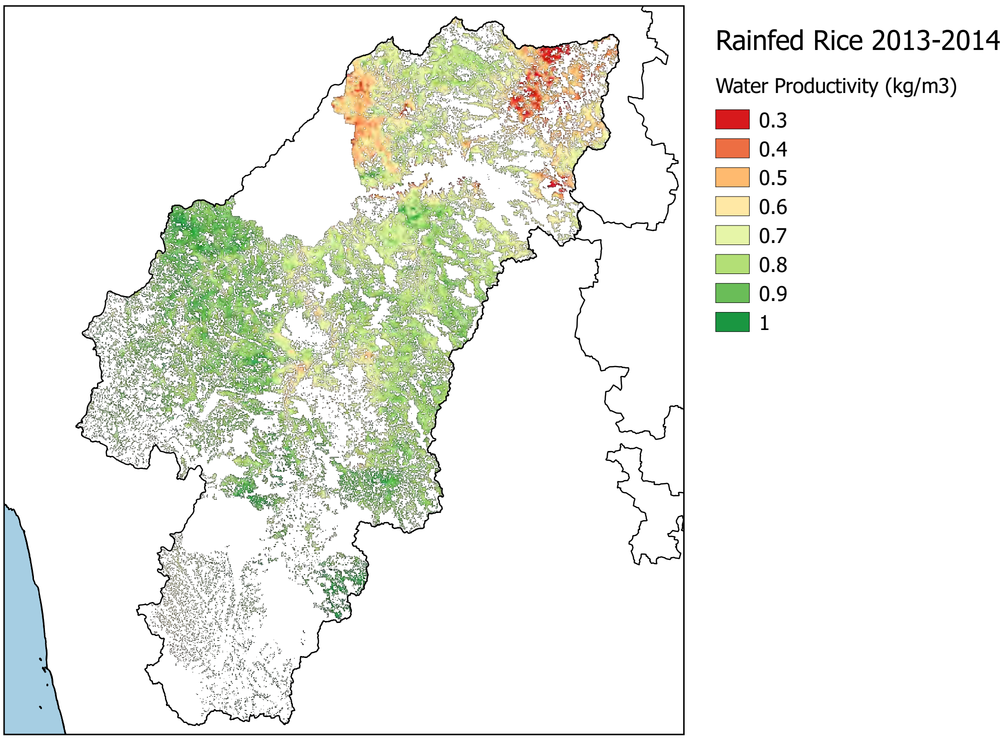




(b) Crop Yield of Rainfed Cereals in the year 2013-2014

Figure 21: Crop Yield of Cereals in the Tungabhadra basin (2013-2014)





(b) Water Productivity of Rainfed Rice in the year 2013-2014

Figure 22: Water Productivity of Cereals in the Tungabhadra basin (2013-2014).

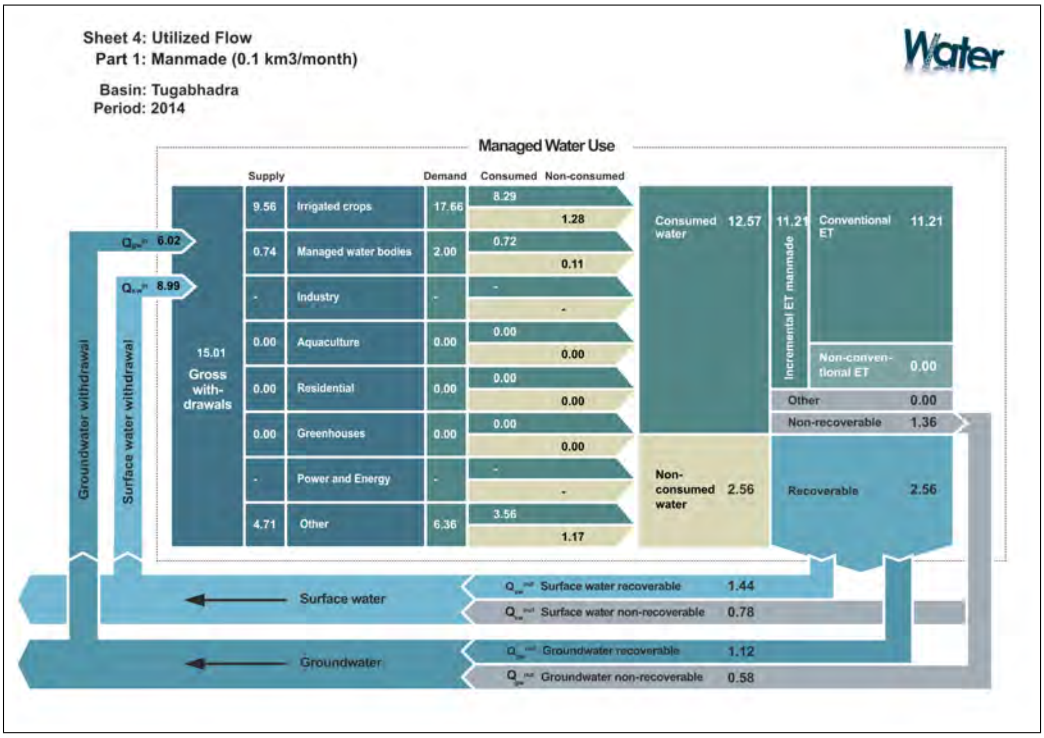
6.4 Sheet 4: Utilized Flows

59. The estimation green and blue water (consumption and withdrawals) is a very relevant piece of information for integrated water resources management. Blue water withdrawals are of particular interest to water managers and should be assessed for both natural and areas modified by human activity. Sheet 4 presents utilized flows (blue water) for the major land use groups in a river basin (Figure 23).

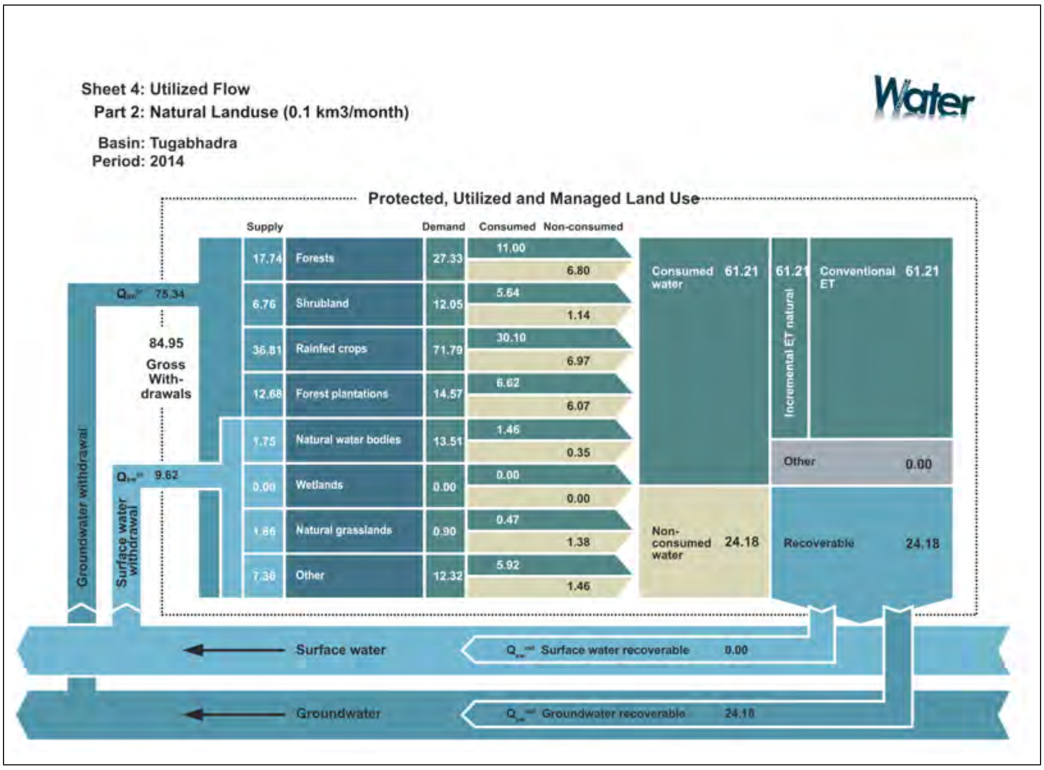
60. We can use Sheet 4 to relate the distribution of ETblue to manmade and natural withdrawals, with the pre-assumption that natural withdrawals are fit for creating healthy ecosystems (Table 8). The majority of blue water withdrawals happen in a natural way (plant uptake and natural flooding) and account for 85% of the withdrawals. Natural areas however are not responsible for the high proportion of "natural withdrawals". Rainfed agriculture and forest plantation consume most of the blue water withdrawals. If we consider the withdrawals of these areas as man-made withdrawals even though they occur naturally, the natural areas only account for 34-39% of the total withdrawals.

Table 8: Blue water consumption partitioning into natural and man-made withdrawals in the Tungabhadra basin. Values in brackets consider withdrawals from rainfed agriculture as man-made withdrawals

Year	ET blue man-made [%]	ET blue natural [%]
2010	16 (61)	84 (39)
2011	15 (64)	85 (36)
2014	15 (66)	85 (34)



(a) Sheet 4 part 1: Utilized Flow Manmade for the Tugabhadra basin (2014).



(b) Sheet 4 part 2: Utilized Flow Natural Landuse for the Tugabhadra basin (2014).

Figure 23: Utilized Flows sheets computed for the year 2014

61. It would also be useful to specify the water stress imposed on natural ecosystems, which is a first indication of the amount of extra available water that should be allocated to environments. The water stress can be inferred from WA+ fact sheet 4 by subtracting supply from demand. The water scarcity is expressed into a volumetric quantity for relating it to the water demand for other water use sectors. In Table 9, we present the Water Scarcity indicators for the Tugabhadra basin during the three analyzed years. Obviously in the wet year, water stresses (both surface and ground water) were the lowest but still significant for natural water bodies. In the dry and average years, water stress is higher. Surprisingly during the average year the total water stress is nearly double than in the dry year. This fact can be explain but analysing the antecedent years (2012 and 2013) that were also relatively dry. The situation in 2014 is therefore the results of several dry years. Natural area and particularly national parks require more water, specially in the dry season for forests and lakes. In 2014, groundwater stress is higher than surface water stress which relates to groundwater dependent ecosystems (mainly forests that rely on groundwater during the dry season).

Table 9: Water Scarcity in the river basin Tugabhadra for the three analyzed years, expressed as volumetric difference between water demand and supply per water use sector. A separation is made to assess groundwater and surface water stresses. The values are expressed in km^3/yr.

	Forests	Shrubland	Forest plantations	Natural water bodies	Wetlands	Natural grasslands	Other	
	Groundwater stress			Surface water stress				Total stress
2010 -wet-	0.0	0.0	0.0	0.68	0.0	0.0	0.0	0.68
	Forests	Shrubland	Forest plantations	Natural water bodies	Wetlands	Natural grasslands	Other	
	Groundwater stress			Surface water stress				Total stress
2011 -dry-	0.0	0.39	0.0	1.13	0.0	0.0	0.31	1.83
	Forests	Shrubland	Forest plantations	Natural water bodies	Wetlands	Natural grasslands	Other	
	Groundwater stress			Surface water stress				Total stress
2014 -average-	0.96	0.53	0.19	1.18	0.0	0.0	0.5	3.36

6.5 Sheet 5: Surface Water

62. Fact sheet 5 describes the surface flow (runoff generated within the basin and interbasin transfer), storage change, surface water withdrawals and return flow to surface water in the analyzed river basin and its sub-basins at monthly and yearly scale. The outflow of each sub-basin is also separated into four sub-components: committed, non-recoverable, non-utilizable, and utilizable (as in Sheet 1). Sheet 5 can be used to assist the planning of infrastructure and testing water allocation options within a river basin, and to prepare (surface) water allocation plans also in dry years. A maximum of nine sub-basins can be identified and analyzed, the user can input the geometry of the sub-basins or can simply supply the tool with the coordinates of the outlets of the sub-basins and the software will

automatically delineate the sub-basins based on the elevation map (DEM from HydroSHED). For the Tungabhadra basin, we used the global and open access HydroSHEDS database in combination with the National river basin data to identify the sub-basins. We have subdivided the basin into seven sub-basins (Figure 24).

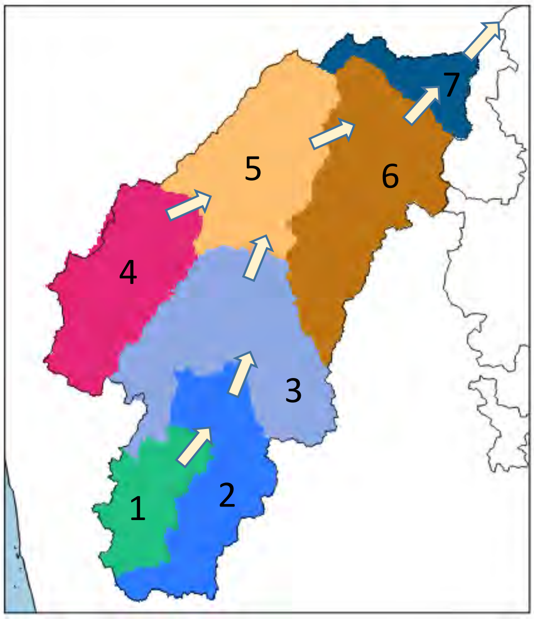


Figure 24: Subdivision of the analysed basin into sub-basins.

63. The example in Figure 25 shows the surface flow components of the sub-basins of the Tungabhadra basin for the year 2014. The seven sub-basins of the Tungabhadra varies in size and hydrological behaviour; they therefore generate different ammounts of surface runoff ranging from 0.11 km^3/yr (sub-basin 7) to 4.3 km^3/yr (sub-basin 1). The ouflow of each sub-basin also depend on the dominant land cover of the sub-basins and therefore the consumption rates. Sub-basin 7, for example, does not produce additional outflow as the entire runoff generated is consumed within the sub-basin.

64. As expected, no or little runoff generates from soils with natural land cover. Modified Land Use and Managed Water Use are the dominant categories in the Tungabhadra basin; in terms of generated volumes they therefore contribute the most. Roughly half of the outflow of each sub-basin is utilizable and 25% is non recoverable. Future possibility of storing and utilizing more surface water should be investigated.

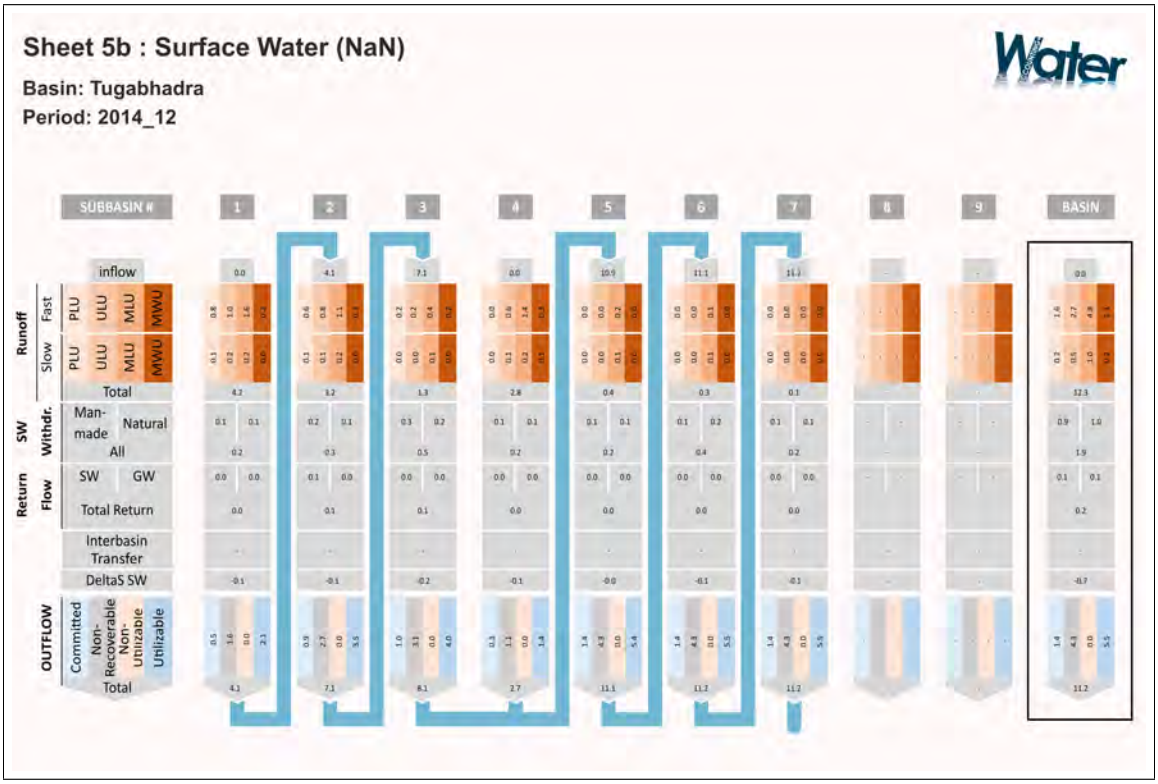


Figure 25: Sheet 5: Surface water for the Tungabhadra basins for the year 2014

6.6 Sheet 6: Groundwater

65. Sheet 6 describes groundwater flow and storage within a river basin. This accounting sheets includes: vertical recharge, capillary rise, vertical groundwater withdrawals, return flow to groundwater from groundwater and from surface water withdrawals, groundwater storage change, groundwater discharge (baseflow), and groundwater flow (Figure 26).

66. These fluxes and storages are expressed as total volume within the basin but also subdivided per land use type. Negative values indicate a decrease in storage. Sheet 6 as well as Sheet 5 are strongly based on simulation results, and therefore on either PCRGLOB-WB (global hydrological model) or Water-Pix and Surf-Wat (pixel-based and RS-based water balance and river flow models). For this analysis we did not consider groundwater flow as results from PCRBLOB-WB were not satisfactory and the implementation Water-Pix and Surf-Wat is still in testing phase. Additional analysis is therefore needed to accurately estimate groundwater flow in the two analysed basins.

67. The example in Figure 26, refers to the groundwater-related fluxes that occurred in Tungabhadra in 2011. In this particular year the storage change is negative and thus the natural recharge and return flows to groundwater are not sufficient to prevent the declining

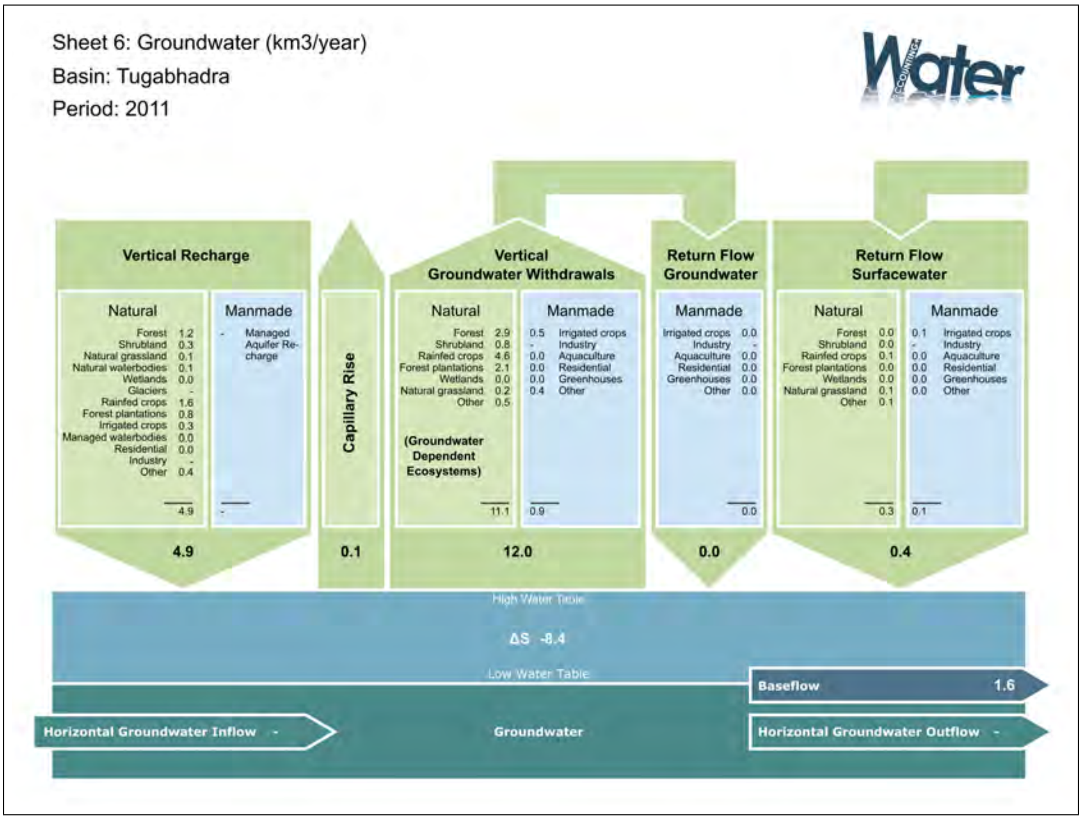


Figure 26: Sheet 6: Groundwater for the Tungabhadra basin for the year 2011

of the water table elevation. A summary of Sheet 6 major components for the analysed years is presented in Table 10. In the Tungabhadra basin the groundwater storage change is negative in all analysed years including 2010. This is surprising since 2010 was a wet year and groundwater recharge is high (6.2 km^3/yr). The dry year shows the lowest groundwater recharge (4.9 km^3/yr). Noticeable is the fact that groundwater withdrawals always exceed the groundwater recharge and in some extreme cases groundwater recharge is only one third of the withdrawals. These parameters should be carefully validated and monitored to avoid groundwater overexploitation. More analysis is therefore needed to draw final conclusions and more historical years should be analyzed to evaluate long term trends and identify regions where overexploitation is occurring or might occur in the near future.

68. If we analyse the monthly results, we notice that the groundwater storage change is negative during most of the year and that only few months contribute to compensate for the loss in storage (September to November). This means that not just during the dry season the water table elevation decreases but also partially during the wet season. It is therefore important to monitor these changes and relate them to changes in water and land management.

Table 10: Summary of the major flow components that can be derived from Sheet 6 (Groundwater). Values are expressed in km^3/yr

Tugabhadra	2010	2011	2014
Groundwater recharge	6.2	4.9	6.4
Withdrawals	18.3	12.0	8.1
Total return	0.8	0.4	0.3
Baseflow	3.1	1.6	1.9
Storage change	-14.5	-8.4	-3.4

6.7 Sheet 7: Ecosystem Services

69. Sheet 7 reports on Ecosystem services produced within a basin by consuming water resources. It expressed provisioning and regulating services and the benefit from the consumption of water, and relates them to land use categories (Figure 27).

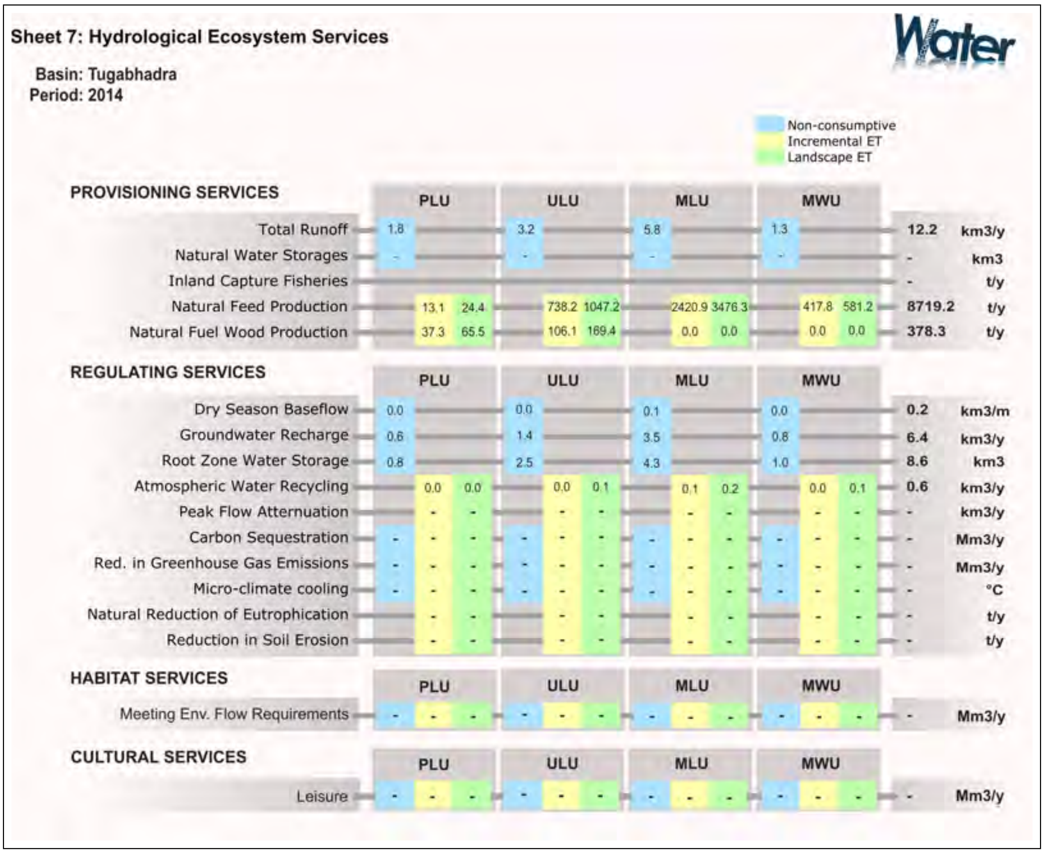


Figure 27: Sheet 7: Ecosystem service provided by the Tungabhadra basin in 2014

7 Conclusions

70. Karnataka is facing great challenges in satisfying its growing water demand. Seasonal water scarcity, due to the monsoonal climate and increased water consumption rates, are threatening safe access to water. Water resources are not, or might not be in the near future, sufficient to satisfy growing demands from competing sectors such as agriculture, industrial and domestic. Sustainable water management strategies are fundamental to support a year-round clean and affordable water supply. There is a strong need for increasing agriculture production for internal consumption and for contributing to the economic development of region.

71. Competition and conflicts over access to water in the dry season are becoming apparent. Increasing water allocations for economic development is only wise if more storage facilities are created. The flow in the dry season depends entirely on water stored during the wet season. Climate change may affect the natural availability of water resources. It is inevitable that the temperature rise will enhance the actual evapotranspiration, and hence consumptive use of agro-ecosystem will increase.

72. The benefits of water consumption are mainly of an agricultural nature. Many forests in the protected areas are however under water stress as additional water would be need for these ecosystems.

73. The grey water consumption is high, likely due to a combination of untreated waste water discharge and agro-chemicals used in the monoculture rice systems.

74. A portion of consumed water appears to be non-beneficial. This is mainly related to the extensive wet soils that are moist from rainfall or from flooding irrigation. Land use and agricultural planning should get more attention, as currently large volumes of water are consumed without economical services.

75. This pilot study is meant to make the Governmental officials, universities and NGO's aware of these new remote sensing technologies. Training and capacity building has been provided. In the future, the Ministries should employ these technologies and validate the results with the conditions encountered in the field.

8 Recommendations

- Store more water during the wet season. This can be achieved locally from filling ponds, artificial recharge, local movable gates in small embankments etc. Local harvesting of water will make rural population less vulnerability to climate change and natural disasters.

- Groundwater is a great water buffer that can carry over water from the wet season to the dry season. Recharge should be promoted and pumping should be regulated in order to keep the aquifer system fit.
- Constantly monitor surface and groundwater change is a priority to avoid possible overexploitation.
- Protect pristine forested areas and other natural ecosystems by allocating additional water to ecosystems.
- Expand irrigation systems to reduce adverse impact of erratic rainfall, and evaluate the shift to less water intensive crops.
- The environmental water requirements should be included in the water allocation plan. They constitute a major component of the blue water resources utilization.
- Provide more attention to grey water consumption, i.e. consumptive use of water due to pollution.
- New maps of crop types should be developed and kept updated to monitor water consumption and improvements in agriculture.