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India: Water Accounting in Kali Sindh and Wainganga River Basins

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For Asian Development Bank

Asian Development Bank

By Kalyan Kanuri, https://commons.wikimedia.org/wiki/File:Godavari_old_and_new_bridges.jpg

Water Accounting in Selected Asian River Basins: Pilot study in Madhya Pradesh (India)

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Executive Summary

1. Madhya Pradesh is facing great challenges in satisfying its growing water demand. Seasonal water scarcity is threatening safe access to water and it is, or it 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. 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 Madhya Pradesh 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 two river basins in Madhya Pradesh. 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 two selected river basins were analyzed for three historical years:

2011, 2012 and 2013. 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 two analysed basins have different morphology and climatic conditions. Wainganga has higher mountains in the North part of the basin and receive more rainfall (1500-2000 mm/yr) than the Kali Sindh basin (1100-1600 mm/yr).
- They both have a monsoonal climate and most of the runoff is generated within three months per year.
- On a yearly scale the water yield (difference between rainfall P and actual evapotranspiration ET) is positive in both basins. In the Kali Sindh however some areas have negative water yields (up to -180 mm/yr). The additional water consumed in these areas must come from runoff generated in other areas of the basin or from groundwater (blue water).
- Natural areas have limited spatial extent in both river basin as they are heavily modified by anthropogenic activities (mainly agriculture). More than 95% and 73% of the basins surface is covered by agriculture and urban areas (Kali Sindh and Wainganga respectively).
- Even on a yearly scale, the Kali Sindh basin has no utilizable water meaning that all the available water is already utilized. In addition, the basin is not able to meet its environmental flow requirements, and has high rates of non-recoverable flow (polluted water).
- Most of the blue water consumed in the Kali Sindh basin is due to human activity (mainly irrigation).
- On a yearly scale the Wainganga utilizes roughly 50% of the available water leading to and average of 8.5 km^3/yr of water that flows unutilized downstream. However, during dry months, the utilizable outflow is reduced to nearly 0 km^3/yr even when water is taken from storage.
- 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
- In the Kali Sindh basin, agriculture (both rainfed and irrigated) is responsible for most of the water consumption.
- Non-beneficial consumption, or water consumed without producing for purposes other

than the intended, is high (60-70% of the total ET). Kali Sindh is slightly more efficient having a lower non-beneficial consumption fraction. This might be due to the already limited available water resources.

- Most of the beneficial ET generates benefits to the agriculture sector (50-70% of the beneficial consumption). In the Wáininga basin also natural areas are consuming water beneficially (33% of the benficial consumption), and finally 7% and 12% is beneficial for the economy (Wainganga and Kali Sindh respectively).

- Values of agriculture production, and water productivity, are generally low (cereals reaching 1,500-3,000 kg/ha) if compared with the world average (6,000 kg/ha). Irrigated areas produce more and their production rate is comparable with the India average.

- In Kali Sidh, the Dewas district seems to have the most productive areas for gram and soybean, and in the Wainganga the Seoni district, located in the North part of the basin, has the highest prodcution.

- Water stress, estimated as the volumetric difference between demand and suppy, was estimated for natural ecosystems. Wainganga has higher water stress than the Kali Sindh basin even if it receives more rainfall. More water should therefore be allocated for the environment to preserve the health of the ecosystems in protected and non-protected natural areas.

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 Madhya Pradesh are irrigation, industry, domestic supply and sanitation, groundwater, natural disasters and the environment. In the irrigation sectors many activities are ongoing (new irrigation schemes are planned and old schemes are being renovated) to increase agriculture production with limited water resources. 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 Madhya Pradesh in this study. The inception phase report describes the planned steps to implement WA+ in the two selected river basins in Madhya Pradesh: Kali Sindh and Wainganga. 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. Arnaud Cauchois, ADB Principal Water Resources Specialist, was the point of contact for Madhya Pradesh together with Mr. Beau Freeman, PPTA (Project Preparatory Technical Assistance) team leader and Mr. Y.C. Sharma, Superintended Engineer at PICU Bhopal. 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 basins in Madhya Pradesh and for the training and capacity building component with the support of Dr. Claire Michailovsky. Potential recipient organization in Madhya Pradesh is the Water Resources Department (WRD) at BODHI. During our activity in Madhya Pradesh we were unable to engage with more organizations.

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 Madhya Pradesh Water Resources Department and ADB India in the development/update of the future National Water Resources Development Plan of Madhya Pradesh by:

a. applying the WA+ procedure to estimate, on a monthly scale, available and exploitable water resources for the two selected river basins in Madhya Pradesh. Monthly and yearly accounts are produced for selected historic years for the period 2000-2014 (2011, 2012, and 2013),

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 and the small size of trainees group, we believe additional support is needed to ensure that recipient organizations will become fully independent. 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 Madhya Pradesh 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. This is a short period for the sake of a limited working budget. 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 analysis started in February 2016 and ended in May 2018. In this project we applied the Water Accounting + procedure to two selected river basins in Madhya Pradesh (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.

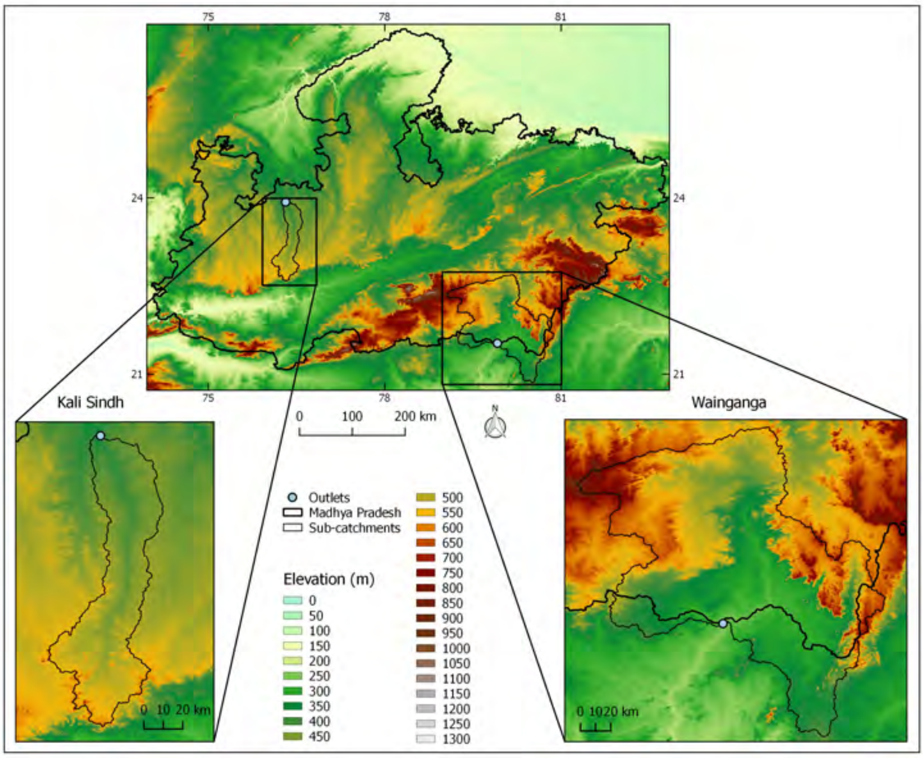


Figure 1: WA+ was implemented in two river basins in Madhya Pradesh: Kali Sindh and Wainganga.

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 following river basins in Madhya Pradesh: (a) Kali Sindh, (b) Wainganga.
- 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, mid-term and final reports.

4 Training and Workshops

23. 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 (Delhi and Bhophal): 18-23 May 2016
  - preparatory meeting with ADB representative and local focal point in the Ministry;
  - informal training session. Major topics covered: familiarization with QGIS, hydrological modelling (QSWAT) and Python programming.
- First training session (Bhopal): 12-18 September 2016
  - Training for technical staff (5 participants). Topics: fundamentals of Water Accounting: WA+ fact sheets, how to use the WA+ Python toolbox, Remote Sensing vegetation indices (NDVI and LAI), Reference ET (FAO56 method), Consumptive and non-consumptive use, split ET into E-T-I, beneficial and non-beneficial consumption, theory on Green and Blue water consumption.
- Second training session and dissemination workshop (Bhopal): December 2016
  - 12-19 December: training for technical staff (5 participants). Topics: Python and QGIS hands-on training, Energy balance modelling, Fact sheets 1, 2, 3, Remote Sensing computation of crop yield and crop water productivity.
  - 20 December: Dissemination workshop (25 participants). Topics: Introduction to WA+ framework, progress on WA+ activity, discussion on next-steps.

5 Input Data and Data Validation

24. 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. Very limited data has been made available for validation of WA+ results.

5.1 Land Use Land Cover Map

25. Of particular importance is to obtain or produce a high-resolution, reliable and thematically-detailed land use land cover map of the two river basins in Madhya Pradesh. An initial map of crop dominance was obtained from GCAD (Global Crop Area Database) developed by the U.S. Geological Survey (USGS) and the International Rice Research Institute (IRRI)with 1 km spatial resolution (Figure 2)[1]. This map however only covers certain crop types with a coarse resolution and non-crop types are absent.

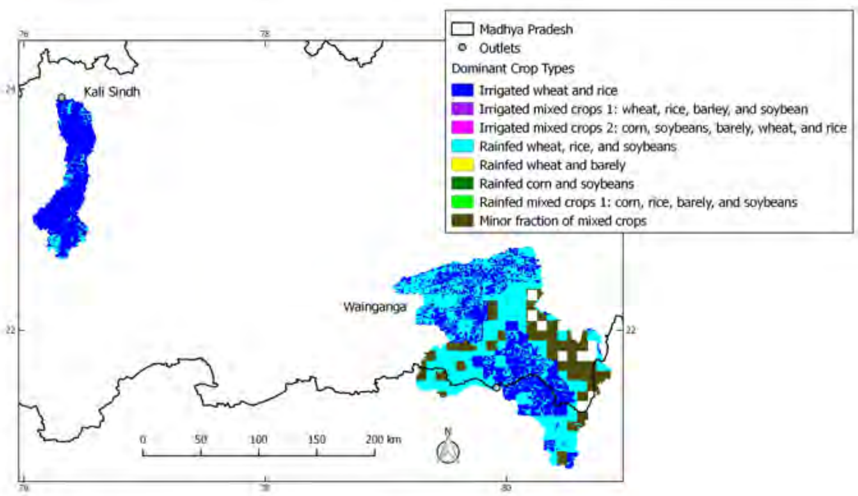
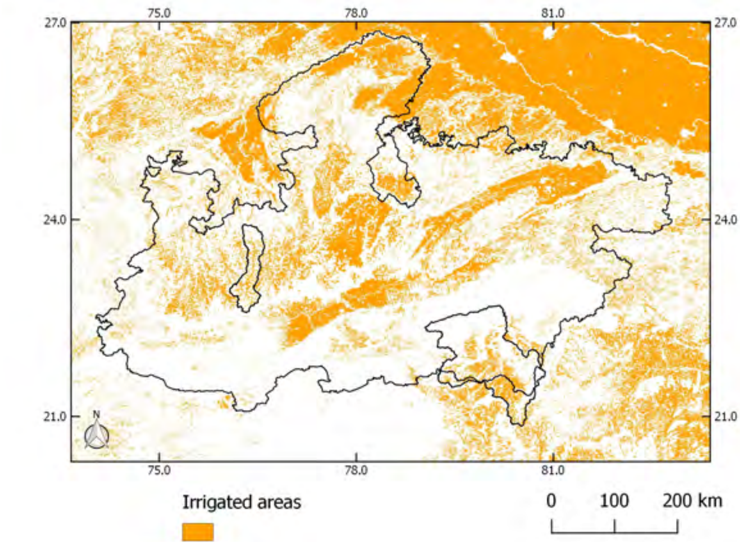


Figure 2: Crop dominance map of the two selected catchments (source USGS and IRRI).

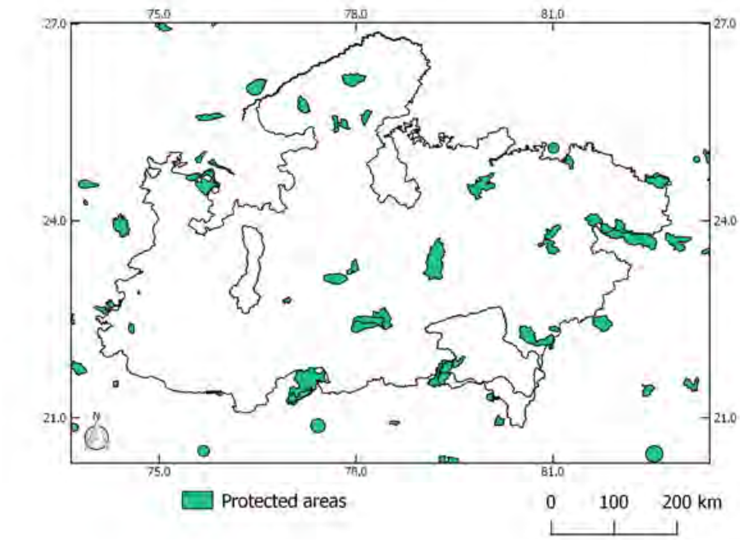
26. To produce the final Land Use Land Cover (LULC) map according to the standard Water Accounting + classification (80 classes), we combine the information from the previous map with other open access data, namely: the map of protected areas obtained from the World Database of Protected Areas (*https://www.protectedplanet.net*), and an irrigation map developed as an ensemble of three data sources. Data used for producing irrigated

[1]Thenkabail P.S., Knox J.W., Ozdogan, M., Gumma, M.K., Congalton, R.G., Wu, Z., Milesi, C., Finkral, A., Marshall, M., Mariotto, I., You, S. Giri, C. and Nagler, P. 2012. Assessing future risks to agricultural productivity, water resources and food security: how can remote sensing help?. Photogrammetric Engineering and Remote Sensing, 78(8): 773-782, August 2012.

rainfed masks for India are: ESA-CCI-LC ($https://www.esa-landcover-cci.org/$), GIAM-IWMI ($http://waterdata.iwmi.org/Applications/GIAM2000/$), GLOBCOVER ($http://due.esrin.esa.int/page_globcover.php$). The two input maps are displayed in Figure 3. Additionally, for crop diversification, data for major crops per district were used (National Innovations on Climate Resilient Agriculture -NICRA-, $http://www.nicra-icar.in/nicrarevised/$). The final result was used to compute the Water Accounting + sheets for the two river basins in Madhya Pradesh (Figure 4).

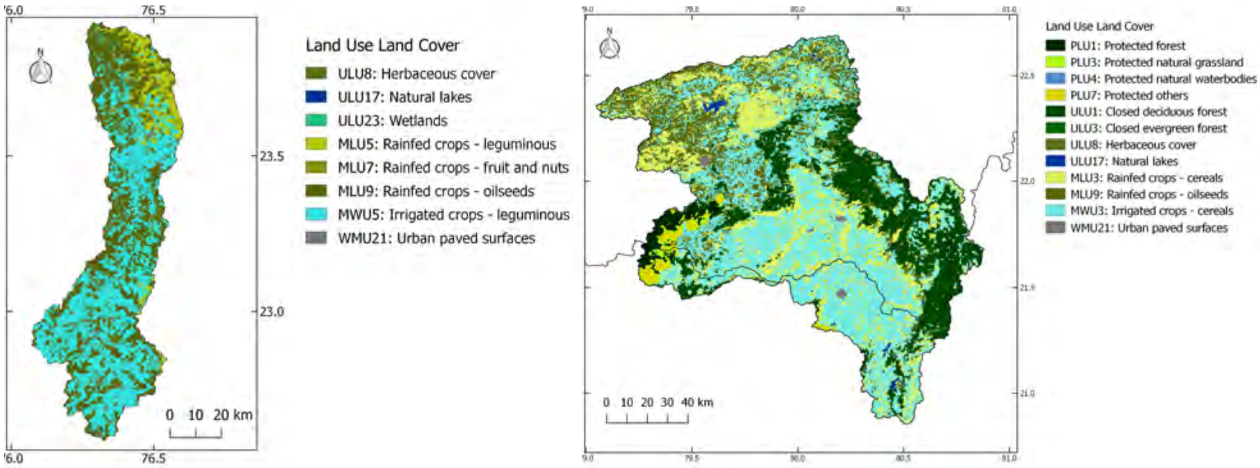


(a) Irrigated mask



(b) Protected areas

Figure 3: Irrigated mask of India developed for this study and the protected areas that were used to create various water and land management categories required by WA+.



(a) LULC map for Kali Sindh

(b) LULC map for Wainganga

Figure 4: Final Land Use Land cover map, produced for this study according to the WA+ standard classification scheme.

27. 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. Below we describe the major assumptions.

28. *Wainganga*

Two major districts are present in Wainganga: Balaghat and Seoni. In Balaghat the most dominant kharif crop is rice (in terms of area covered), while rabi crops are wheat and linseed. The area covered by the rabi crops combined reaches less than 10% of the area covered by rice. In the Seoni district kharif crops are rice and soybean, and rabi cropswheat and chickpeas (with wheat covering about 2/3 of the area). The identification of rabi/kharif crops was done using NDVI profiles (MODIS data from 2014 and 2015). The rules for selecting a specific crop are explained in Table 2.

Table 2: Rules for selecting a crop types in Wainganga basin

Crop Type	NDVI temporal values and irrigated mask
Irrigated Wheat	NDVI(Jan) or NDVI(feb) > 0.6 & Irrigated crop mask = 1
Rainfed Wheat	NDVI(Jan) or NDVI(feb) > 0.6 & Irrigated crop mask = 0
Irrigated Rice	NDVI(Oct) > 0.6 & Irrigated crop mask = 1
Rainfed Soybean [a]	NDVI(Oct) > 0.6 & Irrigated crop mask = 0
Rainfed Rice	NDVI(Oct) > 0.6 & Irrigated crop mask = 0 & not soybean

[a]Soybean is assumed to be single cropped and only grown in the northern part

29. *Kali Sindh*

In Kali Sindh we have considered three major districts: Dewas, Rajgarh, and Shajapur. Major rabi and kharif crops per district are listed in Table 3. the final classification was developed by NDVI profiles analysis and visual inspection of remote sensing imageries. The rules for selecting a specific crop, based on NDVI values are explained in Table 4. Because Gram is the dominant crop type and no additional information was available we have consider that only Gram, Soybean and Oranges are produced in Kali Sindh and no cereals yield and water productivity are computed in this study.

Table 3: Major crops per district in Kali Sindh basin

District	Kharif	Rabi
Dewas	Rainfed Soybean	Irrigated Gram & Irrigated Wheat [a]
Rajgarh	Rainfed Soybean	Irrigated and Rainfed Gram, Irrigated Wheat [b]
Shajapur[c]	Rainfed Soybean	Irrigated Gram & Wheat [d]

[a]Gram covers about 2/3 of the Kharif crops area
[b]30% of the total is rainfed, 60% of the total is Gram
[c]Orchard are also considered in Shajapur
[d]Gram crop covers about 2/3 of the total area

Table 4: Rules for selecting a crop types in Kali Sindh basin

Crop Type	NDVI temporal values and other information
Orchards	NDVI(May) $>$ 0.3 & Cultivated land in Shajapur
Irrigated Gram	NDVI(Jan) or NDVI(dec) $>$ 0.55 & Irrigated crop mask $=$ 1 & not orchards
Rainfed Soybean	NDVI(Sep) $>$ 0.5 & Irrigated crop mask $=$ 0 & not orchards
Rainfed Gram [a]	NDVI(Jan) $>$ 0.6 & Irrigated crop mask $=$ 0 & not orchard

[a]rainfed soybean and gram overlap (double cropping)

30. 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

31. An overview of these categories for the two analyzed catchments is presented in Figure 5. A summary of the different land cover types and respective areas for the two basins is displayed in Table 5. In the next sections we also discuss more in details the situation of each catchment.

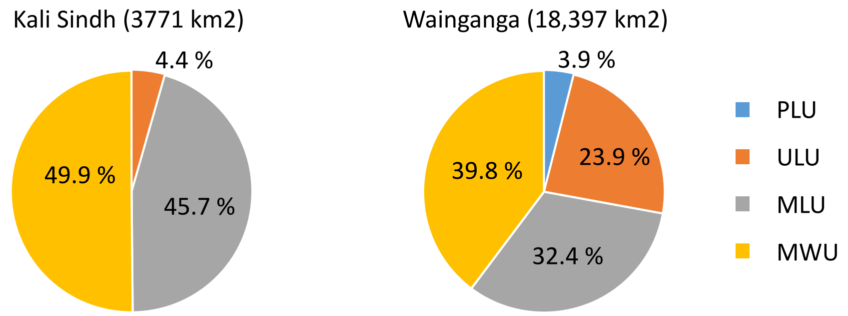


Figure 5: Distribution of the four major WA+ land use land cover category in the two analyzed catchments in Madhya Pradesh.

Table 5: Distribution of land use land cover types in the two analysed river basins.

Kali Sindh

LULC	type	Area [km2]
ULU8	Herbaceous cover	159.0
ULU17	Natural Lakes	5.7
ULU23	Wetland	1.6
MLU5	Rainfed crops - leguminous	297.3
MLU7	Rainfed fruits and nuts	8.2
MLU9	Rainfed crops - oilseed	1,416.2
MWU5	Irrigated crops - leguminous	1,864.6
MWU21	Urban paved surfaces	19.0

Wainganga

LULC	type	Area [km2]
PLU1	Protected forest	358.7
PLU3	Protected natural grassland	115.1
PLU4	Protected water bodies	1.3
PLU7	Protected others	253.2
ULU1	Closed deciduous forest	3,479.8
ULU3	Closed evergreen forest	35.6
ULU8	Herbaceous cover	810.7
ULU17	Natural Lakes	108.5
MLU3	Rainfed crops - cereals	3,827.5
MLU9	Rainfed crops - oilseed	2,163.3
MWU3	Irrigated crops - cereals	7,267.3
MWU21	Urban paved surfaces	93.6

5.2 Elevation

32. The two analysed basins have different elevation and climatic conditions (Figure 6). Kali Sindh and Wainganga have similar average elevation, 470 and 460 m respectively, but different extreme values. Elevation ranges from 350 to 730 m in the Kali Sindh basin and from 230 to more than 1000 m in the Wainganga.

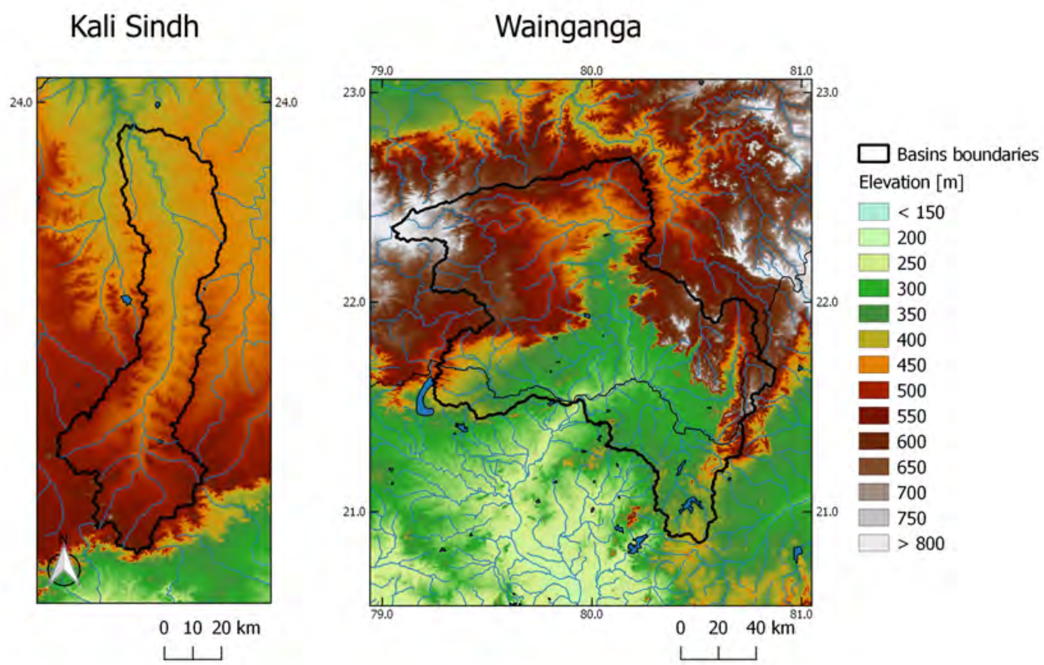


Figure 6: Digital Elevation Map of the two analysed basins in Madhya Pradesh (source: USGS HydrSHED).

5.3 Rainfall Data

33. We collected monthly RS precipitation for the entire Madhya Pradesh for the period 2000-2014. In the Inception report we presented the comparison of two remote sensing products, TRMM and CHIRPS, for the two river basins and we selected CHIRPS for the subsequent analysis. We selected three recent consecutive years for both basins for the creation of Accounting sheets (Table 6). Spatially distributed maps for the selected years are displayed in Figure 7.

34. The Wainganga basin receives more rainfall than the Kali Sindh basin (in average 450 mm/yr additional rainfall). In the Wainganga basin most of the rain occurs in the Northern part where elevation is higher. During the wet year (2013) however rainfall reaches up to

2000 mm/yr in the valley close to the outlet. Rainfall in the Kali Sindh basin is more evenly distributed throughout the basin ranging from 1400 to 1900 mm/yr in the wet year and from 900 to 1200 mm/yr in the driest selected year (2012).

Table 6: Rainfall average in the two river basins for the selected years. Values are expressed in mm/yr.

Basin	2011	2012	2013
Kali Sindh	1268	1043	1627
Wainganga	1514	1518	1972

35. The Water Resource Department of Madhya Pradesh has provided rainfall records from 16 rain gauge stations. These stations only cover the Nothernpart of the Wainganga basin. We have computed the Nash-Sutcliffe (NS) efficiency to compare the RS-based rainfall measurements with the rain gauge measurements. More than 85% of the stations have a NS >= 0.5 (good agreement) and 50% have a NS>= 0.75 (very good agreement) (Figure 8). In no stations has been noted poor agreement (<= 0.25) and no systematic bias can be observed, therefore the CHIRPS rainfall products were used as they are provided from the USGS standard websites. In Figure 9, rainfall recorded by satellite and rainfall record from ground stations are compared in scatter plots (three stations with good agreement and three station with poor agreement).

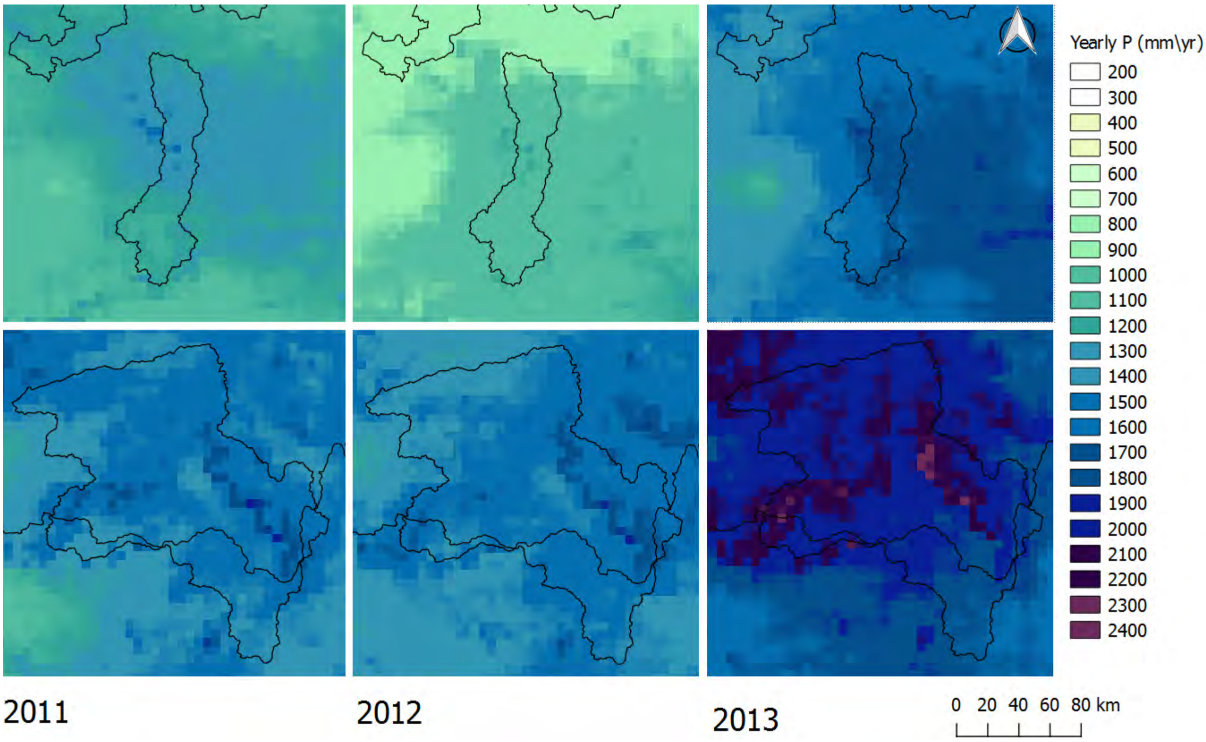


Figure 7: Spatially distributed Remote Sensing yearly rainfall data for the selected years (CHIRPS).

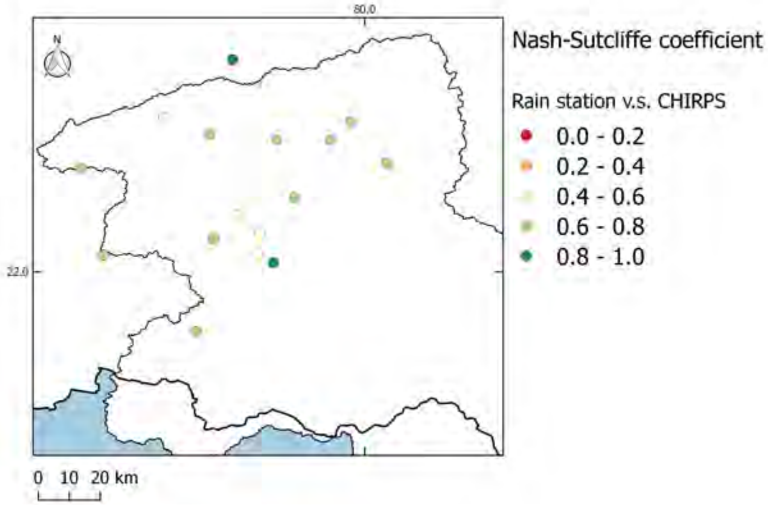
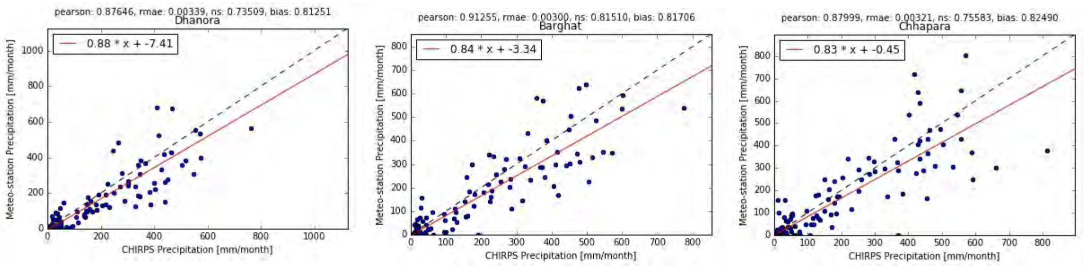
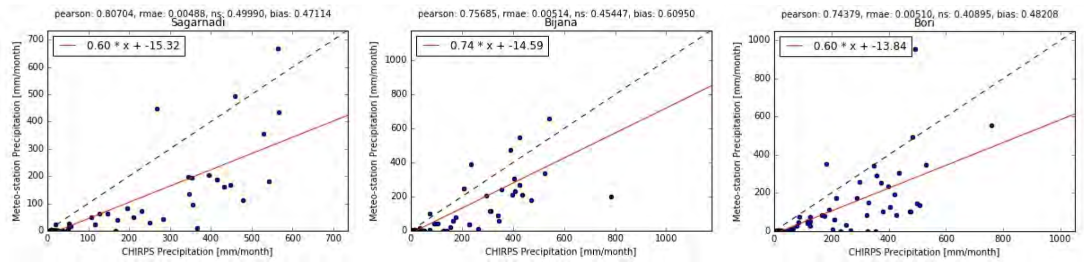


Figure 8: Statistical comparison of the Remote Sensing precipitation product (CHIRPS) and gaged rainfall data from 16 station for the period 2000-2015 (monthly values, Nash-Sutcliffe statistics, source ground data: Water Resources Department of Madhya Pradesh).



(a)



(b)

Figure 9: Scatterplots of remote sensing rainfall and rain gauge records for (a) three stations with good agreement and (b) three stations with poor agreement.

5.4 Other Open Access (Remote Sensing) Data

Actual Evapotranspiration and Water Yield

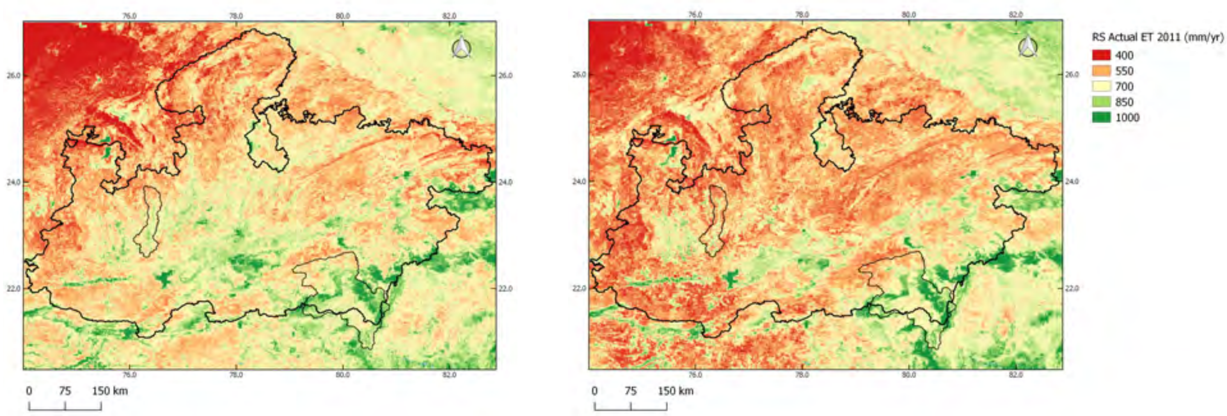
36. In the inception report the reader can find the comparison of different Remote Sensing based Actual Evapotranspiration (ET) products for Madhya Pradesh. Most of the RS products presents similar spatial variability but a wide range of absolute values. To increase the reliability of actual ET estimates, we have developed monthly maps Actual Evapotranspiration (250 m resolution) for entire Madhya Pradesh 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 10, we show the yearly total Actual ET for Madhya Pradesh and surroundings for average years (2010 and 2011). ET ranges from less than 400 mm/yr to more than 1000 mm/yr and the inter-annual variability is not very pronounced. The lowest values (red color in Figure 10), lower or equal than 400 mm/yr, are localized in the North and North-West areas which receive the least precipitation and have the lowest vegetation cover. The highest values of ET (green color) are localized in the South-East part of the State. More specifically:

a. Narmada valley: from lakes and reservoirs, and irrigated areas;

b. Wainganga basin: from reservoirs and forested areas where precipitation is the highest (Figure 11).

The average Actual ET for Madhya Pradesh for was around 660 and 610 mm/yr for the year 2010 and 2011 respectively.

37. We compared Actual ET with RS-based rainfall data and created maps of Water Yield,



(a) Average year actual ET 2010 (b) Average year actual ET 2011

Figure 10: Total yearly Actual Evapotranspiration data for the average years (Ensemble ET developed by IHE-Delft on bases of seven different RS-based ET products).

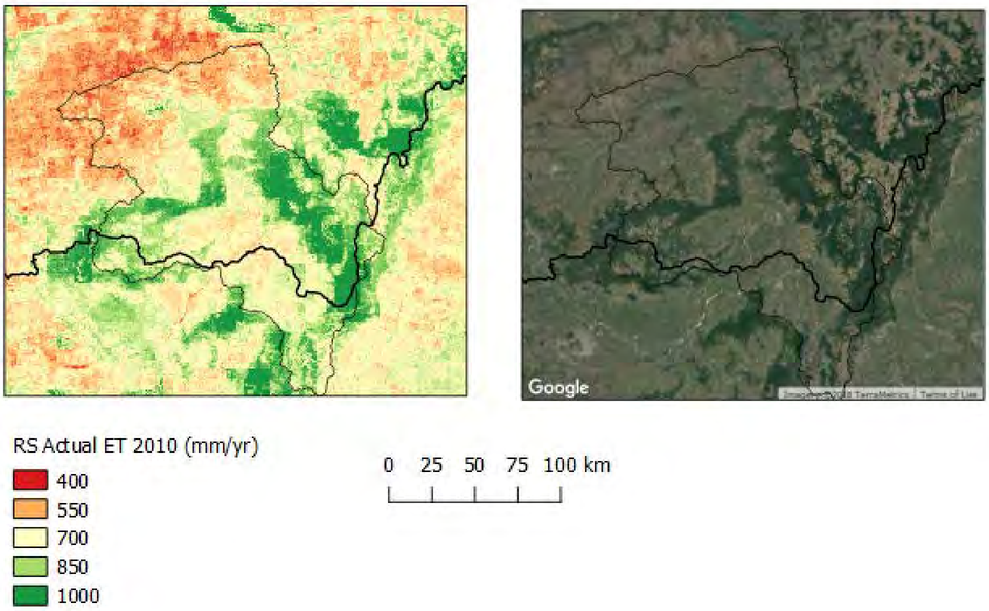


Figure 11: Higher values of actual ET correspond to forested areas in the Wainganga river basin.

both monthly and yearly, by subtracting ET from P (Figure 12 shows spatially-distributed results for P-ET during 2010). This simple calculation provides relevant information on water consumption, water scarcity and water excess.

38. As expected, most of the runoff is generated at the center North of Madhya Pradesh in the mountain areas. The excess of more than 1500 mm/yr forms a substantial contribution to the available and utilizable water in the Wainganga and surrounding basins. In this particular year none of the two basins presents negative water yield values which means that, on a yearly scale, P is higher than ET. In 2008, a relatively dry year, negative values of the water yield are present in Kali Sindh basin reaching up to -180 mm/yr (Figure 13). In the red areas in Figure 13 the actual ET is higher than precipitation on a yearly scale. The water evaporating form 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.

39. In Table 7, we provide a summary of Precipitation (P), Actual Evapotranspiration (ET) and Water Yield (P-ET) for the two analyzed basins with a break down to the four water management land use categories.

40. As expected Water Yield is generally highest during the wet year and lowest during the dry year. In the Kali Sindh basin, the water yield of the wet year is double than in the dry year, which implies a high yearly variability. In the Kali Sindh, LU classes belonging to the

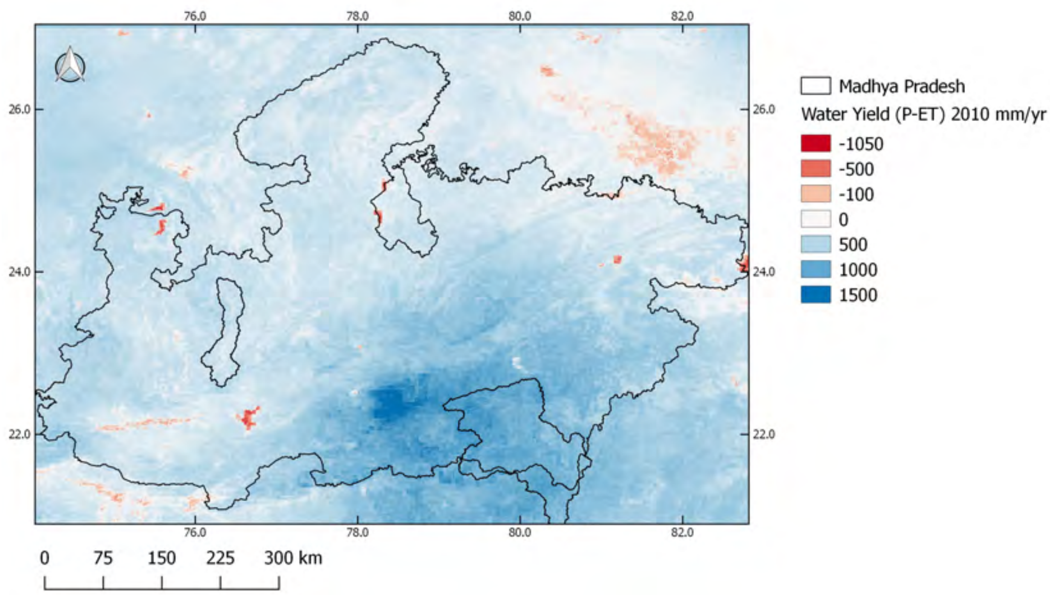


Figure 12: Water Yield (P-ET) for the year 2010, values are expressed in mm/yr.

Table 7: 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	2011 -average-			2012 -dry-			2013 -wet-		
LULC	P	ET	P-ET	P	ET	P-ET	P	ET	P-ET
ULU	1282	523	760	1022	526	497	1623	629	993
MLU	1277	573	705	1032	597	435	1628	695	933
MWU	1259	649	610	1053	692	361	1625	773	852
Wainganga	2011			2012			2013		
LULC	P	ET	P-ET	P	ET	P-ET	P	ET	P-ET
PLU	1576	855	721	1583	778	805	2124	1091	1033
ULU	1575	913	663	1596	882	714	2001	1172	829
MLU	1488	675	814	1472	668	805	1974	868	1105
MWU	1493	715	778	1499	682	817	1937	968	969

Managed Water Use group (MWU, i.e. irrigated agriculture) have the lowest water yield in all analysed years (up to 150 mm/yr less than other groups). This lower water yield is due to higher ET in these areas as rainfall is similar to other groups. In the Wainganga basin there is not a clear separation between water yield among different LULC classes, only the Utilized Land Use areas seems to generate a lower water yield. The Wainganga basin has higher water yields than the Kali Sindh basin (100-450 mm/yr of additional potential runoff).

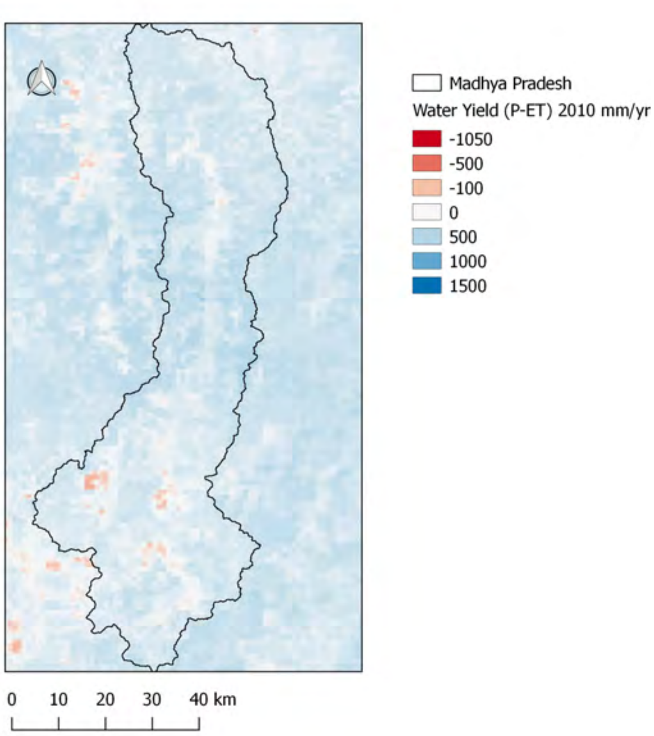


Figure 13: Water Yield (P-ET) for the year 2008 in the Kali Sindh basin, values are expressed in mm/yr.

41. The monthly variability of Water Yield (P-ET) is also very informative. In Figures 14-15, we present the monthly dynamics of P-ET for the two analyzed basins in the dry year (2012). Negative values of P-ET are visible 8-9 months per year (dry season and beginning and end of wet seasons). Water Yield reaches up to about 400 and 500 mm/month in July 2012 in the Kali Sindh and Wainganga basins respectively. The lowest Water Yield values are in October (-50 and -80 mm/month for Kali Sindh and Wainganga) when soils are still wet from the rain of the previous months or areas are irrigated.

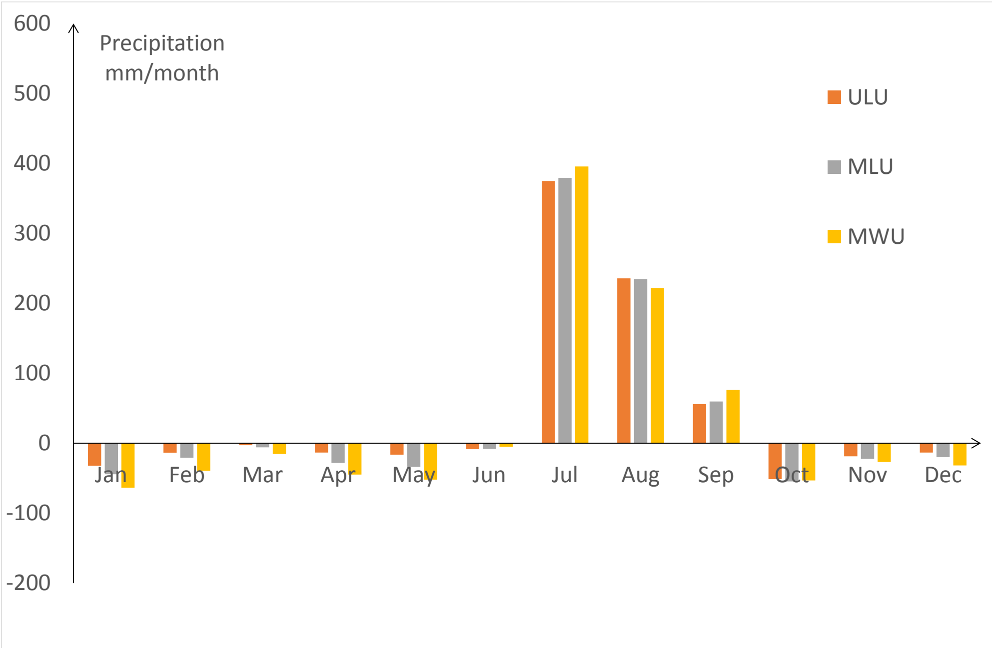


Figure 14: Monthly Water Yield (P-ET) of the three water management land use classes in the Kali Sindh basin for the year 2012 (dry year).

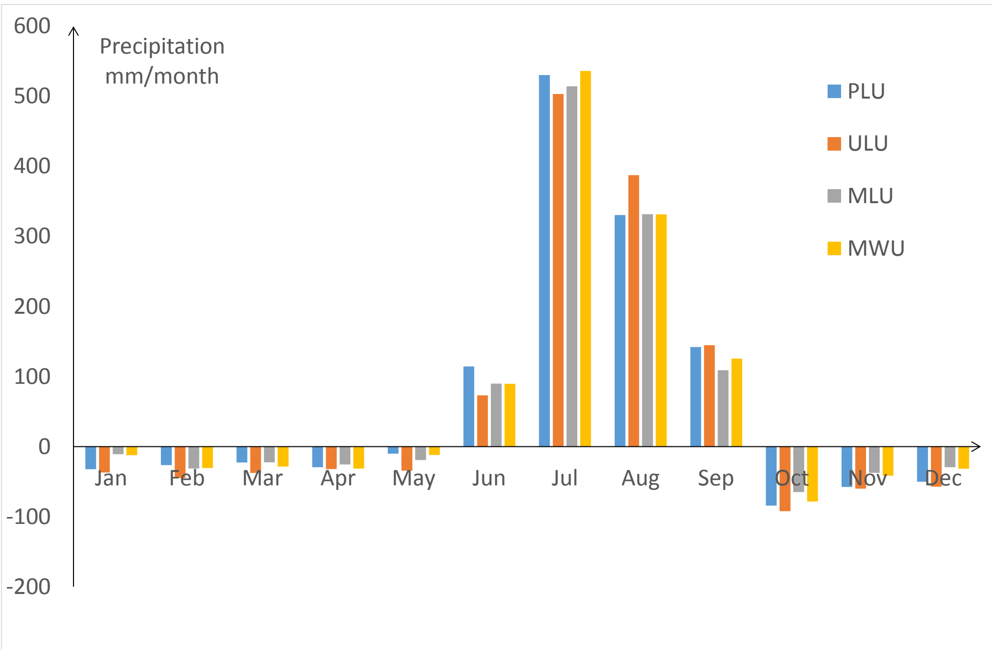


Figure 15: Monthly Water Yield (P-ET)of the four water management land use classes in the Wainganga basin for the year 2012 (dry year).

Other (RS) data collected and processed

42. 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

43. 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 16. 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).

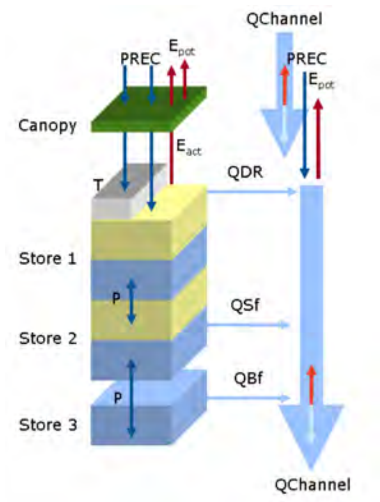


Figure 16: Schematic representation of the water balance computed by the global scale model PCR-GLOBWB.

44. 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. The Department of Water Resources of Madhya Pradesh has kindly provided data for six stations in Wainganga and one station in Kali Sindh (Figure 17). We used these data to compared 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 Wainganga basin, seems to match with ground measurement, peaks are however overestimated by the model (Figure 18). In other locations however, calibration is necessary due to reservoir operations not yet included in the computations (i.e. Deoghat station). In the Kali Sindh basin the records we received stop in 2008 and do not cover the analysed years. In Figure 19 we however compare the trends of measured river flow -1976/2008- and simulated river flow -2011/2013-; magnitude of the flow and temporal dynamic seems to be reasonable. These river flow simulations, together with PCRGLOB-WB, are used to compute Fact Sheets 1 (Resource Base) and 5 (Surface Water).

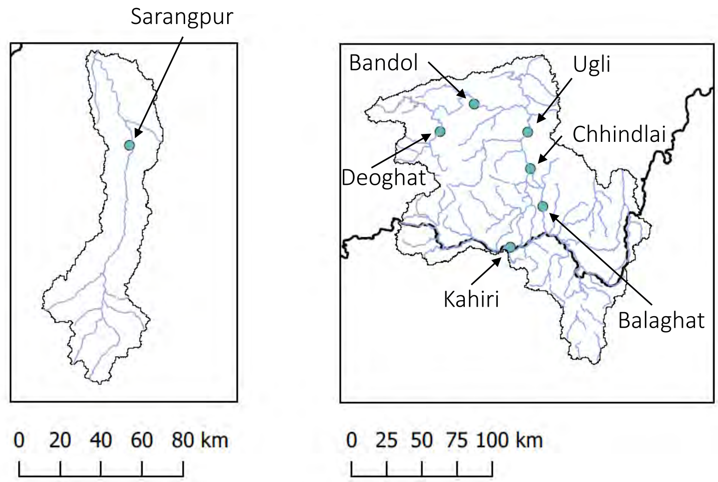


Figure 17: Location of river flow measurements stations provided by the Department of Water Resources of Madhya Pradesh for the WA+ study of Kali Sindh and Wainganga basins.

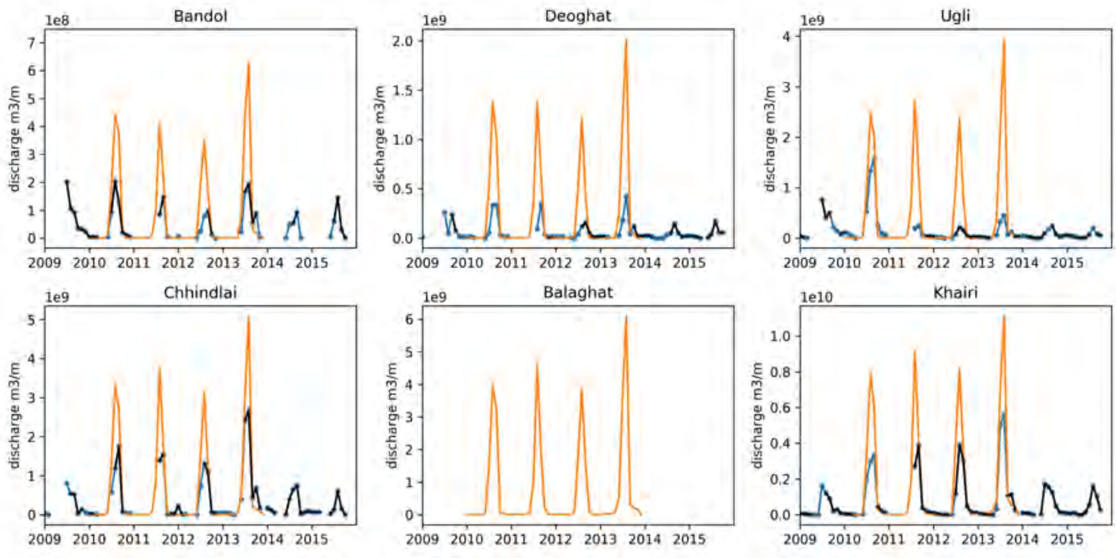


Figure 18: Comparison of WaterPix-SurfWat simulated flow with river flow measurements in six different station in the Wainganga basin.

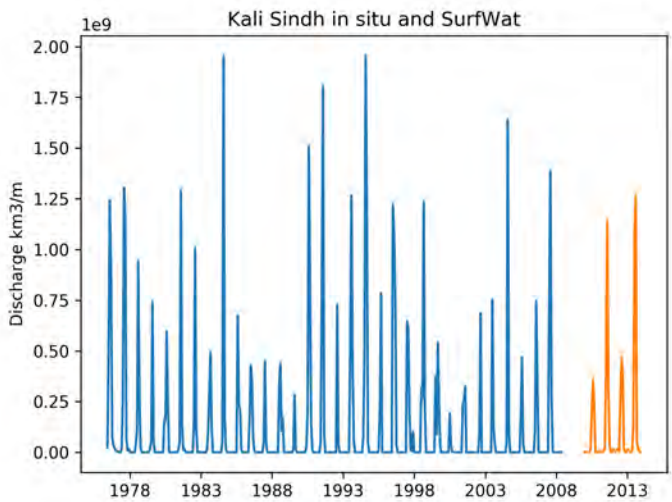


Figure 19: Comparison of WaterPix-SurfWat simulated flow with river flow measurements in one station in the Kali Sindh basin.

6 Water Accounts for the two selected river basins in Madhya Pradesh

45. In this section, we will describe the major results of the Water Accounts for the two selected river basins in Madhya Pradesh, 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: $http://wateraccounting.org/projects.html$.

46. The partitioning of land use categories by river basins is displayed in Table 8. Both river basins are heavily modified by human activity (mainly agriculture). Natural areas (PLU: Protected Land Uses and ULU: Utilized Land Uses) in Kali Sindh only account for 4.4 % and 27.9% in Wainganga (3.9% of the total area has a protected status).

Table 8: Partitioning of land use categories for analysed basins in Madhya Pradesh. PLU = Protected Land Use, ULU = Utilized Land Use, MLU = Modified Land Use, and MWU = managed Water Use

Basin	PLU [%]	ULU [%]	MLU [%]	MWU [%]
Kali Sindh	0.0	4.4	45.5	50.1
Wainganga	3.9	23.9	32.4	39.8

6.1 Sheet 1: Resource Base

47. 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.

48. An example of Sheet 1 is presented in Figure 20 and Figure 21 for the year 2011 for Kali

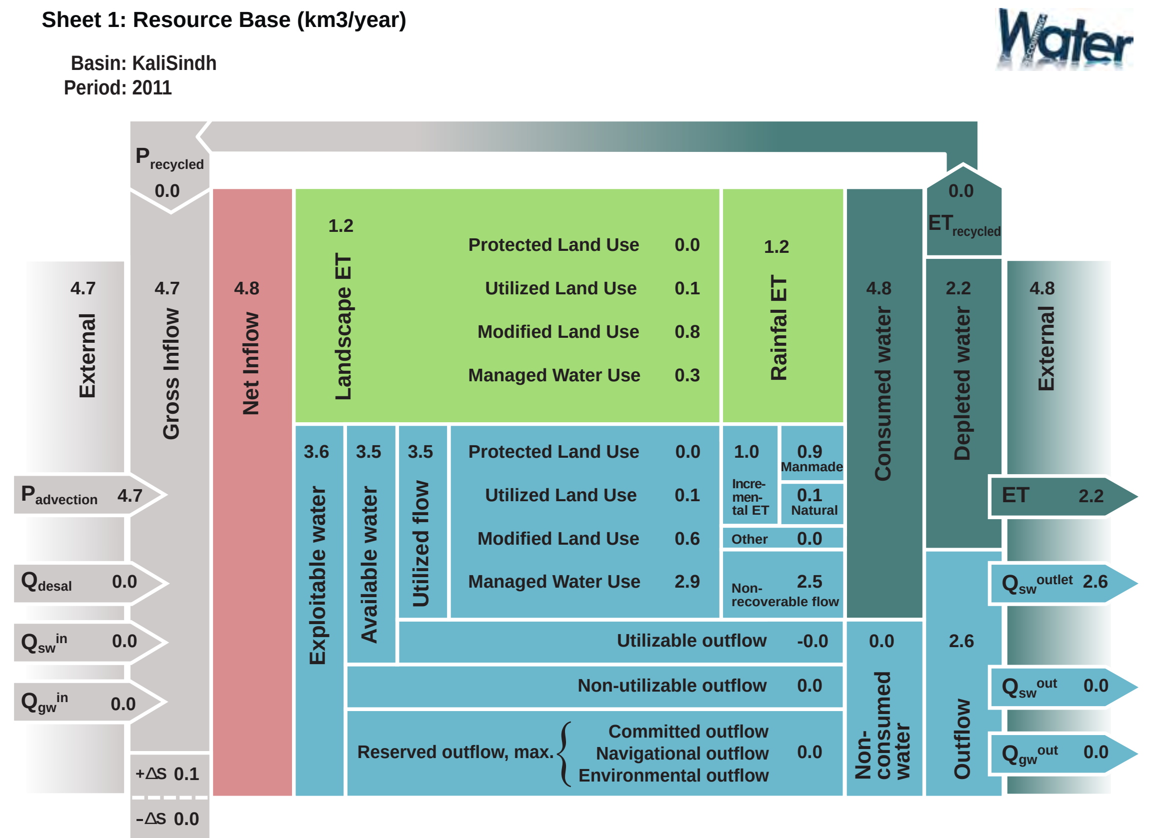


Figure 20: Resource Base sheet for the Kali Sindh basin during the year 2011.

49. The Kali Sindh basin has no utilizable outflow and at this rate of consumption (4.8 km^3/yr) is not able to fulfil the minimum flow requirements (Reserved outflow) even by taking 0.1 km^3/yr from storage (Figure 20). The utilized flow (3.5 km^3/yr) is a large fraction of the net inflow (4.8 km^3/yr). Non-recoverable flow (or polluted water) is computed using global maps of graywater footprint. Values of non-recoverable flows are high in the Kali Sindh basin and reaches 2.5 km^3/yr in 2011. The rate of moisture recycling (ET recycled and P recycled on top of Figure 20) is negligible. Low values of ET recycled are however

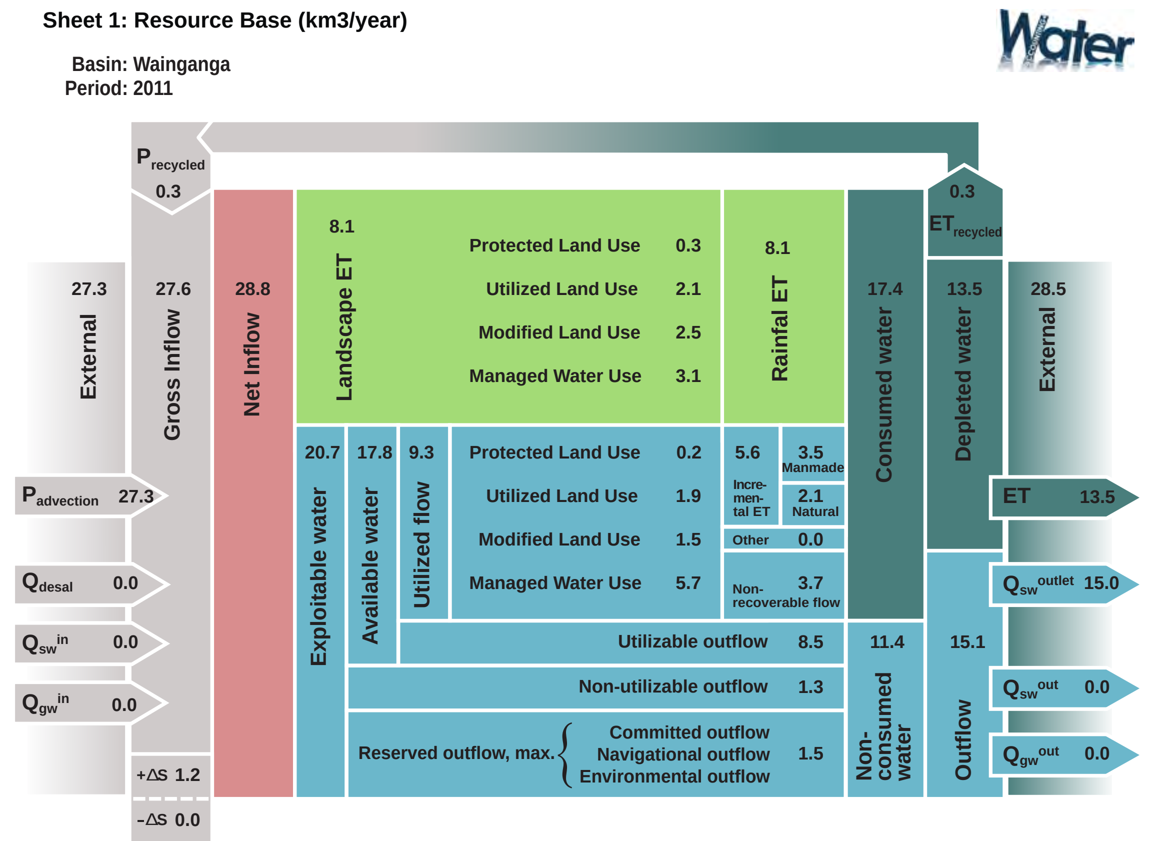


Figure 21: Resource Base sheet for the Wainganga basin during the year 2011.

normal for small river basins. ET green (or Landscape ET) is slightly higher than ET blue (or incremental ET) and most of the blue water consumption happen in areas modified by anthropogenic activities (Mandmade ET is 90% of the total blue ET).

50. In the Wainganga basin the utilizable outflow is only 8.5 km^3/yr while the total consumption reaches 17.4 km^3/yr. On a yearly scale the basin is able to fulfil the minimum flow requirements (1.5 km^3/yr) which means 8.5 km^3/yr could be utilized for future developments (Figure 21). However in this particular year 1.2 km^3/yr are taken from storage, this parameter needs to be monitored to assess if this is a systematic situation that can lead to overexploitation of surface and groundwater resources. Non-recoverable flow is also high in the Wainganga basin and reaches 3.7 km^3/yr in 2011. The rate of moisture recycling is not negligible (0.3 km^3/yr). Figure 21 only portrays a yearly situation; additional information can be derived from the monthly analysis of water resources conditions, specifically in dry months. Figure 22 presents an example of such monthly information for the Wainganga basin in January 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 Wainganga basin.

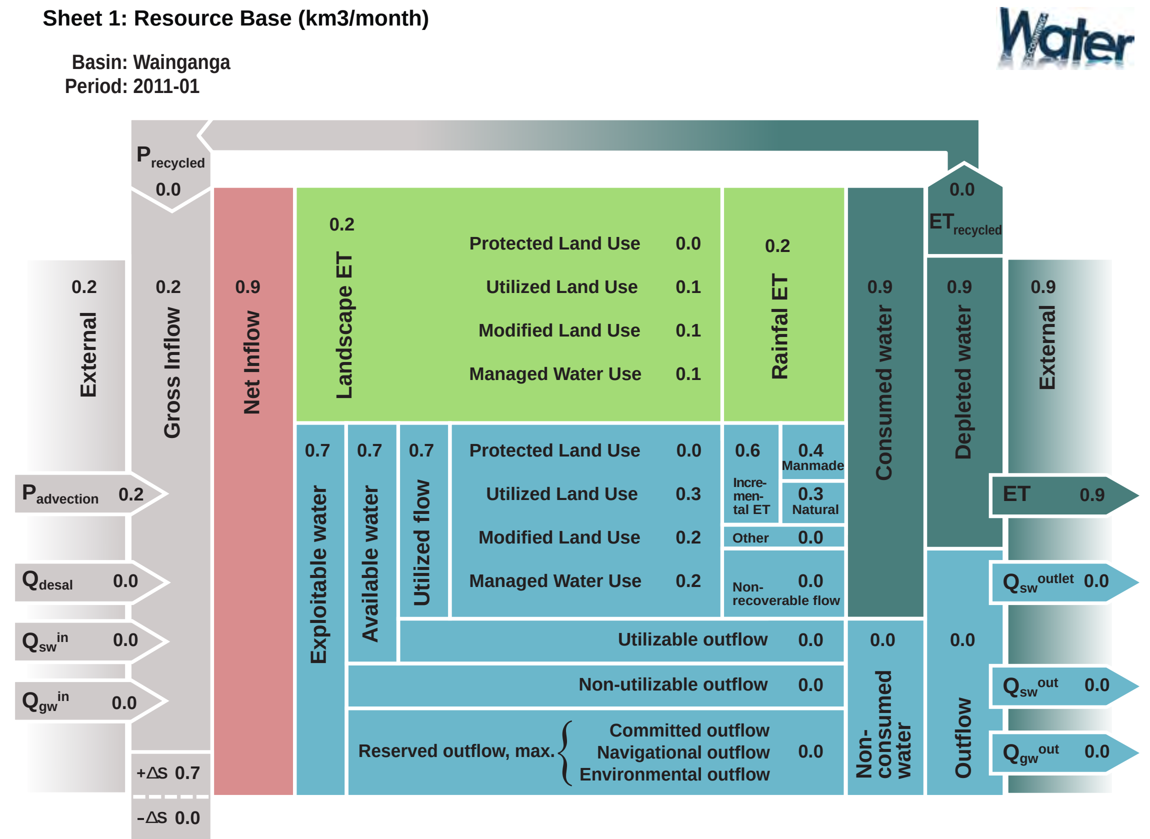


Figure 22: Resource Base sheet for the Wainganga basin during the month of January 2011.

51. In Table 9, we present a comparison of the two analyzed catchments in terms of parameters that can be directly extracted from Sheet 1. We focus on two particular elements of Sheet 1, being the Utilizable Outflow and the Exploitable Water Resources. Exploitable water resources is the 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 9 depicts the annual situation, and that monthly conditions may vary greatly.

52. The fifth column in Table 9 is the ratio between Utilizable Outflow and the Available Water. This parameter gives indications on the space for water development of the basin. The Kali Sindh basin utilizes in average all the available water and it results in being, on a yearly scale, a closed river basin where water is not even sufficient to fulfil the minimum

environmental flow requirements. The Wainganga basin utilizes more than 50% of the available water but additional volumes could be allocated for further developments in the basin.

Table 9: Summary of some components of the Resource Base sheet (U_O = Utilizable Outflow, A_W = Available Water).

Basin	P $[km^3/yr]$	ET $[km^3/yr]$	U_O $[km^3/yr]$	U_O/ A_W [%]
Kali Sindh	4.8	2.4	0.0	0.0
Wainganga	30.4	14.9	10.0	48

53. Sheet 1 describes the water balance at the river basin scale. We can therefore look at the temporal variation of the water balance and analyse seasonal variability. In Figure 23 and Figure 24, we present the major components of the water balance for the two basins. Even though in the Wainganga volumes are five times higher the temporal trends are similar. Water stored during the wet season is then depleted in the dry season.

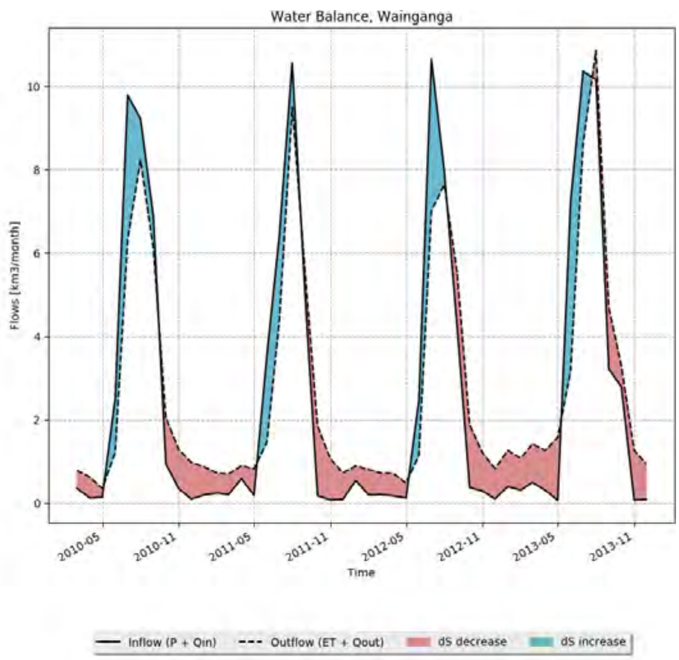


Figure 23: Water balance temporal evolution in the Kali Sindh basin for the analysed years (2011-2013).

54. Overexploitation of surface and groundwater can be identified by analysing the evolution of the storage change in Sheet 1 or the cumulative storage change over time (Figure 25 and Figure 26). Because of the monsoonal climate, water storage in the two basins steadily increases and can reach to an intensity of $+0.7$ km^3/month and 4 km^3/month in the Kali Sindh and Wainganga respectively (if we exclude the first dry months). At a total basin

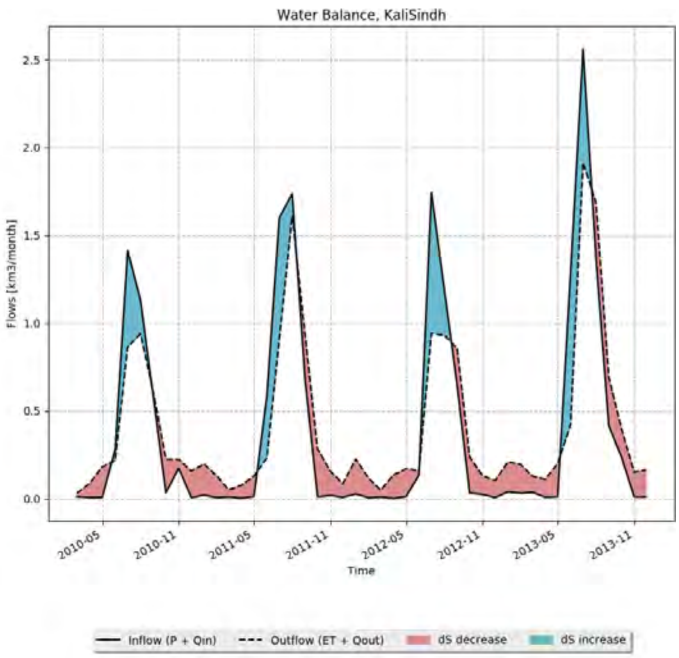


Figure 24: Water balance temporal evolution in the Wainganga basin for the analysed years (2011-2013).

area of about 3,800 km^2 (Kali Sindh) and 18,500 km^2 (Wainganga), this is an equivalent depth of 180 mm/month and 210 mm/month. Delta S decreases again during the dry season, and seems not to recover completely in 2013 in the Wainganga basin. The previous years were relatively dry and this could be the cause of the cumulative decrease in storage. 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.

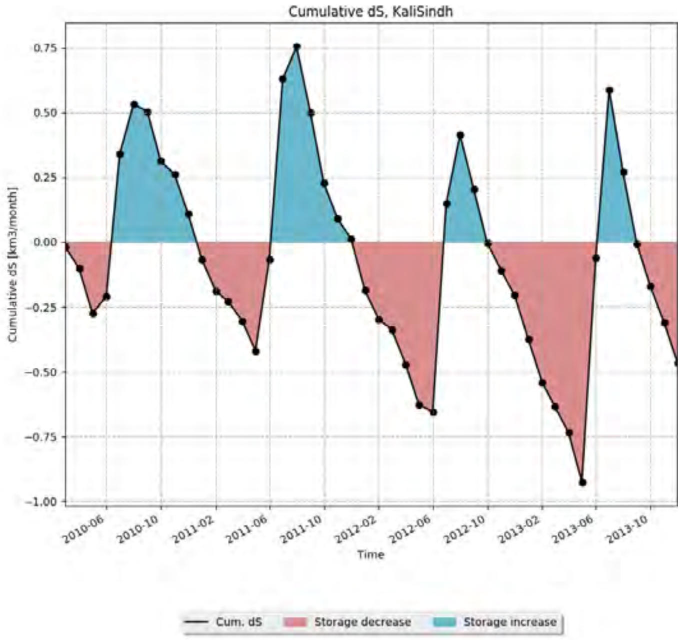


Figure 25: Temporal evolution of the storage change in the Kali Sindh basin during the analysed years (2011-2013).

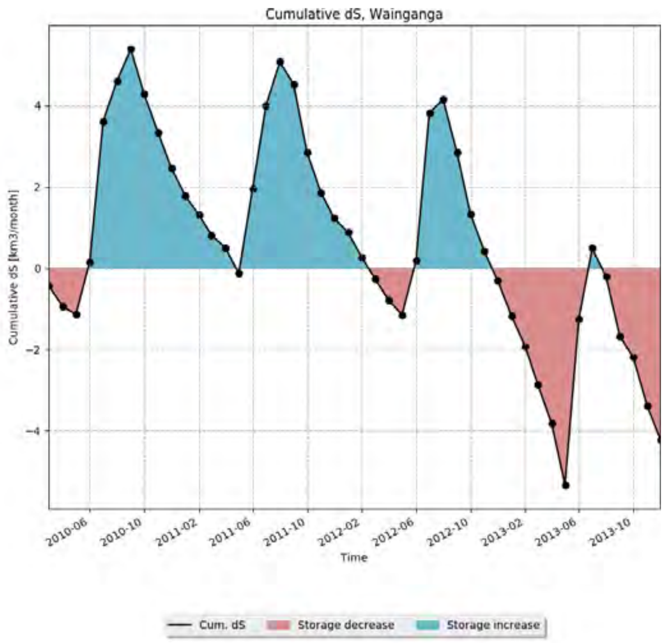


Figure 26: Temporal evolution of the storage change in the Wainganga basin during the analysed years (2011-2013).

6.2 Sheet 2: Evapotranspiration

55. 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 27 and Figure 28 where we show the situation in 2011 for the Kali Sindh and Wainganga basin.

56. In 2011 the total ET consumption in the Kali Sindh was 2.3 km^3/yr and in the Wainganga basin 13.7 ^{3}/yr. Rainfed and irrigated crops are the responsible of most of the water consumption in the Kali Sindh basin while in the Wainganga basin also natural areas (protected and non-protected) significantly contribute to total water consumption in the basin. A non-negligible part of ET in Wainganga basin is therefore non-manageable.

57. Non-Beneficial water consumption is very high for both analyzed catchments (between 63% to 70% of the total ET, see Table 10). 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 and flooded irrigation. In the Kali Sindh basin the proportion of Beneficial Consumption is slightly higher than in the Wainganga basin and this might be due to the fact that Kali Sindh is already a closed river basin and that water needs to be used more efficiently.

Table 10: Summary of Beneficial Consumption (BC) and Non-Beneficial Consumption (N-BC) for the two analysed river basins in Madhya Pradesh. The values are averages of the analyzed years.

Basin	BC [km^3/yr]	Relative BC [%]	N-BC [km^3/yr]	Relative N-BC [%]
Kali Sindh	0.9	37.1	1.5	62.9
Wainganga	4.5	30.1	10.5	69.9

58. 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 Wainiganga basin is presented in Figure 29 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)

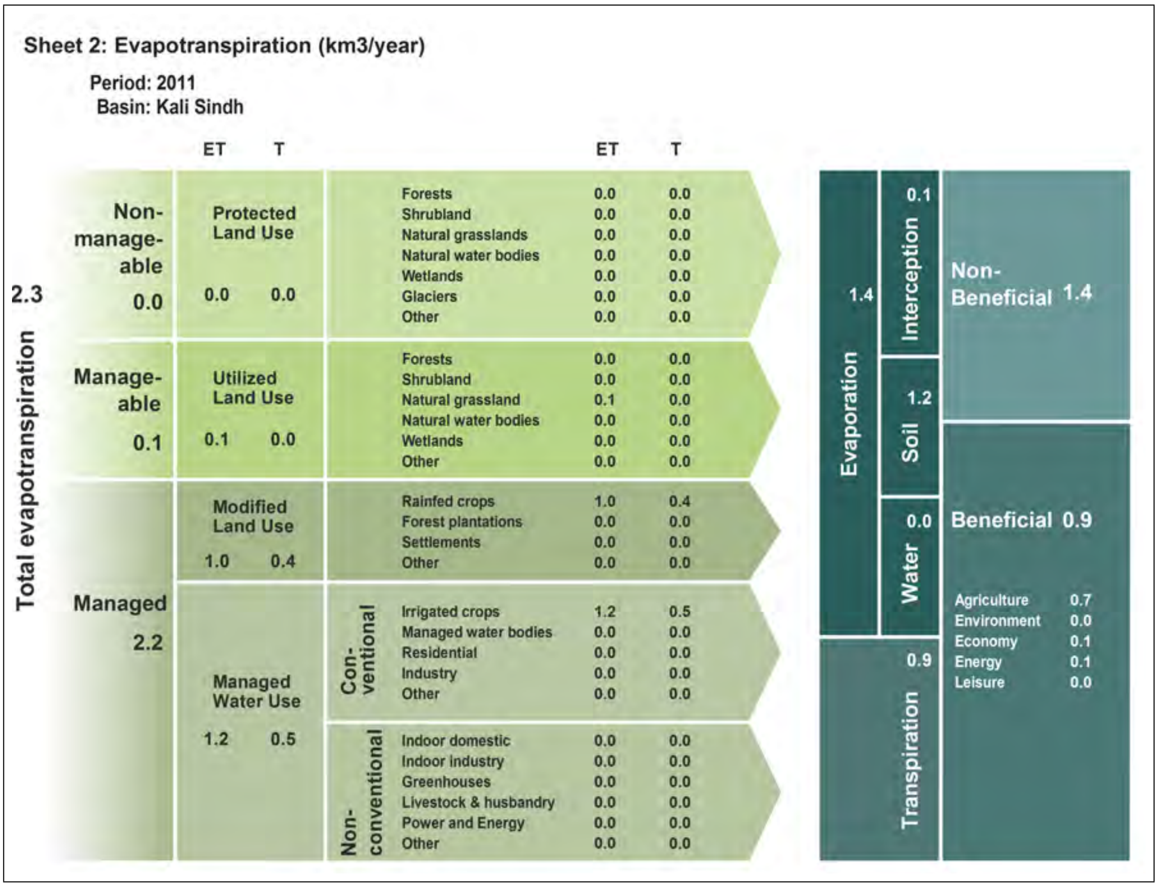


Figure 27: Evapotranspiration sheet for the Kali Sindh basin during the year 2011.

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.

59. 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 30, the reader can see the break down of the Beneficial Consumption in these categories for the two river basins in Madhya Pradesh. Water Consumption in these two basins is primary beneficial for the Agriculture (between 53 and 71% of the beneficial consumption), while only a very limited fraction is consumed providing leisure benefits, producing energy or economical value (the maximum value is 14% in the Kali Sindh basin for energy production). The Kali Sindh basin is also the least natural basin and water consumption for agriculture has the highest beneficial fraction due to the intensive agricultural activity.

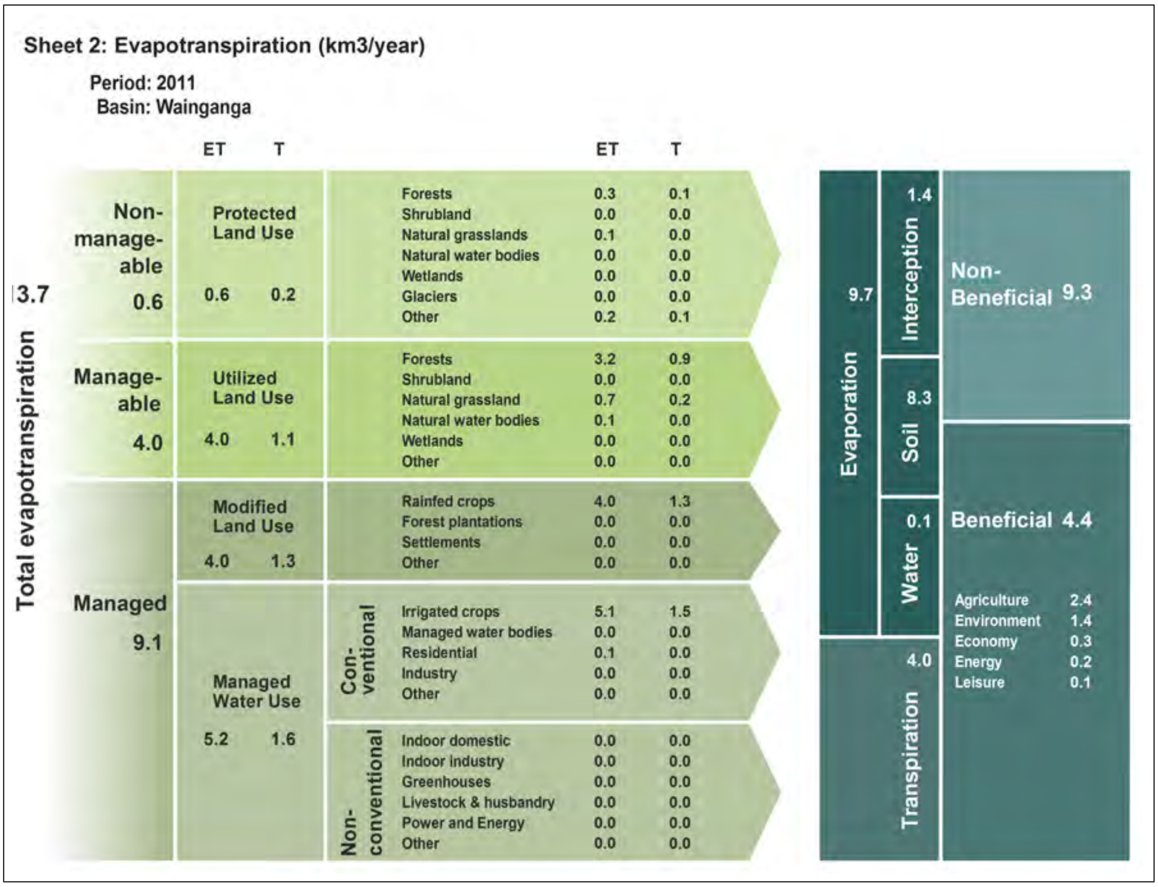


Figure 28: Evapotranspiration sheet for the Wainganga basin during the year 2011.

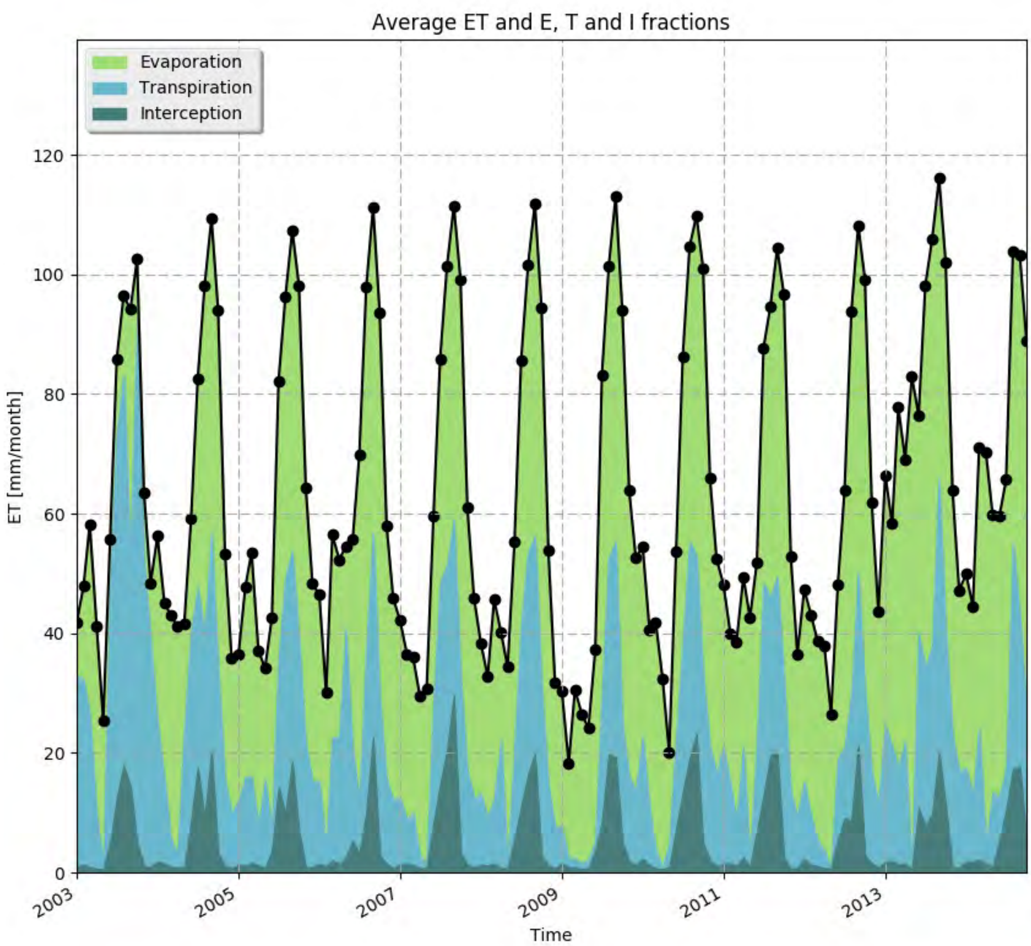


Figure 29: Temporal variation of ET components (evaporation, transpiration and interception) in the Wainganga basin.

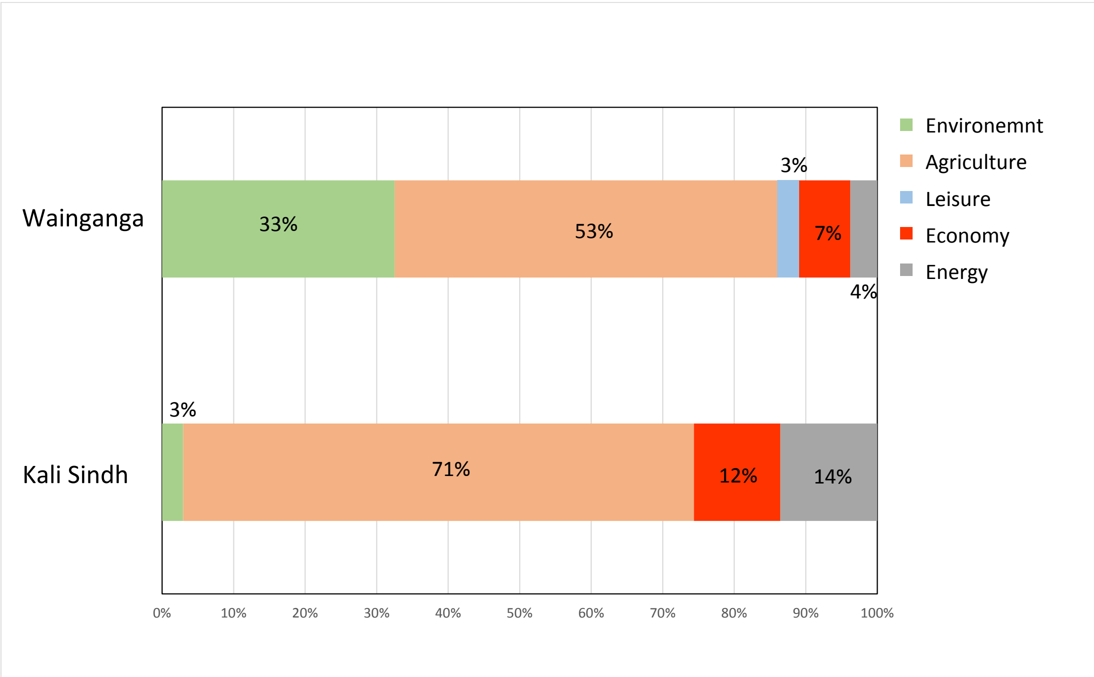
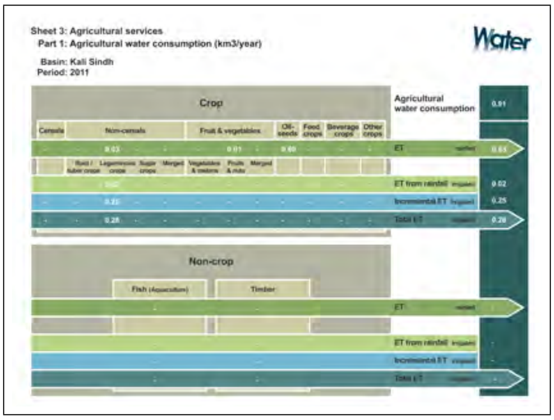


Figure 30: The beneficial consumption is further subdivided into five groups that refer to the services produced: Environment, Agriculture, Leisure, Economy, and Energy.

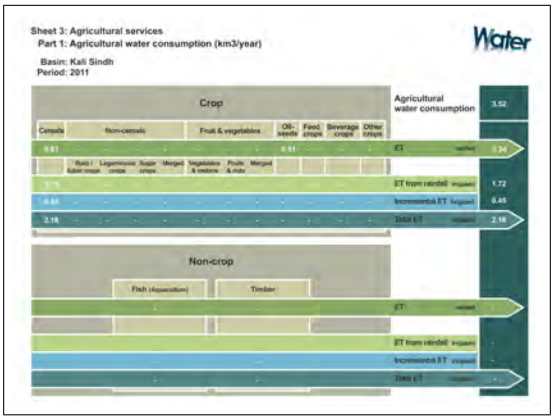
6.3 Sheet 3: Agricultural Services

60. 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 31a and Figure 31c) and part 2 the land and water productivity (Figure 31b and Figure 31d).



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

(b) Sheet 3 part 2: Land productivity and water productivity for the Kali Sindh basin (2011).



(c) Sheet 3 part 1: Agricultural water consumption for the Wainganga basin (2011).

(d) Sheet 3 part 2: Land productivity and water productivity for the Wainganga basin (2011).

Figure 31: Agricultural services sheets for the two analysed basins in 2011

61. We have estimated Crop Yield and Water Productivity (ratio between crop yield - production- and Actual ET -consumption-) solely using Remote Sensing data in the Kali

Sindh and Wainganga basins. The major crops analysed and the crop seasons considered are summarized in Table 11. The results of the yearly Sheets 3 are summarized in Table 12 where the values for cereals are the totals of wheat and paddy rice for the Wainganga basin. The values of agricultural production and water productivity of cereals are generally low if compared with world average (world average: 6000 kg/ha) but irrigated areas are in line with the average production in India (3000 kg/ha). Irrigated area have generally higher yield and higher water productivity as compared to the rainfed systems, partially because they can cover two crops per year, while the rainfed systems have one rotation per year.

Table 11: Major crops a crop seasons analysed for the Kali Sindh and Wainganga basins.

Basin	Crop Type WA+	Specific Crop Type	Start season	End Season
Kali Sindh	Leguminous Rainfed	Gram	1 December	1 February
	Leguminous Irrigated	Gram	1 December	1 March
	Fruits & Nuts Rainfed	Oranges	1 January	21 December
	Oil Seed Rainfed	Soybean	1 June	30 November
Wainganga	Cereals Rainfed	Rice	1 August	1 October
	Cereals Rainfed	Wheat	1 December	1 February
	Cereals Irrigated	Rice	15 July	15 October
	Cereals Irrigated	Wheat	15 November	1 March
	Oil Seeds Rainfed	Soybean	15 July	1 October

Table 12: Summary of the results of Sheet 3 for the two analysed basins in Madhya Pradesh. Values are yearly averages for the basin.

Kali Sindh 2011	Crop Type	Area [km2]	Yield [kg/ha]	Food Prod. [Mt/season]	ET [km3/season]	WP [kg/m3]
	Leguminous Rainfed	297.3	779	0.023	0.03	0.84
	Leguminous Irrigated	1863.6	1347	0.251	0.28	0.89
	Fruits & Nuts Rainfed	8.2	12037	0.010	0.01	1.77
	Oil Seeds Rainfed	1416.2	1066	0.151	0.6	0.25
2012						
	Leguminous Rainfed	297.3	791	0.024	0.03	0.81
	Leguminous Irrigated	1863.6	1105	0.206	0.26	0.78
	Fruits & Nuts Rainfed	8.2	9548	0.008	0.01	1.27
	Oil Seeds Rainfed	1416.2	944	0.134	0.59	0.23
2013						
	Leguminous Rainfed	297.3	806	0.024	0.03	0.86
	Leguminous Irrigated	1863.6	1223	0.228	0.30	0.74
	Fruits & Nuts Rainfed	8.2	12109	0.009	0.01	1.50
	Oil Seeds Rainfed	1416.2	1159	0.164	0.64	0.25
Wainganga 2011	Crop Type	Area [km2]	Yield [kg/ha]	Food Prod. [Mt/season]	ET [km3/season]	WP [kg/m3]
	Cereals Rainfed	3827.5	1771	0.678	0.83	0.81
	Cereals Irrigated	7267.3	3187	2.32	2.18	1.06
	Oil Seeds Rainfed	2163.3	1228	0.266	0.51	0.52

2012						
	Cereals Rainfed	3827.5	1448	0.554	1.45	0.38
	Cereals Irrigated	7267.3	2507	1.821	2.10	0.87
	Oil Seeds Rainfed	2163.3	949	0.205	0.50	0.41
2013						
	Cereals Rainfed	3827.5	1797	0.688	0.91	0.76
	Cereals Irrigated	7267.3	3167	2.30	2.43	0.95
	Oil Seeds Rainfed	2163.3	1298	0.281	0.56	0.50

62. In the Kali Sindh basin, the Dewas district seems to have the most productive areas for gram and soybean (Figure 32). The most productive areas for gram have however the lowest values of Water Productivity meaning that large volumes of water are consumed in these areas for producing up to 1500 kg/ha of gram. The opposite is true for soybean, areas with the highest production have also the highest Water Productivity which however only reaches 0.35 kg/m^3. Large variations in Water Productivity exists in the Kali Sindh basin, specially for gram. In the top right image in Figure 32, the reader can see the Water Productivity map for irrigated gram for the year 2013. The values ranges from less than 0.5 kg/m^3 in red and more than 1.2 kg/m^3 in blue. Agricultural area in blue produce more than double the amount of crop with the same amount of water than areas in red. These areas are localized at the central part and at the outlet of the basin.

63. In Figure 33, we show, as an example, the spatial distribution of wheat yield generated from rainfed and irrigation systems for the Wainganga in 2013, and its Water Productivity. The highest values of the yield belong to irrigated areas in the North part of the basin (Seoni district) and reaches values of 1.3 t/ha. These areas also have the highest values of Water Productivity in the basin, up to 1.6 kg/m^3. The North part of the basin also produces soybean reaching up to 1.6 t/ha and a water productivity of 0.6 kg/m^3 (Figure 34). Rice is also produced in the Wainganga basin and in Figure 35 we present the spatial distribution of crop yield and Wate Productivity for rainfed and irrigated systems. In irrigated areas around double yield is produced (up to 2.2 t/ha) while Water Productivity is only slightly higher (up to 0.6 kg/m^3 and up to 0.7 kg/m^3 in rainfed and irrigated areas respectively). These values of Water Productivity are however low, well below the world average of 1.1 kg/m^3.

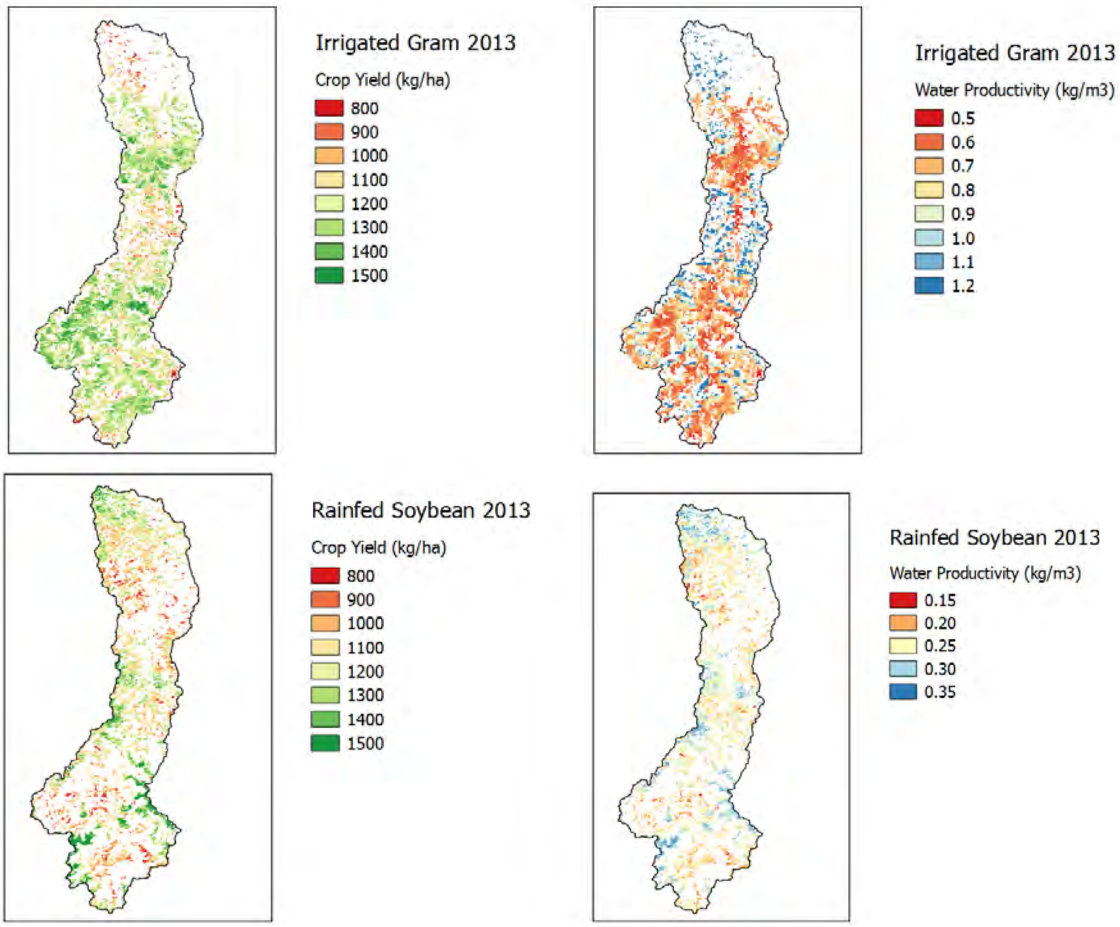


Figure 32: Crop Yield and Water Productivity of Irrigated Gram and Rainfed Soybean in the Kali Sindh basin for the year 2013.

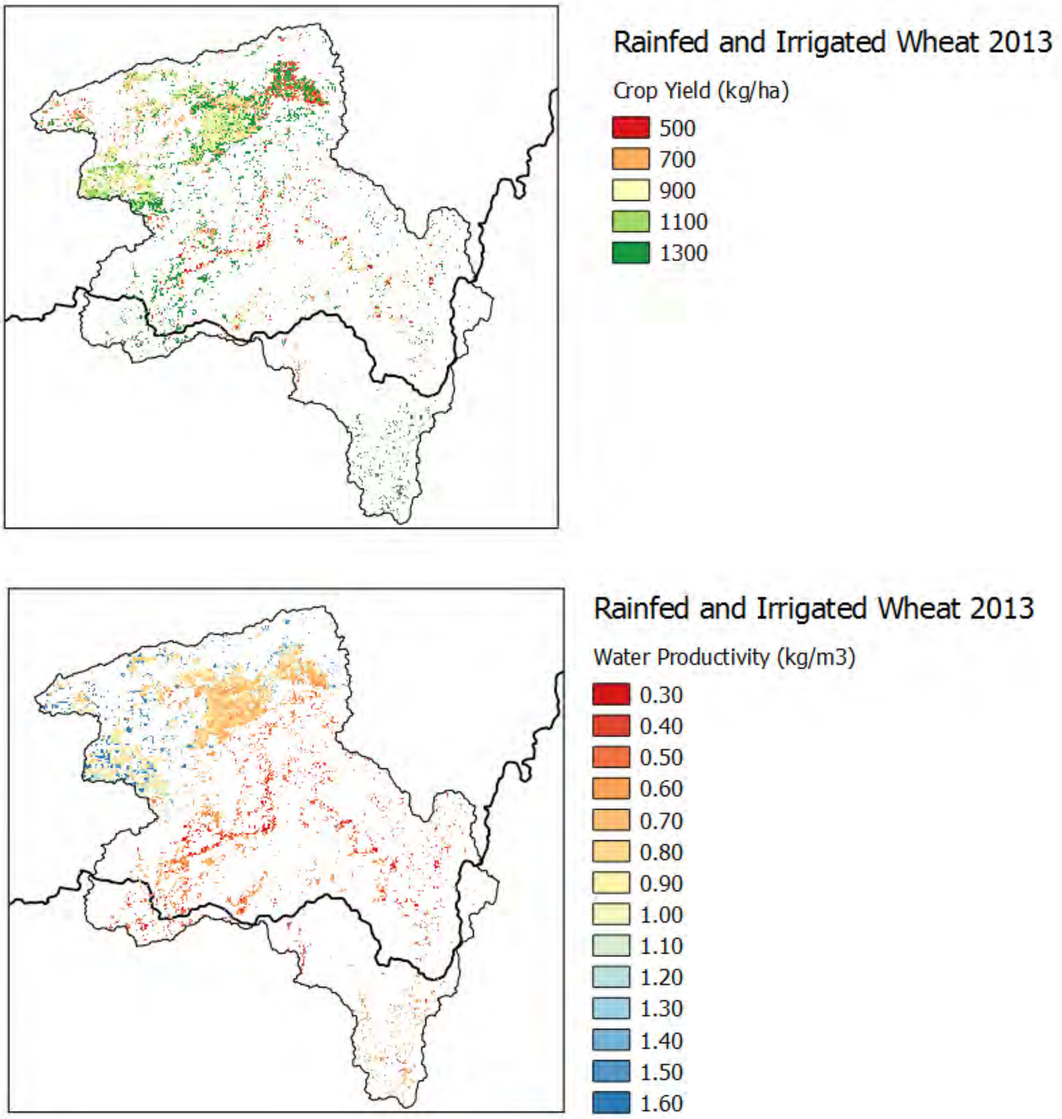


Figure 33: Crop Yield and Water Productivity of Rainfed and Irrigated Wheat in the Wainganga basin for the year 2013.

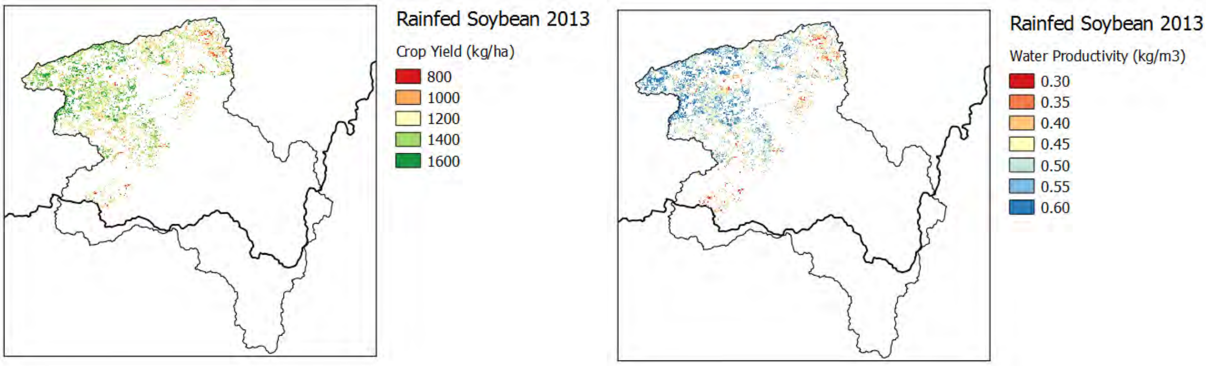


Figure 34: Crop Yield and Water Productivity of Rainfed Soybean in the Wainganga basin for the year 2013.

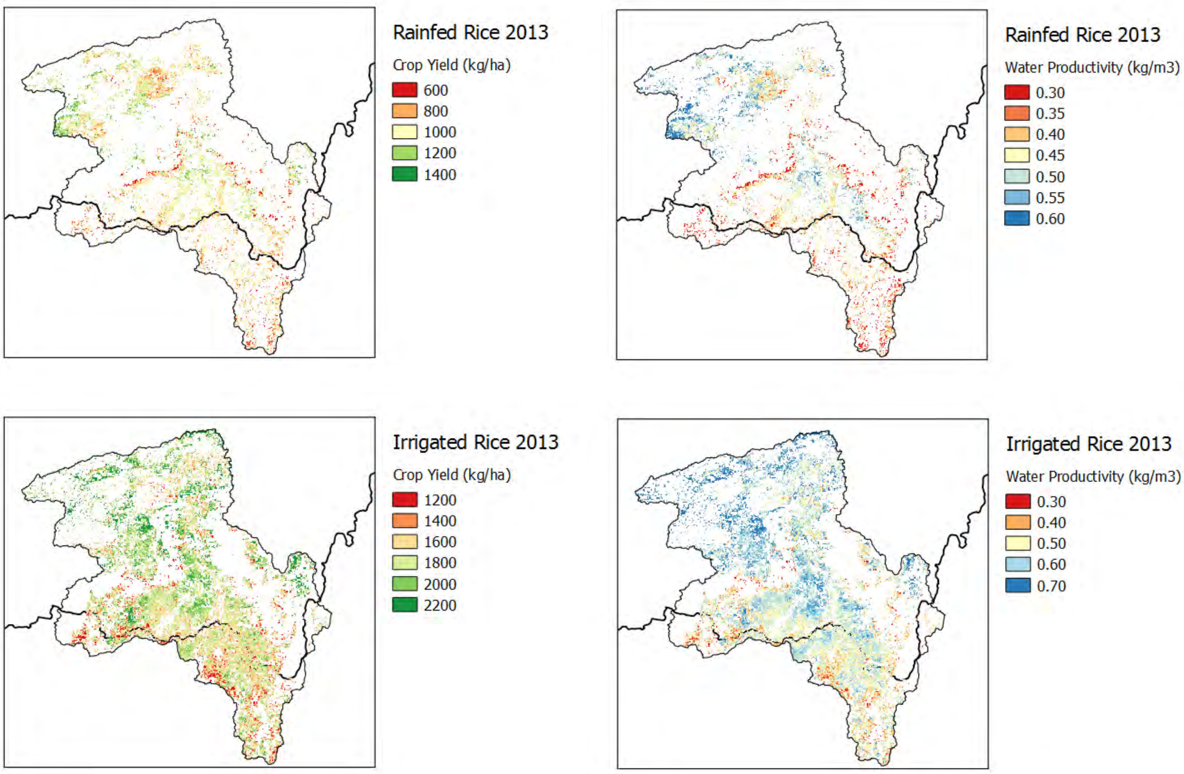
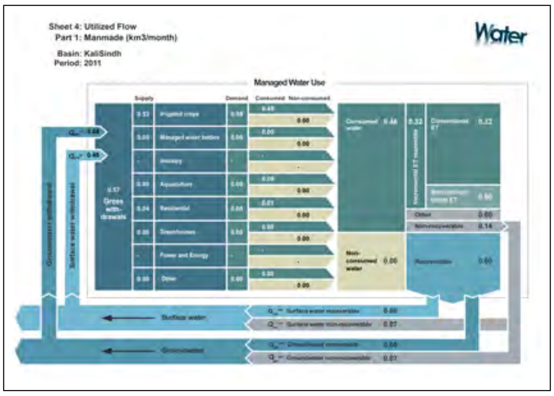


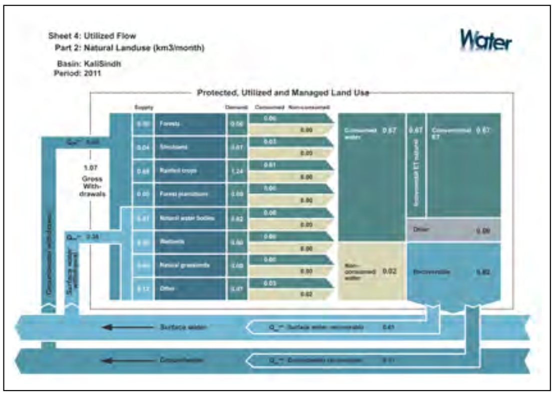
Figure 35: Crop Yield and Water Productivity of Rainfed and Irrigated Rice in the Wainganga basin for the year 2013.

6.4 Sheet 4: Utilized Flows

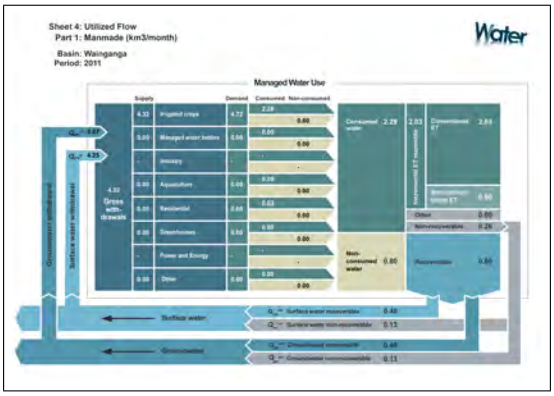
64. The estimation green and blue water (consumption and withdrawals) is a very relevant piece of information for integrated water resources management. Blue water withdrawals are of particular interest to water managers and should be assess for both natural and areas modified by human activity. Sheet 4 presents utilized flows (blue water) for the major land use groups in a river basin (Figure 36).



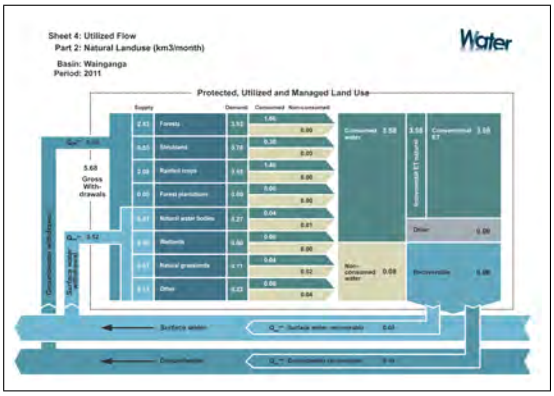
(a) Sheet 4 part 1: Utilized Flow Manmade for the Kali Sindh basin (2011).



(b) Sheet 4 part 2: Utilized Flow Natural Landuse for the Kali Sindh basin (2011).



(c) Sheet 4 part 1: Utilized Flow Manmade for the Wainganga basin (2011).



(d) Sheet 4 part 2: Utilized Flow Natural Landuse for the Wainganga basin (2011).

Figure 36: Utilized flows sheets for the two analysed basins in 2011

65. 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 13). In both basins, the majority of blue water withdrawals happen in areas where the land has been modified by human activities and can be attributed mainly to irrigated agriculture. The Wainganga basin has more natural land cover areas which are responsible for 37% of the blue water withdrawals (forests and natural water bodies). Water bodies rely on surface water, while forests root deep and use groundwater during the dry season and can be considered partially groundwater dependent ecosystems.

Table 13: Blue water consumption partitioning into natural and man-made withdrawals for the two analyzed basins. The values are an average of the selected years.

Basin	ET blue man-made [%]	ET blue natural [%]
Kali Sindh	91.4	8.6
Wainganga	63.0	37.0

66. 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 14, we present the Water Scarcity indicators for the two river basins in Madhya Pradesh during the three analyzed years. Obviously in the wettest year, water stresses (both surface and ground water) were the lowest but still significant in the Wainganga basin. Natural areas in the Wainganga basin, even if they receive more rainfall than the Kali Sindh basin, are more water stressed. Natural area and particularly national parks require more water, specially in the dry season. Water stress values in the Kali Sindh basin are low because most of the area of the basin is no longer covered by natural vegetation.

Table 14: Water Scarcity in the two river basins in Madhya Pradesh 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.

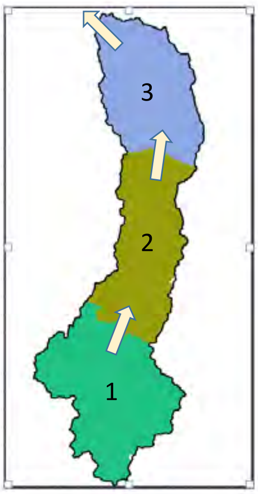
2011 -average-								
	Forests	Shrubland	Forest plantations	Natural water bodies	Wetlands	Natural grasslands	Other	
Basin	Groundwater stress			Surface water stress				Total stress
Kali Sindh	-	0.03	-	0.01	-	0.0	-	0.04
Wainganga	1.10	0.26	-	0.20	-	0.04	0.09	1.69
2012 -dry-								
	Forests	Shrubland	Forest plantations	Natural water bodies	Wetlands	Natural grasslands	Other	
Basin	Groundwater stress			Surface water stress				Total stress
Kali Sindh	-	0.0	-	0.0	-	0.0	-	0.0
Wainganga	0.42	0.11	-	0.16	-	0.03	0.03	0.75
2013 -wet-								
	Forests	Shrubland	Forest plantations	Natural water bodies	Wetlands	Natural grasslands	Other	
Basin	Groundwater stress			Surface water stress				Total stress
Kali Sindh	-	0.01	-	0.0	-	0.0	-	0.01
Wainganga	0.30	0.11	-	0.14	-	0.0	0.0	0.55

67. Groundwater stress is higher than surface water stress which relates to groundwater dependent ecosystems (mainly forests that rely on groundwater during the dry season).

Noticeable is also the fact that the driest year is not the year with the highest water stress. Seasonal variability of rainfall, temperature and cloud coverage plays a great role in this context and the average year results in having the highest water stress for all the analyzed basins.

6.5 Sheet 5: Surface Water

68. 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 Kali Sindh and Wainganga basins, 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 Kali Sindh basin into three sub-basins and the Wainganga into five sub-basins (Figure 37).



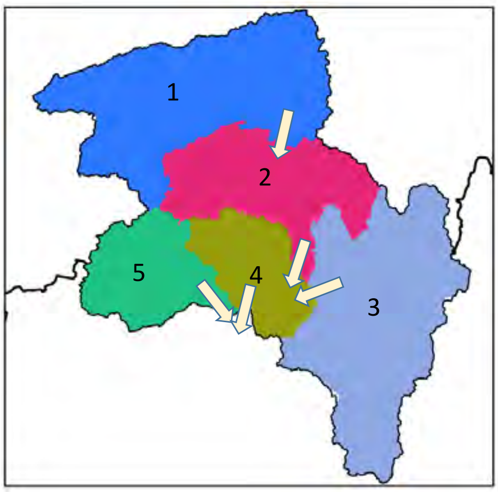


Figure 37: Subdivision of the analysed basins into sub-basins.

69. The examples in Figure 38 and Figure 39 show the surface flow components of the sub-basins of the Kali Sindh and Wainganga basins for the year 2011. The three sub-basins of the Kali Sidh basin are very comparable in size and hydrological behaviour and they generate similar rates of surface runoff (about 1 km^3/yr). No or little runoff generates from soils with

natural land cover and, as noted in Sheet 1, the entire outflow is considered non-recoverable or polluted (Figure 38). Surface withdraws represent 1/3 of the generated runoff in the sub-basins and return flow to surface water is limited (max 0.1 km^3/yr).

70. The sub-basins of the Wainganga basin differs in size and runoff generation ratio(Figure 39). Sub-basins 1 and 3 are the largest and combined produce about 60% of the total runoff, while the other three sub-basins have a variable contribution from 10 to 17 %. Approximately 25% of outflow of each sub-basin is not recoverable. A large portion of the outflow is however utilizable (9.2 km^3/yr), future possibility of storing and utilizing more surface water should be investigated in sub-basin 2 and 4 that have the highest volumes of utilizable water (4.5 and 8.1 km^3/yr).

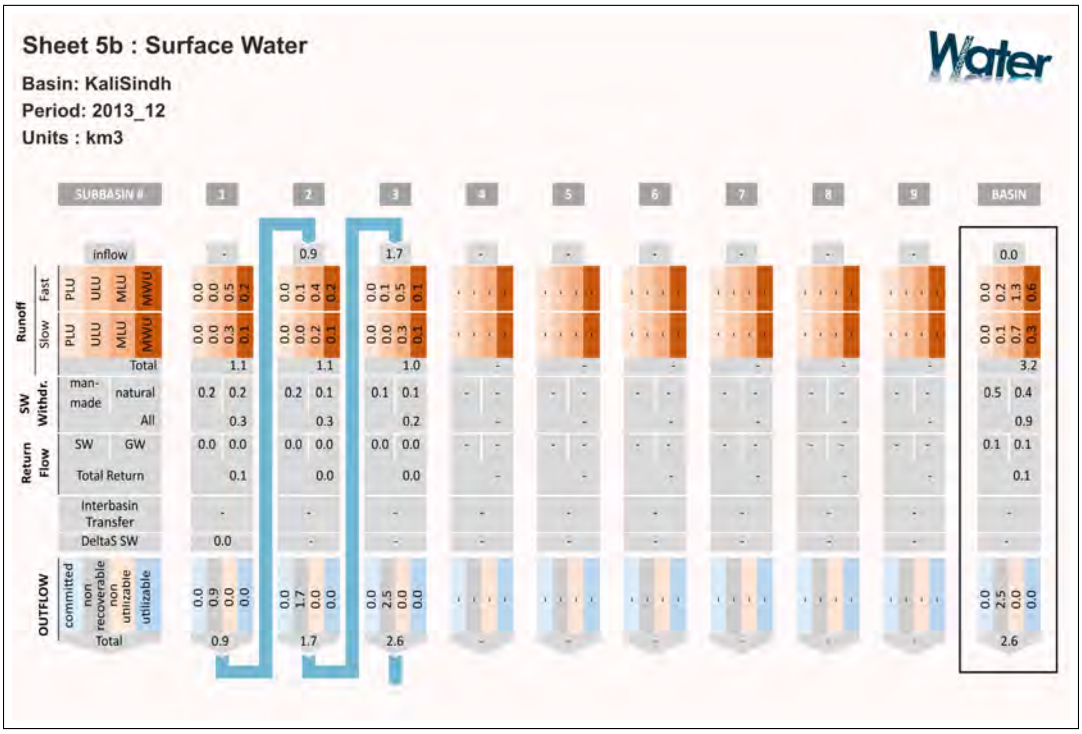


Figure 38: Sheet 5: Surface water for the Kali Sindh basins for the year 2011

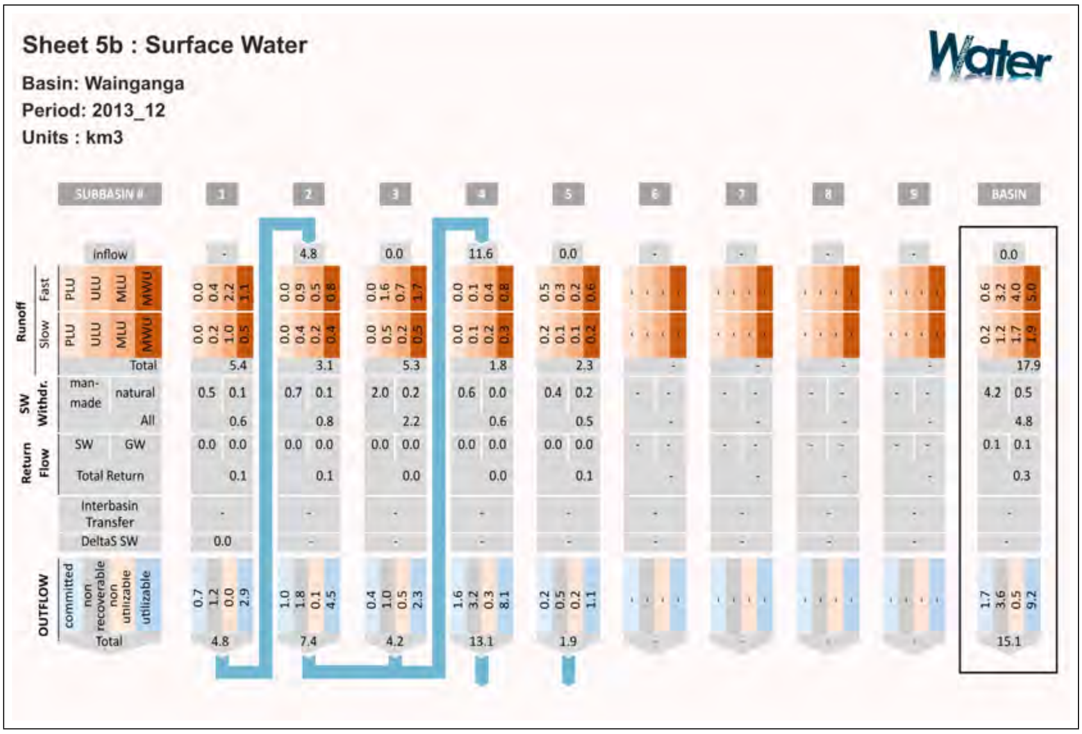


Figure 39: Sheet 5: Surface water for the Wainganga basins for the year 2011

6.6 Sheet 6: Groundwater

71. 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 40 and Figure 40).

72. 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.

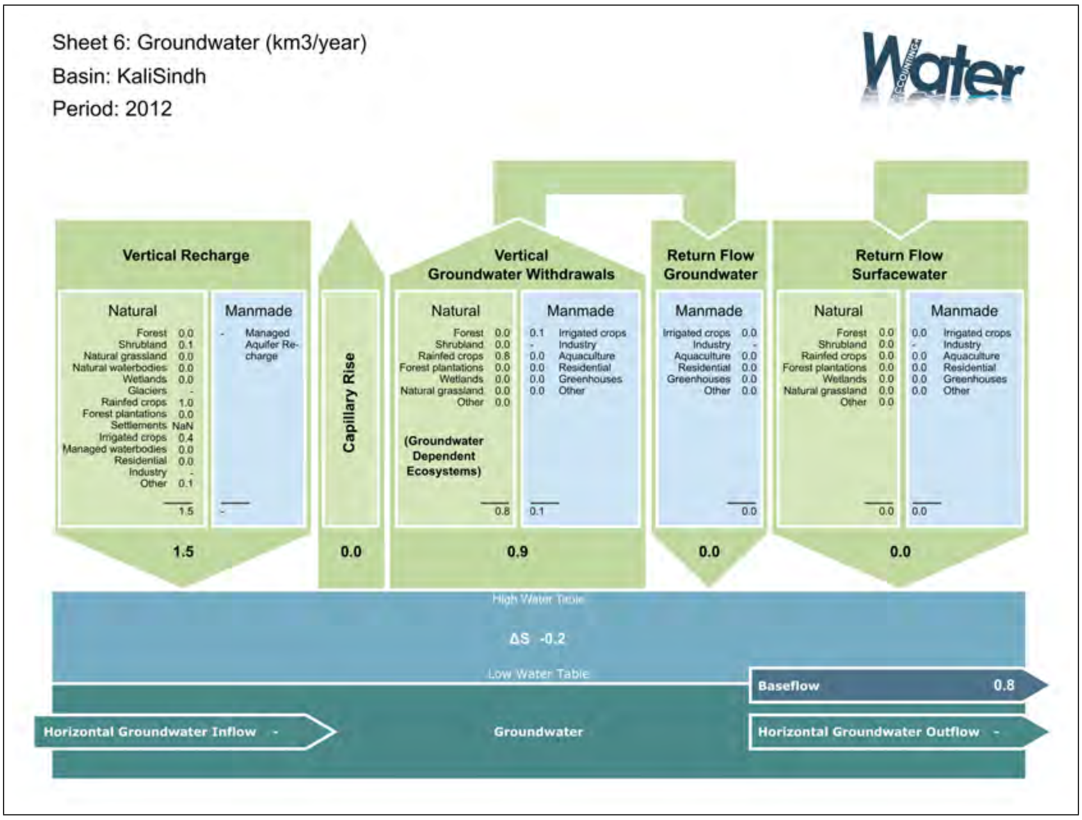


Figure 40: Sheet 6: Groundwater for the Kali Sindh basins for the year 2012

73. The example in Figure 40 and Figure 41, refers to the groundwater-related fluxes that occurred in Kali Sindh and Wainganga in 2012. In this particular year the storage change is negative in both basins and thus the natural recharge and return flows to groundwater are

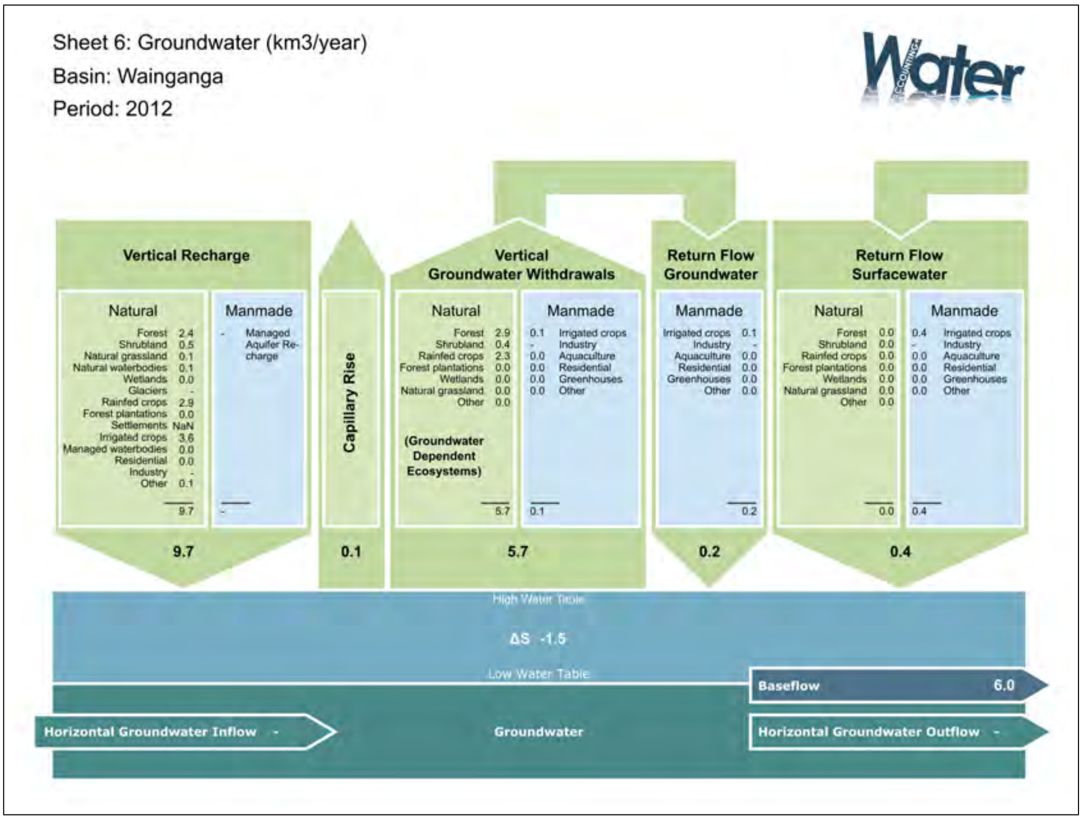


Figure 41: Sheet 6: Groundwater for the Wainganga basins for the year 2012

not sufficient to prevent the declining of the water table elevation. The two analysed basins in Madhya Pradesh show different conditions which vary mainly due to the seasonal climate variations and anthropogenic activity (Table 15). In the Wainganga basin storage change is negative also in 2013. This is surprising since 2013 was a wet year and groundwater recharge is the highest. Groundwater recharge however is always almost double than groundwater withdrawals. The fact that the groundwater system does not follow the rainfall variability (dry, wet and average years) can be explained by the different dynamics between surface and groundwater. Groundwater flow is usually several orders of magnitude slower than surface processes. 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 might occur.

74. If we analyze 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 (June to August). 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 15: Summary of the major flow components that can be derived from Sheet 6 (Groundwater) for the two analyzed basins. Values are expressed in km^3/yr

Wainganga	2011	2012	2013
Groundwater recharge	10.0	9.7	10.6
Withdrawals	5.2	5.7	5.2
Total return	0.5	5.7	5.2
Baseflow	5.1	6.0	7.5
Storage change	+0.2	-1.5	-1.8
Kali Sindh	2011	2012	2013
Groundwater recharge	1.8	1.5	2.4
Withdrawals	0.8	0.9	0.9
Total return	0.1	0.0	0.1
Baseflow	1.1	0.8	1.6
Storage change	0.0	-0.2	+0.1

7 Conclusions

75. Madhya Pradesh is facing great challenges in satisfying its growing water demand. Seasonal water scarcity, due to the monsoonal climate and increased water consumption rates, is threatening safe access. 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.

76. Competition and conflicts over the 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.

77. The benefits of water consumption in two analysed basins in Madhya Pradesh are mainly of an agricultural nature. Many forests in the protected areas of the Wainganga basin are however under water stress as additional water would be need for these ecosystems.

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

79. A remarkable large 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.

80. 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 flood water seasonally. 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 in the Wainganga basin 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.
- Increase the yield of rice by 25% using better varieties, technologies and agricultural extension services. This can be achieved by setting up an exchange with agronomic experiences from other States in India or internationally related to crop protection, seed quality and other essential agronomic practices.
- 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. It is currently about 25% of the total consumption.
- New maps of crop types should be developed and kept updated to monitor water consumption and improvements in agriculture
- Future water accounting studies should also investigate neighbouring basins to evaluate if possibilities for interbasin transfer of water exist.