

CROP WATER FOOTPRINT ASSESSMENT FOR SUSTAINABLE AGRICULTURE IN SELECTED SUB-BASINS OF RIVER GANGA

गंगा नदी के चयनित उप-नदी क्षेत्रों में संपोषणीय कृषि
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MALI SANTOSH SAMBHAJI



**DIVISION OF AGRICULTURAL ENGINEERING
INDIAN AGRICULTURAL RESEARCH INSTITUTE
NEW DELHI-110 012**

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CROP WATER FOOTPRINT ASSESSMENT FOR SUSTAINABLE AGRICULTURE IN SELECTED SUB-BASINS OF RIVER GANGA

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MALI SANTOSH SAMBHAJI

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Approved by the Advisory Committee:

Chairman

(Dr. D. K. Singh)

Co-Chairman

(Dr. A. Sarangi)

Member

(Dr. D. K. Das)

Member

(Dr. Manoj Khanna)

Member

(Dr. S. S. Parihar)

Dr. D. K. Singh
Principal Scientist
Water Technology Centre
Indian Agricultural Research Institute
New Delhi-110 012

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This is to certify that the thesis entitled, **“CROP WATER FOOTPRINT ASSESSMENT FOR SUSTAINABLE AGRICULTURE IN SELECTED SUB-BASINS OF RIVER GANGA”** submitted to the Faculty of Post-Graduate School, Indian Agricultural Research Institute, New Delhi, in partial fulfilment of the requirements for the award of degree of **DOCTOR OF PHILOSOPHY** in **AGRICULTURAL ENGINEERING (SOIL AND WATER CONSERVATION ENGINEERING)** is a bona fide research work carried out by **MALI SANTOSH SAMBHAJI, Roll No. 09931** under my guidance and supervision, and that no part of this thesis has been submitted for any other degree or diploma. It is further certified that all the assistance and help availed during the course of investigation as well as sources of information have been duly acknowledged by him.

Date:
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Advisory Committee

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LIST OF SYMBOLS

Symbol	Unit	Description
ET_0	mm	Reference crop evapotranspiration
ET_c	mm	Potential evapotranspiration
ET_a	mm	Actual crop evapotranspiration
P_{eff}	mm	Effective rainfall
K_c	-	Crop Coefficient
μ	-	Mean
K	mm/day	Hydraulic Conductivity
R^2	-	Coefficient of determination
c	-	Crop index
t	-	Time step
d	-	District index
n	-	APU index
N	-	Number of clusters in a basin
k	-	Cluster index
s	-	Cropping season index
i	-	Index for type of agriculture
N_{app}	kg/ha	Nitrogen application rate
N_{leach}	kg/ha	Quantity of nitrogen leached
lf	-	Leaching fraction
rl	mg/lit	Recommended level of nitrogen
CWU_{blue}	m ³ /ha	Blue crop water use
CWU_{green}	m ³ /ha	Green crop water use
CWU_{grey}	m ³ /ha	Green crop water use
CWU_{tot}	m ³ /ha	Total Crop water use
A	ha	Cultivated area of crop
Y	ton/ha	Crop yield
Y_a	ton/ha	Average crop yield
Y_m	ton/ha	Maximum crop yield
VWC_{green}	m ³ /ton	Green virtual water content
VWC_{blue}	m ³ /ton	Blue virtual water content
VWC_{grey}	m ³ /ton	Grey virtual water content
VWC_{total}	m ³ /ton	Total Virtual water content
$Prod$	Ton	Production of crop c
WF_{ls}	million m ³	Water footprint of livestock
$WF_{dom+ind}$	million m ³	Water footprint of domestic and industrial sector

List of symbols...continued

Symbol	Unit	Description
$APop$	-	Animal population
WR_d	m^3/yr	Drinking water requirement of animal
a	-	Type of animal
g	-	Animal age group
$GW_{dom+ind}$	million m^3	Groundwater withdrawal for domestic and industrial sectors
Q_{cons}	ton	Quantity of consumption
Pop_{rural}	-	Rural population
Pop_{urban}	-	Urban Population
q_{rural}	ton/yr	Per capita consumption in rural areas
q_{urban}	ton/yr	Per capita consumption in urban areas
p_j	-	j^{th} processed product of a crop
pf_j	-	Product fraction for j^{th} processed product
WF_{blu}	million m^3	Blue water footprint
WF_{cons}	million m^3	Water footprint of consumption
WF_{prod}	million m^3	Water footprint of production
WF_{grn}	million m^3	Green water footprint
WF_{gry}	million m^3	Grey water footprint
WF_{rb}	million m^3	Water footprint of river basin
NR	Rs/ha	Net returns
NR_{avg}	Rs/ha	Average net returns
V_{mp}	Rs	Value of main product
Q_{mp}	ton/ha	Quantity of main product
V_{bp}	Rs	Value of by-product
Q_{bp}	ton/ha	Quantity of by-product
C_{cult}	Rs/ha	Cost of cultivation
WA_{blu}	million m^3	Blue water availability
R_{act}	million m^3	Actual runoff from the basin
$Min\ z$	-	Minimize objective function z
$Max\ z$	-	Maximize objective function z
$\forall k$	-	For all value of k
IA	ha	Irrigated area
PWF_{blue}	million m^3	Present blue water footprint of a basin

LIST OF ABBREVIATIONS

<i>AESR</i>	:Agro Ecological Sub Region
<i>APU</i>	:Agriculture Production Unit
<i>AWHC</i>	:Available Water Holding Capacity
<i>BD</i>	:Bulk Density
<i>BWS</i>	:Blue Water Scarcity
<i>CWR</i>	:Crop Water Requirement
<i>DEM</i>	:Digital Elevation Model
<i>DWR</i>	:Dilution Water Requirement
<i>EFR</i>	:Environmental Flow Requirement
<i>EWP</i>	:Economic Water Productivity
<i>FC</i>	:Field Capacity
<i>GCA</i>	:Gross Cropped Area
<i>GIA</i>	:Gross Irrigated Area
<i>GIS</i>	:Geographic Information System
<i>HWSD</i>	:Harmonized World Soil Database
<i>ICAR</i>	:Indian Council of Agricultural Research
<i>ISRO</i>	:Indian Space Research Organization
<i>LULC</i>	:Land Use Land Cover
<i>ME</i>	:Mean Error
<i>MoA</i>	:Ministry of Agriculture
<i>OCK</i>	:Ordinary Co-Kriging
<i>OK</i>	:Ordinary Kriging
<i>RFA</i>	:Rainfed Area
<i>RMSE</i>	:Root Mean Square Error
<i>SD</i>	:Standard Deviation
<i>SRU</i>	:Spatial Resolution Unit
<i>VWB</i>	:Virtual Water Balance
<i>VWC</i>	:Virtual Water Content
<i>WCR</i>	:Water Consumption Ratio
<i>WF</i>	:Water Footprint
<i>WP</i>	:Wilting Point
<i>WPL</i>	:Water Pollution level

INTRODUCTION

Water is the vital resource to sustain civilizations and economic development and most importantly, agriculture. Agriculture is the largest consumer of freshwater, accounting for about 99% of the global consumptive water footprint (Hoekstra and Mekonnen, 2012). The consumptive water use for producing food and fodder crops is expected to increase at 0.7% per year from its estimated level of 6400 Gm³/yr in 2000 to 9,060 Gm³/yr in order to adequately feed the global population of 9.2 billion by 2050 (Rosegrant *et al.*, 2009). Although available in abundance in some regions, increasing number of river basins of arid and semi-arid regions are facing problem of water scarcity as well as deterioration of water quality, due to population growth and increased water use (Wada *et al.*, 2011; Jose *et al.*, 2010; Vorosmarty *et al.*, 2010). About one-third of the world population are suffering from different levels of water stress (Oki and Kanae, 2006), while water scarcity is likely to affect two thirds of the world population over the next decades (Oki and Kanae, 2006; Vorosmarty *et al.*, 2000). Rapid industrialization and urbanization, expansion of agriculture and climate change are prime reasons of water scarcity. In most countries, the increase in water use was largely related to increased production of agricultural products for domestic consumption and export (Hoekstra and Chapagain, 2007a).

In India, the per capita water availability of many river basins is declining over the years due to sustained pressures of population, agriculture and industrial expansion besides changing climate scenarios. This is particularly evident from the fact that the per capita availability has decreased from 1816 m³/year in 2001 to 1545m³/year in 2011 (Jha, 2013). Water resource planning and management at river basin scale focuses on increasing the water availability and improving water quality besides ensuring environmental flows to sustain riparian ecology. The quantum of water resources use and availability are the two prime inputs in basin level management and their assessments has become a major focus of research in many areas of the world. Generally, these two estimates are compared to assess the water scarcity at any geographical scale. Traditionally, total water withdrawal for various purposes (e.g. agricultural, domestic and industrial) is considered as an indicator of total freshwater

use. However, water withdrawal is not the best indicator of water use at catchment scale because water withdrawals partly return to the catchment (Perry, 2007). Therefore, it makes more sense to express blue water use in terms of consumptive water use (Hoekstra *et al.*, 2011).

New paradigms and approaches of water use, e.g. virtual water content (VWC) and water footprint (WF) have been emerging in scientific communities to promote efficient and sustainable water uses, and for water resources planning and management (Zeng *et al.*, 2012; Aldaya and Iltis, 2008). Virtual water content of a commodity is the volume of water that is actually used to produce the commodity, measured at the place where the commodity is actually produced (Allan, 1993,1994). Information on VWC can be used to translate the commodity trade flow (import-export) into water use and the virtual water flow. Regional differences in the amount of water needed to produce a unit of crop biomass or yield can benefit the mitigation of regional water scarcity. A nation can preserve its domestic water resources by importing water intensive products (*i.e.* products having high virtual water content) instead of producing them domestically, thus importing water in virtual form and saving domestic water resources (Hoekstra and Chapagain, 2007b). Virtual water transfer in the form of international trade in agricultural goods is increasingly recognized as a mechanism to save domestic water resources and achieve national water security (Liu *et al.*, 2007, Hoekstra and Chapagain, 2008). Therefore, virtual water import can be considered as an alternate source of water.

Water footprint (WF) is a consumption-based indicator of water use and refers to all forms of freshwater use (consumption and pollution) that contribute to the production of goods and services consumed by the inhabitants of a given geographical region (Hoekstra and Chapagain, 2008). Water footprint of production is the sum of direct and indirect water use of domestic water resources only, while the WF of consumption is the sum of direct and indirect water use of domestic and foreign water resources used for domestic consumption. Water footprint can be divided into blue, green and grey water footprints. The green WF measures the volume of rainwater consumed during the growing period of the crop and the blue WF measures the volume of surface and groundwater consumed. Whereas, the grey WF measures the volume of freshwater that is required to assimilate the nutrients and pesticides leaching besides

surface runoff from crop fields, based on natural background concentrations and existing ambient water quality standards (Hoekstra *et al.*, 2011). The water footprint (WF) offers a quantifiable indicator to measure the volume of water consumption per unit of crop area, as well as the volume of water pollution (Hoekstra and Chapagain, 2008; Hoekstra *et al.*, 2011). The Water Footprint can be regarded as a comprehensive indicator of fresh water resources appropriation (Hoekstra *et al.*, 2011). Furthermore, in semi-arid and arid regions, knowledge of virtual water content of crops can be useful to determine the optimal use of water. Therefore, it is imperative to establish whether the water used is contributed from rainwater (green water) or surface water and/or groundwater (blue water) (Chapagain *et al.*, 2006; Falkenmark, 2003).

Water footprint can be assessed at the product, process, individual or regional level. At different geographical levels, the WF has distinct applications. For example, a national government may be interested in knowing its dependency on foreign water resources. A river basin authority may be interested to know whether the aggregated water footprint of human activities within the basin violates environmental flow requirements or water quality standards at any time or not. The river basin authority may also want to know to by how much the scarce water resources in the basin are allocated to low-value export crops (UNEP, 2011).

The interest from the governmental sector in WF has now begun to arise as it is evident from the fact that in 2010, the Spanish government enacted a regulation to incorporate WF analysis in the process of developing river basin management plans (Aldaya *et al.*, 2010). Also, to promote efficient use of water the recent National Water Policy (2012) of India emphasized on evolving water footprints and water auditing benchmarks on use of water resources for different purposes, (MOWR, 2012). The water footprint assessment involves four major phases (Hoekstra *et al.*, 2011). First phase is about setting the goals and scope of the WF assessment study. Second phase deals with accounting of water footprints. In third phase, the water footprint is evaluated on its sustainability issues including the social and economic perspectives. In the final phase, response options, strategies or policies are formulated to reduce the water footprints at regional scales.

Several water footprint studies have been undertaken at global, national and river basin scale. At river basin scale, the water footprint analysis has been used to

address water management strategies as well as certain policy issues. The work by Dumont *et al.* (2013) analysed the green and blue water footprint of the Guadalquivir basin (Spain), with an emphasis on the groundwater footprint and its consequences on current and future depletion of surface water of the basin. The study indicated that reframing the water governance setting by integrating flexibility and equity based on water footprint information could lead to increased water availability in the basin. Aldaya and Llams (2008) analysed the hydrologic and economic aspects of water footprint in the semiarid Guadiana basin and identified the regions with high virtual water-low economic value crops to facilitate a more efficient allocation and use of water resources, providing a framework for policy formulation. Liu *et al.* (2012) applied the analysis of grey water footprint to 1000 river basin across the globe and concluded that the water pollution level values generally increased between 1970 and 2000.

In most of the studies, water footprint analysis has been done up to assessment phase only. Although recognised as an important part in the water footprint assessment, majority of the studies did not include grey water footprint analysis. After quantification of blue, green and grey water footprints, next comes the phase of sustainability assessment. Very few studies (Mekonnen *et al.*, 2012; Hoekstra *et al.*, 2012) actually investigated the sustainability of the estimated water footprints at global or national scale. There are a few studies in which sustainability of only blue water footprints has been assessed at river basin scale. Zeng *et al.* (2012) analysed the sustainability WF of Heihe River Basin in China and found that blue WF exceeded blue water availability during eight months per year and also on an annual basis leading to violation of environmental flow requirement norms.

The VWC and WF analysis integrates a large range of sectors and issues, thus providing a potentially appropriate framework to support more optimal water management practices by informing production, water allocation and trade decisions (Aldaya *et al.*, 2009). Therefore, assessment of water footprints and its sustainability at river basin scale is extremely important. Available literatures suggested that no study has been carried out to assess the WF of any basin in India. Besides this, a systematic procedure for assessment of water footprints at basin level is not available. The purpose of the study was to develop a methodology for WF assessment at river basin scale using the information on soil, land use, climate, crop production and crop productivity. The

study also aimed at assessing the share of blue, green and grey water agricultural water footprints of Gomti and Betwa river basins in India with a focus on all phases of WF analysis *i.e.* accounting, sustainability assessment and response formulation. Since, the WF is sensitive to the resolution at which it is assessed; effort was made to delineate appropriate spatial resolution units for WF assessment at basin scale. Hydrological analysis of the virtual water and water footprint of these river basins were carried out considering blue, green and grey water use for agricultural production. The study also evaluates the extent to which available blue water resources are allocated to low value crops. On the basis of blue and green WF, the crop and water management strategies were proposed for sustainable agricultural water use within the basin and their impact on WF was also assessed. This study would facilitate more efficient allocation of water to different crops at basin scales and can provide a framework for policy formulation related to crop production and trade.

The research was undertaken with following objectives.

- To develop methodology for assessing crop water footprints.
- To assess the crop water footprints in selected sub basins of river Ganga.
- To develop sub-basin level sustainable crop and water management strategies.

2.1 General

Water, the natural renewable resource, once available in abundance, is now becoming more and scarcer. In many parts of the world, freshwater withdrawal from ecosystems is greater than nature's ability to 'renew' this precious resource (WWF, 2010; Hoekstra *et al.*, 2009). It is estimated that up to two-thirds of the world population will experience water scarcity over the next few decades (Alcamo *et al.*, 2000; Vorosmarty *et al.*, 2000) and slightly more than one billion people living in arid regions will face absolute water scarcity by 2025 (Rosegrant *et al.*, 2002).

Growing water scarcity has led to an increased interest in water resource planning and management. Traditional water resource management strategies focus on supply side management. Emphasis has been on to satisfy the water users without analysing the demand and supply situation. Among all, demand from agriculture sector is the largest consuming about 92 % of the global freshwater use (Hoekstra and Mekonnen, 2011). This would lead to a situation where many countries would prefer to import of water intensive agricultural commodities instead producing them locally to save their water resources. In this context concept of virtual water flow becomes extremely important. Virtual water content of a commodity is the volume of water that is actually used to produce the commodity, at the place where the commodity is actually produced (Allan, 1993, 1994). With the virtual water content, the production and trade of a crop can be translated into the water use and the virtual water flow of crop. A nation can preserve its domestic water resources by importing water intensive commodities instead of producing them domestically (Chapagain *et al.*, 2006). Water thus saved can be used to produce alternative, higher-value agricultural crops and to support environmental services.

In line with the concept of virtual water, the concept of the water footprint (WF) has been introduced to create a consumption-based indicator of water use (Hoekstra & Hung, 2004; Hoekstra & Chapagain, 2007). The WF is defined as the total volume of freshwater that is used to produce the goods consumed by the inhabitants of a

geographical region. Water used in crop production for consumption in a region constitutes internal WF while the water use related to consumption of imported products constitutes external WF.

The WF is divided into blue, green and grey water footprints. The blue component refers to the use of groundwater and surface water during the production of a commodity, the green component refers to the use of rain water for crop growth, and the grey component refers to the quantity of water required to dilute the water polluted during the production of the commodity (Falkenmark & Rockstrom, 1993; Chapagain *et al.*, 2006). Level of dilution is set at drinking water quality standards. The WF is a comprehensive indicator of human appropriation of fresh water. Including the grey water footprint is justified in view of increasing instances of pollution from the use of chemicals and fertilizers requires which freshwater to dilute the polluted water.

Several studies have highlighted the utility of the WF concept at different spatial scales. At national level, concept of WF is applied to understand nations' dependency on foreign water resources (Mubako and Lant, 2013; Qiang *et al.*, 2013). Bulsink *et al.* (2010) quantified interprovincial virtual water flows related to trade in crop products from Indonesian province and concluded that significant external WF is relieving the water scarcity on this island. In view of the large variation in per capita WF, Ge *et al.* (2011) suggested that efficient use of water resources in China can be achieved through the use of advanced technology, improved efficiency of water use, reduced virtual water content of products and nation-wide readjustment of industrial structure.

Mubako and Lant (2013) quantified the water footprints and internal virtual water flows for the forty-eight contiguous states in US and found that some Midwestern states are exporting more virtual water than they withdraw or consume domestically. Hoekstra and Chapagain (2007) showed that both Morocco and the Netherlands import more water in virtual form (in the form of water-intensive agricultural commodities) than they export, which makes them dependent on water resources of other countries.

At river basin scale, the concept has been applied to know whether the WF of human activities within the basin violates environmental flow requirements (Zeng *et al.*, 2012) and also to assess the extent that the scarce water resources in the basin are allocated to low-value export crops (Aldaya and Llams., 2008). Vanham (2013)

assessed the virtual water balance for agricultural products in river basins located in the European Union (EU28) and classified the basins into positive and negative net virtual water importers. [Dumont *et al.* \(2013\)](#) analysed the WF of Guadalquivir basin in Spain and concluded that to reduce the pressure on water resources of the basin, groundwater use in newly established irrigated olive groves could have been obtained by reducing the area and water allocated to crops with low water productivity.

The review of literature suggests that the concept of water footprint can be used as an efficient tool in management of water resources and guiding trade policies. The WF has wide applicability at various spatial scales. The available literature on WF analysis at river basin scale showed that none of the study considered all four phases of WF analysis. Most of the studies were restricted to WF assessment only with very few extending it up to the phase of sustainability analysis.

Although, the river basins of India are experiencing chronic water shortages and that the exports from India are on the rise, no study has so far been reported for any river basin in India. The present study was undertaken to develop a methodology to assess the WF of Indian River basins. The main aim of the study was to assess the virtual water content of crops, water footprints and virtual water flows in Gomti and Betwa river basins of India. The study also evaluates the sustainability of the blue and grey WFs in the basins. Management alternatives are proposed and their impact on WF of the basin is also evaluated.

2.2 Research area I: Development of methodology for water footprint assessment at river basin scale

2.2.1 General

Assessment of water footprint at river basin level requires precise assessment of virtual water content (VWC). The blue, green and grey VWC of a crop is obtained by dividing the blue, green and grey water use of the crop by crop yields. Since, crop water use depends on climate, soil and crop parameters ([Allen *et al.*, 1998](#)), it varies both in time and space. Approaches to estimate VWC and WF are presented in following sections.

2.2.2 Approaches to estimate blue, green and grey VWC

Many researchers have used the Penman-Monteith method to estimate reference crop evapotranspiration (ET_0). In this approach, the crop evapotranspiration (ET_c) is obtained by multiplying the ET_0 with crop coefficient (Allen *et al.*, 1998). FAO CROPWAT model use this method for estimating ET_c .

Hoekstra and Chapagain (2007) and Chapagain *et al.* (2006) used the FAO CROPWAT model for estimating crop water footprints. Several studies (Mekonnen and Hoekstra, 2010; Mekonnen and Hoekstra, 2011; Mekonnen and Hoekstra, 2013) used a grid-based dynamic water balance model to estimate the crop evapotranspiration and yield over time, with a time step of one day using a resolution of 5' x 5' grid size. Many other regional and river basin level studies used the FAO CROPWAT model to estimate the blue and green component of crop evapotranspiration. Due to limitation of CROPWAT in estimating ET_0 and effective rainfall (P_{eff}) at larger spatial scales, the physically based hydrological models are also being used by some researchers to assess virtual water flow. The resolution of these models ranged from 282 sub-basins in Impact-Water (Cai and Rosegrant, 2002), 1^0 in H07 (Hanasaki *et al.*, 2008), 0.5^0 in GEPIC (Liu *et al.*, 2009; Liu *et al.*, 2007) and LPJmL (Rost *et al.*, 2008) and 0.1^0 in WATERSIM (Fraiture, 2007).

Hanasaki *et al.* (2010) simulated natural and anthropogenic virtual water flows using H08 model for 15 years from 1985 to 1999. Using global trade data and the simulated virtual water content of major crops they estimated the global virtual water flows. Miguel *et al.* (2012) developed a crop water use model (CWUModel) to compute the WF of cereals in the Duero river basin in Spain. To estimate the global consumptive water use in cropland, Liu and Yang (2010) used the GEPIC model (GIS-based environmental policy integrated climate model), which was designed to simulate the spatial and temporal dynamics of the major processes of the soil–plant–atmosphere–management system. GEPIC model used the Hargreaves method to calculate reference evapotranspiration (ET_0) at a daily time step. Siebert and Doll (2010) developed a new global crop water model GCWM to compute consumptive water use (evapotranspiration) and virtual water content of crops at a spatial resolution of $5^0 \times 5^0$.

In all the studies that reported the grey WF, grey component of the water footprint was calculated by multiplying the nitrogen application rate with nitrogen leaching fraction and dividing this by the maximum acceptable concentrations of nitrogen as per drinking water quality standards. In case of rice, [Chapagain and Hoekstra \(2011\)](#) considered a flat rate of nitrogen leaching equal to 5% of the nitrogen application rate and used the permissible limit nitrogen concentration as 50 mg N/l to estimate the volume of water required to dilute the polluted water to the permissible limit.

2.2.3 Approaches to estimate WF

The two methodological approaches proposed for WF assessment are – Top down and Bottom-up ([Chapagain & Hoekstra, 2004](#); [Hoekstra & Chapagain, 2008](#)). In the top-down approach, the water footprint of national consumption is calculated as the total use of domestic water resources plus the virtual water flows entering the country minus the virtual water flows leaving the country. In the bottom-up approach, the sum of all goods and services consumed within the nation is multiplied with their respective virtual water content in order to calculate the water footprint of national consumption. The WF studies for Morocco ([Hoekstra and Chapagain, 2007](#)) and Spain ([Aldaya *et al.*, 2010](#)) used the top-down approach as the required data was readily available. The WF studies for the Netherlands ([Oel *et al.*, 2009](#)), the UK ([Chapagain and Orr, 2008](#)) and Germany ([Flachmann, 2012](#)) used the bottom-up approach.

Selection of an approach to estimate the WF depends on the scale of WF assessment and type of availability of data. Since this study mainly focuses at river basin scale, the bottom-up approach was preferred to estimate the WF of livestock and agricultural production and top-down approach was used for estimating the WF industrial and domestic sectors.

2.2.4 Resolution of VWC and WF assessment

Studies on WF assessment indicated that the accuracy of WF assessment depends on spatial resolution. Spatial resolution is the size of the spatial unit within which climate, soil and crop parameters are assumed to be uniform such that intra-unit variation in VWC can be assumed negligible.

Hoekstra and Mekonnen (2011) applied a spatial resolution of $5^0 \times 5^0$ for estimating the WF of crop production, industrial production and domestic water supply. At the global level, grid based soil moisture balance models have been used to estimate the crop water requirements and crop WF at 5x5 arc-minutes (Siebert and Doll, 2010; Mekonnen and Hoekstra, 2010), $30' \times 30'$ (Fader *et al.*, 2011; Rost *et al.*, 2008) and $1^0 \times 1^0$ degree (Hanasaki *et al.*, 2010) spatial resolution. Other studies on global WF accounting of different crops used 'country' as a SRU (Hoekstra and Chapagain, 2007, Chapagain *et al.*, 2006, Chapagain and Hoekstra, 2007). All the national WF accounting studies considered 'province' as a SRU for estimating crop water requirements and WFs. Climate and soil variability within these units can affect the blue and green crop water use. Studies suggested that ET_c varies in space even within a smaller region (Ni *et al.*, 2014; Alexandrov and Hoogenboom, 1999; Heinemann *et al.*, 2002).

To account the spatial variability in ET_c within the basin Feng *et al.* (2012) divided the yellow river basin into upper, middle and lower regions based on water resources, economic structure, household incomes and consumption patterns. Aldaya and Llamas (2008) carried out analysis of water footprint of Gaudiana river basin in Spain using crop water use and VWC estimated at provincial level.

The review presented above suggests that it is necessary to decide the spatial resolution for realistic assessment of ET_c and WF so that the uncertainties in WF analysis can be minimized.

2.3 Research Area II: Assessment of virtual water content of crops and water footprint

In view of the recurring water shortages, it is necessary to evolve optimal crop and water management and trade strategies at river basin scale. Since, river basin is recognized as the basic spatial unit for water resource development and management, the optimal plans must be worked out for every river basin. It has now been established that the concept of WF has wide applicability in tackling the water scarcity related issues at various spatial scales. The VW concept together with the water footprint links a large range of sectors and issues, thus provides a potentially appropriate framework to support more optimal water management practices by informing production and trade decisions (Aldaya *et al.*, 2010).

In previous studies, the concept of WF has been applied to assess the basin level virtual water imports and exports. [Vanham \(2013\)](#) assessed the virtual water balance for agricultural products in river basins located in the EU28 (European Union and Croatia) and found that overall the EU28 is a net VW importer for agricultural products. However, river basins in densely populated and industrialised regions of western were identified as net VW importers and those in sparsely populated regions like in Iberian Peninsula (Guadiana, Ebro, Duero) were net virtual water exporters.

The specific application of WF concept to understand the structure of groundwater use has also been studied. Analysis of WF of Guadalquivir basin with special emphasis on groundwater revealed that there was rising trend in WF from groundwater which was ascribed to development of irrigated olive groves from groundwater ([Dumont *et al.*, 2013](#)). Contribution of various water use sectors in total water use and water pollution can be worked out with the help of WF analysis. [Zeng *et al.* \(2012\)](#) estimated the WF of yellow river basin in China as 1768 million m³ during 2004–2006. Agricultural production was the largest water consumer, accounting for 96 % of the WF (92 % for crop production and 4 % for livestock production). The remaining 4 % was for the industrial and domestic sectors.

[Aldaya and Llams \(2008\)](#) carried out the hydrologic and economic analysis of WF in the Spanish side of the semiarid Guadiana river basin and concluded that high virtual-water low-economic value crops are widespread in the upper and middle Guadiana regions. On the basis of regional virtual water balances, they proposed that different sections of the Guadiana basin should have different trade strategies. They also suggested that this type of analysis could facilitate a more efficient allocation and use of water resources, providing simultaneously a transparent interdisciplinary framework for policy formulation.

Regional trade of goods and services indicates that the consumption in one region of basin is linked to water consumption in other regions. [Feng *et al.* \(2012\)](#) developed a Multi-Regional Input-Output model (MRIO) and showed that all three reaches (upper, middle and lower) of the basin are net virtual water exporters, indicating that production and consumption activities outside the basin also put pressure on the water resources in the YRB. They suggested for reducing the VW export so that the saved virtual blue water could be used for producing other crops.

In India, there are water scarce regions with per capita water availability less than 1000 m³/year, which is either caused by the lack of natural water resources or a result of over exploitation of groundwater resources for irrigation purposes (CGWB, 1989; Bobba *et al.*, 1997). With expected increase of Indian population to 1.6 billion in the year 2050 (United Nations, 2004) and increasing trend of agricultural exports in recent decades (FAO, 2006), the total food demand in India will increase in the near future. The water scarcity in India is also exaggerated with the increase in water pollution caused by extensive use of fertilizers and pesticides and through disposal of untreated industrial waste (Agrawal *et al.*, 2010; Singh *et al.*, 2004). It looks like today's problems related to freshwater scarcity and pollution will be aggravated in the future due to a significant increase in demand for water and a decrease in availability and quality.

Although the utility of the WF concept has been well established, so far only one national level WF assessment study has been reported for India. In the context of inter linking of rivers, Kampman (2008) assessed the virtual water flows and WF in the Indian states to find out reasons for water scarcity in water scarce regions and to examine the feasibility of interlinking of rivers in providing water to water scarce regions.

In order to develop basin specific crop and water management plans it is important that WF analysis should be carried out at basin level. Despite of the fact that water scarcity in India is on the rise, no study has been reported for any river basin in India. It has been revealed that out of 20 major river basins in India, 14 basins are in a water-stressed condition (Gaur and Amerasinghe, 2011). Therefore, the present study was undertaken to assess the virtual water content of crops and assess the WF of three important water user sectors (agriculture, domestic and industry) within the Gomti and Betwa river basins of India.

2.4 Research Area III: Sustainability assessment and optimal cropping patterns to reduce crop water footprints

2.4.1 General

This research area focuses on sustainability assessment of the water footprints of the basin. After setting the goal and objectives of the WF assessment study and estimating the WFs, next comes the question of sustainability of the WFs within the basin. Since, WF cover all forms of water use i.e. blue, green and grey, it can be used to assess the sustainability of water consumption patterns within the basin. Withdrawal of water in excess of its natural rate of replenishment or polluting water sources beyond acceptable limits creates the concerns regarding sustainability of water resources. WF is considered as better indicator of sustainability over other indicators, such as ‘total water withdrawal’. Water withdrawal is not the best indicator of water use when one is interested in the effect of the withdrawal at the scale of the catchment as a whole, because water withdrawals partly return to the catchment ([Perry, 2007](#)).

2.4.2 Sustainability assessment

Sustainability assessment involves identification of sustainability criteria, identification of hotspots within the river basin and quantification of the primary and secondary impacts in the hotspots. A hotspot is a specific period of the year in a specific catchment in which the water footprint is unsustainable in specific period of the year i.e. it exceeds the water availability or water quality standards ([Hoekstra *et al.*, 2011](#)).

Researchers have used WF based indices as sustainability criterions to identify hotspots and the water scarcity in regions ([Zeng *et al.*, 2012](#); [Jefferies *et al.*, 2012](#)). Blue water scarcity index (BWSI) is the ratio between blue WF and blue water availability. When BWSI exceeds 100% the sustainability of water footprint becomes a concern. Also, when the Water Pollution Level (WPL), which is the ratio between dilution water requirement and available runoff, exceeds the value of 100%, the grey water footprint becomes unsustainable.

[Hoekstra *et al.* \(2012\)](#) determined blue water scarcity for more than 400 river basins of the world covering about two-thirds of the global population and three-quarters of the irrigated region. In about half of the river basins examined, representing 2.7 billion people, blue water scarcity was found to be “severe” during at least 1 month of the year. In about 1 out of 12 of the basins, representing 500 million people, blue

water scarcity was “severe” for at least 6 months of the year, and in 12 of the river basins, “severe” blue water scarcity was experienced all year long for all the months.

[Liu *et al.* \(2012\)](#) made a worldwide estimation of the past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to the world's major rivers. This study showed that, at present, in two-thirds of the basins, the assimilation capacity for nitrogen and phosphorus has been fully consumed. High water pollution levels were generally found in rivers in tropical–subtropical areas. Their results indicated that many rivers may become more polluted with dissolved N and P in the future. [Zeng *et al.*, \(2012\)](#) analysed the sustainability and blue water scarcity (BWS) within the Heihe River Basin (HRB) in northwest China. The average annual BWS in HRB was 154 %. Based on this they concluded that runoff in the HRB was significantly modified by human activities. The value of BWS greater than 100 % indicates that water consumption for human activities are not sustainable and human WF was partly met at the cost of environment water flows.

Based on the review presented above, the WF based sustainability criteria such as BWS and WPL can be considered as the better indicators of sustainability at river basin scale and can also be used to assess the sustainability of WFs within Indian River basins.

2.4.3 Response formulation

Sustainability of the WFs within a catchment can only be ensured with proper land and water management practices. It is necessary to evaluate the response of WFs to various management alternatives. Response formulation is the phase in which recommendations regarding options to reduce the different components of the water footprint are formulated ([Hoekstra *et al.*, 2011](#)). In view of the estimated WFs, several management alternatives can be proposed in the response formulation phase taking land, water and profits and political issues into account however, the “right actions” would lead to an overall decrease in total WF and its localised impacts ([UNEP, 2011](#)).

[Chapagain and Orr \(2008\)](#) analysed the WF of United Kingdom and proposed the response options for businesses, government and consumers. In case of Germany, [Sonnenberg *et al.* \(2009\)](#) proposed that agricultural subsidies of the EU should only be paid in the case of proven responsible utilisation of water and the financial means for sustainable management of aquifers and river catchments should be raised. [Kampman \(2008\)](#) reported that the river interlinking project in India would mainly reduce local

water scarcity whereas water scarcity needs to be reduced significantly at a national level. He suggested that increase in the water productivity as only the long term solution to ensure sustainability of water footprints.

At river basin scale, several researchers have proposed change in cropping patterns or a drastic reduction of the irrigated surface as a management alternative to reduce WFs ([Aldaya *et al.*, 2010](#); [Aldaya and Llams, 2008](#)). Improving water resource allocation for bigger economic, social and environmental productivity, increased water reuse, less aggressive agricultural production has been proposed by [Dumont *et al.* \(2013\)](#). Regarding sustainability of grey WF, [Aldaya *et al.* \(2010\)](#) stressed on strict control of the extraction of water and the use of chemical products for agricultural purposes as measures to reduce WFs. From economic point of view, reducing the production of low value-high VWC crops and reforms in water pricing were identified as possible response options at river basins scale ([Zeng *et al.*, 2010](#)). Several global, national and river basin studies recognized that reducing the export of virtual blue water and using the saved water for producing higher value added but lower water-intensive goods as the best strategy to ensure sustainability of the WFs ([Feng *et al.*, 2012](#); [Vanham, 2013](#)).

From the review presented above it is evident that several management alternatives have been proposed to ensure the sustainability of WFs at various spatial scales. However, none of the study quantitatively assessed the response of WFs to suggested options for possible WF reduction. Since, agriculture is the major contributor to total WF within the Indian river basins, optimizing the cropping pattern is often a key to achieving more sustainable water use. This study makes a substantial step beyond quantifying and mapping the water footprint of crop production by identifying the crops responsible for water scarcity and developing optimal cropping patterns as a response option to reduce the WF and improve the sustainability of water footprints.

MATERIALS AND METHODS

3.1 General

There exists a pronounced spatio-temporal variation of water availability in river basins of India. Quantitative assessment of the blue, green and grey water footprint (WF) can help in understanding the pressure on the freshwater resources within the basins. The overall objective of this study was to quantify and analyse the blue, green and grey WFs in the Gomti and Betwa river basins. The study also provides preliminary estimates on WF of livestock, industrial and domestic sectors within the basins. Further, the virtual water inflows and outflows were quantified for both basins. Further, the study assessed the blue water scarcity and water pollution level within these basins at a monthly time step, thus providing more useful information on water scarcity. Quantitative assessment on response of blue and green water footprints were undertaken for devising management alternative for reduction of water footprints. Acquisition of data from different sources and subsequent analysis carried out to estimate the water footprint is presented below.

3.2 Data sources

Assessment of water footprints is a data intensive task and requires the information on several aspects. Type of data required and the sources from which it was obtained for the purpose of this study are presented in Table 3.1.

3.3 Description of the study area

The present study was carried out for Gomti and Betwa river basins located in the northern and central part of India, respectively (Fig 3.1). Both the rivers are tributaries of Ganga and are important from the agriculture production view point. Gomti River originates from the *Fulhar Jheel* in *Madhotanda* located 30 km east of the Pilibhit town in Uttar Pradesh and after flowing through incised valley, it ultimately confluences with River Ganga near *Saidpur Kaithi* in Ghazipur near Varanasi. It travels approximately 940 km and drains about 31240 km² area of the central-eastern part of the Uttar Pradesh.

Table 3.1 Data used in water footprint analysis and sources of data acquisition

Sr. No	Type of data and year of record	Source
1.	Digital Elevation Model	SRTM DEM, NASA, (srtm.csi.cgiar.org)
2.	Agro Ecological Sub Regions	NBSSLUP, ICAR
3.	Soil properties	FAO Harmonized World Soil Datasets Version 1.2, (eusoils.jrc.ec.europa.eu)
4.	Land use land cover (2011)	Bhuvan Thematic Services, ISRO, (bhuvan-noeda.nrsc.gov.in)
5.	Crop parameters	Department of Economics and Statistics, Min of Agriculture, Government of India and FAO irrigation and drainage paper no-56
6.	District wise cropped area and production statistics (2011)	Department of Economics and Statistics (eands.dacnet.nic.in)
7.	District wise and crop wise irrigated and rainfed area (2011)	Department of Economics and Statistics (lus.dacnet.nic.in/dt_lus.aspx)
8.	State wise and crop wise value of primary and secondary products, cost of cultivation (2010-11)	Department of Economics and Statistics (eands.dacnet.nic.in/Cost_of_Cultivation.htm)
9.	District wise annual utilizable ground water resource (2009)	Central Ground Water Board, Ministry of Water Resources, Government of India
10.	Canal rosters (2004-2007)	State Water Resources Agency, UP Water Sector Restructuring Project, Irrigation Department, Lucknow India
11.	District wise human population (2011)	Primary Census Abstract, (censusindia.gov.in)
12.	District wise livestock population (2007)	Department of Animal Husbandry and Fisheries, Ministry of agriculture, (dahd.nic.in) and Annual Report, Uttar Pradesh Livestock Development Board
13.	Per capita consumption of crop and crop products (2012)	National Statistical Organisation, National Sample Survey Office, Ministry of Statistics and Programme Implementation, Government of India

Gomti river basin is extended between the latitude of 25°23'13" to 28°46'59" N and longitude of 79°57' 34" to 83°11'14" E. Sitapur, Lucknow, Sultanpur, and Jaunpur are four major cities situated on its banks.

The Betwa River originates from Barkhera in Raisen district of Madhya Pradesh. The Betwa River runs over 590 km prior to its confluence with Yamuna near Hamirpur in Uttar Pradesh. Betwa River drains an area of about 43120 km² out of which 29329 km² is in Madhya Pradesh and 13791 km² is in Uttar Pradesh state. Betwa basin extends between the latitude of 22°59'57" to 26°03'23" N and longitude of 77°05' 51" to 80°13'01" E.

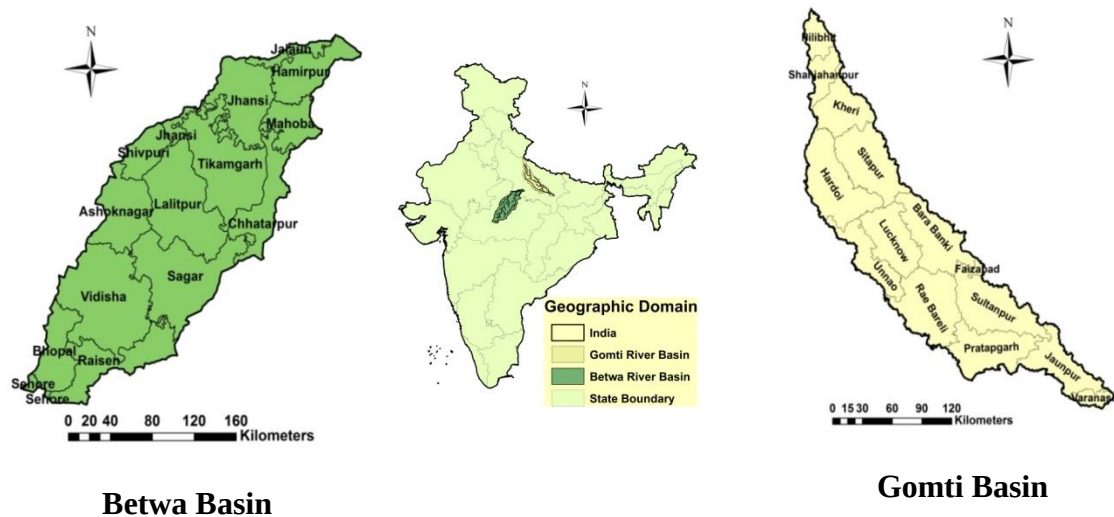


Fig 3.1 Location of the Gomti and Betwa basins

3.4 Delineation of the selected basins

First step in assessment of WF at river basin scale is to delineate the sub watersheds of basins. The SRTM Digital Elevation Model having 90 m spatial resolution was used for delineation of basins. The delineation procedure involved preparation of depression-less DEM, development of flow direction and flow accumulation raster images, creation of pour points and finally the watershed delineation. Using the junctions of a stream network derived from flow accumulation raster as pour points, outlets of the basins were identified. Watersheds were delineated using Watershed tool available in Hydrology tool box of ArcGIS® 9.3 software package.

3.4.2 Climate

The climate of the Gomti basin is semi-arid to sub humid tropical with average annual rainfall at different locations varied from 850 to 1100 mm. The mean minimum and maximum temperature over the basin is 4.5° to 46.0° C with daily mean sunshine

of 8 hours. The relative humidity varied between 10-90 per cent. The potential evapotranspiration experienced in the basin is nearly 1300 mm. The climate of the upper Betwa basin is hot dry sub-humid while in lower reaches it is characterised as hot moist semi-arid. The annual precipitation and evaporation are 1138 mm and 787mm, respectively and mean and annual runoff is about 351mm. The minimum and maximum temperature of the basin ranges from 3°C to 43°C, respectively.

3.4.3 Topography and Soils

The shape of the Gomti basin is nearly oblong in nature. Topography is nearly undulating with high terrains at upstream end of the basin. Majority of the surface area of the Gomti Basin is generally flat with slope towards S and SE directions with altitude varying from 200 m to 62 m amsl. The soils of the Gomti basin are very fertile and represent the vast track of the riverine alluvium of the Gangetic plain with 'loam' as major textural class. There is variation in the sand, silt and clay content of soil textural classes across the basin.

The Betwa basin is saucer shaped with sand stone hills around its periphery and clays underlain by Deccan trap basalts. Elevation ranges from 266m to 706m above mean sea level. It flows in a North-Easterly direction through Madhya Pradesh and enters into Uttar Pradesh near village Bangawan of Jhansi district. Betwa basin demonstrated wide variation in soil texture with clay and sandy loam as the major classes.

3.4.4 Land use and cropping pattern

The major land use classes observed in the Gomti and Betwa basin are shown in Fig 3.2. The land use in Gomti basin can be broadly categorized as: agriculture, non-agriculture, pasture fallow, forest, etc. Major crops cultivated in the basin are paddy, wheat, sugarcane, potato, and other vegetable crops depending on irrigation facilities. As per estimates, the gross cultivated area is about 82.8 % of the total geographical area. Shrub and waste lands contributes about 6.83 % of geographical area of the basin, while water bodies cover about 2.11 % area. The gross cropped area of the Gomti basin is 2.48Mha and about 85 % of it was under irrigated agriculture.

In Betwa basin, agriculture is the dominant land use and covers about 68 % of the total geographical area of the basin. Chickpea, soybean and wheat are the major

crops grown in the Betwa basin. Forest is the second largest land use and shares about 14.9% of the basin area. Shrub and waste lands are spread over 8.6 % of the geographical area of the basin. Because of limited irrigation facilities, Betwa basin is dominantly rainfed with about 38% of GCA under irrigation.

3.5 Delineation of agricultural production units (APUs)

The study basins were divided into smaller homogeneous units in terms of soil, agro-ecology and district administrative boundaries. Since, the soil and climatic properties of an agriculture production unit (APU) will remain fairly uniform, an APU was considered as the highest resolution for estimation of crop evapotranspiration (ET_c) and assessment of WF. Therefore, further division of an APU will not necessarily improve the accuracy of WF assessment. Thematic layers pertaining to soil type, agro ecological sub regions, basin boundary and district boundaries were overlaid and APU polygons were delineated for each district using *intersect* geo-processing operation in ArcGIS.

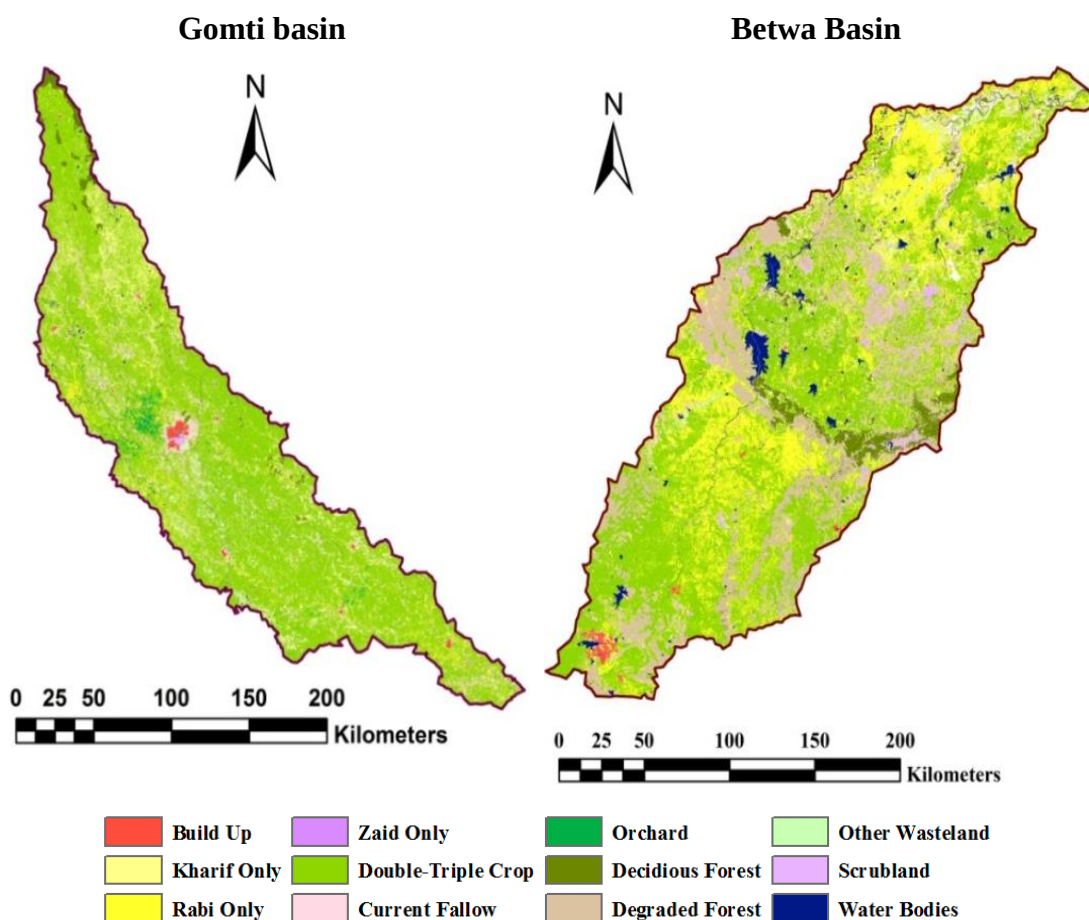


Fig 3.2 Land use map of the Gomti and Betwa basins

3.6 Assessment of crop evapotranspiration (ET_c)

Potential evapotranspiration of a specified crop (ET_c) was estimated from reference evapotranspiration (potential evapotranspiration of reference crop, ET_0) and crop coefficients (K_c). The evapotranspiration from a reference surface without shortage of water is known as the reference evapotranspiration and is denoted as ET_0 . The FAO CROPWAT model was used to estimate the evapotranspiration of a crop (ET_c). The CROPWAT model estimates ET_0 over the cropping season using Penman-Monteith equation. The crop evapotranspiration (ET_c) was estimated from the reference evaporation (ET_0) using the crop coefficients (K_c). Detailed discussion on CROPWAT 8.0 is presented in chapter IV.

3.7 Mapping of ET_c variability using geostatistical approach

Mapping the variability in ET_c is useful in understanding the spatial patterns of crop evapotranspiration over the basin and in delineation of homogeneous units. In order to develop the continuous surfaces of ET_c within the basin, the estimated point ET_c values at each APU were interpolated using geostatistical interpolation methods based on statistical autocorrelation of variables. In this study, the fitted semivariogram models of the Ordinary Kriging and Ordinary Co-Kriging were evaluated and variability maps were developed using the best performing interpolation method.

3.8 Defining spatial resolution units (SRU)

Assessment of WF at high resolution is data intensive and requires considerable inputs in terms of labour and money. Therefore, the resolution can be reduced from APU level to some lower level to account for variation in ET_c . In order to delineate the appropriate spatial resolution unit (APU), a geographical clustering approach was applied to spatially averaged interpolated ET_c values of crops obtained for each APU. The k-means clustering algorithm was used to group the APUs. Numbers of clusters within a basin (*i.e.* homogeneous units) were decided using the agglomeration schedule in hierarchical clustering and elbow criteria. The goal was to form the groups of APUs such that the variation in ET_c of a crop within a cluster is minimised and the difference in mean ET_c of various clusters is maximised. Henceforth, the delineated spatial resolution units are referred as ‘SRU’.

3.9 Data disaggregation to SRU level

Since many of the datasets required in WF assessment studies are maintained at administrative levels (*i.e.* district, state or national), the proportionality factor based approach was used in this study to disaggregate these data sets at desired spatial

resolution. Proportionality factors were based on the district level statistics and portion of the district geographical area present in the basin. Proportionality factors were developed for cropped area, irrigated and rainfed area, human and livestock population and groundwater availability and withdrawal.

3.10 Assessment of virtual water content (VWC)

The blue, green and grey virtual water content of the crops was estimated as the ratio of water use to the corresponding yield of different crops. Blue and green components of total crop water use were assessed using ‘irrigation schedule’ option and the USDA method for effective rainfall, respectively. Grey water use (*i.e.* dilution water requirement) was estimated using crop specific nitrate application rates, leaching fractions and the recommended level of nitrogen (kg/m^3) as per water quality standards for drinking purpose. In order to estimate the VWC under rainfed conditions, a linear relationship between grain yield and evapotranspiration as proposed by Doorenbos and Kassam (1979) was used to get crop yields under rainfed conditions. Details of VWC assessments are presented in Chapter-V.

3.11 Water footprints of crop production

Water footprint of crop production was calculated by multiplying VWC (m^3/ton) of each crop within the APU with its production (ton) and then summing up for all APUs and all crops. The procedure to estimate the cropped areas under irrigated and rainfed crops and corresponding yields has already been described in previous sections. The SRU wise datasets on VWC and WF were obtained as average of all the APU level within the SRU.

3.12 WF of livestock (WF_{ls})

Livestock population was estimated using the district wise livestock density of the basins. WF of livestock was estimated using the approach suggested by Dumont *et al.* (2013). The WF of livestock was estimated considering the varying drinking water needs for animals of different types and age groups.

3.13 WF of industrial and domestic sectors

Groundwater use for domestic and industrial sectors was estimated using the district wise groundwater withdrawal information and the geographic area factor. Blue WFs of domestic and industrial sector was estimated for both basins considering 10 % of the total withdrawal as blue consumptive water use. Referring the procedure adopted in Hoekstra and Mekonnen (2012), the part of the return flow disposed into the

environment without prior treatment was considered as the measure of grey WF of these sectors.

3.14 Net returns

The net returns per hectare of a crop under irrigated and rainfed areas were derived from SRU level crop productivity and average net returns from main and by-products of a crop. Crop wise and state wise data on cost of cultivation and production and prices of main and by-products of a crop was used to estimate net returns per hectare in each SRU of basins.

3.15 Economic water productivity of blue water

Economic water productivity (EWP) is an useful indicator in assessing the economic efficiency of blue water use. Using EWP, the low value water intensive crops can be identified, which helps in deciding future cropping patterns. Economic water productivity of blue water was obtained for crops under irrigated agriculture by dividing the gross returns (Rs) of particular crop from entire basin with blue WF (m^3) of crop production within the basin.

3.16 Production and consumption of crops within the basin

Bottom-up approach was considered to estimate the consumption of crops and crop products selected in the study basins. The state level per capita consumption of agricultural commodities in urban and rural areas obtained from NSSO (NSSO, 2012) and the SRU wise population data was used to obtain the consumption of selected crops covering about 33 major crop products. The basin level crop production was estimated by aggregating the SRU level production obtained as the product of cropped areas and respective productivity values.

3.17 Virtual water balance

Virtual water export from the basins was estimated as the product of VWC and quantity of the product exported from the basin. On annual basis, quantity of production in excess of total consumption within the basin was considered as quantity of export from the basin. Total consumption of a crop produce includes consumption requirement of human population, seed and wastage at farm and market level. Quantity of virtual water export and import was estimated by multiplying the quantity of export or import of commodity by the associated virtual water content. Net virtual water balance was also worked out for study basins.

3.18 Surface and ground water resources

Availability of surface water in the SRUs was assessed with the help of NRCS-CN method (USDA). SRU wise weighted curve number was obtained from the CN values derived for each soil type and land use combination and was used in estimation of runoff. Since, utilizable runoff is the quantity of estimated runoff after accounting for environmental flow requirements (EFR), the EFR of Gomti and Betwa basin was estimated using the Variable Flow Method (VFM) methodology suggested by Pastor *et al.* (2013). Groundwater resources of the districts within the basin boundary were estimated using the data on groundwater withdrawal (CGWB, 2009) and geographic area factor estimated for each district.

3.19 Environmental Sustainability of blue and grey WFs

Sustainability analysis involved comparison of blue and grey WFs with water resource availability for human consumption. Sustainability of blue and grey WFs was assessed at monthly time step using the ‘Blue Water Scarcity’ (BWS) and ‘Water Pollution Level’ (WPL) as sustainability criterions for blue and grey WFs respectively.

3.20 Evaluating response of WFs to management alternatives

Response formulation is the last phase of WF analysis in which the response of WFs is evaluated and strategies are proposed to reduce the WF. In present study, the response of WFs of agriculture sector was considered in developing basin level water allocation strategies. Three scenarios were considered for minimizing the WF of agriculture sector. Optimization models for basin level and SRU wise reallocation of cropped areas were developed such that the crop WF is reduced. The detailed information on objective function and development of models for two independent scenarios is presented in Chapter-VI. Solution of developed optimization models were accomplished using Open Solver 2.1[®] add-in interface in MS Excel[™]. Open Solver 2.1[®] is based on the concept of COIN-OR CBC optimization algorithm (Mason and Dunning, 2010).

Development of methodology for water footprint assessment at river basin scale

Abstract

Crop evapotranspiration (ET_c) is an important parameter in assessment of water footprint (WF) of agriculture. The resolution of ET_c estimation significantly influences the accuracy of water footprint estimates. This paper illustrates a methodology that uses an integrated approach employing a multivariate geostatistics and non-parametric clustering protocol to delineate the spatial resolution units (SRU) for water footprint assessment. On the basis of soil, climate and district boundaries, the Gomti and Betwa basins were divided into 21 and 27 Agricultural Production Units (APU), of the *Gomti* and *Betwa* river basins, respectively and crop evapotranspiration was estimated in each APU using FAO CROPWAT model. The spatial variability maps of ET_c revealed distinct spatial trends for *kharif* and *rabi* crops in both basins. In Gomti basin, pronounced variation in ET_c was observed in case of *rabi* crops (sugarcane 141 mm and peas 144 mm) than *kharif* crops (pearl millet 23 mm). In Betwa basin maximum and minimum variation was observed in case of sesame (124 mm) and chickpea (40 mm). On the basis of APU level mean ET_c of crops, four distinct SRUs were delineated for Gomti and Betwa basins. Results showed that, compared to basin or agro ecological sub-region, the ET_c variability within the delineated SRUs was significantly lower indicating SRU as a better resolution for WF assessment. A methodology to downscale district level datasets to basin scale and WF assessment of crop and livestock production, industrial and domestic uses is proposed. The methodology includes estimation of blue and green consumptive use of crops for assessment of green and blue WFs, respectively and dilution requirement of nitrate fertilizer as an indicator of grey WF. Protocols for estimation of WF of livestock production and industrial and domestic uses were also developed.

Key words: Water footprint, crop evapotranspiration, variability mapping, kriging, spatial resolution

4.1 Introduction

Water footprint is an emerging indicator of freshwater consumption and has wide applicability in devising production and trade related strategies at different geographic scales. The water footprint of the people in a region is defined as the total amount of water that is used to produce the goods and services consumed by the inhabitants of the region (Hoekstra, 2011). Water footprint has been recognized as comprehensive indicator of human appropriation of available fresh water. Application of WF concept to water resource management at basin level requires precise assessment of virtual water content (VWC) of commodities. Virtual water content of a crop is the ratio between crop yield and the crop evapotranspiration (ET_c). The crop evapotranspiration is function of soil, climate and crop factors (Allen *et al.*, 1998) and varies both in space and time implying that crop evapotranspiration needs to be estimated in a spatially explicit way. It is necessary to decide upon the resolution of ET_c estimation and consequently the WF assessment. Resolution for water footprint assessment was defined as the size of the spatial unit within which the climate, soil and crop parameters were uniform such that intra-unit variation in VWC was negligible.

At the global level, grid based soil moisture balance models have been used to estimate the crop water requirements and crop WF at 5x5 arc-minutes (Siebert and Doll, 2010; Mekonnen and Hoekstra, 2010), 30 x 30 arc-minutes (Fader *et al.*, 2011; Rost *et al.*, 2008) and 1 x 1 degree (Hanasaki *et al.*, 2010) spatial resolution. Other studies on global WF accounting (Hoekstra and Chapagain 2007; Chapagain *et al.*, 2006; Chapagain and Hoekstra, 2007) of different crops had used ‘country’ as a SRU. So far, global consumptive water use covering both the elements has mainly been assessed with coarse spatial resolutions or at the national level. At national or basin scale, the size of the SRU considered for ET_c assessment is very large. Climate and soil variability within these units can affect the blue and green crop water use. Studies (JingLei *et al.*, 2013; Alexandrov and Hoogenboom, 1999; Heinemann *et al.*, 2002) suggested significant spatial variation of ET_c even within a smaller region. The WF assessment at national level, e.g. United States (Mubako and Lant, 2013), China (Ge *et al.*, 2011),

India (Kampman, 2008), the Netherlands (Oel *et al.*, 2008) and Indonesia (Bulsink *et al.*, 2010), used ‘province/state’ as SRU to estimate crop water requirements.

At river basin scale specific criteria or procedure to define the appropriate resolution is not available. Feng *et al.* (2012) estimated the WF of yellow river basin using upper, middle and lower regions of the basin as spatial unit for WF assessment. Aldaya and Llamas (2008) carried out analysis of water footprint of Gaudiana river basin in Spain using crop water use estimated at provincial level.

The resolution of *ETc* assessment has significant impact on the estimates of water footprint. Global WF of wheat at resolution of 5’x5’ was estimated as 941.42 km³ (Siebert and Doll, 2010) while at 30’x30’ resolution it was estimated as 678.3 km³ (Fader *et al.*, 2011). In most of the recent WFP studies, decision on spatial resolution at which the *ETc* was estimated was based mainly on spatial scale at which the data is available and capability of the selected crop evapotranspiration estimation model. The crop evapotranspiration within the well-defined existing units, such as district, province or country, cannot be assumed to be uniform. Climate of India varies from tropical to temperate. Large intra state variation in rainfall and temperature leads to spatial as well as seasonal variation in *ETc*. If water footprint accounting is done taking ‘state’ or ‘country’ as spatial resolution for *ETc* assessment, it will be unrealistic and can lead to erroneous WF estimates. Therefore, within a basin, the spatial units should be delineated such that intra-unit variations in *ETc* are kept to minimum. Delineation of such homogeneous areas will not only reduce the time and money involved but also provide the managers with guidelines for planning data collection activities and allocating budget and manpower resources.

In this study, a methodology comprising of geostatistical interpolation and cluster analysis techniques is proposed to define the spatial resolution for WF assessment at basin scale. Geostatistics provides a set of statistical tools for spatial interpolation and analysing spatial variability. Geostatistical method provides regular gradient of variability, which are more realistic than the mound-and-valley combination provided by the Inverse Distance Weighing (IDW) and Inverse Square Distance (ISD) methods of interpolation under deterministic statistics (Kumar, 2010; Sarangi *et al.*,

2006; Sarangi *et al.*, 2005). Geostatistics has been increasingly used to map the variability parameters like precipitation (Sarangi *et al.*, 2005), crop evapotranspiration (Sharma and Irmak, 2012), groundwater table and hydro-geochemical processes (Gundogdu and Guney, 2007) and climatic parameters (Ibrahim, 2011). The interpolated *ETc* maps can be used to assess the WF at any desired resolution at basin scale. High resolution estimates of VWC will improve the accuracy of WF accounting but the expenses on data collection would also be very high. Therefore, the cluster analysis procedures was applied to combine the higher resolution units into low resolution units called clusters. A cluster is a geospatial unit within which the variation in *ETc* of a crop is negligible.

WF assessment at basin scale also requires several datasets to be disaggregated at the river basin level. These datasets includes gross cropped area, crop wise cultivated areas and surface and ground water irrigated area. In order to determine the consumption of a commodity within a basin, it is necessary to work out the population. In India, these datasets are generally available at the scale of administrative units like tehsil, district, state or country which can directly be used to assess the WF at these well-defined administrative scales. However, the boundaries of river basin do not exactly follow the boundaries of administrative units. Under such circumstances, it necessary to develop some relational factors that can downscale the available datasets at administrative scale to basin scale. WF assessment studies at river basin level are rare largely due to the lack of statistical data at the river basin level.

In view of this, the present study was planned with the twin objectives of defining appropriate spatial resolution of WF assessment and to devise a methodology to derive the crop and population related datasets to suit the selected resolution of WF assessment of Gomti and Betwa rivers basins in India. Finally, a framework is proposed for accounting of WF.

4.2 Materials and Methods

4.2.1 The study area

The present study was carried out for Gomti and Betwa sub-basins of Ganga River. Detailed description of the study basins is presented in Section 3.4 in Chapter III. Administrative districts in both the basins are shown in Fig. 4.1.

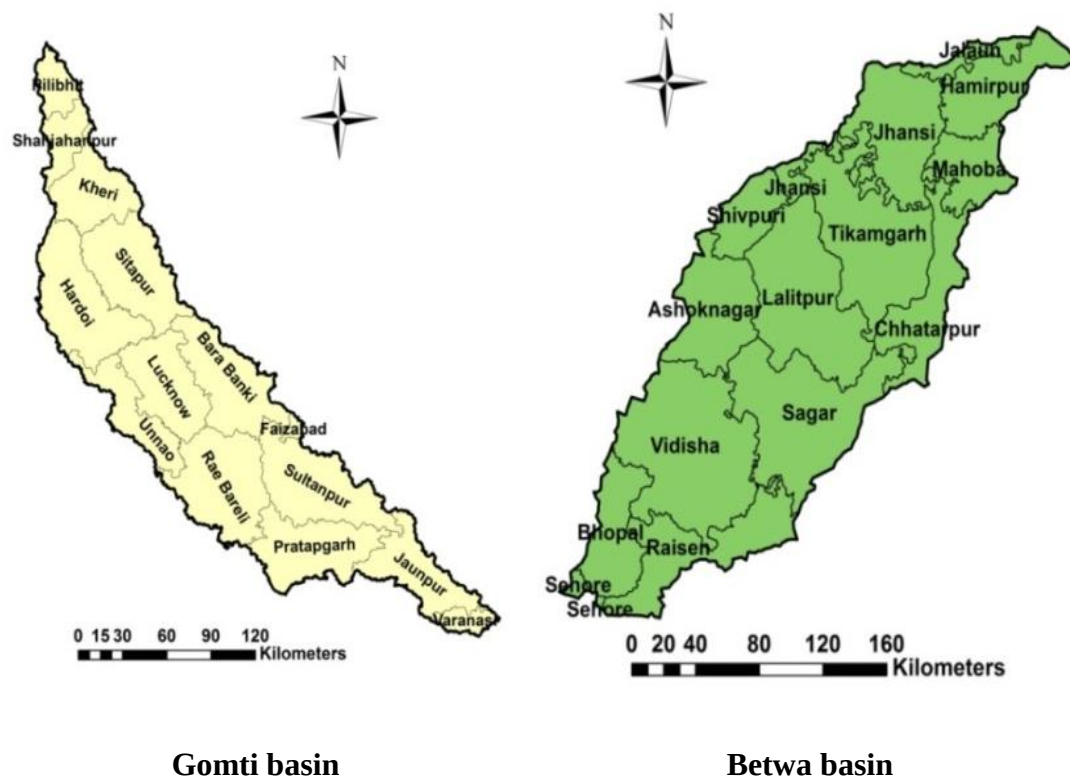


Fig 4.1 Administrative districts in Gomti and Betwa basins

Agriculture is the dominant land use in these basins and the major crops cultivated are paddy, wheat, sugarcane, potato, and other vegetable crops depending on availability of irrigation facilities. Assessment of ET_c was done for a normal year for which annual rainfall of majority of the basin districts was within the predefined standard variation of -19 to +19 % of the normal rainfall of the respective district (IMD, 2012). Spatial distribution of rainfall, mean minimum and mean maximum temperature during *kharif* and *rabi* seasons for the two basins is shown in Fig 4.2 and Fig 4.3, respectively. Gomti basin receives scanty winter season (Rabi) rainfall while in Betwa basin the rainfall is sufficient to support the winter crop.

4.2.2 Delineation of agricultural production units

In order to estimate the ET_c at high resolution, the study basin was divided in to smaller units, called Agricultural Production Unit (APU), which were based on homogeneity in soil, climate and district boundaries. It is believed that the climate and soil properties of an APU will remain fairly uniform and further division of an APU will not necessarily improve the accuracy of WF assessment. Therefore, APU can be considered as the smallest unit (highest resolution) for assessment of crop evapotranspiration. Delineation of APUs requires information on basin boundary, district administrative boundaries, soil types, and major climatic regions of the basin. Since statistical data related to area and production of crops is maintained at district level and is easily available, defining APUs for each district separately will help in partitioning of these datasets to APU level. The boundaries of two basins were delineated using digital elevation data obtained from SRTM (USGS, 2012). The standard process of delineation, such as creating a depression-less DEM, flow direction, flow accumulation, pour points, and watershed delineation protocol was used.

Information on soil properties was derived from FAO Harmonized World Soil Datasets (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008). The HWSD is a global soil raster datasets and contains information on 17 soil parameters for two soil layers (0-30 and 30-100 cm). The soil properties viz. sand, silt and clay percentage and bulk density were obtained as arithmetic average of values for two soil layers. Other soil properties viz. field capacity, wilting point and maximum infiltration rate were determined using the HWSD data and pedotransfer functions for Indian soils developed by Adhikari *et al.* (2008). The Agro-Ecological Sub Region (AESR) maps of the basin were extracted from the AESR map of India developed by NBSSLUP, ICAR (Gajbhiye and Mandal, 2000). These AESRs are based on the major climate types observed in the India. Thematic layers pertaining to soil, AESR, basin boundary and district boundaries were overlaid and APU polygons were formed for each district using *intersect* feature in ArcGIS.

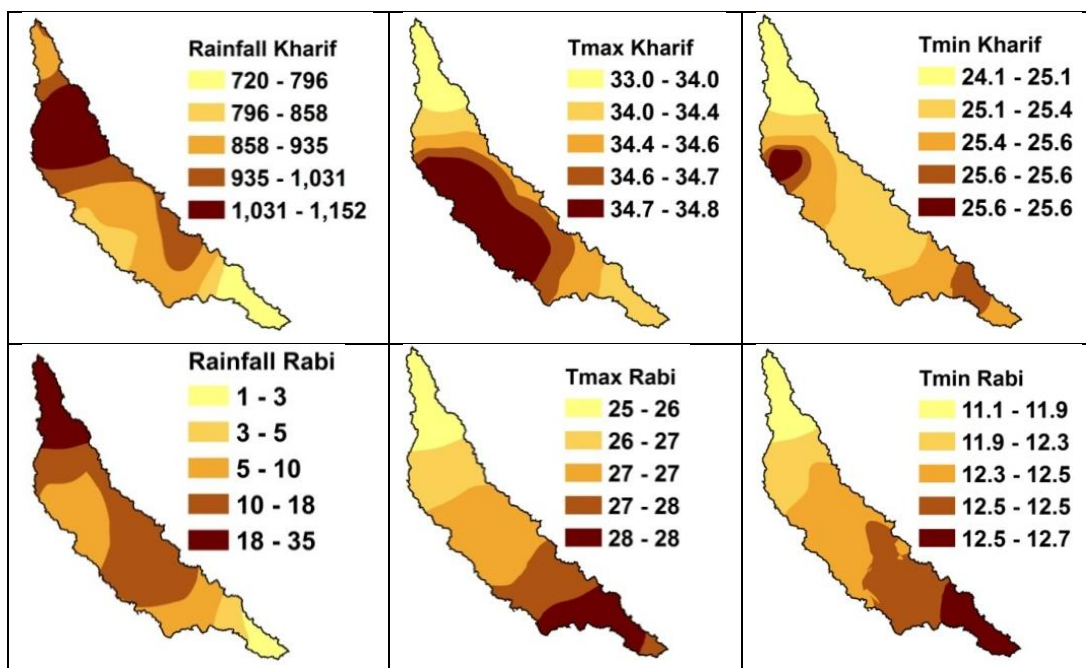


Fig. 4.2 Spatial distribution of annual rainfall (mm), mean maximum temperature ($^{\circ}\text{C}$) and mean minimum temperature ($^{\circ}\text{C}$) in Gomti basin during *Kharif* and *Rabi* season of 2011

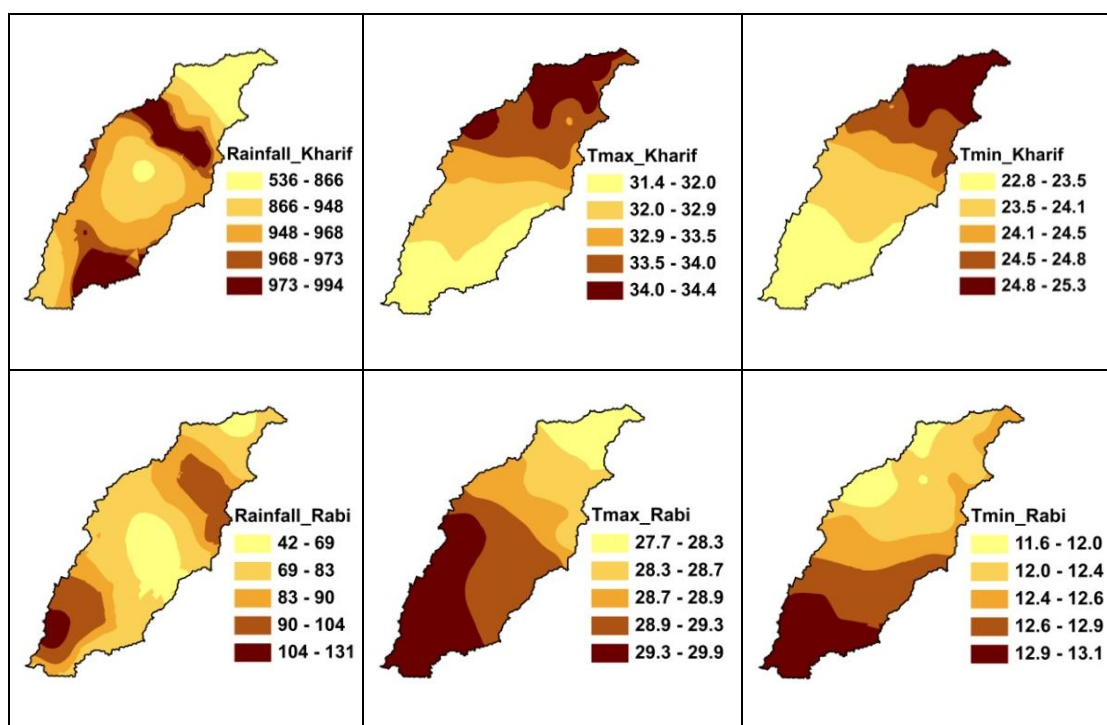


Fig. 4.3 Spatial distribution of rainfall (mm), mean maximum temperature, $T_{\max}$ ($^{\circ}\text{C}$) and mean minimum temperature, $T_{\min}$ ($^{\circ}\text{C}$) in Betwa basin during *Kharif* and *Rabi* season of 2011

4.2.3 Assessment of crop evapotranspiration

Crop evapotranspiration was estimated for each of the delineated APUs of basins. The FAO CROPWAT model (FAO, 2012; Allen *et al.*, 1998) was used to estimate the consumptive water use of a crop. CROPWAT model estimates reference crop evapotranspiration (ET_0) over the cropping season using Penman-Monteith equation. The equation uses standard climatological records of air temperature and solar radiation. The crop evapotranspiration (ET_c) was estimated from the reference evaporation (ET_0) using the crop coefficients. Values of crop coefficient (K_c) for initial, middle and end stage and crop rooting depths were adopted from FAO irrigation and drainage paper No-56 (Allen *et al.*, 1998). CROPWAT also requires information on rooting depth of crops and critical depletion to be specified for each crop (Table 4.1). Critical depletion is the percentage of the available soil water that depletes between irrigations without serious plant moisture stress (Allen *et al.*, 1998). The crop sowing and harvesting dates for the state of Uttar Pradesh and Madhya Pradesh were adopted from information published by Department of Economics and Statistics, Ministry of Agriculture, Government of India (MoA, 2011) and ICAR (available at www.icar.org). The climatic data derived from gridded daily time series data of India Meteorological Department (IMD) available from National Initiative on Climate Resilient Agriculture (NICRA-ICAR, 2012) was used to estimate CWR at each APU level.

4.2.4 Mapping ET_c variability using geostatistical approach

In order to develop the continuous surfaces of ET_c within the basin, the estimated point ET_c values were interpolated over the basin. Ordinary Kriging (OK) and Ordinary Co-Kriging (OCK) interpolation methods were selected and the best-fit semivariogram model was selected on the basis of R^2 and RSS statistical parameter of the fitted model. Kriging was selected as it is most robust and is frequently used to account for data fluctuations and consideration of a global trend (Webster and Oliver, 2001; Johnston *et al.*, 2001).

Table 4.1 Crop parameters used in assessment of crop evapotranspiration

Crop	Date of Sowing (dd/mm/2011)		Length of growth stage, days				Crop coefficient (Kc)			Rooting depth, m	Critical depletion factor
	Gomti	Betwa	Ini	Dev	Mid	Late	Ini	Mid	End		
Black Gram	05/07	05/07	20	30	35	15	0.4	1.1	0.3	0.6	0.55
Chick Pea	25/10	20/10	20	30	45	25	0.4	1	0.35	0.6	0.50
Groundnut	10/07	05/07	25	35	45	25	0.4	1.15	0.6	0.5	0.50
Lentil	15/10	15/07	15	25	55	35	0.4	1.05	0.5	0.6	0.50
Maize	01/07	05/07	20	30	40	15	0.3	1.2	0.5	1.0	0.55
Paddy	05/07	10/07	20	30	50	30	1.05	1.2	0.75	0.5	0.20
Pearl Millet	01/07	**	20	30	45	25	0.3	1	0.3	1.0	0.55
Peas	05/11	05/11	20	30	35	15	0.4	1.1	0.3	0.6	0.35
Pigeon pea	01/07	15/06	20	40	60	30	0.4	1.15	0.35	1.2	0.60
Potato	20/10	**	25	30	45	30	0.5	1.15	0.75	0.4	0.35
Rapeseed	15/10	15/10	20	30	40	25	0.35	1.1	0.35	1.0	0.60
Sesame	01/07	01/07	20	30	40	20	0.35	1.1	0.3	1.0	0.60
Sorghum	05/07	05/07	20	25	40	25	0.3	1.05	0.6	1.0	0.55
Soybean	**	01/07	15	20	60	20	0.4	1.15	0.5	0.6	0.50
Sugarcane	05/03	**	30	50	180	60	0.4	1.25	0.75	1.2	0.65
Wheat	20/11	15/11	15	25	50	30	0.7	1.15	0.3	1.2	0.55

**Crop not selected in basin due to negligible area under these crops

Prior to semivariogram fitting and actual kriging, an exploratory spatial data analysis was carried out for both primary and secondary variates to ascertain the normality, trend and presence of any outliers. The performance of the two algorithms, OK and OCK, was assessed and compared using cross validation statistics in terms of mean error (ME) and root mean square error (RMSE). The kriging interpolation of crop evapotranspiration values was carried out for the best variogram model. The geostatistical analysis extension module of ArcGIS 9.3™ was used for analysis and the interpolated surfaces of *ETc* were developed using the best performing interpolation method.

4.2.5 Delineating Spatial Resolution Units

On the basis of kriged mean *ETc* values of crops, the APUs were combined using the clustering approach. Data clustering is a method of creating groups of objects or clusters in such a way that objects in one cluster are very similar and objects in different clusters are quite distinct (Yan et al., 2001). The k-means clustering algorithm was used to group the APUs. The k-means algorithm was selected as it is not based on distance measures such as Euclidean distance, but uses intra-cluster variation as a measure to form homogenous clusters (Mooi and Sarstedt, 2011). Numbers of clusters within a basin (homogeneous units) were decided using the elbow criteria. The elbow criterion is a common rule of thumb to determine optimum number of clusters for k-means clustering (Madhulatha, 2012). The goal was to form the groups of APUs such that the variation in *ETc* of a crop within a cluster is minimised and the difference in the mean *ETc* of various clusters is maximised. After completion of this analysis, the delineated area of each homogeneous unit was obtained using GIS.

4.2.6 Downscaling district level datasets to SRU level

Water footprint assessment of crops at basin scale requires information on cultivated areas, irrigated and rain fed areas of crops at the same resolution adopted in the study. Proportionality factors based approach is proposed in this study to develop these data sets at desired spatial resolution. Proportionality factors were derived using the district level crop area statistics. In this approach, the gross cropped area (GCA) of a SRU is used to develop other required datasets. The GCA of APU was extracted from LULC maps of Madhya Pradesh and Uttar Pradesh obtained from ISRO.

Estimation of cultivated area of particular crop in APU was based on the assumption that the ratio of cultivated area of a crop to gross cropped area in an APU is same as that at district level. Cultivated area of a crop in APUs and SRUs was obtained using Eq.1 and Eq.2, respectively.

$$GCA[c, k] = \sum_{d=1}^i \sum_{u=1}^j GCA[c, u, d, k] \dots \dots \dots (1)$$

$$GCA [c, u, d, k] = \frac{GCA[c, d]}{GCA [d]} \times GCA[u, d, k] \dots (2)$$

Where, $GCA [c, k]$ is the gross cropped area of crop c in spatial resolution unit k ; $GCA [c, u, d, k]$ is the gross cropped area of crop c in agricultural production unit u of the district d in $SRU k$; $GCA [d]$ is the gross cropped area of district d , $GCA [c, d]$ is the gross cropped area of crop c in district d ; $GCA[u, d, k]$ is the gross cropped area of agricultural production unit u in district d of $SRU k$; i is the number of districts in spatial resolution unit and j is number of APUs in the district.

The estimation of gross irrigated area (GIA) of a crop in SRU was based on the assumption that the ratio of irrigated area of a crop to cultivated area of that crop in an APU is same as that at district level. Irrigated area of a crop in APUs and SRUs were obtained using Eq.3 and Eq.4.

$$GIA[c, k] = \sum_{d=1}^i \sum_u^j GIA[c, u, d, k] \dots \dots \dots (3)$$

$$GIA [c, u, d, k] = \frac{GIA[c, d]}{GCA [c, d]} \times GCA[c, u, d, k] \dots (4)$$

Where, $GIA [c, k]$ is the gross irrigated area of the crop c in spatial resolution unit k , $GIA [c, u, d, k]$ is the gross irrigated area in agricultural production unit u of the district d in $SRU k$; $GIA[c, d]$ is the gross irrigated area of crop c in district d ; $GCA [c, d]$ is the gross cultivated area of crop c in district d ; $GCA [c, u, d, k]$ is the gross cropped area of crop c in agricultural production unit u of the district d in $SRU k$.

4.2.7 Water footprint assessment methodology

Water footprint of the livestock can be estimated considering consumptive water use in producing feed, drinking and service needs. Service needs include consumptive use in washing and cleaning of animals and barns. Drinking water needs of different animals like cattle, buffalo, bullocks, goat, sheep, pig can be obtained from published information specific to the region of the study. The total annual water requirement per animal was multiplied with animal population within the basins to get the WF of livestock. Animal population within the basin can be worked out by multiplying the district wise animal population density with area of the district within the basin. Water footprint of domestic and industrial sectors is estimated using the district level groundwater withdrawals for these sectors and water consumption ratio (WCR). Water consumption ratios as proposed by Hoekstra et al (2011) is the ratio between volume of water consumed to the total volume of water withdrawal. Groundwater withdrawal for the part of the district within the basin can be obtained by multiplying the district level values with the geographical area factor. Geographical area factor is the ratio between geographical area of the district within the basin to total geographical area of the district. The general methodology for WF assessing of agriculture, livestock and domestic and industrial sector is presented in Fig 4.4.

FAO CROPWAT model provides the estimates of blue and green consumptive water use of the crops required in assessment of blue and green water requirements of crops. Blue water use in a particular time step is crop evapotranspiration or effective rainfall, whichever is minimum. Grey water use is the amount of water required to dilute the quantity of pollutant leached to a level of drinking quality standards. Pollutant load in agriculture is mainly from leaching of fertilizer and was obtained by multiplying fertilizer application rate with leaching fractions. With the help spatial datasets on irrigated and rainfed areas of the basins within each SRU, the WF of a basin can be worked out adopting the steps presented in Fig 4.4.

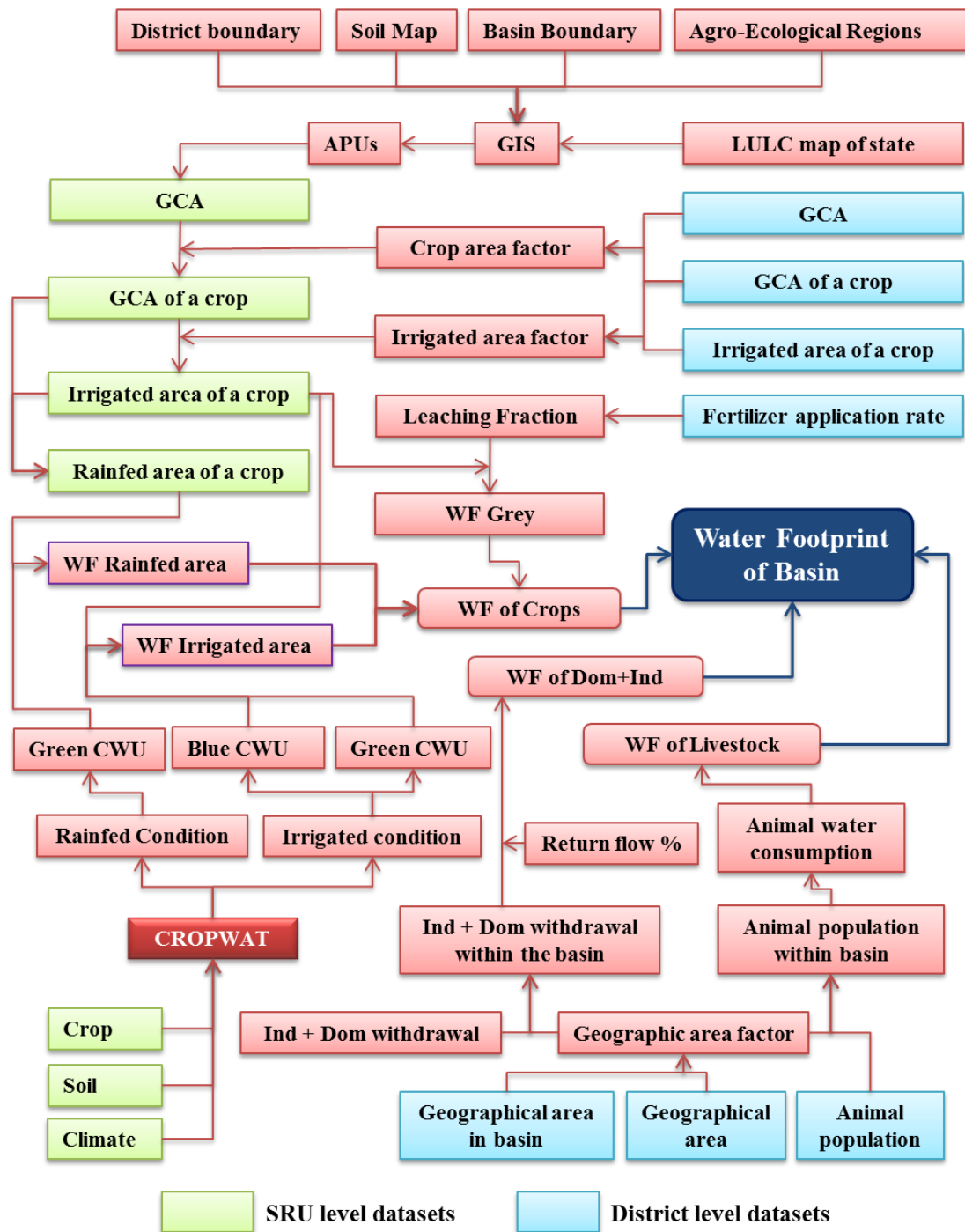


Fig. 4.4 Methodological framework for water footprint assessment at basin scale

4.3 Results and discussions

4.3.1 Soils of the basins

The information on major soils of the basins as obtained from HWSO is presented in Fig 4.5. The soils of the Gomti basin represent the vast track of the riverine alluvium of the Gangetic plain with ‘loam’ as major textural class. There is variation in the sand, silt and clay content of this class across the basin. Betwa basin has wide variation in soil types with clay and sandy loam as the major classes. The other important properties of the soil required in estimation of *ET_c* of crops are presented in Table 4.2.

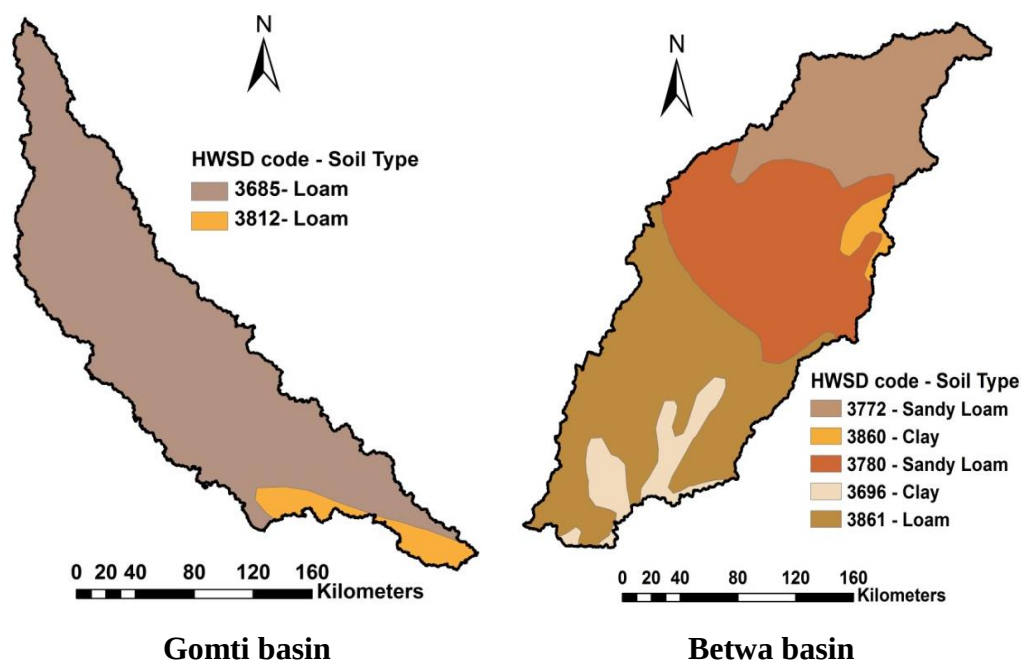


Fig 4.5 Soils maps of the Gomti and Betwa river basins

4.3.2 Agro-ecological sub regions

The areal coverage and the description of agro-ecological regions of Gomti and Betwa basins are presented in Fig 4.6 and Table 4.3, respectively. Climate of the Gomti basin is hot moist semi-arid and is characterised by two agro-ecological regions viz. 4.3 (Ganga Yamuna Doab) and 9.2 (Madhya Bharat Plateau). This type of climate is suitable for most of the crops cultivated in India. Climate of Betwa basin ranges from hot dry sub-humid in upper reaches to hot moist semi-arid in the lower reaches.

Table 4.2 Properties of soils in Gomati and Betwa basins

Basin	Soil Code	Texture Class	Particle distribution			Bulk density (g/cc)	Field capacity (%)	Wilting point (%)	Available water holding capacity mm/m	Hydraulic conductivity mm/day
			Sand (%)	Silt (%)	Clay (%)					
Gomti	3685	loam	42	36	22	1.37	25.23	10.4	148.4	102.2
	3812	loam	47	32	21	1.42	23.76	10.0	138.1	116.8
Betwa	3772	Sandy loam	79	10	11	1.40	13.4	5.6	78.3	242.0
	3860	Clay (light)	16	29	55	1.45	40.4	24.9	154.7	59.1
	3780	Sandy loam	79	10	11	1.40	13.4	5.6	78.3	242.0
	3696	Clay (light)	21	28	51	1.43	38.1	23.2	149.5	64.7
	3681	Loam	42	36	22	1.37	25.2	10.4	148.4	102.2

Table 4.3 Description of Agro-ecological region in the Gomti and Betwa basins

Agro-climatic sub-region	Climate	Soil Type
4.3 Ganga Yamuna Doab, Rohilkhand and Avadah Plain	hot, moist semi-arid	Deep loamy alluvium
4.4 Madhya Bharat Plateau and Bundelkhand Uplands	hot, moist semi-arid	Deep loamy and clayey mixed Red and Black
9.2 Rohilkhand, Avadh and south Bihar Plains	hot, dry sub-humid	Deep loamy alluvium-derived
10.1 Malwa Plateau, Vindhyan Scarpland and Narmada Valley	hot, dry sub-humid	Medium and deep clayey Black soils
10.3 Vindhyan Scarpland and Bundelkhand Plateau	hot, dry sub-humid	Deep loamy to clay mixed Red and Black

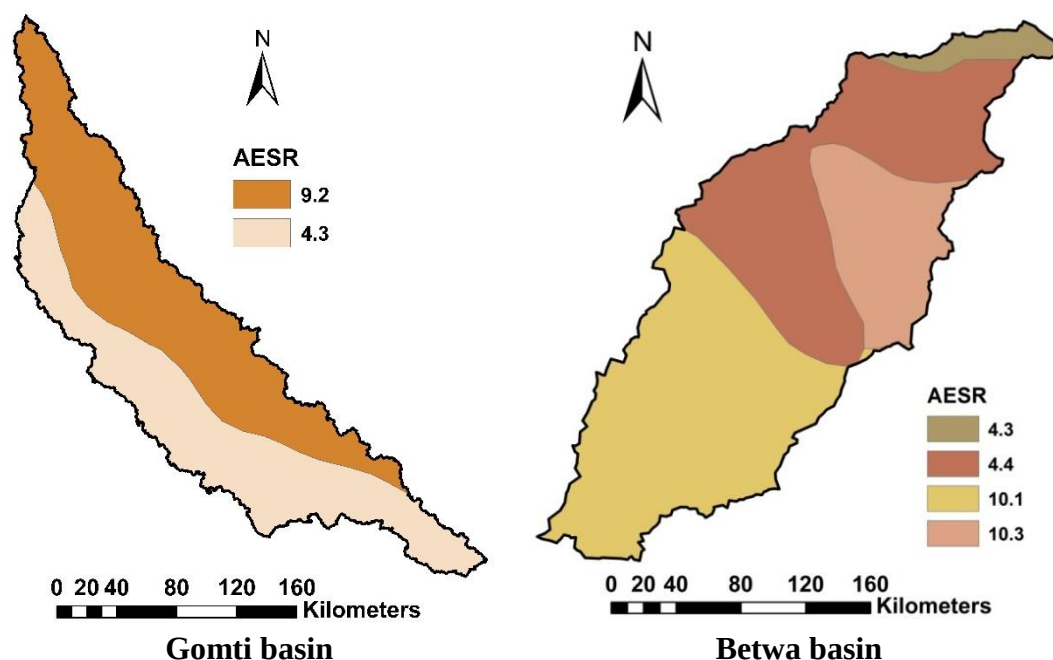


Fig.4.6 Agro-ecological regions in the Gomti and Betwa river basins

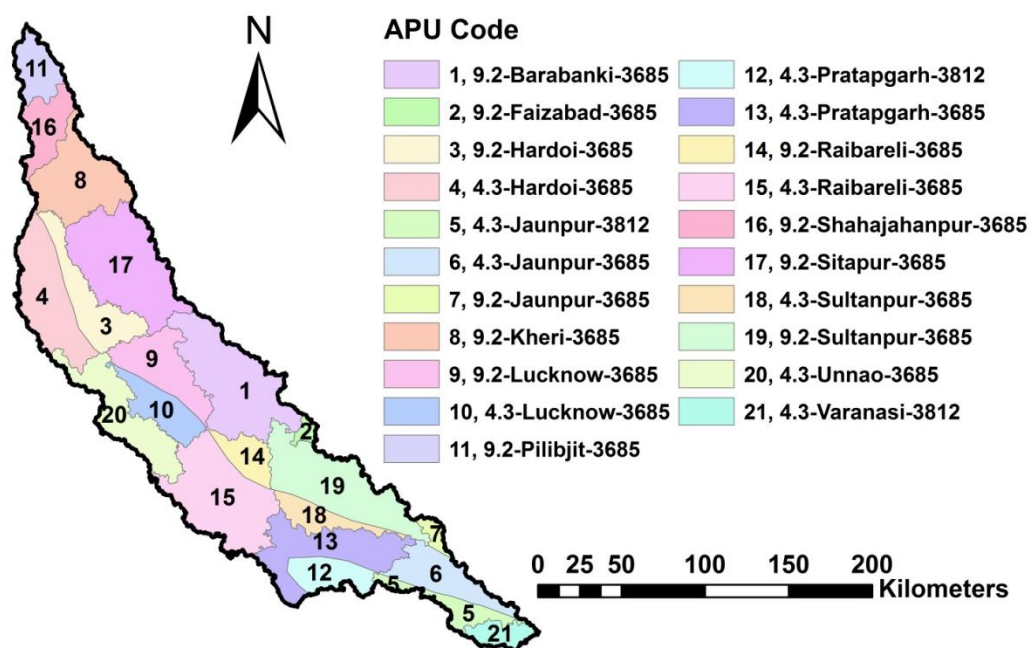
4.3.3 Agricultural Production units

Gomti and Betwa basins cover, full or part of 14 administrative districts each. Based on the combination of district boundaries, soil types and agro-ecological regions, the Gomti and Betwa basins were divided into 21 and 27 agricultural production units (APUs) respectively. The delineated APUs of the basins are presented in Fig 4.7. The delineated APUs were considered as homogeneous units in terms of ET_c of crops.

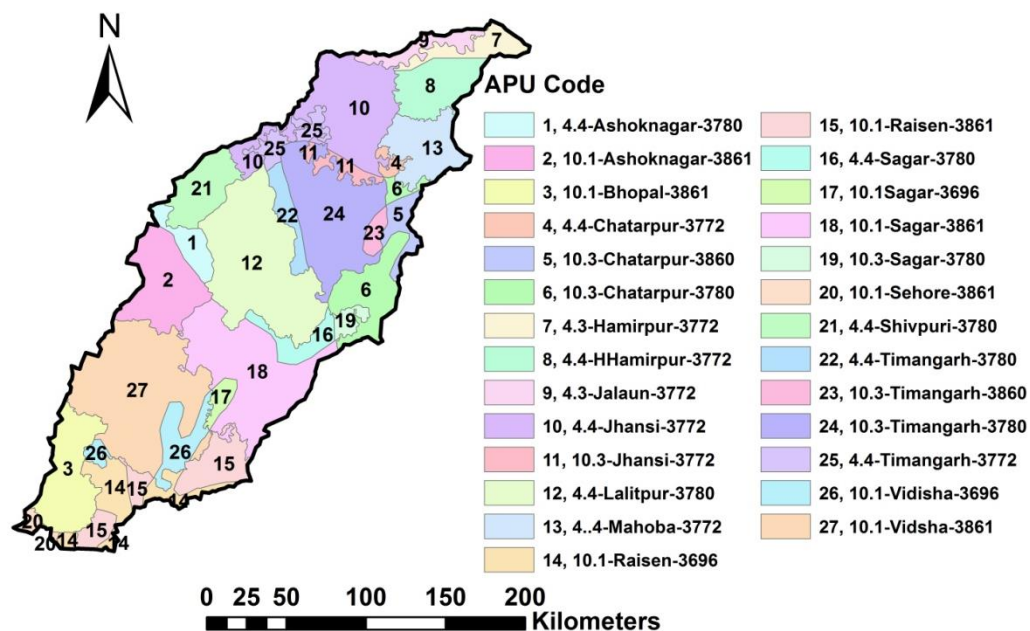
4.3.4 Variation in ET_c at basin level

The evapotranspiration of 15 and 12 major crops of the Gomti and Betwa basins was estimated for the delineated APUs using FAO CROPWAT model. APU wise estimates of ET_c are given in Appendices-I and II. The crop evapotranspiration was estimated under the condition of optimum soil moisture availability. The options in CROPWAT were selected such that an irrigation event is scheduled on the day when soil moisture falls below the specified critical depletion. The descriptive statistics (Table 4.4) shows that there is wide variation in the crop evapotranspiration across the basins. The maximum variation in ET_c was observed in case of sugarcane crop with a range of about 128 mm followed by potato (66.8 mm), lentil (60.4 mm) and wheat (57.7 mm). In Betwa basin the ET_c of sesame crop varied significantly (range = 62.6 mm)

across the basin followed by paddy (58.2 mm), pigeon pea (58.2 mm) and soybean (54.3 mm). In case of other crops the variation in ET_c remained in the range of 22.9-49.4 mm.



a. Gomti basin



b. Betwa basin

Fig 4.7 Delineated agricultural production units in the Gomti and Betwa basins
(Explanation of APU code: APU number, AESR code - District name- Soil code)

Table 4.4 Crop evapotranspiration (ET_c) variation in the Gomti and Betwa basins

Crop Evapotranspiration (ET_c) parameters								
Crop	Gomti Basin				Betwa Basin			
	Minimum ET_c , mm	Maximum ET_c , mm	Mean ET_c , mm	Standard deviation	Minimum ET_c , mm	Maximum ET_c , mm	Mean ET_c , mm	Standard deviation
Paddy	475.9	503.6	490.7	9.0	465.0	523.2	496.4	17.8
Millet	347.4	370.2	359.9	7.3	--	--	--	--
Maize	444.2	472.5	459.0	9.0	382.6	409.5	395.0	7.6
Groundnut	482.6	509.8	495.6	9.6	503.4	551.3	526.4	13.1
Pigeon pea	516.5	553.2	538.5	9.2	529.7	587.9	559.6	17.3
Sorghum	416.9	442.0	429.0	7.7	358.0	396.7	377.5	10.4
Sesame	346.0	373.0	362.8	8.6	349.4	412.0	386.8	15.7
Black gram	404.5	450.8	439.6	12.7	294.2	334.5	316.1	13.1
Soybean	--	--	--	--	442.8	497.1	470.5	16.7
Wheat	302.6	360.3	341.7	17.1	388.5	436.3	406.9	12.8
Chickpea	272.6	321.0	304.2	14.9	301.6	336.5	314.4	9.4
Potato	321.2	388.0	362.2	17.8	--	--	--	--
Mustard	265.7	307.5	294.9	12.6	304.7	343.3	322.8	10.8
Lentil	307.7	368.0	345.4	15.8	291.4	334.9	313.0	12.7
Peas	253.9	303.3	285.3	13.4	372.4	415.2	392.9	12.2
Sugarcane	1414.3	1542.3	1508.0	35.3	--	--	--	--

4.3.5 Evaluation of ordinary kriging (OK) and ordinary co-kriging (OCK)

Spatial variability maps of ET_c for the Gomti and Betwa basins were prepared using the ET_c estimates of 21 and 27 APUs of Gomti and Betwa basins. In case of OK the estimated values of ET_c was the primary and the only variable used, while in case of OCK, in addition to ET_c , seasonal mean minimum ($T_{\min}$) and seasonal mean maximum ($T_{\max}$) temperatures were used as co-variates. The exploratory data analysis performed on the primary variate (ET_c) and the co-variates revealed that the data are not exactly normally distributed. Transformation of ET_c data using ‘logarithmic’ or ‘box-cox’ methods did not show any improvement in results. Also, the Voronoi map generated for point ET_c datasets with the highest entropy parameter did not show presence of any outliers. So, the original data on ET_c at 21 and 27 locations, in case of Gomti and Betwa respectively, was subjected to ordinary kriging and ordinary co-kriging.

Statistical parameters were used to select the best fit model to predict the spatial variability in the crop evapotranspiration. On the basis of R^2 and RSS, the spherical model was observed to be the better fitting semivariogram model for all crops in both the river basins. It was observed from the fitted semivariogram that OCK with $T_{\max}$ as covariate resulted in R^2 values ranging from 0.71 to 0.93 for various crops in Gomti and 0.78 to 0.98 in Betwa basin (Table 4.5 and Table 4.6). In Gomti basin, R^2 of the fitted semivariogram model was higher for OK (paddy, millet, maize, sesame and black gram) but the prediction accuracy (ME and RMSE) was better in case of OCK with $T_{\max}$ as covariates (Table 4.5). The cross validation statistics for OK and OCK for both the basins showed that the mean error of the ET_c estimation was close to zero for all the interpolation methods and that the difference between ME observed in OK and OCK was very small, however, RMSE was considerably different. Therefore the best performing OCK method with $T_{\max}$ as covariate and spherical semivariogram model was used to develop the interpolated surfaces for crop evapotranspiration within the two river basins.

Table 4.5 Performance evaluation parameters for interpolation of crop evapotranspiration in Gomti basin

Crop	Ordinary Kriging			Ordinary Co-Kriging					
	R ² for fitted model	ME	RMSE	R ² for fitted model		Covariates			
				Covariates		T _{min}		T _{max}	
				T _{min}	T _{max}	ME	RMSE	ME	RMSE
Paddy	0.96	0.30	2.48	0.30	0.71	0.33	2.65	0.22	2.13
Millet	0.97	0.06	2.58	0.35	0.74	0.08	2.66	-0.02	2.21
Maize	0.88	0.15	2.89	0.50	0.78	0.13	2.87	-0.06	3.40
Groundnut	0.82	0.38	5.07	0.60	0.81	0.31	4.74	0.11	3.08
Pigeon pea	0.82	0.44	6.78	0.81	0.84	0.30	5.71	0.12	4.22
Sorghum	0.82	0.60	6.09	0.68	0.82	0.40	6.30	0.28	5.65
Sesame	0.99	0.08	3.08	0.76	0.79	0.12	3.24	0.01	2.77
Black gram	0.88	0.06	4.73	0.73	0.86	0.49	3.75	0.32	2.35
Wheat	0.92	0.76	5.81	0.92	0.91	0.53	4.91	0.35	3.41
Chickpea	0.92	0.29	4.28	0.92	0.92	0.09	2.59	-0.04	1.72
Potato	0.92	-0.72	4.26	0.92	0.93	-0.20	2.74	-0.37	2.67
Rapeseed	0.92	0.02	5.47	0.92	0.92	-0.19	3.07	-0.35	3.02
Lentil	0.92	0.03	4.14	0.92	0.93	-0.13	2.42	-0.25	2.40
Peas	0.90	-0.01	4.95	0.86	0.89	-0.25	2.91	-0.39	3.34
Sugarcane	0.87	1.19	14.73	0.87	0.88	0.43	8.20	0.28	6.22

Table 4.6 Performance evaluation parameters for interpolation of crop evapotranspiration in Betwa Basin

Crop	Ordinary Kriging			Ordinary co-kriging					
	R ² for fitted model	ME	RMSE	R ² for fitted model		Covariates			
				Co-variates		T _{min}		T _{max}	
				T _{min}	T _{max}	ME	RMSE	ME	RMSE
Paddy	0.97	0.11	9.49	0.95	0.97	0.03	6.39	0.11	5.15
Maize	0.51	0.28	13.30	0.88	0.87	0.46	13.49	0.42	13.16
Groundnut	0.97	0.02	8.58	0.96	0.97	-0.04	6.53	0.01	5.88
Pigeon Pea	0.98	0.12	9.51	0.95	0.98	0.05	6.79	0.11	5.82
Sorghum	0.91	0.11	8.12	0.97	0.97	0.17	6.77	0.13	6.72
Sesame	0.45	0.77	5.64	0.67	0.78	0.70	5.28	0.69	5.00
Black gram	0.97	0.01	7.10	0.95	0.97	0.03	4.50	0.08	3.73
Soybean	0.98	0.13	9.49	0.94	0.97	0.05	6.40	0.12	5.63
Wheat	0.91	-0.19	5.83	0.95	0.91	-0.30	5.35	-0.14	4.23
Chickpea	0.89	-0.16	3.98	0.71	0.91	-0.24	3.80	-0.12	3.11
Mustard	0.93	-0.09	4.78	0.99	0.94	-0.18	3.73	-0.04	2.92
Peas	0.93	-0.04	6.08	0.93	0.93	-0.14	4.05	0.01	4.00
Lentil	0.96	-0.38	8.66	0.94	0.93	-0.05	8.53	-0.32	7.06

4.3.6 Variability in crop evapotranspiration

The interpolated surfaces were generated for selected 15 and 12 crops of the Gomti and Betwa river basins and the variability maps are presented in Fig. 4.8 and Fig.4.9, respectively. For all the *kharif* crops and sugarcane, the centre of highest *ETc* was at the central region of the Gomati basin (Fig 4.8). *ETc* was highest in western side of this central region which includes Lucknow, Unnao and Rae Bareli districts of Uttar Pradesh. In case of *rabi* crops, the *ETc* increased from upper to lower reaches of the basin. Upper most districts of the basin, namely, Pilibhit and Shahajahanpur, showed lowest *ETc* while the districts Jaunpur and Varanasi districts, located near the outlet of the basin, showed highest *ETc* for *rabi* crops. The spatial distribution of *ETc* of *kharif* and *rabi* crops closely resembled the temperature distribution pattern within the basin (see Fig. 4.2). *ETc* of *kharif* and *rabi* crops showed similar spatial distribution as that of mean maximum temperature and mean minimum temperature respectively.

In case of Betwa basin, the CWR of all the *kharif* crops showed an increase from south-east part to northern part of the basin (Fig 4.9). The spatial pattern of *ETc* of *rabi* crops showed reversed trend and it increased from north-eastern part to south-west part of the basin. The spatial patterns of *ETc* observed for *rabi* and *kharif* seasons followed the same spatial distribution patterns as that of principal meteorological parameters like seasonal mean minimum and maximum temperatures during respective season. The three major agronomical row crops grown in Betwa basin viz. wheat, chickpea and rapeseed showed large spatial variability in *ETc*. Arithmetic mean of *ETc* values contained in all the interpolated cells within the APU was considered as mean CWR of an APU.

The results of the variability mapping showed that the spatial variation in the climatic parameters across the basin lead to significant spatial variability in *ETc*. Since agriculture is the dominant land use covering thousands of hectares of land, a slight deviation in real *ETc* values may significantly affect the WF estimates. Therefore, in the context of WF assessment the intra basin variation in *ETc* cannot be neglected.

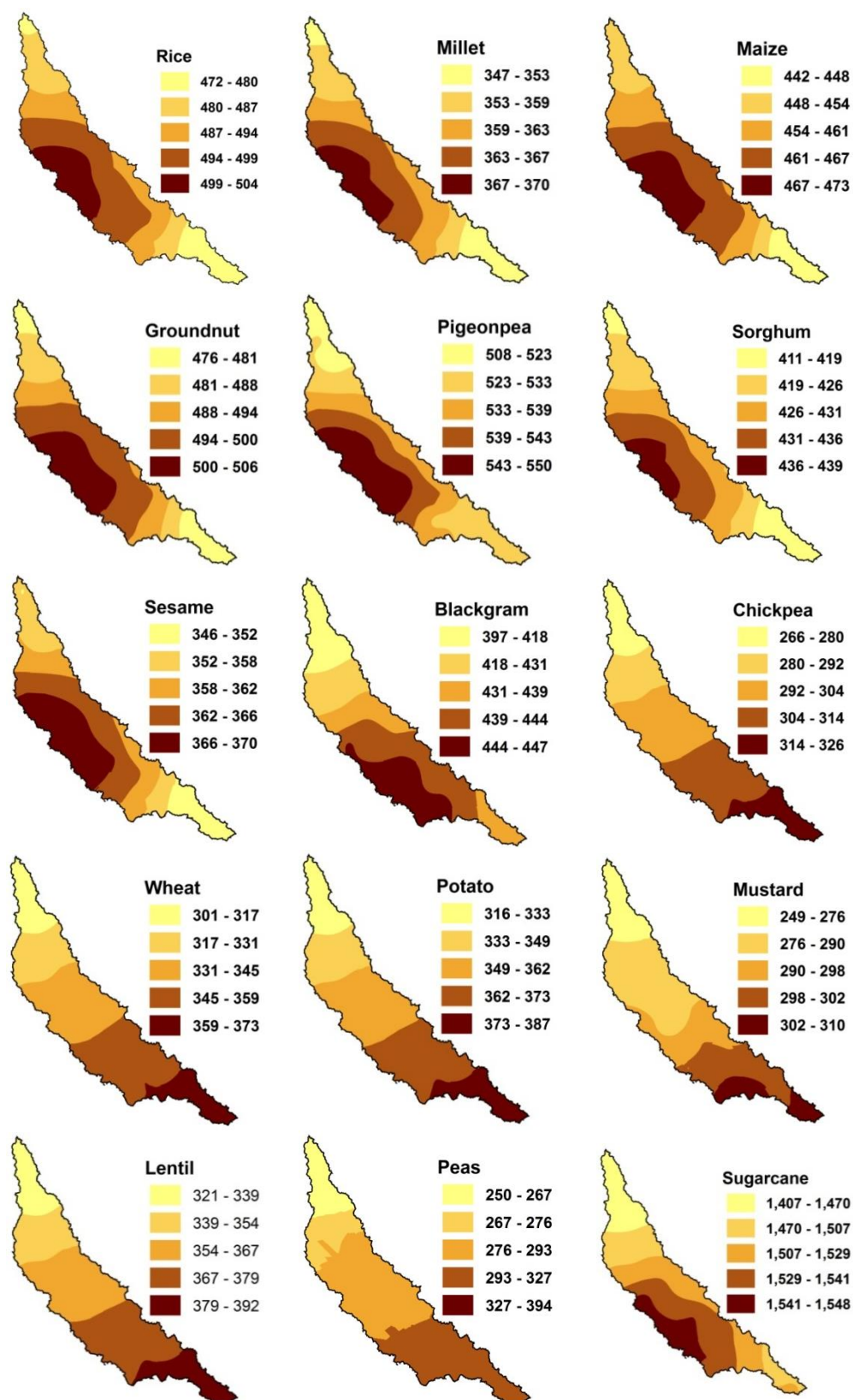


Fig 4.8 Spatial distribution of crop evapotranspiration (ET_c , mm) in Gomati basin

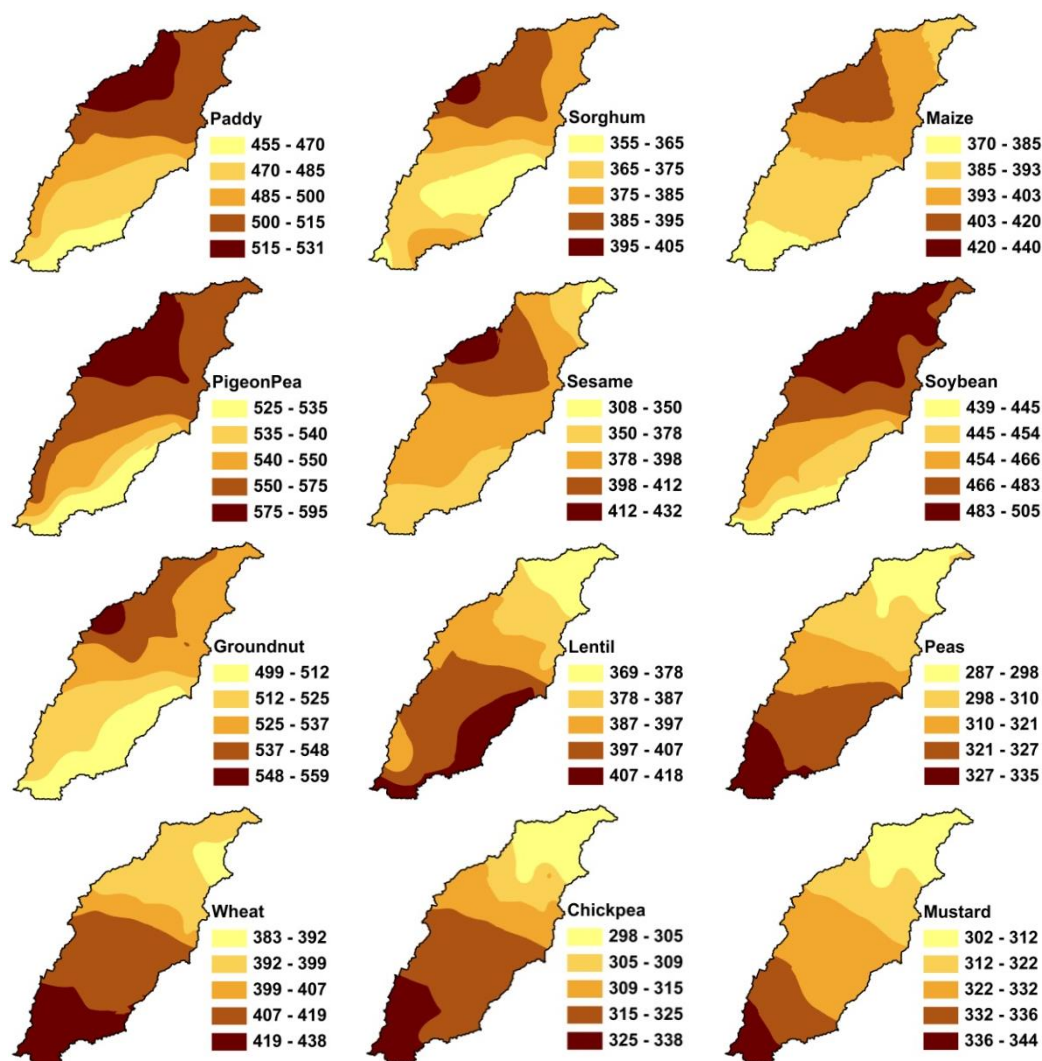


Fig 4.9 Spatial distribution of crop evapotranspiration (ET_c , mm) in Betwa basin

In case of both basins, significant spatial correlation was observed between the ET_c values of crops of a particular season. The correlation matrices are presented in Appendix III. In Betwa basin also, there was significant correlation between spatial ET_c values of *kharif* and *rabi* crops while in Gomti basin the ET_c values of *kharif* and *rabi* crops were poorly correlated. The ET_c of sugarcane showed good correlation with *rabi* crops. High degree of correlation in ET_c of crops of a particular season indicates that spatial estimates for only one representative crop from each season are adequate to delineate the spatial resolution units within the basins.

4.3.7 Spatial Resolution Units

APU level mean ET_c of crops was estimated as average of interpolated values of all the grid cells of an APU. With the help of agglomeration schedule plot and the elbow rule, four numbers of clusters were identified for both the basins. On the basis of mean ET_c , the APUs were combined using K-means clustering approach with number of APUs as n data points and number of crops in a basin as the d -dimensions of the K-means clustering. The subdivisions of the basin as obtained from k-means clustering are presented in Fig 4.10.

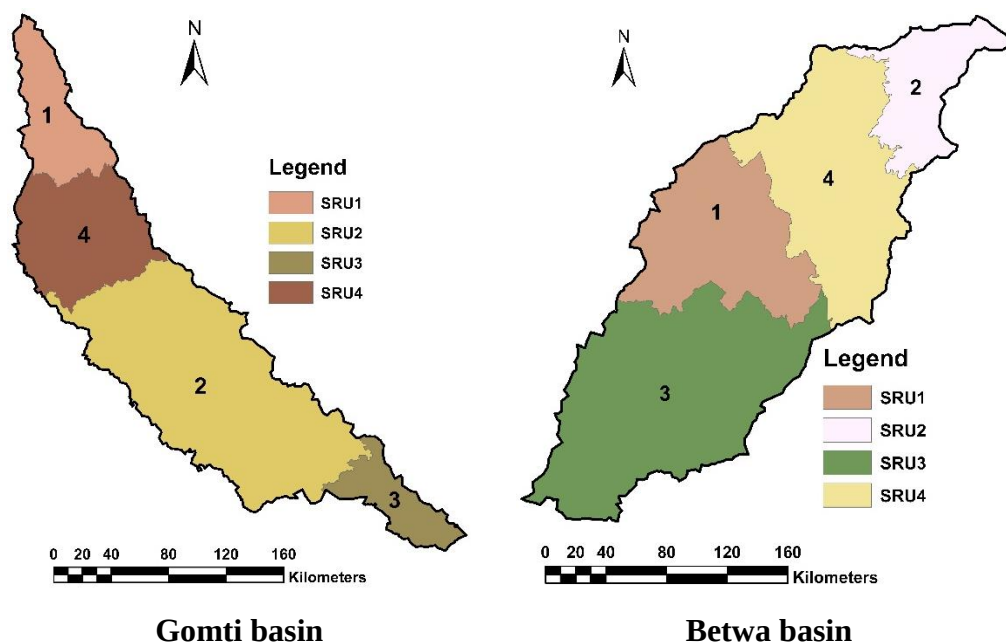


Fig. 4.10 Delineated spatial resolution units in river basins

4.3.8 Suitability of AESRs and delineated clusters as SRU

High variability in ET_c of crops within agro ecological sub regions (AESR) (Tables 4.7 and 4.8) precludes the use of AESRs as SRU for WF assessment. In case of Betwa basin, low ET_c variability in AESR4.3 was mainly because of its small size. Compared to AESRs, spatial variation in ET_c of crops in delineated clusters was significantly reduced. Therefore, the delineated clusters can be used as spatial resolution unit (SRU) for WF assessment. The cluster wise mean and range of ET_c values of different crops for Gomti and Betwa river basins are presented in Table 4.9 and 4.10. In Gomti basin the *kharif* crops had high mean ET_c values in SRU2 and SRU3 while for *rabi* crops, it was high in SRU3. Sugarcane followed the same pattern

as that of *kharif* crops. For these two crops lowest ET_c was in SRU1. There was reversed trend in mean ET_c of clusters because of reversal of temperature pattern during *kharif* and *rabi* season (Fig 4.2). The temperature pattern showed close resemblance with the crop evapotranspiration.

Table 4.7 Crop evapotranspiration variability in different AESRs in Gomti basin

Crops	AESR 4.3		AESR 9.2	
	Mean ET_c , mm	ET_c Range, mm	Mean ET_c , mm	ET_c Range, mm
Rice	488.3	29.0	489.4	26.8
Millet	359.1	21.2	359.4	19.3
Maize	457.9	27.3	458.1	25.5
Pigeon pea	536.2	21.2	532.0	32.4
Sorghum	425.4	25.5	425.6	23.4
Groundnut	491.7	25.5	490.6	23.7
Sesame	358.6	21.5	359.5	19.8
Sugarcane	1523.9	45.9	1495.2	125.2
Black gram	439.6	21.3	428.7	45.2
Wheat	352.4	41.9	334.4	57.2
Chickpea	309.6	34.1	294.4	47.9
Mustard	297.7	23.9	284.2	48.0
Potato	367.8	39.5	349.9	56.3
Peas	287.0	21.5	277.0	30.6
Lentil	373.3	38.7	355.6	56.1

Table 4.8 Crop evapotranspiration variability in different AESRs in Betwa basin

Crops	AESR 4.3		AESR 4.4		AESR 10.1		AESR 10.3	
	Mean ET_c , mm	ET_c Range, mm	Mean ET_c , mm	ET_c Range, mm	Mean ET_c , mm	ET_c Range, mm	Mean ET_c , mm	ET_c Range, mm
Paddy	508.8	3.1	507.6	45.0	477.1	34.1	502.8	35.2
Sorghum	382.4	1.5	383.5	35.3	368.3	20.5	379.5	25.7
Maize	392.3	2.6	400.0	17.9	387.2	12.3	399.0	11.3
Groundnut	535.7	1.8	534.8	40.1	512.8	25.4	529.9	24.6
Pigeon pea	569.5	1.5	570.6	48.0	541.4	34.3	565.4	35.3
Sesame	357.4	6.0	394.0	51.8	378.9	18.8	396.4	22.1
Soybean	483.9	2.6	481.1	44.3	452.1	29.0	476.0	32.0
Wheat	393.2	0.2	399.9	29.0	421.3	26.3	401.7	20.6
Chickpea	302.2	0.1	309.7	18.8	324.8	19.0	310.8	14.1
Lentil	373.3	1.9	387.8	33.0	404.9	17.5	390.0	23.2
Mustard	305.9	2.5	318.2	22.7	334.5	13.3	318.7	16.8
Peas	293.5	4.2	306.9	28.9	326.7	16.8	309.2	23.1

In Betwa basin, the SRU3 covers almost entire upper part of the basin, whereas the other three clusters were in lower reaches of the basin (Fig 4.6b). All the *rabi* season crops showed high *ETc* values in SRU3 and lowest in SRU2 (Table 4.10). In case of *kharif* crops the highest mean *ETc* was observed in SRU4 while the lowest was in SRU3.

Table 4.9 Crop evapotranspiration variability in different SRUs in Gomti basin

Crops	SRU1		SRU2		SRU3		SRU4	
	Mean <i>ETc</i> , mm	<i>ETc</i> Range , mm	Mean <i>ETc</i> , mm	<i>ETc</i> Range , mm	Mean <i>ETc</i> , mm	<i>ETc</i> Range , mm	Mean <i>ETc</i> , mm	<i>ETc</i> Range , mm
Paddy	486.1	7.3	494.9	16.7	476.5	0.8	498.6	5.2
Millet	356.1	6.3	363.9	12.0	348.4	2.4	364.7	2.0
Maize	453.5	6.5	464.7	14.3	444.5	0.6	462.6	2.4
Groundnut	485.2	4.7	501.8	15.5	483	0.7	500.1	3.3
Pigeon pea	521.9	8.9	544.9	15.5	532.3	3.7	539.9	3.7
Sorghum	423.6	5.0	432.9	15.7	417.4	0.8	435.1	4.7
Sesame	360.1	3.4	367.2	12.1	348	4.9	368.9	2.3
Black gram	411.6	12.3	447.2	8.3	440.1	4.1	439.2	9.6
Wheat	308.4	9.8	349.1	19.4	355.8	13.1	328.6	2.6
Chickpea	276.8	6.8	309.2	16.7	320.7	0.8	291.7	1.7
Potato	328.8	13.1	367.5	19.2	382.4	9.0	349.1	2.4
Mustard	269.2	5.9	301.3	10.1	303.8	6.0	285.5	1.4
Lentil	313.8	10.7	351	11.3	361.6	10.1	334.6	3.0
Peas	259.7	10.1	289.9	14.9	299.4	6.5	275.2	1.8
Sugarcane	1434.2	32.4	1533	19.3	1505.6	2.7	1493	10.8

(For all the crops the cluster means are significantly different at 95 % confidence interval)

Table 4.10 Crop evapotranspiration variability in different SRUs in Betwa basin

Crops	SRU1		SRU2		SRU3		SRU4	
	Mean <i>ETc</i> , mm	<i>ETc</i> Range , mm	Mean <i>ETc</i> , mm	<i>ETc</i> Range , mm	Mean <i>ETc</i> , mm	<i>ETc</i> Range , mm	Mean <i>ETc</i> , mm	<i>ETc</i> Range , mm
Paddy	502.1	10.9	509	3.1	475.3	17.7	514.7	12.6
Maize	397.3	5	393	3.4	387.4	9.8	404.9	8.4
Groundnut	531.3	8.6	535.2	2.1	511	14.4	539.3	15.6
Pigeon pea	566	12	570	2.3	539	17.5	577.7	13.9
Sorghum	380.2	9.7	382.7	1.7	366	19.5	388.6	11.6
Sesame	394.3	8.3	359.9	16	378.2	10	405.4	14.4
Soybean	475.9	10.3	483.4	2.6	450.4	14.5	487.2	13.7
Wheat	403.9	13.9	391.6	4.7	421.5	20.4	397.5	6.1
Chickpea	313.2	9.6	302	0.6	324.5	17.1	308.1	7.3
Mustard	323.1	15.2	306.9	4.2	333.8	15	316	12.2
Peas	312.4	13.1	295	5.9	326.9	12	303.9	10.6
Lentil	391.9	14.4	374.2	3.8	405.9	17.0	385.8	10.4

(For all the crops the cluster means are significantly different at 95 % confidence interval)

4.3.9 SRU level crop databases for Gomti and Betwa

The data downscaling procedure proposed in this study was used to generate crop specific basin level information on cultivated, irrigated and rain fed areas. The APU wise gross cropped area under all crops was obtained from LULC maps of the states obtained from LULC images provided by ISRO. Major portion (82.5 %) of the gross cropped area of Gomti basin was under paddy, wheat and sugarcane. In both the basins wheat crop had highest cultivated and irrigated area. Irrigated area under most of the *kharif* crops and lentil crop was negligible. Due to provision of vast canal network and natural hydrogeological setup, the Gomti basin has enough water to support the irrigated agriculture round the year. Irrigated area under all the selected crops in Gomti basin was 2.11 Mha which was considerably higher than that of Betwa basin (1.11 Mha). The spatial dataset on geographical, gross cropped, irrigated and rainfed areas at district and APU level are presented in Appendices IV to VII.

These estimated datasets were main inputs in assessing WF of a river basin. The blue and green VWC of crops can be estimated for each SRU, respectively using blue or green crop water use and associated crop productivities. Blue and green water footprint of a SRU is the blue and green water use of all the crops within the SRU, which can be obtained by multiplying VWC of crop by the corresponding crop production values in a SRU. WF of the basin can be estimated by using the methodology outlined in section 4.3.7. Productivity of crops in different SRUs is presented in Appendices VIII and IX.

This study demonstrates a framework for delineation of appropriate spatial resolution for WF assessment at river basin scale. Since, WF is most sensitive to reference crop evapotranspiration (ET_0) and crop coefficient (K_c) (Zhuo et al., 2014), it is necessary to find out best possible resolution so that the uncertainty in estimates of WF can be minimized. In present study, the SRU obtained by clustering of APUs was of coarser resolution as compared to APU, still SRU is a better option in the sense that ET_c variability within the SRU was in acceptable limits. Instead of collecting the crop and climate data at 21 or 27 locations (APUs), researchers can collect the data of only

four SRUs for assessing the crop water footprint. Also, time and efforts required for running the *ETc* estimation code for each APU will be greatly reduced.

It is worth mentioning here that, in present study SRUs were delineated based on *ETc* estimated for all crops at all APUs. However, with the high degree of spatial correlation observed within crops of particular season, it is possible to delineate the SRUs using the *ETc* estimated for any one crop of respective season, thus, reducing the number of crops in data collection process. In case of Betwa basin, paddy and wheat can be considered as representative crops for *kharif* and *rabi* seasons respectively as they share the largest cultivated area in respective seasons.

Shi and Zeng, (2014) delineated the homogeneous zones based on clustering of gridded values of parameters obtained by kriging interpolation. However, the boundaries of zones so obtained may not follow the district boundaries. In present study, clustering was applied at APU level so that entire APU was assigned to particular cluster. Since, in India, population and crop related statistics is maintained at district level, the concept of APUs proposed in this study will be useful in downscaling of such administrative unit level data to SRU level.

4.4 Conclusions

Methodology to delineate the homogeneous units based on spatially interpolated maps of crop evapotranspiration and geographical clustering of Agricultural Production Units (APUs) on the basis of mean *ETc* has been suggested. High degree of correlation between spatial patterns of *ETc* indicated that it is possible to delineate the spatial resolution units (SRUs) using APU level *ETc* estimates of any one representative crop. This will reduce the data requirement in delineation of SRUs. Defining spatial resolution unit on the basis of Agriculture Production Units (APUs) is capable of retaining original administrative structure of the basin. Following major conclusions were drawn from the study.

- There was large spatial variation in crop evapotranspiration within the basin and Agro Ecological Sub Regions therefore WF assessment should be done at SRU level.
- The methodology suggested in this study accounts the spatial variability of crop evapotranspiration within the basin and would provide better assessment of crop WF.
- Application of developed methodology can reduce the data and time requirement in crop water footprint assessment.
- The proposed methodology is for WF assessment is flexible enough to be replicated for other river basins in India.

Assessment of virtual water content of crops and water footprint of Gomti and Betwa river basins in India

Abstract

Freshwater scarcity is a growing concern. New indicators like virtual water content (VWC) and water footprint (WF) are increasingly being used to address the problem of water scarcity at global, national and river basin scale. The aim of this study was to quantify VWC, WF and virtual water flows within the Gomti and Betwa river basins in India. Blue, green and grey components of WFs of crop production under irrigated and rainfed conditions were assessed at high spatial resolution. The findings show that the WF of Gomti and Betwa was about 12773 and 9186 million m³. Crop production was the largest water consumer water and accounted for about 95.5% and 96.4% of the WF in Gomti and Betwa basins respectively. Rest of the WF was from livestock, domestic and industrial sectors. The blue WF accounted for 47.3% and 43.6% in the total WF of Gomti and Betwa basins respectively while share of grey WF was about 9.1% and 10.9% of total WF. Domestic and industrial sector contributed about 38.3% and 17.9% to grey WF in Gomti and Betwa basins respectively. Contribution of rainfed agriculture to WF was higher in Betwa basin (42.6%) than that for Gomti (11.2%) which was mainly due to aridity in the Betwa basin. Overall, both basins were assessed as net VW importers. Maize and potato in Gomti and sesame, soybean and groundnut in Betwa basin were identified as most efficient crops in terms of economy of blue water use. Compared to Betwa, economic productivity (EWP) of blue water was higher in Gomti basin. In both the basins, considerable portion of available blue water is being used for the production on low value-water intensive crops. The results indicated that the application of an integrated approach using the water footprint and EWP can be helpful to improve the water resources planning and management at river basin scale.

Keywords: Virtual water content, water footprint, economic water productivity, virtual water flow.

5.1 Introduction

Freshwater is renewable but finite natural resources are essential for both human life and economic development. Its availability and quality show enormous temporal and spatial variations and is sensitive to human influence and environmental degradation. Increasing scarcity of this important resource is directly linked to human activities (Postel *et al.*, 1996; Vorosmarty *et al.*, 2000, 2010). With accelerated population and economic growth, many areas of the world are experiencing either current or potential shortages of water, as well as deterioration of water quality (Shiklomanov, 2000). It is estimated that, there are about 800 million people lacking a safe supply of freshwater (Ban Ki-moon, 2012). The situation in India is not very different. India had the capacity to store about 200 billion m³ of water and an irrigated area of about 90 Mha (World Bank, 2005). However, due to rapid development, increasing population and iniquitous distribution of water, the demand for this natural resource exceeds the supply by great margin (UNICEF, 2013). The water demand from agriculture is set to increase tremendously. In order to ensure food security in India, availability of quality water needs to be increased. Governmental strategies on sustainable water management solely focus on supply-side and largely ignoring the potential for demand side management. The growing water scarcity problem has led to an increased interest in assessment of water resource and water consumption.

It is necessary to find new approaches and tools for integrated water resources management to maintain a balance between human resource use and ecosystem protection (Dudgeon *et al.*, 2006; Vorosmarty *et al.*, 2010). Comparatively new indicators such as virtual water content (VWC) and water footprint (WF) have emerged to promote efficient, equitable and sustainable water uses. The water footprint concept was first introduced in 2002 by Arjen Hoekstra at the International Expert Meeting on Virtual Water Trade, held in Delft, The Netherlands (Hoekstra and Hung, 2002). Water footprint (WF) is a consumption-based indicator and can be considered as the total volume of virtual water embodied in the final products consumed by a country's or region's people.

The VWC of a commodity is the volume of water that is actually used to produce the commodity, measured at the place where the commodity is actually produced (Allen, 1993, 1994). Virtual-water trade refers to the transfer of water in

virtual form from one place to another as a result of product trade. The water footprint can be divided into a blue, a green and a grey water footprint. Blue component covers use of groundwater and surface water during the production of a commodity, green component covers use of rain water for crop growth, and grey component explains water required to dilute the water that is polluted during the production of the commodity.

Previous studies on WFPs focused mainly on process, product, regional, national and global level. The available literature suggests that there are still very few studies focusing on specific river basins (UNEP, 2011), especially for those located in arid and semi-arid regions. Water footprint assessment at river basin scale provides the basis for integrated water resources management and sustainable water uses.

In India, government strategies on water resource management are mainly based on supply-side management, without due consideration to demand side management. At present, considerable interstate trade of agricultural commodities takes place making inhabitants of a region to consume water from not only in their own region but beyond through the consumption of imported commodities. Therefore, while developing water resource management solutions within a geographical region, virtual water flows should be accounted. A number of studies have recognized the usefulness of the concept of virtual water for analysing production patterns and associated water flows (Dietzenbacher & Velazquez, 2007; Zeitoun *et al*, 2010). In this paper, we aim to develop a comprehensive water footprint assessment framework to assess the virtual water flows within the Gomti and Betwa river basin located in northern India and to assess the water footprints of production and consumption within the basin.

The aim of this study is to analyse the virtual water, water footprint and virtual water flows at river basin scale. Using the concept of the WF, water use and the water use structure (sector wise water use) were analysed for suggesting sustainable development strategies. The main objective was to assess the WF at a river basin level with a bottom-up approach. Gomti and Betwa river basin in northern India were selected for the study. In Betwa basin, the extensive use of water in the upper and middle parts of the basin as well as extensive storages built on the river has led to a decrease in water resources in the downstream. In Gomti basin availability of canal water is the major factor in progress of agriculture and has no water shortages. Still

Gomti basin was selected to understand the crop-wise virtual water outflows, which is an indication of basins potential to serve peoples of other regions. Previous researchers focused on crop water requirement, water productivity and irrigation demand in these river basins (Cai *et al.*, 2010; Amarasinghe *et al.*, 2005), but a comprehensive WF assessment considering multiple sectors and multiple types of water (e.g. green, blue and grey water) has not been done before. In present study, the blue, green and grey water use for agriculture is estimated. Such an assessment is a key to better understanding the entire picture of water consumption at the river basin level, and identifying ways to improve water management.

5.2 Materials and Methods

In order to assess WF in the river basins, WF of crop production, livestock and industrial and domestic sectors were estimated. In case of crops, the blue, green and grey components of WF were assessed. Since, contribution of rainfall in total water use of livestock, domestic and Industry is negligible, only blue WF is assessed for these sectors. In this study only nitrate leaching was considered in estimating grey WF. Water footprints was assessed for the normal year for which annual rainfall of majority of the basin districts was within the predefined standard variation of -19 to +19 % of the normal rainfall of the respective district (IMD, 2013). The WF of crop production was assessed for major crops of Gomti and Betwa basin which represent about 89.8% and 81.0 % of the gross cropped area (GCA) of the districts in Gomti and Betwa river basins respectively. Crops included in the study were cultivated on a large areas, therefore neglecting other crops will not lead to errors in the WF of the entire river basin. There are few rainfed crops whose area has considerable share in gross cropped area, therefore WF of crop production was estimated separately for rainfed and irrigated areas.

5.2.1 The study area

The present study was carried out for two important basins, namely Gomti and Betwa. The detailed description of the study area is presented in Section 3.3 in Chapter III. Agriculture is a major economic activity in both the basins.

5.2.2 Data sources

The WF of river basins was estimated at high spatial resolution. The spatial resolution for WF assessment was delineated from Agricultural Production Units (APU). An APU was defined as the homogeneous unit in terms of soil and climate. In order to delineate the APUs, information on major soil types was derived from FAO Harmonized World Soil Datasets (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008). The HWSD is a global soil raster datasets and contains soil parameters for two soil layers (0-30 and 30-100 cm). Other soil properties required in estimation of crop evapotranspiration like, field capacity, wilting point and maximum infiltration rate were determined using the HWSD data and pedotransfer functions for Indian soils developed by Adhikari *et al.*, (2008). The Agro-Ecological Sub Region (AESR) maps of the basin were extracted from the AESR map of India developed by NBSSLUP, ICAR (Gajbhiye and Mandal (2000). Thematic layers pertaining to soil, AESR, basin boundary and district boundaries were overlaid and APU polygons were formed for each district using *intersect* feature in ArcGIS.

APU level statistical datasets related to cultivated, irrigated and rainfed area were obtained using proportionality factors developed from district level datasets. There are 14 districts each in Gomti and Betwa basins. The district level data on cultivated, irrigated and rainfed area and crop production and productivity were obtained from Directorate of Economics and Statistics, Ministry of Agriculture, Government of India (MoA, 2012). Area of each district within the basin was estimated from digitized district boundary coverage in ArcGIS 9.3 software. Gross cropped area of each APU within the district was obtained from land use-land cover images obtained from Bhuvan thematic data services of ISRO (2012). In order to estimate the cultivated area of a crop in APU, it was assumed that the ratio of cultivated area of a particular crop in an APU to total GCA of the APU is same as that of the district from which that APU is delineated. Similarly, the irrigated area of an APU is obtained by multiplying the GCA of a particular crop in an APU with irrigated area factor (IAF). IAF is the ratio of irrigated area of a crop in a district to the GCA of that crop in a district. The rainfed area was obtained as the difference between GCA and irrigated area of a crop in an APU. Crop production in an APU was obtained as the product of cultivated area under a crop and the average productivity of a crop in the district.

Animal population in the district within the basins was estimated by multiplying the district level population density for a particular type of animal with the geographical area of the district within the basin. The district level livestock population data was obtained from online statistical data base of India (Indiastat, 2013). Human population was also estimated following the same procedure. The data on consumption of food commodities per capita per year in urban and rural areas was obtained from National Sample Survey Office (NSSO, 2012).

5.2.3 Water footprints of crop production

Assessment of WF requires precise and spatially explicit information on green, blue and grey VWC of crops. VWC (m^3/t) of primary crops is the ratio between the volume of water used during the entire period of crop growth (m^3/ha) and the corresponding crop yield (t/ha). The crop water requirement was estimated using the CROPWAT model (Allen *et al.*, 1998; FAO, 2012). ‘Irrigation schedule’ option in CROPWAT was used to estimate the green water use (CWU_{green} , m^3/ha) at daily time step. The CROPWAT model needs climate, crop and soil parameters to model evapotranspiration and crop irrigation requirements. The crop evapotranspiration (ET_c) was estimated from the reference evaporation (ET_0) using the crop coefficients. Values of crop coefficient (K_c) for initial, middle and end stage and crop rooting depths were adopted from FAO irrigation and drainage paper No-56 (Allen *et al.*, 1998). CROPWAT also requires information on rooting depth of crops and critical depletion to be specified for each crop. Critical depletion is the percentage of the available soil water that can be allowed to deplete between successive irrigations without serious plant moisture stress (Allen *et al.*, 1998). The crop sowing and harvesting dates for the state of Uttar Pradesh and Madhya Pradesh were adopted from information published by Department of Economics and Statistics, Min of Agriculture, GOI (MoA, 2011) and Crop Science Division of ICAR. The climatic data derived from gridded daily time series data of India Meteorological Department (IMD) available from National Initiative on Climate Resilient Agriculture (NICRA-ICAR, 2012) was used to estimate ET_c .

The green crop water use (CWU_{green}) (m^3/ha) is the volume of the total rainfall that is actually used for evapotranspiration by the crop over the complete growing period and was estimated using the Eq 1.

$$CWU_{green}[c, N] = 10 * \sum_{t=1}^i \text{Min}(P_{eff}[c, t, N], ET_c[c, t, N]) \dots \dots (1)$$

Where, $CWU_{green}[c, N]$ is the green water use of crop c in N^{th} APU, $P_{eff}[c, t, N]$ is the effective rainfall (mm) for crop c in N^{th} APU and at time step t , $ET_c[c, t, N]$ is the evapotranspiration (mm) of crop c in N^{th} APU and at time step t , i is the number of time steps considered throughout the growing period and N is the APU number. The factor 10 was added to convert mm into m^3/ha and the summation is done over the complete length of the growth period at daily time steps. Min stands for ‘minimum of’ the two quantities in the bracket.

Blue water use (i.e. irrigation water requirement) was estimated as the difference between seasonal crop evapotranspiration and effective rainfall. The blue water use is the portion of irrigation water actually used by the crop, over its complete growing period. It is the amount of irrigation water evapotranspired by the crop in addition to effective rainfall. Blue water use is zero if the entire crop evapotranspiration requirement is met from effective rainfall. Total blue water use (CWU_{blue} , m^3/ha) in crop production was obtained using Eq.2 as follows;

$$CWU_{blue}[c, N] = 10 * \sum_{t=1}^i (ET_c[c, t, N] - P_{eff}[c, t, N]) \dots \dots (2)$$

Where, $CWU_{blue}[c, N]$ is the blue water use (m^3/ha) of crop c in N^{th} APU, $ET_c[c, t, N]$ is the evapotranspiration (mm) of crop c in N^{th} APU at time step t and $P_{eff}[c, t, N]$ is the effective rainfall (mm) for crop c in N^{th} APU and at time step t . The factor 10 is added to convert blue water use from mm to m^3/ha and the summation was done over the complete length of the growth period at daily time steps. The dilution water requirement of a crop ($DWR[c]$, m^3/ha) is the volume of water that is required to dilute the nitrate leached to the groundwater to a desired level and was estimated using Eq. 3 as follows;

$$DWR[c] = \frac{N_{app}[c] * lf[c]}{rl} \dots \dots (3)$$

Where, $N_{app}[c]$ is the amount of nitrogen fertilizer applied (kg/ha) to the crop c throughout growing season, $lf[c]$ is the nitrogen leaching fraction (ratio between N_{leach} and N_{app}) for a crop c and rl is the recommended level of nitrogen (kg/m³) as per water quality standards for drinking purpose.

The green, blue and grey VWC (m³/t) can be estimated as the ratio of respective water use by the crop yields (Eq.4, Eq.5 and Eq.6).

$$VWC_{green}[c, N] = \frac{CWU_{grn}[c, N]}{Y[c, N]} \dots \dots (4)$$

$$VWC_{blue}[c, N] = \frac{CWU_{blu}[c, N]}{Y[c, N]} \dots \dots (5)$$

$$VWC_{grey}[c, N] = \frac{DWR[c]}{Y[c, N]} \dots \dots \dots (6)$$

Where, $Y[c, N]$ is the yield (t/ha) of crop c in N^{th} APU. It is worth mentioning here that, due to lack of information on nitrogen leaching fractions under different soil types, the lf is assumed to be same throughout the river basin. Also we assume that, since the nitrogen application rate is comparatively lower, the nitrogen leaching under rainfed conditions is negligible. It is worth to mention here that the VWC_{grey} do not refer to an actual water use, but to a required water use. The total VWC of a crop can be estimated using Eq. 7 as follows;

$$VWC_{tot}[c, N] = VWC_{grn}[c, N] + VWC_{blu}[c, N] + VWC_{gry}[c, N] \dots \dots (7)$$

WF of crops under rainfed and irrigated conditions were estimated separately. In case of rainfed crops, the blue component of WF is zero. Since, crop growth and yield under rainfed conditions are affected by water stress, a linear relationship between yield and evapotranspiration (Eq. 8) as proposed by Doorenbos and Kassam (1979) was used to get crop yields under rainfed conditions.

$$1 - \frac{Y_a}{Y_m} = K_y \left(1 - \frac{\sum ET_a[t]}{\sum CWR[t]} \right) \dots \dots (8)$$

Where, K_y is the yield response factor (water stress coefficient), Y_a is the actual harvested yield (t/ha), Y_m is the maximum yield (t/ha), ET_a is the actual crop evapotranspiration (mm). The K_y values are available in Doorenbos and Kassam (1979).

Water footprint of crop production was calculated as the summation of product of VWC (m^3/t) of each crop within the APU with its production (t). The procedure to estimate the cropped areas under irrigated and rainfed crops and corresponding yields has already been described in previous sections. Eq.9 was used to estimate the WF of a crop in the basin.

$$WF[c, rb] = \sum_{c=1}^n \sum_{N=1}^N \sum_{i=1}^2 \{VWC_{tot}[c, N, i] * Prod[c, N, i]\} \dots \dots (9)$$

Where, $WF[c, rb]$ is the WF of crop production within the river basin rb , c is the crop index, N is the number of APUs and i is the type of agriculture; 1-Irrigated, 2-rainfed.

5.2.4 Water footprint of livestock (WF_{ls})

The consumptive use of livestock consists of three components: the water used to produce crops for animal feed, the drinking water requirement and cleaning water requirements of livestock (Mekonnen and Hoekstra, 2012). In Gomti and Betwa river basins, the animal feed mostly comes from crop residues and other products of maize, sugarcane, sorghum, pearl millet and de-oiled cakes of soybean and groundnut. Therefore, major portion of feed water requirement (WF of animal feed) is already accounted in WF of crops and was not considered as suggested by Dumont *et al.* (2013). In case of live animals, the processing water requirement is the water required for servicing (cleaning of animals and barns). It is obvious that major portion of water consumed in servicing returns to water bodies in the basin and consumptive use of water in servicing can be neglected. Hence, the WF of livestock mainly comes from drinking water, which is dominantly 'blue'. The WF_{ls} was estimated considering the varying drinking water demand for animals of different types and age groups (Eq.10).

$$WF_{ls}[rb] = \sum_{N=1}^4 \{APop[a, g, N] * WR_d[a, g]\} \dots \dots (10)$$

Where, $WF_{ls}[rb]$ is the WF of livestock within the basin, $APop[a, g, N]$ is the population of animal type a in the age group g and $WR_d[a, g]$ is the drinking water requirement of animal type a in the age group g . Animal types considered in this study were cattle, buffalo, sheep, goat, horse, donkey and pig. In order to calculate the monthly WF of livestock production WF_{ls} was equally distributed in each month.

5.2.5 Water footprint of industrial and domestic sectors

The main source of industrial and domestic water use in Gomti and Betwa river basins is groundwater. The district wise groundwater withdrawal for domestic and industrial uses was obtained from Central Ground Water Board (CGWB, 2011). However, much of the water abstracted by industries is returned to the catchment from which the water is withdrawn, therefore it does not count as consumptive water use. Since the domestic and industrial water use is greatly influenced by human population, the district level domestic and industrial water withdrawal data was rescaled to basin level using population factor. Population factor is the ratio between populations of a district within the basin to the total population of district. The WF of industrial and domestic sectors is estimated by multiplying water withdrawal with a water consumption ratio (WCR) (Eq.11).

$$WF_{dom+ind}[d] = \sum_{N=1}^4 GWW_{dom+ind}[d] * WCR \dots \dots (Eq. 11)$$

Where, $WF_{dom+ind}[d]$ is the water footprint of domestic and industrial sector in district d , $GWW_{dom+ind}[d]$ is the groundwater withdrawal for domestic and industrial purposes in district d and WCR is the water consumption ratio. In present study the value of WCR was taken as 0.1 (i.e. 90 % return flow). As followed by Hoekstra and Mekonnen (2012), it was assumed that the part of the return flow disposed into the environment without prior treatment was a measure of the grey WF.

5.2.6 Economic water productivity of blue water (EWP)

Economic water productivity of blue water for irrigated crops was obtained by dividing the gross returns (Rs) of particular crop from entire basin with its blue WF (m^3). The all India level average market prices of crop products were obtained from Directorate of Marketing & Inspection (DMI), Ministry of Agriculture, Government of

India (Agmarknet, 2014) which recorded the prices at 908 markets located all over India (Appendix X).

5.2.7 Virtual water export

Virtual water export from the basins was estimated as the product of VWC and quantity of the product exported from the basin. On an annual basis, total production of a commodity in a basin minus total consumption within the basin was considered as quantity of export from the basin. Total use of a crop produce includes consumption requirement of humans, seed and wastage at farm and market level. The state level per capita consumption of agricultural commodities was obtained from NSSO (NSSO, 2012) (Appendix XI). With the help of APU level population data and the per capita consumption of commodities, the basin level consumption of selected crops was estimated considering 33 major crop products (Appendix XII).

Processing of primary products into proceed product involves some loss of weight of the primary crop. Consumption of primary product is calculated by dividing quantity of processed product consumed by the product fraction (Hoekstra *et al.*, 2011). Product fraction (pf) is the quantity of the output product (kg) obtained per unit quantity of input product (kg). Values of product fractions considered in this study are presented in Appendix XIII. Consumption of a crop can be obtained from per capita consumption data on processed crop products and using Eq.12.

$$Q_{cons}[c, N] = \sum_1^j \frac{Pop_{rural}[N] * q_{rural}[p_j, c] + Pop_{urban}[N] * q_{urban}[p_j, c]}{pf_j} \dots (12)$$

Where, $Q_{cons}[c, N]$ is quantity of crop c consumed in N^{th} APU; $Pop_{urban}[N]$ and $Pop_{rural}[N]$ are the urban and rural population of N^{th} APU; $q_{urban}[p_j, c]$ and $q_{rural}[p_j, c]$ is the per capita consumption of a product p_j derived from crop c in urban and rural areas; pf_j is the product fraction for j^{th} product and j is the number of products derived from crop c and considered in the study.

The consumption for seed was estimated by multiplying recommended seed rate with the gross cropped area under a crop. The post-harvest losses were estimated using the fixed percentage approach. Farm produce involves losses at farm level, during

storage and transport. According to a World Bank (1999) study, the post-harvest losses of food grains in India are 7-10 per cent of the total production from farm to market level and 4 to 5 % at market and distribution level. Sharon *et al.* (2014) reported that post-harvest losses account for 9.5% of total pulses production. In present study, the wastage at farm and market level was estimated conjunctively, considering the loss of 10% of total production for all the crops.

The VW balance for agricultural products (VWE) is defined by Eq.13;

$$VWB = WF_{cons}[c] - WF_{prod}[c] \dots \dots (13)$$

$$WF_{cons}[c] = VWC_{blu+grn}[c] * Q_{cons}[c] \dots \dots (14)$$

$$WF_{prod}[c] = VWC_{blu+grn}[c] * Q_{prod}[c] \dots \dots (15)$$

Where, $Q_{cons}[c]$ and $Q_{prod}[c]$ are the quantities of crop c consumed and produced within the basin; $WF_{cons}[c]$ and $WF_{prod}[c]$ are the WF of production and consumption respectively.

5.3 Result and Discussion

Virtual water content and WF in both the basins were estimated separately for irrigated and rainfed area. The estimated blue and green components of crop evapotranspiration under irrigated and rainfed conditions at each APU in Gomti and Betwa are presented in Appendices XIV to XIX. As estimated using the Bhuvan LULC raster datasets, the gross cropped area of Gomti and Betwa basins was about 2.48 Mha and 2.90 Mha, which is about 79% and 67 % of the total geographical area of respective basins. Irrigated agriculture constitutes about 85% and 38% of the gross cropped areas within the Gomti and Betwa basins, respectively.

The prevailing cropping pattern of Gomti basin showed that paddy and wheat are the most commonly grown crops during kharif and rabi seasons respectively, covering 29.7 % and 45.57 % of the annual gross cultivated area (Table 5.1). Third most important crop is Sugarcane whose share is about 7.21 % of the GCA. Pulses and oilseeds are being cultivated on very small scale.

Table 5.1 Irrigated and rainfed areas in Gomti and Betwa basin for 2011

Crops	Area-Gomti Basin			Area-Betwa Basin		
	Irrigated area, ha	Rainfed area, ha	Percent Irrigated, %	Irrigated area, ha	Rainfed area, ha	Percent Irrigated, %
Wheat	1127555	5561	99.5	681275	246166	73.5
Paddy	721896	18117	97.6	1181	48912	2.4
Sugarcane	158390	19812	88.9	--	--	--
Mustard	46826	9623	83.0	5502	43010	11.3
Black gram	0	54227	0.0	0	149889	0.0
Maize	2718	49063	5.2	6	45508	0.0
Potato	40628	4142	90.7	--	--	--
Lentil	0	35469	0.0	0	241578	0.0
Pigeon pea	26	30532	0.1	17	29703	0.1
Sorghum	40	21683	0.2	0	63496	0.0
Pearl Millet	79	18819	0.4	--	--	--
Chickpea	1143	14667	7.2	244524	445454	35.4
Sesame	35	15717	0.2	1	39990	0.0
Peas	15109	0	100.0	146459	0	100.0
Groundnut	124	9954	1.2	9243	61314	13.1
Soybean	--	--	--	21657	379809	5.4

The area under vegetable crops (peas and potato) was also small. Irrigated area under paddy and sugarcane is about 97.5 % and 88.3% of cultivated area under these crops respectively. Other than paddy, large portion of the cultivated area under kharif crops remains rainfed. Rabi crops like mustard, potato and peas are also cultivated under irrigated conditions and more than 80% of the cultivated area under these crops is also irrigated.

Wheat, chickpea, soybean and lentil are four major crops of Betwa basin and share about 31.9%, 23.8%, 13.8% and 8.3 % of the GCA. Although paddy is a staple crop in the basin, cultivated area under paddy is less than 2 % of GCA. Compared to Gomti basin, Betwa basin has very small area (1109.9 thousand ha) under irrigation (Table 5.1). Wheat, chickpea and peas are the major crops cultivated under irrigated condition; still considerable portion of wheat (26.5 %) is under rainfed condition. Considering all the crops, about 85.04% and 38.21 % area is irrigated in Gomti and Betwa basins, respectively.

5.3.1 Virtual water content of crops (VWC_c)

Among all the crops studied, virtual water content of sesame crop was highest at 20724 m³/t and 16908 m³/t in Gomti and Betwa basin respectively (Table 5.2). This was mainly because of extremely low productivity of sesame. Black gram, groundnut and pigeon pea also had high VWC in both the basins. It is noteworthy that, compared to Gomti basin, the VWC of paddy and wheat is higher in Betwa basin. Other cereals have VWC values ranging from 1586 to 4555 m³/t. Sugarcane and potato have low VWC (298 m³/t and 277 m³/t, respectively) in Gomti basin due to higher productivities. Against the common perception, virtual water content of paddy and sugarcane was comparatively lower. Paddy has highest grey VWC of 660 m³/t and 995 m³/t in Gomti and Betwa basins respectively, followed by mustard (630 and 873 m³/t) and wheat (497 and 757 m³/t). SRU wise blue, green and grey VWC of crops under irrigated condition and green VWC under rainfed condition are given in Appendices XX to XXII.

Table 5.2 Virtual Water Content of various crops under irrigated and rainfed conditions

Crops	Virtual water Content (m ³ /t)					
	Gomti basin			Betwa basin		
	VWC under irrigated condition		VWC under rainfed condition	VWC under irrigated condition		VWC under rainfed condition
	Total VWC	Proportion of blue VWC [†]		Total VWC	Proportion of blue VWC	
Black gram	7466	64.6	7747	8912	45.7	9316
Groundnut	6399	15.4	7182	5718	66.8	4246
Maize	4555	2.3	3278	3430	60.8	2921
Pearl Millet	3459	23.0	3294	--	--	--
Pigeon pea	6355	49.8	6744	6505	56.7	6378
Paddy	3018	14.2	1653	8209	49.5	6622
Sesame	20724	14.6	22103	16908	53.0	16133
Sorghum	4217	17.1	3641	4045	55.6	6936
Sugarcane	298	60.1	313	--	--	--
Soybean	--	--	--	6493	56.9	5822
Chickpea	3949	96.5	3127	3197	96.7	2179
Lentil	4110	97.7	2971	7324	80.0	4396
Mustard	3664	99.6	2866	6217	92.2	5027
Peas	2018	99.7	--	5069	99.5	--
Potato	277	97.5	--	--	--	--
Wheat	1586	96.3	1040	3252	99.1	1931

[†]Blue water proportion is the percentage share of blue water in total WF of crop under irrigated conditions.

Break up of blue, green and grey components of VWC of irrigated crops is presented in Fig 5.1. Maize being short duration kharif crop had lowest blue VWC of 94 m³/t. Blue water proportion (BWP), estimated as $VWC_{blue}/VWC_{blue+green}$, was in the range of 14.2 to 66.8 % for kharif crops, while it ranged from 80.0 to 99.7 % in case of rabi crops. This indicates the importance green water has significant role in production of kharif crops. Paddy has highest grey VWC of about 660 m³/t and 995 m³/t in Gomti and Betwa basins respectively, followed by mustard (630 and 873 m³/t) and wheat (497 and 757 m³/t).

It is worth mentioning that higher or lower VWC does not mean higher or lower water use per hectare of area. It depends on water use as well as crop yields. Some crops had low VWC under rainfed conditions. This is mainly because crop yields do not decrease in direct proportion to water stress.

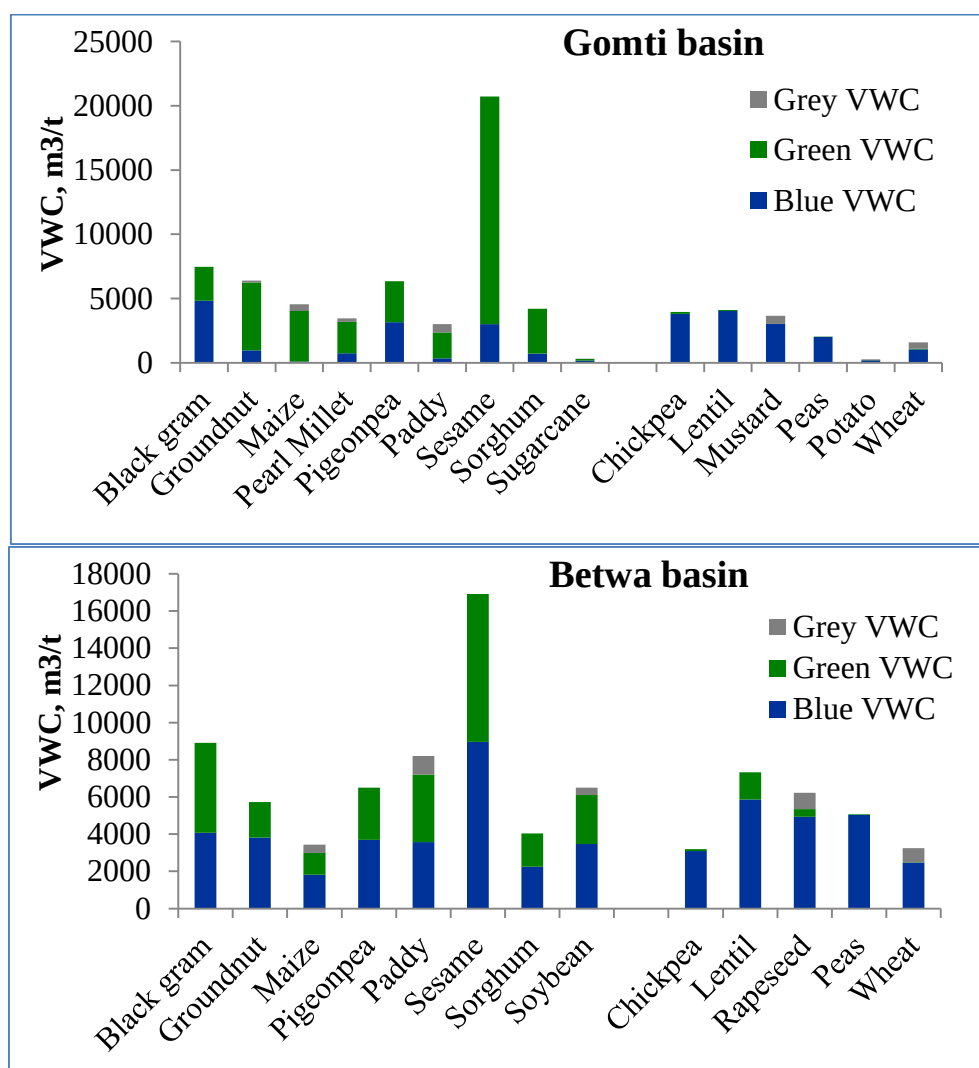


Fig 5.1 Blue, green and grey VWC of various crops under irrigated condition

Yield reduction depends on sensitivity of the crops to moisture stress, which was included in the present analysis using the yield response function proposed by Doorenbos and Kassam (1979). When comparing the VWC of the different crops in Gomti and Betwa, there were some differences, which may be due to the difference in evapotranspiration and yields in these basins.

5.3.2 Water footprint of crop production (WF_c)

The annual WF of crop production (WF_c) in Gomti and Betwa was 12196 million m^3 and 8855 million m^3 respectively (Table 5.3). Wheat recorded highest WF of 4263 million m^3 and 3951 million m^3 in Gomti and Betwa basins, respectively. Mustard in Betwa and chickpea in Gomti basins recorded lowest WF. In Gomti basin, share of blue water in irrigated agriculture was about 56% (5908 million m^3) while that in Betwa was about 80% (4025 million m^3). Rainfed agriculture showed significant contribution in crop production in both the basins. However, green water use in rainfed agriculture in Betwa basin was much higher (3868 million m^3) as compared to 1363 million m^3 in Gomti basin.

Table 5.3 Water footprint of crop production in Gomti and Betwa basins

Crop	Water footprint (million m^3)			
	Gomti basin		Betwa basin	
	WF of Irrigated area	WF of Rainfed area	WF of Irrigated area	WF of Rainfed area
Black gram	0.0	233.3	0.0	414.8
Groundnut	0.8	66.9	49.7	174.2
Maize	18.3	258.7	0.0	149.4
Pearl millet	1.5	74.7	--	--
Pigeon pea	0.1	152.6	0.1	143.4
Paddy	3839.2	63.3	8.1	161.6
Sesame	0.1	103.9	0.0	133.3
Sorghum	0.2	88.1	0.0	273.8
Soybean	--	--	111.5	1483.6
Sugarcane	2373.3	231.8	--	--
Chickpea	3.5	17.3	774.0	346.1
Lentil	0.0	39.0	0.0	171.8
Mustard	143.1	18.0	20.3	42.5
Peas	43.7	0.0	445.4	0.0
Potato	156.7	4.4	--	--
Wheat	4252.0	11.5	3577.6	374.0
Total WF	10832.5	1363.5	4986.6	3868.5

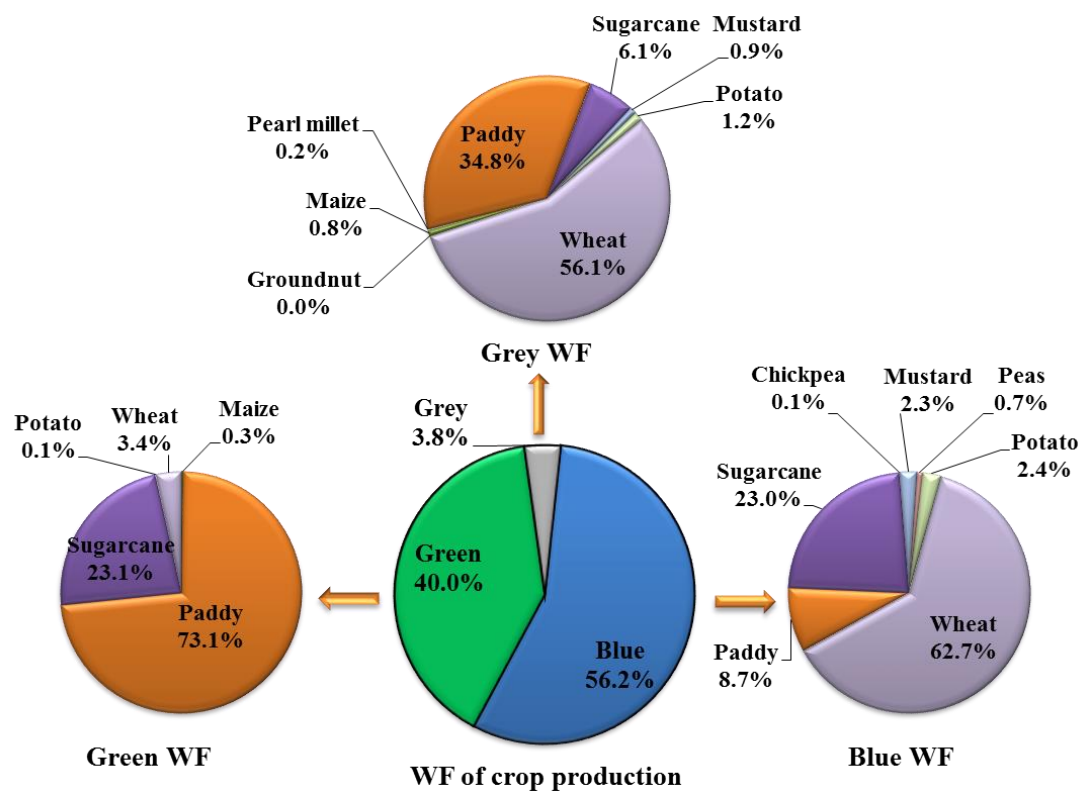


Fig 5.2 Crop wise share in green, blue and grey water footprint of crop production in the Gomti river basin (note: crops with < 0.1% shares in WF are not shown)

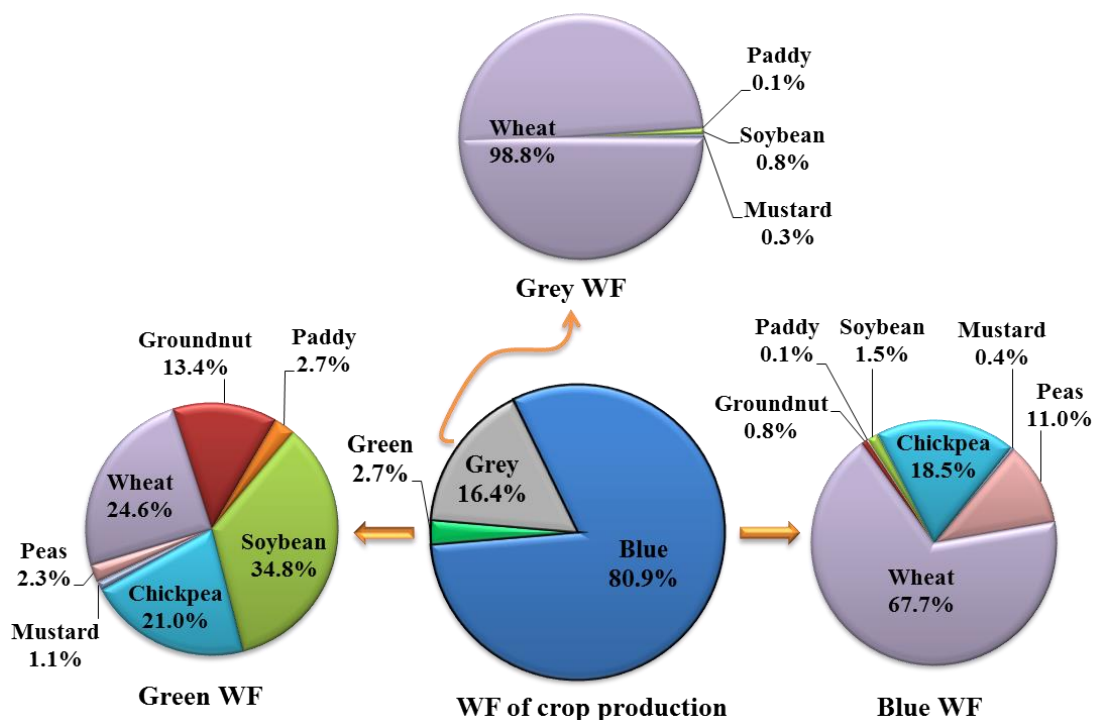


Fig 5.3 Crop wise share in green, blue and grey water footprint of crop production in the Betwa river basin (Note: crops with < 0.1 % shares in WF are not shown)

Black gram, maize, pigeon pea and sugarcane were the major contributors (>64%) to WF of rainfed agriculture in Gomti basin while in Betwa basin, soybean, wheat and black gram contributed about 58% of the WF of rainfed agriculture (Fig 5.3). Grey water use in irrigated agriculture accounted for 3.8% (718 million m³) and 16.4% (827 million m³) in Gomti and Betwa basins respectively (Fig 5.2 and Fig 5.3). Contribution of cereal crops (paddy, wheat, maize and pearl millet) in WF_c was about 70 % and 51% in Gomti and Betwa basins, respectively. Because of their large cultivation areas, paddy, wheat and sugarcane accounted for about 88 % of WF_c in Gomti, and wheat, soybean and chickpea shared about 75.28 % of total WF_c in Betwa basin. These results are in line with the WF of paddy and wheat reported for India (Kampman, 2008).

5.3.3 Water footprint of livestock (WF_l)

Annual WF of livestock production in Gomti was about 82.04 million m³ while that in Betwa was estimated at 129.68 million m³. Cattle and buffalo accounted for over 94% and 80 % of WF_l in Gomti and Betwa basin respectively (Fig 5.4). This is mainly due to large population of these animal types. Other than cattle and buffalo, pig also contributes significant portion (17.6 %) to WF_l in Betwa basin. Horse, sheep and donkey showed only small share in WF_l in both the basins.

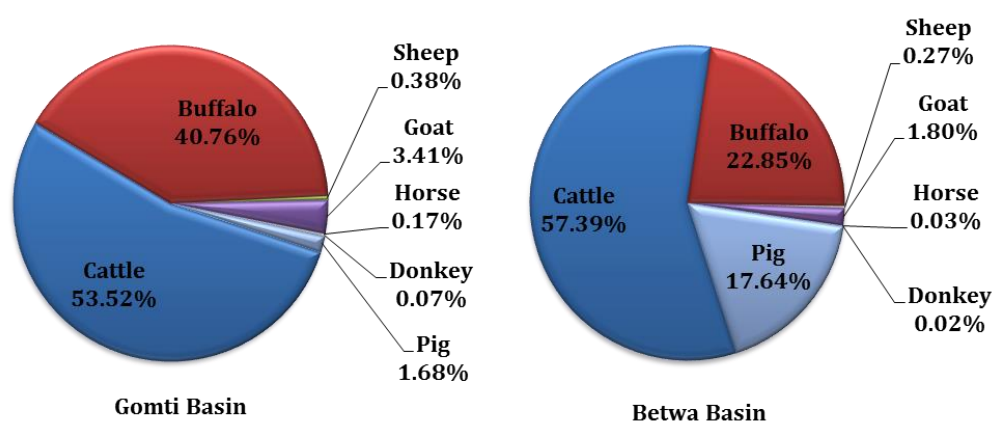


Fig 5.4 Water footprint of livestock

5.3.4 Water footprint of Domestic and industrial use ($WF_{dom+Ind}$)

The WF of domestic and industrial sector was estimated to be 495.7 million m³ and 201.2 million m³ for Gomti and Betwa basin. High population density and presence of processing and manufacturing industries resulted in high blue as well grey WF of

these sectors in Gomti basin. Share of grey WF in $WF_{dom+ind}$ was about 90 % in both the basins.

5.3.5 Water footprint of river basin (WF_{rb})

The WF of river basin was obtained as summation of WF of crop, livestock, domestic and industrial sectors. Annual WF of Gomti and Betwa basins was about 12773 million m^3 and 9186 million m^3 , respectively. Large scale cultivation of water intensive crops like paddy, sugarcane and wheat resulted in higher WF in Gomti basin. Crop production accounted for more than 95% of WF_{rb} (Fig 5.5). Livestock production accounted for 0.6% and 1.4% in Gomti and Betwa basins respectively. The share of domestic and industrial sector in Gomti and Betwa basins was about 3.9% and 2.2%, respectively. Agriculture production (crop and livestock production) was the main activity in both the basin and accounted for more than 96 % of the total WF of the basins. Blue water use by agriculture was about 97.8 % and 96.4% of the total blue water use in the Gomti and Betwa basins, respectively. Further analysis revealed that, for basins as a whole, the blue WF accounted for 47.3% (6040 million m^3) and 43.6% (4176 million m^3), while share of grey WF was about 9.1% (1165 million m^3) and 10.9% (1009 million m^3) in Gomti and Betwa basins respectively. The blue water consumption in Gomti basin is mainly from canal and groundwater while in Betwa basin groundwater is the major source of blue water. In case of Gomti, three major crops, rice, wheat and sugarcane contributed significantly to WF_c while in case of Betwa, wheat, chickpea and soybean were major contributors. Among the all the animals, cattle and buffalo were the largest consumers of freshwater in both the basins.

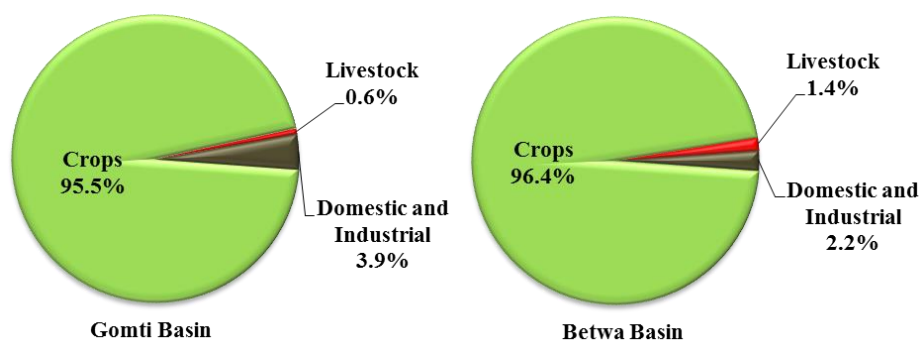
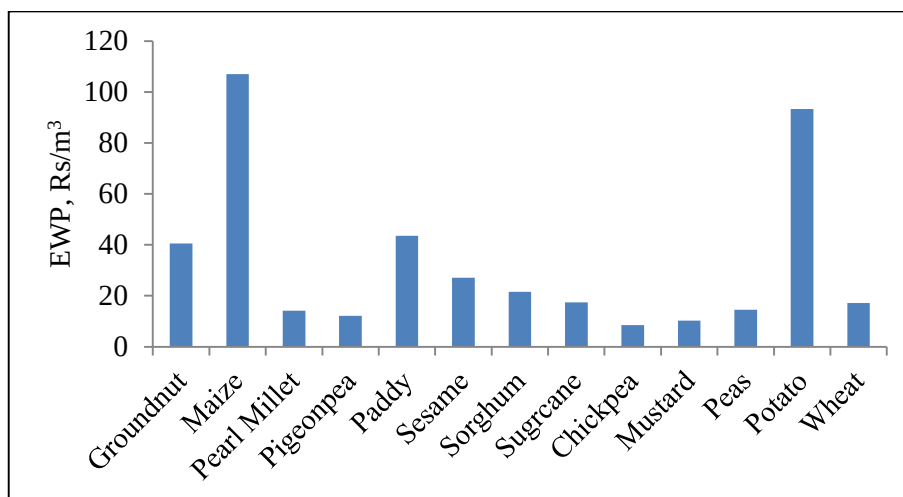


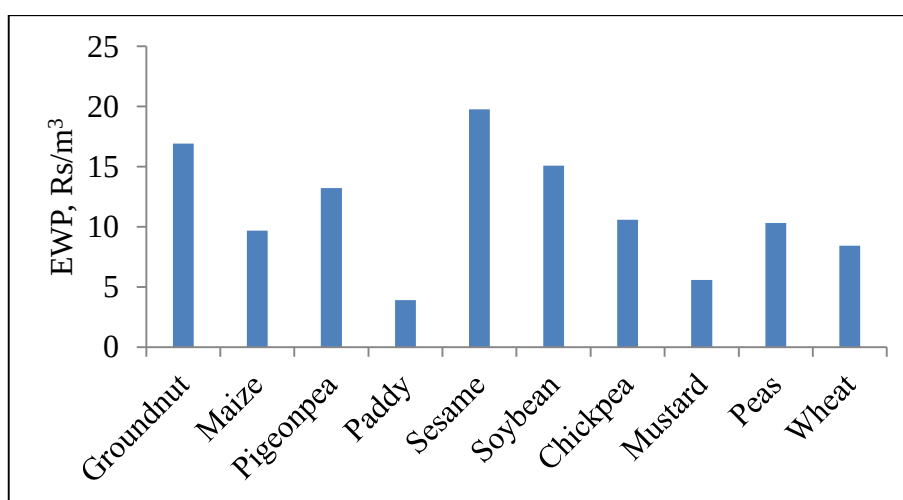
Fig 5.5 Sector wise water footprint in the study basins

5.3.6 Economic productivity of blue water (EWP)

As shown in Fig 5.6, Economic Water Productivity (EWP) significantly varies from crop to crop. Compared to Betwa basin, Gomti basin showed higher EWP values for most of the crops, mainly due to higher productivities of these crops. Crops with lower blue VWC and higher economic value such as maize and potato (107.0 Rs/m³ and 93.3 Rs/m³, respectively) resulted in higher economic water productivities in Gomti basin. In Gomti basin. Considering the importance of blue water, paddy (43.5 Rs/m³) and groundnut (40.5 Rs/m³) are other profitable crops. In Betwa basin, sesame, groundnut, and soybean recorded higher EWP, whereas the EWP values for pigeon pea and chickpea were higher than those estimated for Gomti basin.



(a) Gomti basin



(b) Betwa basin

Fig 5.6 Economic water productivity of blue water

Despite of having low EWP, the crops like paddy, mustard and wheat in Betwa basin and Sugarcane and mustard in Gomti basin are cultivated in vast areas, mainly because, these are either staple food crops or main crops of the basin. The net returns per hectare from these crops were also higher. Another important reason is low input cost of water. Extensive canal networks in Gomti basin provide water at the farmers' field at very cheap rates. In both the basins, groundwater is pumped freely as per the demands. In the absence of any effective policy measures, groundwater dependant basins like Betwa may face water scarcity and environmental degradation in future years.

5.3.7 Virtual water flows and virtual water balance

In order to estimate virtual water flows it was assumed that the production of a crop in excess of consumption is exported out of the basin and the consumption deficit is met by importing crops from other basins. Due to lack of information on location from where the product is being imported and also on the VWC of these imported products, it was assumed that VWC estimated in this study applies to imported crops also. The population of Gomati and Betwa basins is about 29.0 million and 12.14 million, respectively (2011 census). Consumption needs of the population and crop production within the basins is presented in Table 5.4.

Production and consumption patterns of crops revealed that, in Gomti basin, sugarcane, wheat, maize and sorghum are produced in surplus. The WF of export was about 2110 million m³ indicating huge amount of water being consumed to meet the food requirements of other regions. Also the net virtual water inflow in terms of import of other crops was about 4970 million m³ leading to a positive VW balance amounting to 2860 million m³ (Table 5.4). Sugarcane contributed 67.1 % in total VW exports from the basin.

In Betwa basin, VW outflow is through export of groundnut, maize, soybean, sorghum, chickpea and peas and it amounts to 2905 million m³. Import of VW was about 3590 million m³. Betwa basin also showed positive VW balance indicating that about 685 million m³ of VW being imported annually. Virtual water balance clearly indicated that in both the basins VW inflows are higher than VW exports, which makes both the basins as net virtual water importers.

Table 5.4 Virtual water flows in Gomti and Betwa basins

Crop production (t), consumption (t) and virtual water flow (million m ³ /yr)								
Crops	Gomti basin				Betwa basin			
	Production, t	Consumption, t	Crop Export/ Import, t	VW flow [†] , million m ³	Production, t	Consumption, t	Crop Export/ Import, t	VW flow [†] , million m ³ /yr
Black gram	28531	34201	5670	+44	47403	19963	-27440	-256 [†]
Groundnut	11235	20247	9011	+40	60000	24260	-35740	-163
Maize	80560	18112	-62448	-206 [†]	54796	49314	-5483	-16
Pearl Millet	20586	29152	8566	+34	--	--	--	--
Pigeon pea	29056	72709	43653	+246	21077	38331	17254	+97
Paddy	1574035	2326497	752462	+2905	24651	712936	688284	+2657
Sesame	5029	5674	646	+13	10215	11436	1221	+20
Sorghum	24592	3658	-20934	-76	57017	25578	-31439	-218
Soybean	--*	--	--		317739	170973	-146767	-858
Sugarcane	9253473	4384189	-4869284	-1417	0	1151383	1151383	+250
Chickpea	6834	52021	45187	+79	396325	119320	-277005	-761
Lentil	13510	24605	11095	+46	47155	20898	-26257	-115
Mustard	49905	498766	448861	+1431	11524	151100	139577	+445
Peas	19843	86004	66161	+142	142952	49433	-93519	-518
Potato	805184	1187575	382390	+74	0	310353	310353	+60
Wheat	3460801	3103350	-357451	-411	1387061	1446038	58977	+61
Virtual water balance				+2945				+685

[†]“+” sign indicates VW import and “-” sign indicates VW export.

Water allocation scenario in the basins showed that, under present cropping pattern considerable part of blue WF comes from low value-water intensive crops like chickpea, mustard and pearl millet. Since, these crops can yield well even under rainfed conditions, confining them to rainfed areas may result in considerable saving in blue WF. In order to achieve higher economic productivities of blue water, only high value - low water intensive crops needs to be cultivated in irrigated areas. Maximum utilization of green water can be promoted which will lead to savings of blue water resources. In the past decades, several studies concluded that green water management should be emphasized in addition to blue water (Savenije, 2000; Liu *et al.*, 2009).

Farm level practices such as mulching and land levelling can be practiced to make the effective use of rainwater. Presently, in canal irrigated areas of India, water is allocated on per hectare basis, without giving due consideration to crops being cultivated by the farmers. Although, farmers are interested in crops having higher profits per hectare, selecting crop with higher economic productivity of blue water is also desirable. Restrictions can be imposed on farmers' choice of crops such that total blue water use within the basin is minimized. Allocation of crops from high blue WF areas to low blue WF areas can result in significant savings in water. Optimizing the crop planting pattern is often a key to achieving more sustainable water use in arid and semi-arid regions (Zeng *et al.*, 2012). This needs sophisticated optimization tools and comprehensive assessments of production and consumption demands as well as availability of surface and groundwater resources.

Virtual water balance revealed that about 2110 million m³ and 2905 million m³ water is being exported in virtual form from Gomti and Betwa basins respectively. In Gomti basin abundant freshwater supplies are available and the export potential of Gomti basin needs to be harnessed so that food requirements in other parts of the country can be partially fulfilled. Betwa basin, which is already a water scarce semi-arid basin, export of huge amounts of water in virtual form may further add to water scarcity. Instead of exporting water intensive crops, an optimum trade plan can be worked out to make the WFs of the basin sustainable.

It is an established fact that agricultural activities are probably the most significant anthropogenic source of nitrate contamination (Kanwar *et al.*, 1985). Higher leaching of nitrates adds to grey WF. In general, most of the farmers apply the fertilizers

in single soil application or two-three splits during cropping season. The three split application of 120 kg N/ha to flooded paddy resulted in potential leaching of about 20 to 30 % of applied N (Choudhari *et al.*, 2004). A study specifically related to Indo-Gangetic plains (Chhabra *et al.*, 2010) showed that nitrogen loss through leaching in kharif and rabi paddy was of the order of 34.9% and 39.8% of the applied nitrogenous fertilizer. In view of significant grey WF within the basins, use of modern irrigation systems and fertigation technologies needs to be promoted. Also the farmers perception that high fertilizer application leads to higher yields, needs to be addressed.

5.4 Conclusions

This study presents an assessment of water footprint of crop and livestock production, and industrial and domestic uses in Gomti and Betwa basins of northern India. The estimated water resource consumption based on the WF analysis within Gomti and Betwa basins was about 12773 million m³ and 9186 million m³ respectively. Agriculture is the main water consuming sector, accounting for more than 95% of total water consumption in both the basins. Crop production has largest share in grey WF followed by domestic and industrial sector. Both the basins were assessed as net virtual water importers (2860 million m³ in Gomti and 685 million m³ in Betwa). Under prevailing cropping pattern considerable amount of blue water is being used to produce crops having low economic productivity of blue water (EWP). Efficient use of blue water resources can be achieved by allocating water resource to various crops on the basis of EWP. Gomti basin has advantage in term of water availability and its potential used to produce more crops for export in other basins, hence reducing their water scarcity in virtual sense. In Betwa, there is need to reduce the VW exports and allocate the saved blue water to water efficient crops. Improving efficiency of rainwater use and reallocation of cropping patterns can be potential solutions to reduce blue water use in the basins.

Major conclusions drawn from the study were,

- Paddy, sugarcane and wheat in Gomti basin and wheat, chickpea and peas in Betwa basin consume more than 95 % of blue water resources of these basins.
- Grey water footprint in Gomti and Betwa basins indicated that large amount of freshwater would be required to assimilate the pollution.

- Production of crops having low economic water productivity can be limited to meet the consumption needs and saved blue water may be used to cultivate other water efficient crops.
- Water footprint of consumption is higher than water footprint of production in Gomti and Betwa basins indicating that these basins are partially dependant on the water resources of other regions and are net virtual water importers.
- Virtual water balanced should be achieved through virtual water trades, so that efficient use of limited water resources can be realized.

Development of sub-basin level sustainable crop and water management strategies to reduce crop water footprints

Abstract

Water footprint (WF) is an indicator of freshwater use and is increasingly being used to assess the sustainability of water resources at river basin scale. Sustainable development of water resources requires an optimal cropping pattern, efficient irrigation method and effective utilization of rainfall without any adverse effect on water resources of the basin. A study was undertaken to assess the sustainability of blue and grey WF, optimize cropping pattern and analyse the response of WF to different management strategies for suggesting strategies to reduce crop WF in Gomti and Betwa river basins in India. The WF in Gomti basin were sustainable as Blue Water Scarcity Index (BWSI) and Water pollution Index (WPI) were within acceptable limits, while in Betwa basin they exceeded permissible limits for five and two months in a year, respectively indicating unsustainable use of water resources. Optimal cropping pattern to reduce blue WF decreased the irrigated areas under sugarcane, paddy and mustard in Gomti basin and soybean, pea, wheat and groundnut in Betwa basin without altering the prevailing production. This would result in reduction of about 196.0 and 213.5 million m³ in blue WF of Gomti and Betwa basins respectively. Optimal cropping pattern for dry year would reduce the green WF by about 314.8 million m³ in Gomti basin and 1065.2 million m³ in Betwa basin. Results indicated that increasing the crop yields by adopting drip or sprinkler irrigation up to the achievable level can reduce the WF of wheat, sugarcane and potato in Gomti basin by 38.6, 62.7 and 42.7 % and wheat, chickpea and groundnut in Betwa basin by 52.9, 36.6 and 21.5% respectively. Laser levelling of irrigated lands would reduce the WF in Gomti and Betwa basins by 710.0 and 276.4 million m³, respectively. In order to ensure sustainability of WF in the basins, the optimal cropping pattern and improved irrigation practices should be adopted by the farmers.

Keywords: Water footprint, sustainability assessment, optimization, cropping pattern

6.1 Introduction

Freshwater is a renewable resource; however, its annual availability is limited. In many parts of the world annual freshwater use exceeds renewable capacity of the earth-atmosphere system. This has resulted in river flows that are below environmental flow requirements, declining groundwater levels and water pollution (Haberl *et al.*, 2007). The problem is increasing day-by-day due to increasing water demand to meet the requirements of growing population and improving the living standards (World Bank, 1992; Mariolakos 2007). It has been reported that our dependency on water resources will increase significantly in the future which will affect the future food security and environmental sustainability (Alcamo *et al.*, 2003a; Rosegrant *et al.*, 2009). It is estimated that two-thirds of the world population will experience water scarcity over the next few decades (Alcamo *et al.*, 2000; Vorosmarty *et al.*, 2000) and slightly more than one billion people living in arid regions will face absolute water scarcity (less than 500 m³/capita/year) by 2025 (Rosegrant *et al.*, 2002).

In view of increasing water scarcity at global, regional and river basin scale, WF analysis is being increasingly used for management and policy decisions in trade as well as water resource management. WF is a measure of human's appropriation of freshwater resources which measures the 'water use' in terms of volumes *consumed* or polluted per unit of time (Hoekstra *et al.*, 2011). The WF is a geographically and temporally explicit indicator that looks at both *direct* and *indirect* water use of a consumer or producer. Previous studies (Aldaya and Llams, 2008; Aldaya *et al.*, 2010; Dumont *et al.*, 2013) have demonstrated the applicability of WF analysis in devising basin level water management and policy decisions. The work by Dumont *et al.* (2013) analysed the green and blue WF of the Guadalquivir basin (Spain) and suggested that reframing the water governance setting based on WF information, could lead to improving water availability in the basin.

The WF analysis involves a four step approach i) setting goal and scope of the WF accounting, ii) Assessment of WF, iii) sustainability assessment and iv) response formulation (Hoekstra *et al.*, 2009). Assessment of WF is followed by sustainability assessment of WF from environmental, economic and social perspectives. In sustainability assessment the estimated WF are compared with water availability to

locate hotspots. Hotspot can be represented in spatial or temporal terms and can be defined as a spatial region or period of time for which the WF exceed the water availability (Witmer and Cleij, 2012). To trace such hot spots, the WF components are viewed at catchment or sub-catchment level taking into account water consumption and pollutant emissions to water. WFs become a concern when water resources are depleted or polluted due to unsustainable water use, causing environmental, economic or social damage. The goal of sustainability analysis is to analyse how human activities or specific products relate to issues of water scarcity and pollution, and to see how activities and products can become more sustainable from a water perspective (Hoekstra *et al.*, 2011).

Researchers have used WF based ‘water scarcity indices’ as sustainability criterions to identify hotspots and the water scarcity in regions (Zeng *et al.*, 2013; Jefferies *et al.*, 2012). Hoekstra *et al.* (2012) quantified blue water scarcity for more than 400 river basins at a monthly level and found that in 201 basins with 2.67 billion inhabitants, there was severe water scarcity during at least one month of the year. Zeng *et al.* (2012) analysed the sustainability of WF within the Heihe River Basin (HRB) in northwest China. The average annual blue water scarcity in HRB was 154 % indicating that runoff in the HRB was significantly modified by human activities.

Response formulation phase of WF analysis includes devising strategies and management options to reduce the WF and evaluates the impact of such strategies on WF. At basin level, several alternative strategies can be proposed in the response formulation phase. The formulation of response options should take in to account factors such as land and water availability, production needs and consumption requirements within the basin. The “right actions” would lead here to an overall decrease in total WF.

Chapagain and Orr (2008) analysed the WF of United Kingdom and proposed the management options for businesses, government and consumers. In case of Germany, Sonnenberg *et al.* (2009) proposed that agricultural subsidies of the EU should only be paid in the case of proven responsible utilisation of water and raise the financial means for sustainable management of aquifers and river catchments. Kampman, (2008) analysed the WF of Indian states and suggested that the river

interlinking project would mainly reduce local water scarcity, while water scarcity needs to be reduced significantly at a national level. He suggested that increasing the water productivity as only the long term solution to ensure sustainability of WFs. Aldaya *et al.*, (2010) and Aldaya and Llams, (2008) suggested that changing cropping pattern or a drastic reduction of the irrigated surface can reduce the WF of the basins. Dumont *et al.*, (2013) suggested for improvement in water resource allocation for bigger economic, social and environmental productivity, increase water reuse, practicing less aggressive agricultural production as possible management alternative to reduce the WF. Strict control on extraction of water and use of chemical products for agricultural purposes were the management alternatives proposed by Aldaya *et al.*, (2010b). Other possible solutions to reduce the basin level WF includes reducing the production of low value high virtual water content crops and reforms in water pricing (Zeng *et al.*, 2010) and reduction in export of virtual blue water and using it for producing higher value added but lower water-intensive goods (Feng *et al.*, 2012).

Reviewed literature suggested that there is still a large potential for the reduction of agricultural WFs, especially by improving water productivities, changing cropping patterns and revising actual trade patterns. In most of the studies the solutions are focused on agriculture and food demand. At the river basin level water use efficiency can be enhanced by allocating water to crops with highest marginal benefits in terms of water saving. Overall water consumption can be reduced by reallocating crops from the place where it has high WF to the place where it is low. In this study the response of WFs under three management alternatives viz. changed cropping patterns, adoption of improved irrigation systems and laser leveling of irrigated lands was evaluated.

To reduce the WF through reallocation of cropped areas, it is important to decide upon the location and quantum of area allocated to the crops. Generally, the costs and benefits approach is widely used for cropping pattern optimization with the aim of achieving maximum net benefits (Ghasemi *et al.*, 2014). The present study aims at optimizing cropping patterns to minimize the WF of the basins. The basin level readjustment of cropping structure is proposed to ensure an efficient use of limited water resources. The local impacts of WFs were partially addressed by Oel *et al.* (2009) for the Netherlands, Kampman *et al.* (2008) for India and Chapagain and Orr (2009)

for Spain. However, these studies did not consider WF analysis at higher temporal details. Several national and basin level studies limited the scope of WF analysis up to second phase and did not present detailed policy or response implications of the findings. Some of these studies proposed the strategies to reduce WF but did not quantitatively evaluate their impact on WF.

The present study was planned with twin objectives of evaluating the sustainability of blue and grey WF and evaluating the impact of suggested management alternatives on WF within the Gomti and Betwa basins. A comprehensive assessment of sustainability of WFs considering multiple sectors (agriculture, livestock, domestic and industry) and multiple types of water (e.g. blue and grey) has never been done before. Also, no work has so far been reported that evaluates the impact of suggested management alternatives on WFs within the basins. This study makes a substantial step beyond quantifying and mapping the WF of crop production by identifying the crops responsible for water scarcity and developing optimal cropping patterns as a response option to reduce the WF and improve sustainability. The study also presents the impact of improved irrigation methods and laser levelling of irrigated lands on WF in the basins.

6.2 Materials and Methods

6.2.1 The study area

Sustainability analysis and WF response formulation was carried out for the Gomti and Betwa river basins located in northern and central India respectively. The detailed description of the study area is presented in Section 3.4 in Chapter III. Prevailing cultivation practices of the basins reveals that the farmers usually grow crops in two seasons (*kharif* and *rabi*) under both rainfed and irrigated conditions. Paddy, wheat and sugarcane are the principal crops cultivated in Gomti while wheat, chickpea and soybean are the major crops of Betwa basin. Pulses, oilseeds and vegetables are the other crops grown during monsoon and winter seasons. Gomti is a water reach basin with ample groundwater supplies and water available from extensive canal network. In Betwa basin, groundwater is the only major source water for irrigation.

Depending on the spatial variation in the crop evapotranspiration (ET_c), the Gomti and Betwa basins were divided into four distinct spatial regions called spatial resolution units (SRU). The detailed procedure to delineate such SRUs has been presented in Chapter IV. The crop reallocation and management plans are proposed considering SRU as homogeneous unit in terms of crop water requirement and crop WF (m³/ha). Delineated SRUs of Gomti and Betwa basins are shown in Fig. 4.10 in Chapter IV.

Land use land cover raster datasets for the states of Madhya Pradesh and Uttar Pradesh obtained from ISRO (Bhuvan thematic data services) were used to derive gross cropped areas of each SRU within the basin. SRU wise information on cultivated areas under different crops was obtained from crop wise cultivated areas and gross cropped area of the district using the methodology presented in Section 4.2.6 in Chapter IV. Gross cropped area in Gomti basin was 2.67 Mha out of which 2.27 Mha (85.26%) was irrigated, while in Betwa, it was 2.90 Mha out of which only 1.11 Mha (38.21%) was irrigated. Irrigated and rainfed areas of crops in different SRUs is presented in Table 6.1. Productivity of a crop in each SRU was taken as average productivity of districts in SRU. Since, crop growth and yield under rainfed conditions are affected by water stress, a linear relationship between yield and evapotranspiration as proposed by Doorenbos and Kassam (1979) was used to get crop yields under rainfed conditions.

Table 6.1 Irrigated and rainfed areas in delineated SRUs of the basins

River basin	Spatial resolution unit	Irrigated area (ha)		Rainfed area (ha)		Gross cropped area (ha)
		<i>Kharif</i>	<i>Rabi</i>	<i>Kharif</i>	<i>Rabi</i>	
Gomti	SRU1	177620	129680	34360	15480	357140
	SRU2	417720	678730	137130	34320	1267900
	SRU3	82560	127800	37800	4190	252350
	SRU4	205410	295060	86420	22260	609150
Betwa	SRU1	320	229620	135070	179330	544340
	SRU2	150	147000	75570	157410	380130
	SRU3	60	333150	355470	510980	1199660
	SRU4	31590	367990	252500	128490	780570

Note: sugarcane area added to *kharif* season

6.2.2 Net returns from crop production

Economic productivity of the blue water use in the basins (ratio between net economic returns from the basin (Rs) and total blue water use, m³) was also analysed for developed optimal cropping patterns. Net returns from crops under irrigated and rainfed areas was estimated from Eq. 1.

$$NR[k, s, i, c] = NR_{avg}[c] * Y[k, s, i, c]; \quad \forall c, \forall i, \forall s, \forall k \dots \dots (1)$$

where, $NR[k, s, i, c]$ is net return (Rs/ha) from crop c under type of agriculture i in season s in SRU k ; $Y[k, s, i, c]$ is yield (kg/ha) of crop c under type of agriculture i in season s in SRU k ; $NR_{avg}[c]$ is average net return from crop c (Rs/ha). $i=1$ for irrigated agriculture, $i=2$ for rainfed agriculture, $s=1$ for *kharif* and $s=2$ for *rabi* season.

The net returns per hectare from a crop were obtained from state specific data on production of main and by products of crops using Eq.2.

$$NR_{avg}[c] = \frac{\{V_{mp}[c] * Q_{mp}[c] + V_{bp}[c] * Q_{bp}[c]\} - C_{cult}[c]}{Y_{avg}[c]} \dots \dots (2)$$

Where, $Q_{mp}[c]$ and $Q_{bp}[c]$ are the quantities (kg/ha) of main and by-products of crop c ; $V_{mp}[c]$ and $V_{bp}[c]$ are the values (Rs/kg) of main and by-products of crop c ; $C_{cult}[c]$ is the cost of cultivation (Rs/ha) of crop c ; $Y_{avg}[c]$ is the average crop yield (kg/ha). Crop wise and state wise data on cost of cultivation, production and prices of primary and secondary crop products were obtained from Department of Economics and Statistics (MoA, 2011).

6.2.3 Surface and ground water resources

Sustainability assessment of WFs requires estimates of blue water availability (surface and ground water) and runoff volume at monthly time steps. The main source of surface water in Gomti basin is runoff and canal water imported from other basins. Availability of surface water in the SRUs was assessed using NRCS CN method (USDA). Event wise rainfall and runoff for the year 2011 in different SRUs of Gomti and Betwa basins is presented in Appendices XXIII and XXIV, respectively. The

quantity of runoff available for human consumption is the natural runoff minus the environmental flow requirements (EFR). In previous WF studies (Hoekstra and Mekonnen, 2012; WWF, 2012, Zeng *et al.*, 2012) the EFR was estimated using the “presumptive environmental flow standard” defined by Richter *et al.* (2012). Environmental flow methods should take into consideration the natural variability of river flow in order to maintain and/or restore freshwater ecosystems (Acreman and Ferguson, 2009). Therefore, in present study, the EFR of Gomti and Betwa basin was estimated using the Variable Flow Method (VFM) suggested by Pastor *et al.*, (2013). The availability of blue water resources (WA_{blue}) in time step t was estimated using Eq.3.

$$WA_{blue}[t] = SW[t] + GW[t] - EFR[t] \dots \dots (3)$$

Where, $WA_{blue}[t]$ is the available blue water resource (million m^3) at time step t ; $SW[t]$ and $GW[t]$ are the surface and groundwater resources (million m^3) of the basin at time step t ; $EFR[t]$ is the environmental flow requirement (million m^3) at time step t .

In Gomti basin, canal water is supplied from two major canal systems, Sharda canal project and Sharda Sahayak Pariyojna (PlanningCommission, 2007). Monthly availability of canal water in Gomti basin was estimated from the canal rosters obtained from UP State Water Resources Agency (SWRA, 2009). The groundwater resources for the part of the districts, which are within the basin boundary were estimated by multiplying the groundwater withdrawal (CGWB, 2009) with geographic area factor. Geographic area factor is the ratio of geographical area of the district within the basin to total area of the district. Annual water resource availability in Gomti and Betwa basin was estimated at 13.3 and 7.8 BCM (Table 6.2). Imported canal water constituted about 65.0% of the total surface water resources available within the Gomti basin. It is worth mentioning that the water availability presented in Table 6.2 is obtained after accounting for environmental flow requirements.

Table 6.2 Water resources availability in different seasons of Gomti and Betwa basins

Spatial resolution unit	Water availability in Gomti basin (million m ³)		Water availability in Betwa basin (million m ³)	
	<i>Kharif</i>	<i>Rabi</i>	<i>Kharif</i>	<i>Rabi</i>
SRU1	1040.9	713.5	1540.4	418.5
SRU2	4428.4	2991.9	518.1	175.1
SRU3	763.2	518.7	2573.8	782.4
SRU4	1584.5	1257.0	1316.7	478.2
Basin total	7817.1	5481.0	5949.0	1854.1

6.2.4 Virtual water content and WF

The blue and green water requirements of the selected crops in both the basins were estimated using the CROPWAT model (Allen *et al.*, 1998; FAO, 2003). Estimation of grey VWC was based on dilution water requirements of leached pollutants. The dilution water requirement of a crop ($DWR[c]$, m³/ha) is the volume of water required to dilute the amount of nitrate leached to a desired drinking water quality standard. Blue, green and grey VWC of crops was obtained by dividing the blue, green and grey crop water use (m³/ha) by the crop yields (kg/ha). Monthly blue WF of crop production within the basins was obtained by multiplying the cultivated area under a crop by blue crop evapotranspiration during the respective month.

6.2.5 Water footprint of livestock, industrial and domestic uses

Annual WF of livestock was obtained using the methodology outlined in section 5.3.5 of Chapter V. The main source of industrial and domestic water use in Gomti and Betwa river basins is groundwater. WF of industrial and domestic sectors was estimated using the district level data on groundwater withdrawal for domestic and industrial sectors (CGWB, 2011) and using the methodology presented in section 5.3.6 of Chapter V. To obtain the monthly WF of these sectors their annual WF was equally divided over twelve months of the year.

6.2.6 Production and consumption of crops

The basin level information on crop wise production was estimated by summing the SRU level production obtained as product of cultivated area with respective productivity of a crop. The basin population was estimated from district level

population data as a product of district population density and the area of the district within the basin. The state level per capita consumption of agricultural commodities obtained from NSSO (NSSO, 2012) and the population data was used to obtain the basin level consumption of selected crops covering about 33 major crop products.

6.2.7 Sustainability of blue and grey WFs

Sustainability assessment requires the estimates of WFs and the blue and green water availability at river basin level. Sustainability of blue and grey WF was assessed using ‘Blue Water Scarcity Index’ (BWSI) and ‘Water Pollution Index’ (WPI) as sustainability criteria for blue and grey WFs respectively. During certain time step t if WF_{blue} exceeds blue water availability (WA_{blue}), environmental flow requirement in that period is not met. Also if WPI exceeds the value of 100 %, there is concern about the sustainability of grey WFs. BWSI and WPI were estimated using Eq.4 and Eq.5, respectively.

$$BWSI[t] = \frac{WF_{blue}[t]}{WA_{blue}[t]} \times 100; \quad \forall t \dots \dots \dots (4)$$

$$WPI[t] = \frac{\sum_{c=1}^n WF_{grey}[t]}{R_{act}[t]} \times 100; \quad \forall t \dots \dots (5)$$

Where, $BWSI[t]$ is blue water scarcity index at time step t ; $WF_{blue}[t]$ is blue WF of the basin (million m³) at time step t ; $WPI[t]$ is the water pollution index at time step t ; $WF_{grey}[t]$ is total grey WF resulting from all the crops present in the basin at time step t ; $R_{act}[t]$ is the quantity of actual runoff from the basin in time step t . In present study, the sustainability assessment is carried out at monthly time step.

6.2.8 Management practices for reducing WF

Agriculture is the dominant water user sector and accounts for 95.5 % and 96.3% of total WF of Gomti and Betwa basins. Therefore, management strategies to reduce the WF of agriculture were proposed and their impact on WF was evaluated. It is obvious that water saving can be achieved if cultivation area under a crop is allocated to a region in the basin where it has comparatively lower WF. Keeping this in view, a basin level reallocation plan of cropped areas can be developed such that total crop WF is reduced. Linear programming based optimization models were developed for crop

planning in the study area. The detailed information on objective function and development of optimization models for two independent scenarios is given below. In both the scenarios the models were run considering the land and water availability constraints during *khari*f and *rabi* seasons and using SRU as the allocation unit within the basins. In allocation of cropped areas to different regions, SRU is considered as homogeneous unit in terms of crop WF.

6.2.8.1 Optimization model for minimizing blue WF

Optimization of cropping pattern was done with the model objective as minimizing blue WF of irrigated agriculture in such a way that optimal crop plan could maintain at least the current levels of production for each crop within the basin. In this scenario, area under particular crop was allocated to the SRU where it has lowest blue WF. This scenario provides information on possible reduction in WF by relocation of crop growing areas from high WF areas to low WF areas without affecting the total production of crop from the basin.

Objective function: minimize blue WF in the basin (Eq.6).

$$\text{Min } z = \sum_{k=1}^4 \sum_{s=1}^2 \sum_{c=1}^n \{VWC_{blue}[k, s, i, c] * Y[k, s, i, c] * A[k, s, i, c]\}; \quad \forall (i = 1) \dots \dots (6)$$

where, $VWC_{blue}[k, s, i, c]$ is blue virtual water content (m^3/kg) of crop c for the cropping season s in SRU k ; $Y[k, s, i, c]$ is yield (kg/ha) of crop c for the cropping season s for type of agriculture i in season s and in SRU k ; $A[k, s, i, c]$ is area (ha) allocated to crop c for cropping season s in SRU k ; k is the SRU index and gets values from 1 to 4 for both the basins, s is season index, (1= for *khari*f and 2= *rabi*); i is the index for type of agriculture (1= irrigated and 2= rainfed); and c is the crop index, ($n = 15$ for Gomti basin and $n=12$ for Betwa basin).

In above optimization model $A[k, s, i, c]$ is the decision variable and the product $VWC_{blue}[k, s, i, c] * Y[k, s, i, c]$ forms the cost coefficient which indicates the quantity of water added to blue WF with per hectare increase in area under a crop.

The objective function was subjected to following constraints.

- i. *Crop production*: Production of individual crops obtained from both the irrigated as well as rainfed areas of all the SRUs should be greater than or equal to the prevailing level of production of a crop (Eq.7).

$$\sum_{k=1}^4 \sum_{s=1}^2 \sum_{i=1}^2 \langle Y[k, s, i, c] * A[k, s, i, c] \rangle \geq P[c, rb]; \quad \forall c \dots \dots (7)$$

where, $P[c, rb]$ is total production of crop c from the river basin (rb)

- ii. *Irrigated and rainfed area*: For a particular season, the total allocation of irrigated and rainfed area under all the crops should not exceed the available irrigated and rainfed area in the SRU (Eq.8 and Eq.9).

$$\sum_{c=1}^n A[k, s, i, c] \leq IA[k, s]; \quad \forall k, \forall s, \forall (i = 1) \dots \dots (8)$$

$$\sum_{c=1}^n A[k, s, i, c] \leq RFA[k, s]; \quad \forall k, \forall s, \forall (i = 2) \dots \dots (9)$$

where, $IA[k, s]$ is available irrigated area (ha) in SRU k for cropping season s and $RFA[k, s]$ is available rainfed area (ha) in SRU k for cropping season s

- iii. *Crop specific rainfed area*: In order to minimize the blue WF, the optimization model will allocate maximum area for cultivation of crops under rainfed conditions. Sudden increase in rainfed area of the basin may cause an abrupt change in basin equilibrium. Also, part of irrigated area within the basin may remain unutilized. It is also possible that in some years the winter rainfall may not be sufficient to support the production from the rainfed areas, causing economic loss to the farmers. Therefore, to reduce the blue WF, increasing the rainfed area under sugarcane and *rabi* crops beyond certain limit may not be a viable option. In this study, therefore, limit on rainfed area of sugarcane and all the *rabi* crops was fixed at prevailing extent of rainfed areas under these crops (Eq.10 and Eq.11).

$$\sum_{k=1}^4 RFA[c_{rabi}, k] \leq ERFA[c_{rabi}, rb] \dots \dots (10)$$

$$\sum_{k=1}^4 RFA[sc, k] \leq ERFA[sc, rb] \dots \dots \dots (11)$$

where, $RFA[c_{rabi}, k]$ is rainfed area (ha) allocated to *rabi* crop c in SRU k ; $RFA[sc, k]$ is rainfed area allocated to sugarcane in SRU k ; $ERFA[c_{rabi}, rb]$ the prevailing rainfed area (ha) of *rabi* crop c in the river basin and $ERFA[sc, rb]$ is prevailing rainfed area (ha) under sugarcane in the river basin.

- iv. *Water availability*: For each SRU, the use of blue water resources under irrigated agriculture should be limited to available blue water resources within the SRU (Eq.12).

$$\sum_{s=1}^2 \sum_{c=1}^n \langle VW C_{blue}[k, s, i, c] * Y[k, s, i, c] * IA[k, s, i, c] \rangle \leq WA_{blue}[k, s]; \quad \forall k, \forall (i = 1) \dots \dots \dots (12)$$

Where, $WA_{blue}[k, s]$ is blue water availability (m^3) in SRU k for the cropping season s .

- v. *Non-negativity constraints*: The irrigated and rainfed areas under any crop should not be negative (Eq.13).

$$A[k, s, i, c] \geq 0 \dots \dots \dots (13)$$

6.2.8.2 Optimization model to minimize WF of rainfed area

This scenario was considered to work out optimal cropping pattern and the associated WF under low rainfall conditions (moderate drought) in which water saving is as important as feeding the population. It is important to devise a cropping pattern that meets the consumption need of major crops that contribute in routine diet of the people in the basin. Cereals are the staple food in India, while pulses are the main protein supplement in the diet. From consumption point of view, wheat, paddy, maize (for livestock), chick pea, pigeon pea and potato are most important food crops and requirement of these must be met first. Under drought like situations, productivity of rainfed areas is very low; therefore allocation is done in such a way that area under rainfed crops is kept to minimum i.e. WF of rainfed areas is to be minimized. Also, area allocated to principal diet crops should be sufficient to meet the consumption requirements.

Objective function: minimize WF in rainfed areas (Eq.14).

$$\text{Min } z = \sum_{k=1}^4 \sum_{s=1}^2 \sum_{c=1}^n \langle VWC_{green}[k, s, i, c] * Y[k, s, i, c] * A[k, s, i, c] \rangle; \quad \forall (i = 2) \dots (14)$$

Where, $VWC_{green}[k, s, i, c]$ is the green VWC (m^3/kg) of crop c under type of agriculture i in season s and SRU k ; $Y[k, s, i, c]$ is the yield (kg/ha) of crop c under type of agriculture i in season s and SRU k ; $A[k, s, i, c]$ is the area (ha) of crop c under type of agriculture i in season s and SRU k .

Note that this objective function is for $i=2$, which means it minimizes the green WF of rainfed agriculture only. To achieve minimization of WF of rainfed area, model will keep the area under rainfed agriculture to minimum, which was desirable under drought like situation.

The objective function was subjected to the following constraints:

- i. *Crop production:* Under the conditions of limited rainfall and reduced water availability, production of only important crops mentioned above is considered such that consumption needs of these crops are met (Eq.15).

$$\sum_{k=1}^4 \sum_{s=1}^2 \sum_{i=1}^2 \langle Y[k, s, i, c] * A[k, s, i, c] \rangle \geq \text{Cons}[c, rb]; \quad \forall (\text{cimportant crops}) \dots \dots \dots (15)$$

As mentioned earlier, $\text{Cons}[c, rb]$ is total consumption (kg) of crop c in the river basin.

- ii. *Irrigated and rainfed area:* For a particular season, the total allocated irrigated and rainfed area should be less than or equal to the available irrigated and rainfed areas in the SRU (Eq.16 and Eq.17).

$$\sum_{c=1}^n A[k, s, i, c] \leq IA[k, s]; \quad \forall k, \forall s, \forall (i = 1) \dots \dots (16)$$

$$\sum_{c=1}^n A[k, s, i, c] \leq RFA[k, s]; \quad \forall k, \forall s, \forall (i = 2) \dots \dots (17)$$

where, $IA[k, s]$ and $RFA[k, s]$ are irrigated and rainfed area (ha) of SRU k in cropping season s .

- iii. *Blue WF*: The blue WF of optimized cropping pattern should not exceed the prevailing level of blue WF in the basin (Eq.18).

$$\sum_{k=1}^4 \sum_{s=1}^2 \sum_{c=1}^n \langle VW C_{blue}[k, s, i, c] * Y[k, s, i, c] * A[k, s, i, c] \rangle \leq PWF_{blue}[s, rb]$$

where, $PWF_{blue}[s, rb]$ is the prevailing blue WF of the river basin in season s .

- iv. *Water availability*: For a particular SRU, the use of blue water resources under irrigated agriculture should be limited to available blue water resources (Eq.19).

$$\sum_{s=1}^2 \sum_{c=1}^n \langle VW C_{blue}[k, s, i, c] * Y[k, s, i, c] * A[k, s, i, c] \rangle \leq WA_{blue}[k, s]; \quad \forall k, \forall (i = 1) \dots \dots \dots (19)$$

where, $WA_{blue}[k, s]$ is the blue water availability (m^3) in SRU k for the cropping season s .

- v. *Non-negativity constraints*: The irrigated and rainfed areas under any crop should be greater than or equal to zero (Eq.20).

$$A[k, s, i, c] \geq 0 \dots \dots \dots (20)$$

where, $IA[c, k]$ is irrigated area allocated to crop c in SRU k .

The solution to the linear programming model was obtained using the Simplex method available with Open Solver 2.1[®] add-in in MS Excel[™] which uses the COIN-OR CBC optimization engine (Mason and Dunning, 2010).

6.2.9 Water management practices to reduce WF

6.2.9.1 Adoption of efficient water application methods

Virtual water content of a crop is a function of crop water use and corresponding crop yield. Increasing crop yields will reduce the VWC, consequently, reducing the WF of the basin. Potential of drip and sprinkler irrigation systems in increasing crop yields is well established. Therefore, adoption of pressurised irrigation systems (PIS) like drip and sprinkler in irrigated areas was proposed as possible management alternative to reduce the crop WF. Several researchers have documented the increase in crops yields under PIS. Two sets of information on yield improvements under PIS were considered. First case considered the increase in crop yield above the prevailing *average* crop yields of respective SRUs. In second case, maximum achievable yields obtained under PIS

were considered. The second set mainly focused on the use of best management practices like fertigation and optimum irrigation scheduling so that maximum crop yields can be achieved. Increase in crop yields and maximum achievable yields of various crops under PIS as reported in Narayanmoorthy (2013) were used in this study (Table 6.3).

Table 6.3 Increase in crop yields under pressurised irrigation systems

Water application Method	Crop	Increase over prevailing average yields (%)	Maximum achievable yield, q/ha
Sprinkler Irrigation	Wheat	15.0	39.37
	Maize	15.8	18.10
	Chickpea	51.3	21.37
	Mustard	12.1	16.60
	Soybean	28.0	16.34
Drip Irrigation	Sugarcane	33.0	1700.00
	Potato	46.0	344.20
	Groundnut	66.0	28.40
	Peas	23.8	26.60

Source: INCID (1994), NCPA (1990), INCID (1998) and Rajagopal (1998) as cited in Narayanmoorthy, 2013.

6.2.9.2 Reducing WF through land levelling

Laser levelling of land is a proven technology and has showed potential to improve crop yields under irrigated as well as rainfed conditions. Impact of land levelling on crop WF was assessed with the consideration of yield increments that can be achieved through laser levelling of land. Jat *et al.* (2011) showed that with the adoption of laser land levelling the wheat yield in Indo Gangetic Plains improved by about 16.6 %. Kaur *et al.* (2012) reported an increase of about 4.25 % in paddy yields in Punjab. Naresh *et al.* (2013) showed laser levelling increased the rice, wheat and sugarcane yields by about 6.6, 5.4 and 10.9%, respectively. Jat *et al.* (2006) reported an average increase of about 3–19% in yield of various crops under laser levelled fields. Gummert (2012) pointed out that laser levelling in India may increase yield by 5–15%. Kumar *et al.* (2013) observed an average increase of about 15.2 % in yield of paddy, wheat, mustard and pigeon pea. In view of the reported increase in yields under laser levelled fields, in present study a uniform yield increase of 10% was considered for all the crops under irrigated conditions.

6.3 Results and Discussion

6.3.1 Sustainability of blue WF

In both the basins, natural runoff availability is higher during July to October due to high precipitation in these months (Fig. 6.1 and Fig. 6.2). This period receives monsoon rains and crops meet significant portion of their water requirement from rainfall (green WF). Blue WF is high from January to March and October to November than the other months because this is the period of scanty rainfall and crop water requirements are met through irrigation. Comparison of monthly blue WF with monthly blue water availability (Fig. 6.1) in Gomti basin showed that the blue WF is less than the blue water availability there is no concern about sustainability of blue WFs except for the month of January.

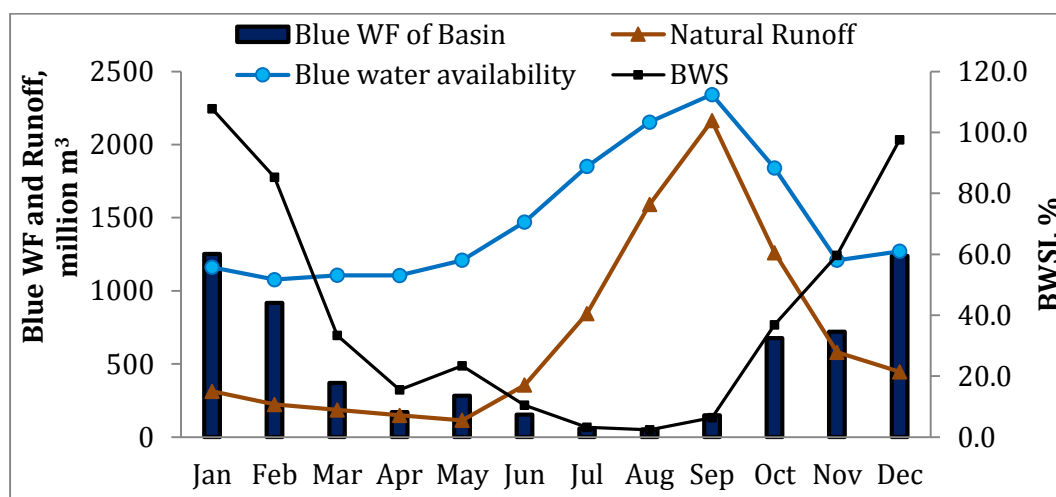


Fig. 6.1 Comparison of monthly blue WF and blue water availability in Gomti basin

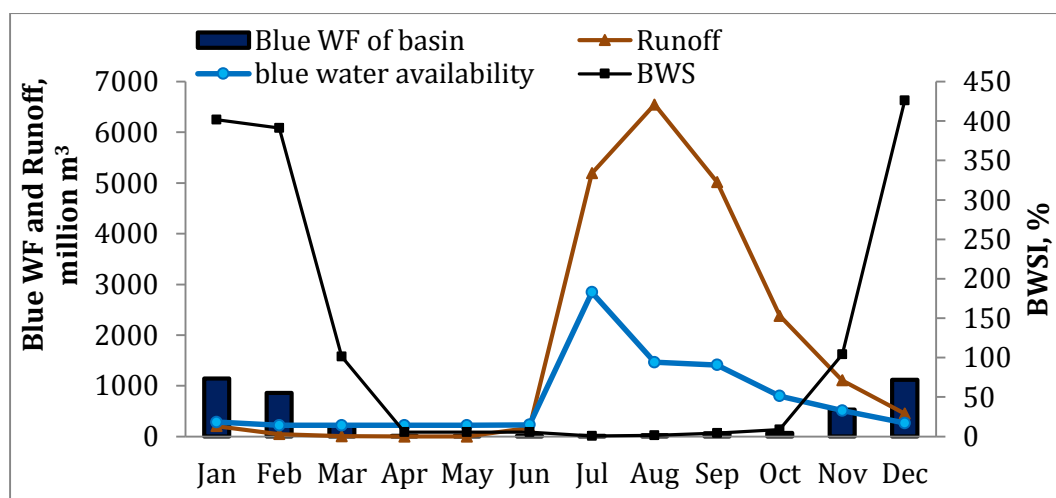


Fig 6.2 Comparison of monthly blue WF and blue water availability in Betwa basin

At a river basin level, blue water scarcity (BWSI) is defined as the ratio of the blue WF to the blue water availability during a certain period. Hoekstra *et al.* (2012) classified BWSI into four levels: low BWSI (<100 %), moderate BWSI (100–150 %), significant BWSI (150–200 %) and severe BWSI (>200 %). According to this classification, only January was in the category of ‘moderate’ water scarcity with BWSI of 107.8 %.

In Betwa basin, the blue WF exceeded blue water availability during January to March, November and December (Fig 6.2). Three months (January, February and December) were characterised with severe BWSI (391 – 426 %) and March (101 %) and November (104 %) were in ‘moderate’ class of BWSI. This shows that runoff in Betwa basin was significantly modified by human activities and blue WF was partly met at a cost of environment flow requirements.

6.3.2 Sustainability of grey WF

Both *kharif* and *rabi* seasons showed grey WF within Gomti basin, while in Betwa it was high during *rabi* season (December, January, February) (Fig 6.3 and Fig 6.4). During March to May, cultivation of crops on smaller areas and application of lesser quantities of fertilizers resulted in low grey WF during these months. Annual grey WF of Gomti and Betwa basin was 1164.5 million m³ and 1008.7 million m³ respectively.

In Gomti basin, throughout the year, assimilation capacity is not fully utilized which indicates that grey WF is sustainable (Fig 6.3). WPI was found to be high in January, February and December (30 to 60 %). In Betwa basin, cultivation of wheat crop with high fertilizer application has resulted in high grey WF in *rabi* season. Non availability of utilizable runoff water resulted in high WPI of 168 and 737 % during January and February months, respectively (Fig.6.4). This shows that during two months, ambient water quality standards are grossly violated.

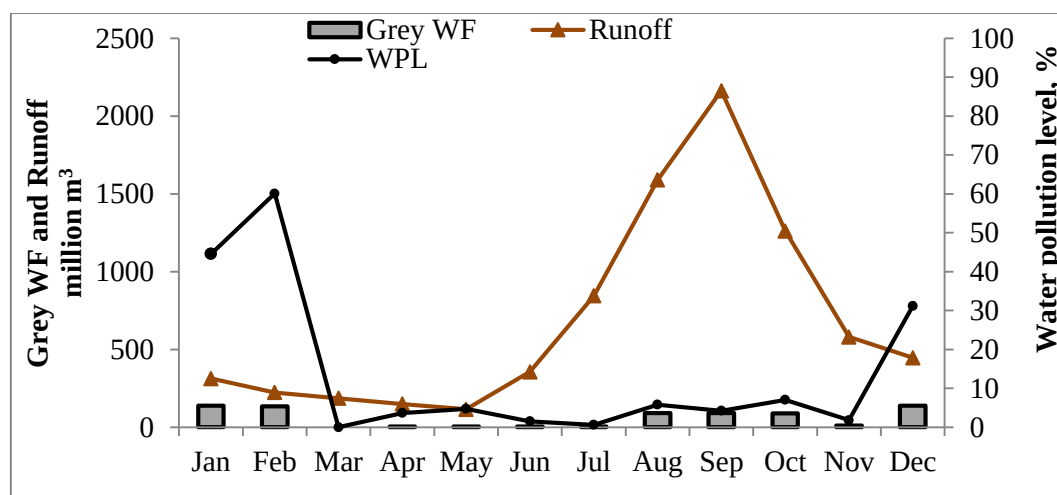


Fig.6.3 Comparison of monthly grey WF and natural runoff for Gomti basin

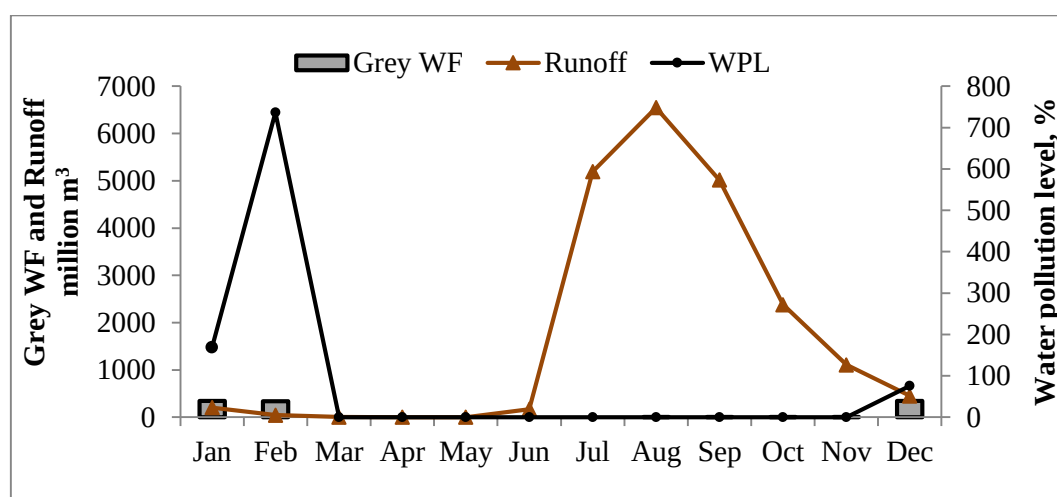


Fig. 6.4 Comparison of monthly grey WF and natural runoff for Betwa basin

6.3.3 Impact of management alternatives on WF of Gomti basin

6.3.3.1 Prevailing cropping pattern

Share of *kharif* and *rabi* crops in gross cropped area of different SRUs is shown in Fig. 6.5a. In all the SRUs wheat and paddy are the two major crops cultivated under irrigated condition during *rabi* and *kharif* seasons respectively. Sugarcane has major share in irrigated and rainfed area of SRU1 and SRU4. Among other crops, maize in *kharif* and chickpea and lentil in *rabi* season are the crops that are cultivated on larger proportions under rainfed conditions.

At basin level, the existing production pattern clearly revealed that paddy in *kharif* season and wheat in *rabi* season have the largest cultivated area covering about 81.8% and 81.1% of the gross cropped area of the basin in respective seasons. This is

followed by sugarcane (0.16 Mha) (Fig.6.6a). Other *rabi* crops like mustard, potato and peas are also cultivated under irrigated conditions and their share is about 7.38 % of total GCA in *rabi* season. Under rainfed conditions, other than maize and black gram, all other *kharif* crops have almost equal share in GCA during *kharif* season. Along with sugarcane, which is an annual crop, lentil and chickpea are other important rainfed crops cultivated in *rabi* season. About 77.5 % of the rainfed area during *rabi* season is occupied by sugarcane, chickpea and lentil. Other pulses and oilseeds were being cultivated on very small rainfed areas.

6.3.3.2 Optimal cropping pattern to minimize blue WF in irrigated area.

The optimal cropping pattern for Gomti basin was determined using the crop and land allocation model and is presented in Fig 6.5b and in Appendix XXVI. Compared to existing cropping pattern, irrigated area under wheat was decreased in SRU1 and SRU3 while that under SRU2 and SRU4 increased. Cultivated area under irrigated paddy in SRU1 and SRU3 was reallocated to SRU2 and SRU4. Since SRU1 had lowest blue water use for sugarcane, almost the sugarcane area was allocated to irrigated and rainfed area of SRU1. There was considerable increase in rainfed Black gram in SRU3. It is interesting to know that the irrigated area under SRU4 and rainfed area under SRU3 have received only two crops as their principal cropping pattern. In general, the crop diversity in each SRU is reduced and the larger areas of suitable crops are allocated to best suiting SRU.

At basin level, major shift in the irrigated and rainfed area of maize and paddy was observed (Fig 6.6b). Under optimal plan, area under paddy and sugarcane decreased and the remaining was allocated to maize, groundnut and sesame. In order to reduce the blue WF, about 2.36 % of the irrigated area of the basin in *kharif* season was not allocated to any crop. Considerable portion (49.0%) of the rainfed area in *kharif* season was allocated to paddy with complete omission of groundnut, maize and sesame. As compared to existing cropping pattern, there was only slight modification in cropped areas in irrigated agriculture in *rabi* season. Since, rainfed areas under the *rabi* season crops was restricted to prevailing rainfed area within the basin, in optimal solution the total basin level rainfed area under *rabi* crops remained unaltered. Although, cultivated areas of most crops remained unaltered at basin level, there were changes in crop allocation patterns at SRU level.

6.3.3.3 Optimal Cropping pattern to minimize green WF in rainfed areas

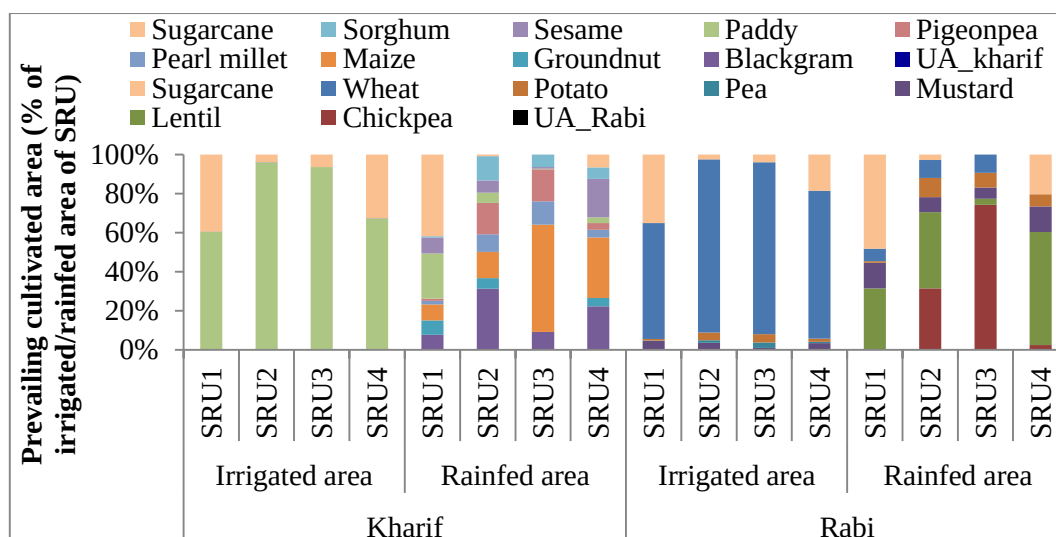
This scenario contributed to understand the structure of WF under drought like situation where production of only most important food crops was considered. Here production was limited on lower side by the consumption needs of the people of the basin and aim was to reduce the areas under rainfed conditions. In optimal pattern under this scenario, production of wheat was restricted only to irrigated areas (Fig 6.5c and Appendix XXVI). To meet the consumption needs, area under both rainfed as well as irrigated paddy was increased considerably in all the SRUs, except SRU4. Chickpea and potato may be cultivated under irrigated conditions in SRU2.

In prevailing cropping pattern, production of wheat was more than the consumption needs while that for paddy, it was less than the consumption. Therefore, total area under paddy increased from 0.74 Mha to 1.01 Mha under optimal plan and that for wheat reduced from 1.13 Mha under existing cropping pattern to 0.84Mha under optimal plan (Fig 6.6c). Since production of only important crops was considered in this scenario, considerable portion of rainfed area during *kharif*, irrigated area during *rabi* and entire rainfed area during the *rabi* season remained unallocated.

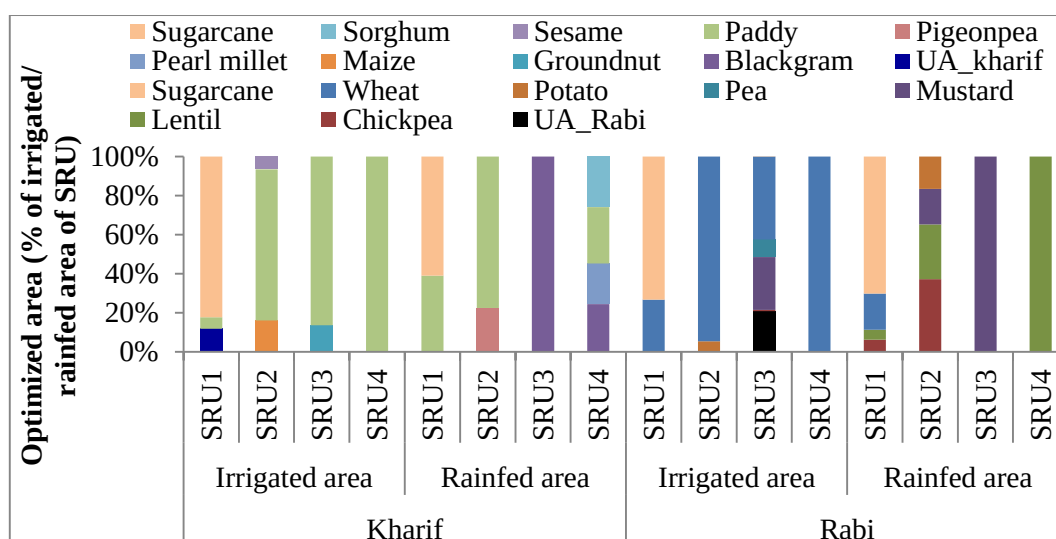
6.3.3.4 Blue water saving and economic water productivity in Gomti basin

The WF of agriculture in Gomti river basin is about 9294.6 million m³ out of which 63.5% is blue (Table 6.4). The crop production in Gomti basin produces net returns of about Rs. 208.2 crore leading to annual net economic productivity of blue water as 3.27 Rs/m³. In scenario I the target was to allocate crops, available land and water resources in such a manner to achieve minimum blue WF. Optimization of cropping pattern to reduce the blue WF of the basin resulted in saving of 196.01 million m³ of blue water with slight increase in net EWP of blue water (3.30 Rs/m³).

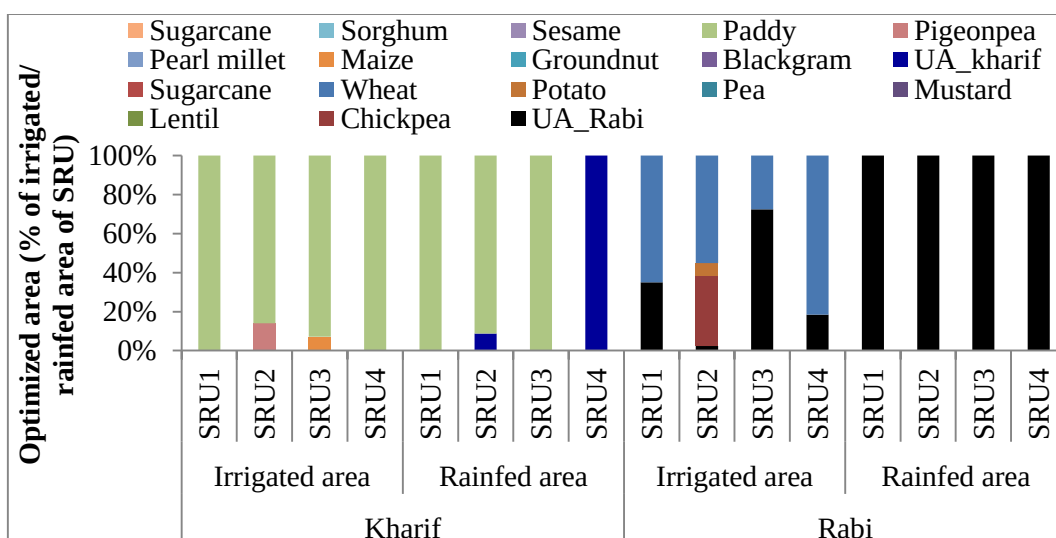
Under Scenario II, green WF of rainfed agriculture was reduced by 314.8 million m³ (Table 6.4) while the net annual returns reduced by about Rs. 74.6 crore, however the consumption need of the important crops were met. Optimization results showed that to meet the crop consumption needs of the basin under limited rainfall condition, the blue WF will be of the order of 4390.8 million m³. This scenario resulted in lowest EWP of blue WF of the basin.



(a) Prevailing cropping pattern



(b) Optimal cropping pattern to reduce blue WF



(c) Optimal cropping pattern to reduce Green WF

Fig. 6.5 Prevailing and optimal cropping patterns in different SRUs during *kharif* and *rabi* seasons under irrigated and rainfed conditions in Gomti river basin (UA_Rabi- Unallocated area in *rabi* season, UA_Kharif: Unallocated area in *kharif* season)

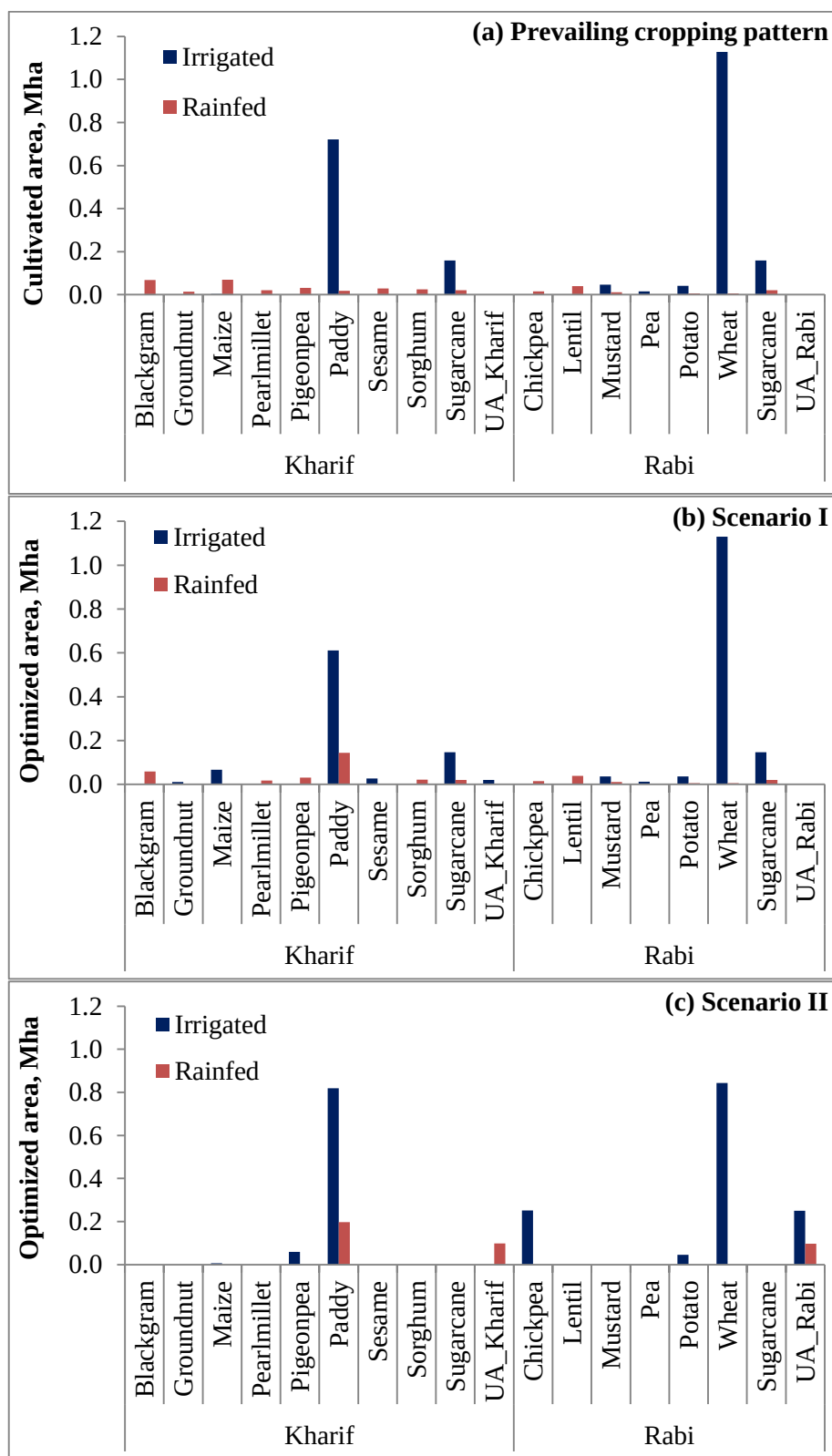


Fig. 6.6 Prevailing and optimal cropping patterns under different scenarios for Gomti basin
(UA_Rabi- Unallocated area in rabi season, UA_Kharif: Unallocated area in kharif season)

Table 6.4 Comparison of net returns and blue water savings under different scenarios for Gomti river basin

Particulars	Prevailing situation		Scenario I		Scenario II	
	Irrigated area	Rainfed area	Irrigated area	Rainfed area	Irrigated area	Rainfed area
Gross cropped area, Mha	2.11	0.37	2.08	0.37	2.02	0.20
Blue water footprint, million m ³	5908.2	0.0	5712.2	0.0	4390.8	0.0
Green water footprint, million m ³	4205.9	1363.7	4041.6	1310.7.8	3809.4	1445.4
Net Returns, Crore, Rs	193.5	14.7	188.6	18.2	126.7	6.9
Total Annual Returns, Crore, Rs		208.2		206.8		133.6
Annual net EWP of blue water, Rs/m ³		3.27		3.30		2.88
Net gain/loss, Crore Rs		--		-1.40		-74.62
Annual savings in Blue water, million m ³		--		196.01		1517.35
Annual savings in Green water, million m ³		--		217.16		314.8

†negative sign indicates loss in net returns; * Scenario I – Minimize blue WF, Scenario II– Minimize WF in rainfed area

6.3.4 Prevailing and optimal cropping patterns for Betwa river basin

6.3.4.1 Prevailing cropping pattern

In Betwa basin, wheat is the major irrigated crop and shares considerable cultivated area in all the SRUs (55.4 to 63.8 %) (Fig 6.7a). This is followed by chickpea which is cultivated under irrigated and rainfed conditions. Other crops like lentil, sesame, soybean and black gram were cultivated mainly as rainfed crops with soybean having largest rainfed area in SRU3.

Betwa basin has a small under irrigation (0.032 Mha) during *kharif* season (Fig 6.8a). Major portion of irrigated area during *kharif* was occupied by soybean (67.5 %) and

groundnut (28.8 %). About 67.4 % of the rainfed *kharif* area was under soybean and black gram. Wheat, chickpea and peas are the main crops under irrigated agriculture covering almost 99.5 % area, while wheat, chickpea and lentil constitute about 95.6 % of the total rainfed area during *rabi*.

6.3.4.2 Optimal cropping pattern to minimize blue WF in irrigated area

The model was run to obtain the optimal cropping pattern for selected crops. To minimize the blue WF, model allocated maximum area under irrigated wheat to SRU1 and SRU4 with simultaneous reduction in SRU2 and SRU3 (Fig 6.7b and in Appendix XXVII). Under rainfed conditions, sorghum and groundnut were allocated to SRU2 and SRU4 respectively. Area under rainfed lentil increased in SRU1 and SRU2 sharing about 36.4 and 45.2 % of total GCA of respective SRUs. In general, diversity of crops in all the SRUs reduced.

In Betwa basin, out of 0.032 Mha irrigated area in *kharif*, about 0.02 Mha was not allocated to any crop (Fig 6.8b). Remaining irrigated area was allocated to black gram. Under prevailing cropping pattern irrigated area was mainly under soybean and groundnut. Replacement of these crops from irrigated area shows that their yields and blue WF under irrigated conditions are matching well with that under rainfed conditions. The area under rainfed soybean, maize, pigeon pea, sesame, sorghum and black gram reduced, while that under groundnut and paddy increased. Irrigated as well as rainfed area under *rabi* crops did not change much with the exception of peas. Irrigated area under peas reduced from 13.6 to 10.5 % of GCA. In *rabi* season, about 3.5 % area irrigated and rainfed area remained unallocated.

6.3.4.3 Optimal cropping pattern to minimize green WF in rainfed areas

Under this scenario, crop production targets were set at consumption needs of the peoples within the basins. By setting these production constraints optimal solution was not found. Analysis of final simplex matrix revealed that land resources of the basin are not sufficient to meet the consumption needs of all the crops considered under this scenario. The data showed that paddy has very low productivity throughout the basin and hence requires huge areas to be brought under cultivation to meet its consumption needs. Therefore the production constraints of paddy in this scenario were modified. After several runs, the optimal solution was obtained by setting the paddy production

at 0.418 million ton while the original constraint on paddy consumption requirement was 0.708 million ton.

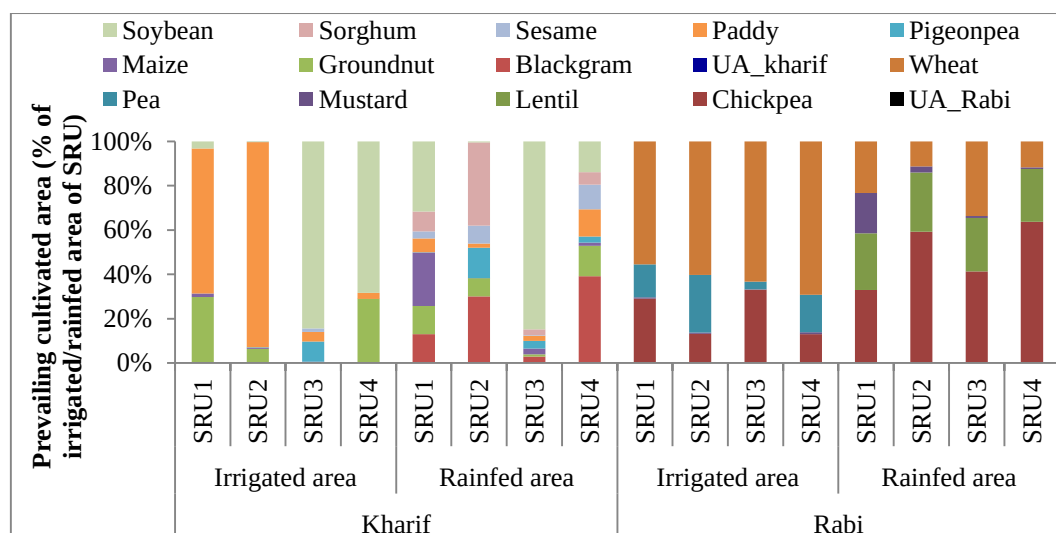
To meet the minimum consumption needs under drought like situation, paddy, wheat, pigeon pea and chickpea were identified as important crops in Betwa basin. The optimal cropping pattern showed that entire irrigated area of SRU1, SRU2 and SRU3 was allocated to wheat (Fig 6.7c and Appendix XXVII). Irrigated area under paddy, chickpea and wheat were allocated to SRU4. Paddy area was allocated to all the SRUs under rainfed conditions. In order to reduce the rainfed area, on an average about 50% of the irrigated and rainfed area under SRU4 and entire rainfed area under SRU1, SRU2 and SRU3 was not allocated to any crop.

At basin level entire irrigated area and about 91.8% of the rainfed area of the basin during *kharif* was allocated to paddy (Fig 6.8c). About 5.3 and 2.9 % of the irrigated area during *kharif* was allocated to pigeon pea and maize respectively. The irrigated area in *rabi* was mainly allocated to wheat, chickpea while some area remained unallocated. Since the requirement of was met from the irrigated area, no crop was allocated to rainfed area during *rabi* season.

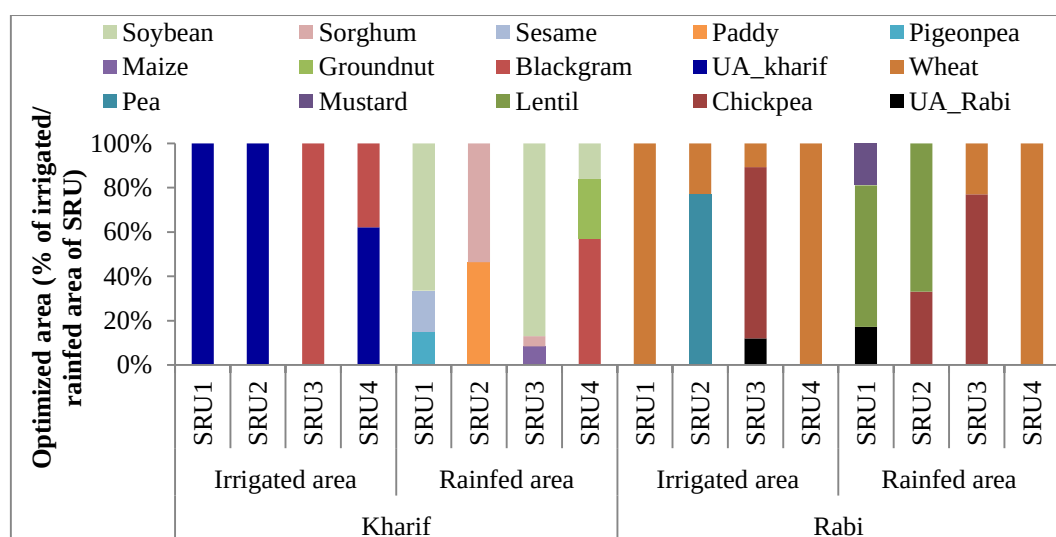
6.3.4.4 Blue water saving and economic water productivity in Betwa basin

Blue water saving and net EWP of blue water under two scenarios of cropping patterns in Betwa basin is presented in Table 6.5. Under existing cropping pattern the total WF of agriculture sector was 8109.6 million m³ and share of blue WF in WF of crop was about 50.4 %. The existing cropping pattern resulted in net returns of about Rs 159.4 crore leading to net EWP of blue water as 2.25 Rs/m³. In general, returns from irrigated agriculture were more than that obtained under rainfed conditions.

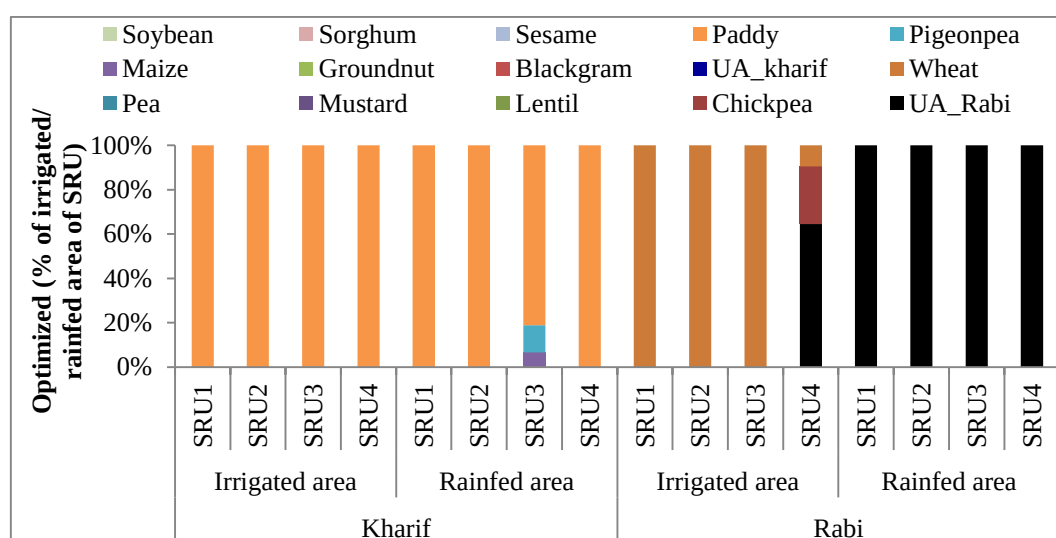
Optimal cropping pattern to reduce the blue WF resulted in savings of 7652.0 million m³ in total WF and saving of 278.9 million m³ in blue WF. The net EWP of blue water also increased to 2.90 Rs/m³. Under Scenario II, since the allocation was restricted to only few important crops, net returns from the basin reduce by Rs 32.73 crore. This scenario exhibited lowest EWP of blue water (2.02 Rs/m³) (Table 6.5).



(a) Prevailing cropping pattern



(b) Optimal cropping pattern to reduce blue WF



(c) Optimal cropping pattern to reduce green WF

Fig. 6.7 Prevailing and optimal cropping patterns in different SRUs during *kharif* and *rabi* seasons under irrigated and rainfed conditions in Betwa river basin (UA_Rabi- Unallocated area in *rabi* season, UA_Kharif: Unallocated area in *kharif* season)

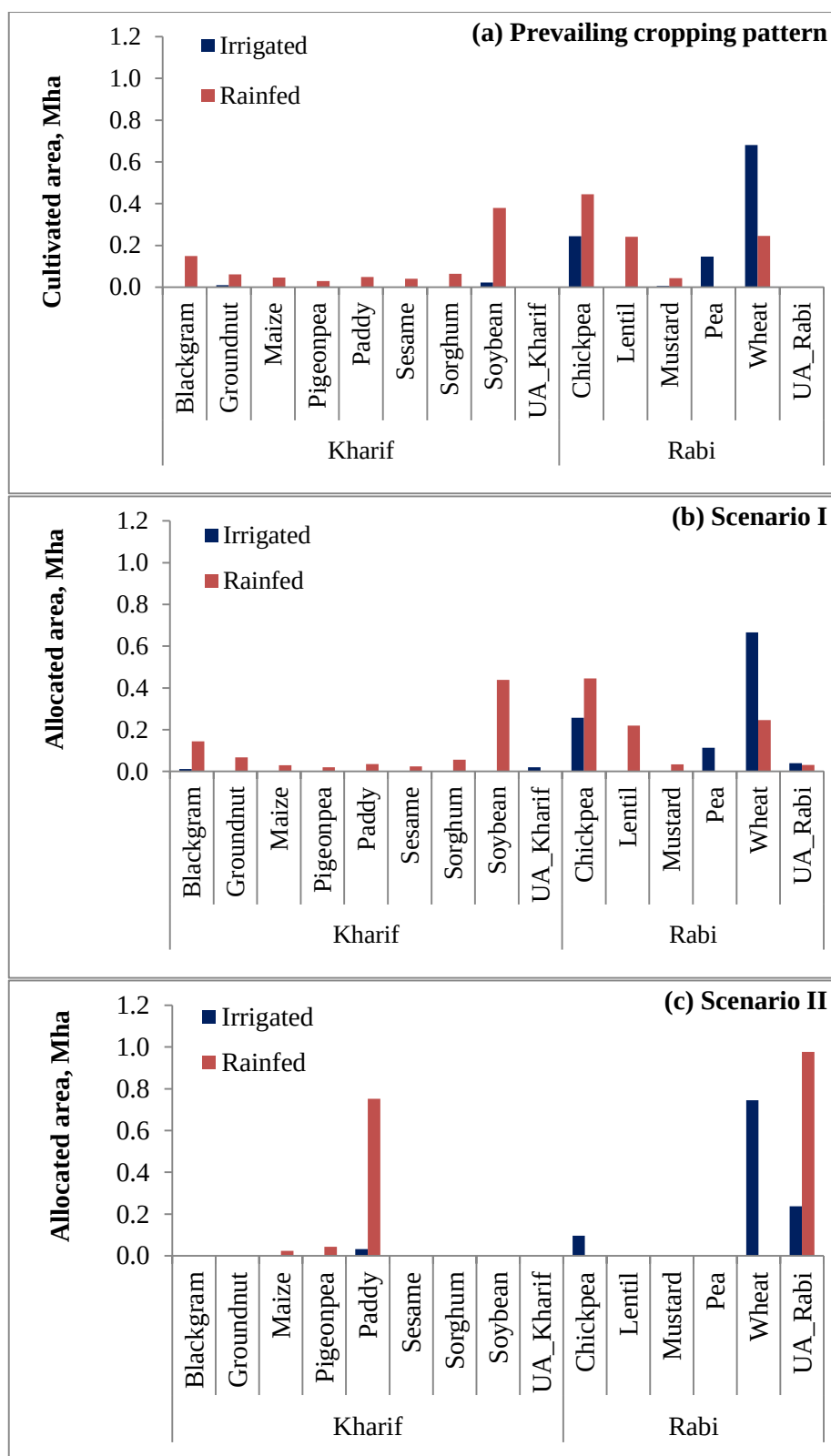


Fig. 6.8 Prevailing and optimal cropping patterns under different scenarios for Betwa basin

(UA_Rabi- Unallocated area in rabi season, UA_Kharif: Unallocated area in kharif season)

Table 6.5 Comparison of net returns and blue water savings under different scenarios for Betwa river basin

Particulars	Prevailing situation		Scenario I		Scenario II	
	Irrigated area	Rainfed area	Irrigated area	Rainfed area	Irrigated area	Rainfed area
Gross cropped area, Mha	1.11	1.79	1.05	1.76	0.87	0.82
Blue water footprint, million m ³	4025.7	0.0	3812.2	0.0	3386.0	0.0
Green water footprint, million m ³	133.2	3868.4	85.7	3754.1	128.2	2803.3
Net Returns, Crore Rs	91.9	67.5	110.7	66.6	68.2	58.5
Total Annual Returns, Crore Rs	159.4		177.2		126.7	
Annual net EWP of blue water, Rs/m ³	2.28		2.90		2.02	
Net gain/loss [†] , Crore Rs	--		17.82		-32.73	
Annual savings in Blue water, million m ³	--		213.56		639.74	
Annual savings in Green water, million m ³	--		114.36		1065.19	

[†]negative sign indicates loss in net returns; *Scenario I – Minimize blue WF, Scenario II– Minimize WF in rainfed area

The optimal cropping patterns suggested in this study were obtained with water as a commodity of prime importance. Although the suggested cropping patterns showed great promise for reducing the WFs, this needs to be seen in view of social and technical aspects. The issues like capital and labour availability should be taken in to account while formulating such management plans. Present agricultural policies have given freedom to the farmers to select the crops of their choice; therefore, willingness of the farmers to deviate from the crops of their choice is an important issue. Reallocation of crops involves certain other technical and economic issues as well. For example, if a sugarcane crop is allocated to particular SRU, this will involve huge cost on transport of sugarcane from place of production to the places where sugar mills are located or may require relocation of mills too. Another important issue that needs attention is equity. Farmers in the SRUs where most remunerative crops are allocated will get more

benefits than in the SRUs where returns on allocated crops are less. This will lead to imbalance in social equity and the concept of benefit sharing may need to be exercised.

6.3.5 Impact of water management alternatives on WF in Gomti basin

The impact of improved irrigation method and land levelling on WF of various crops in Gomti basin are shown in Fig. 6.9. It can be observed that WF of wheat, sugarcane, mustard, potato and pea reduced from 3565 to 2191 million m^3 , 1276 to 476 million m^3 , 1584 to 1484 million m^3 , 226 to 123 million m^3 and 185 to 137 million m^3 respectively, if prevailing levels of crop yields are increased to the level of maximum achievable crop yields under drip and sprinkler irrigation with best management practices. Due to standing water needs, adoption of drip or sprinkler method was not considered in case of paddy. If all the irrigated lands in the basin are properly levelled using laser levellers, the WF of paddy wheat, sugarcane, mustard, potato and peas will be 6016, 3222, 1173, 1570, 210 and 176 million m^3 , respectively. This shows that increasing crop yields through laser levelling and adoption of efficient methods of water application has great potential to reduce the WF of consumption within the basin.

Impact of management practices on blue VW flows and blue WF in Gomti basin are presented in Fig. 6.10. If productivity levels of crops are reached to maximum achievable levels under drip and sprinkler systems, the blue WF of basin will reduce from 7238 to 5183 million m^3 . Levelling of irrigated land will reduce the WF to 6528 million m^3 . This indicates that adoption of improved irrigation practice has higher potential to reduce WF than land levelling. Due to increase in the crop productivities the basin level production of crops was increased. Since consumption of crops is constant, the quantity of extra produce obtained by the adoption of management practices needs to be exported, consequently VW export will increase. In present analysis the VW export increased from 1172 to 2792 million m^3 under the scenario of pressurised irrigation with maximum achievable crop yields. Since, VW imports mainly come from the crops which have very smaller cultivation areas within the basin, the VW imports were reduced marginally. Improvement in yields of crops cultivated on comparatively smaller areas adds very little to total WF of the basin.

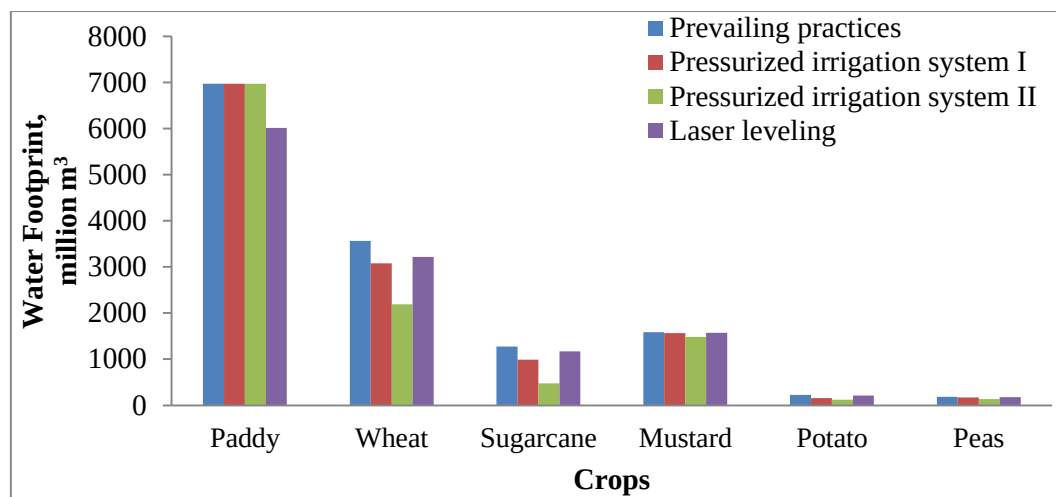


Fig 6.9 Effect of efficient water application method and laser levelling on WF of crops in Gomti Basin

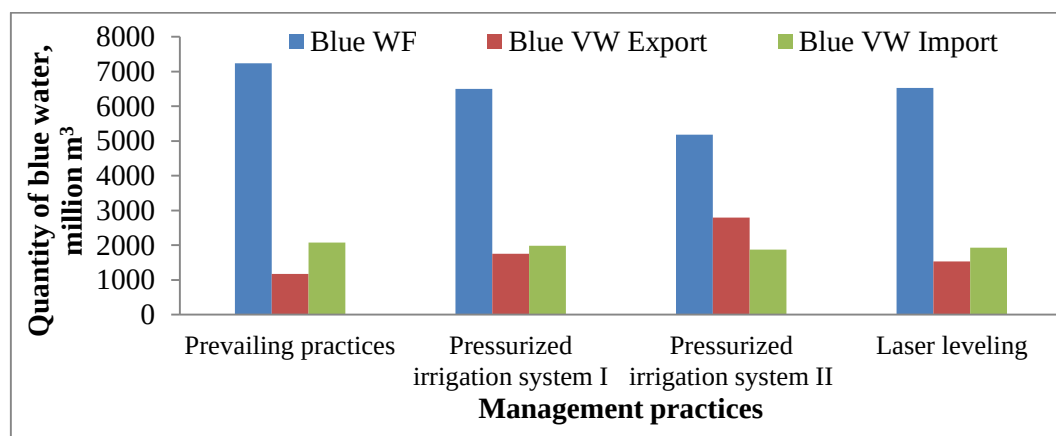


Fig 6.10 Effect of efficient water application method and laser levelling on WF and virtual water flows in Gomti Basin

6.3.6 Impact of water management alternatives on WF in Betwa basin

Changes in WF of crops in Betwa basin under proposed management interventions are shown in Fig. 6.11. Considerable portion of irrigated area in Betwa basin is under wheat, chickpea and pea. Increasing the crop yields to maximum achievable yields with the help of PIS, the WF of wheat, chickpea and pea will reduce from 3549 to 1673 million m^3 , 328 to 208 million m^3 and 274 to 58 million m^3 respectively. The scenario which considered increase in crop yields above present values resulted in crop WFs lesser than that achieved under PIS with maximum achievable yields. Improvement in yields achieved through land levelling reduced the WF of paddy marginally because Betwa basin has very small irrigated area under irrigated paddy, and under prevailing situation the WF of paddy consumption is mainly

through VW imports. Crops having larger irrigated areas showed great potential to reduce their WF though pressurised irrigation as well as through land levelling.

As in case of Gomti, the virtual water import in Betwa basin also did not decrease significantly with improved management practices (Fig 6.12). In Betwa basin also the major portion of VW import is from the crops either cultivated in smaller areas or not cultivated at all. Improving the yields of the exported crops resulted in increased VW exports from the basin. Implementation of drip and sprinkler irrigation methods with better management practices would result in reduction of WF of the basin from 5024 to 2762 million m³. Land levelling practice would reduce the WF of the basin from 5024 to 4748 million m³.

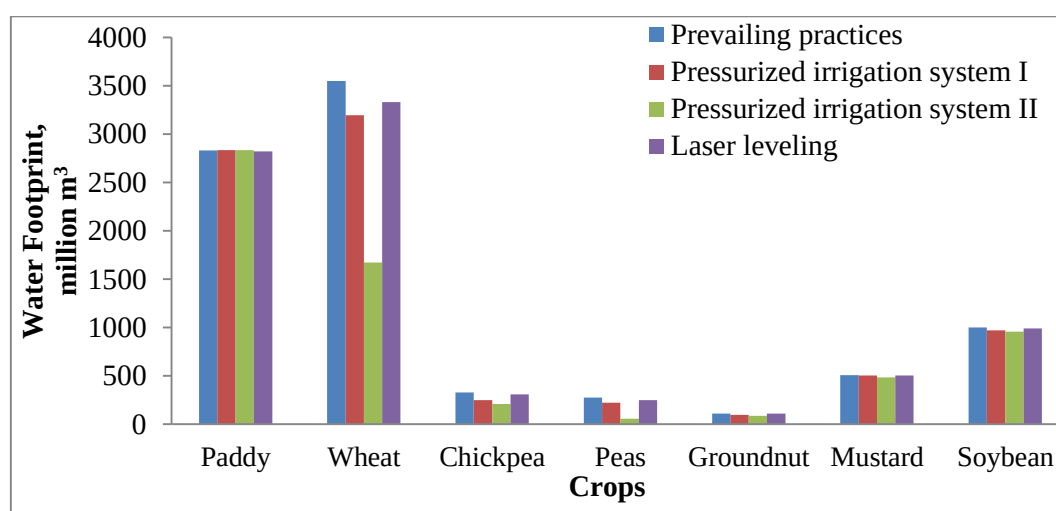


Fig 6.11 Effect of efficient water application method and laser levelling on WF of crops in Betwa basin

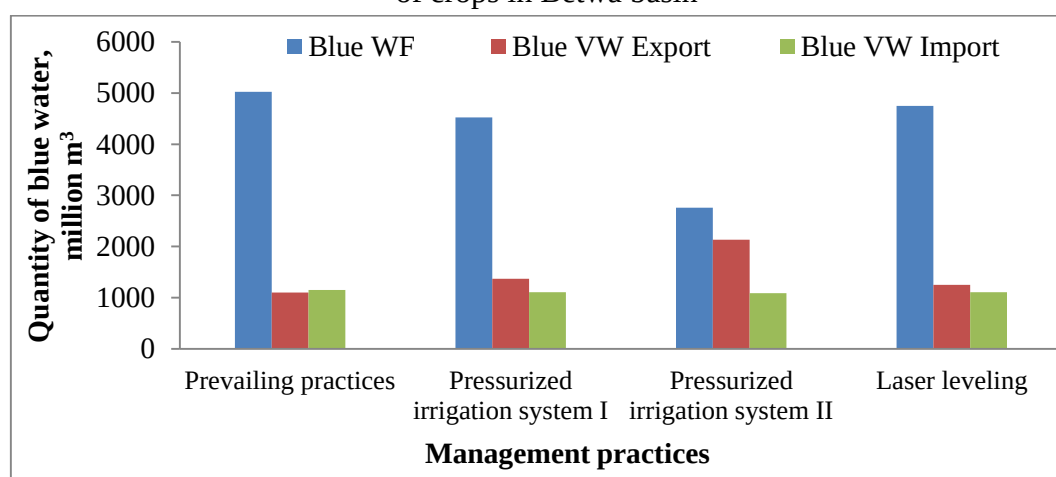


Fig 6.12 Effect of efficient water application method and laser levelling on WF and virtual water flows in Betwa basin

6.4 Conclusions

In this study sustainability of blue and grey WF in Gomti and Betwa basins was assessed at monthly time step and suitable management strategies were evaluated for their impact on blue and green WFs. The major conclusion drawn from the study were,

- Sustainability analysis revealed that the prevailing water consumption pattern in Gomti basin is sustainable.
- The state of the water consumption in Betwa basin clearly revealed the need for reduction of current blue and grey water footprints to reduce the pressure on the environment and to improve water quality.
- Relocation of cultivated areas of crops from regions of high WF to the regions with low WF is a better management strategy to reduce the water footprint at river basin scale. Reduction in WF and better management solutions can be obtained using optimal cropping patterns to suit the varying climatic situations.
- In all the management scenarios green WF had considerable share in total WF of the basin. Therefore, improving green water management and green water use efficiency is important for reliving the pressure on blue water resource and to ensure the food security.
- Replacing flood irrigation by drip or sprinkler irrigation systems and laser levelling of irrigated lands will reduce the WF of crop production in the basins and showed great potential to reduce the net virtual water imports to the basins. This will reduce the dependence of the basins on water resources of other regions.

GENERAL DISCUSSION

Increasing water scarcity in Indian River basins is a major concern which would not only affect different water consuming sectors but also the economic growth of our Country. While the total water resource availability remains constant, water demand has increased considerably due to population growth, increasing urbanization, changing lifestyles and economic growth. In order to meet the food requirements of ever growing population and increasing demand from domestic and industrial sectors, the basin level alternative water management options needs to be explored. Water footprint (WF) is a comprehensive and well established indicator that contributes to a better management of water resources. A whole range of studies have addressed the utility of the WF concept at different geographical settings. Moreover, the concept of WF is especially meaningful in river basins as it represents the scale where water resources are physically connected.

Indian government has proposed a project on interlinking of rivers to transfer water from water surplus basins to water deficit basins. One of the alternatives can be to transfer water from the basins in virtual form. In this context, Verma *et al.* (2009) found that the quantum of inter-state virtual water trade is comparable to the proposed inter-basin water transfers. They suggested that virtual water trade analysis at basin scale with data on actual trade and better estimates of water resources in the donor and recipient basins will be useful in understanding the virtual and physical transfer of water across river basins, and their possible trade-offs. Also, assessing WF at a river basin level is an important step to understand how anthropogenic activities' influence natural water cycles, and serves as a basis for integrated water resources management and sustainable use of water resources (Zeng *et al.*, 2012). Keeping this in view, the virtual water flows and WF of two important river basins viz. Gomti and Betwa, were analysed in this study. Gomti basin is important from irrigated agricultural perspective, whereas Betwa basin is a water scarce basin having dominance of the rainfed agriculture.

Water footprint analysis is a data intensive process. Since the availability of data to undertake WF analysis in India does not comply with basin boundaries, a

comprehensive WF assessment methodology is required that can be applicable in Indian context. At river basin or regional scales, water footprints of the agricultural sector have been studied extensively, focusing on the water footprint of crop production only (Aldaya and Llamas, 2008; Zeng *et al.*, 2012; Sun *et al.*, 2013). However, this study extends it further up to sustainability assessment and response formulation phases of WF analysis.

Research area I: Development of methodology for water footprint assessment at basin scale

The accuracy of crop water footprint assessments depends on the resolution of ET_c estimation and WF assessment. Previous studies (JingLei *et al.*, 2013; Heinemann *et al.*, 2002) suggested that ET_c varies in space even within a smaller region. In previous studies the resolution improvements were visible only at global scales. Different grid based soil moisture balance models have been used to estimate the crop water requirements and crop WF at the resolution of 5x5 arc-minutes (Siebert and Doll, 2010; Mekonnen and Hoekstra, 2010), 30 x 30 arc-minutes (Fader *et al.*, 2011; Rost *et al.*, 2008) and 1 x 1 degree (Hanasaki *et al.*, 2010) spatial resolutions. At basin scale no definitive attempts have been made to decide upon the appropriate resolution of WF assessment.

Therefore, the basic methodological modifications proposed in this study were on defining optimum spatial resolution for WF assessment at basin scale. The concept of agricultural production units (APU) is proposed for defining appropriate spatial resolution for estimation of crop evapotranspiration. An APU was defined as a homogeneous unit in terms of soil and climate. Further, a combined approach employing a multivariate geostatistics and non-parametric clustering protocols was applied to APUs for estimation of ET_c and delineation of appropriate spatial resolution units. In present study, the Gomti and Betwa basins were segregated into 21 and 27 APUs respectively. The evapotranspiration (ET_c) of selected crops was estimated at each APU using FAO CROPWAT model. Using the proposed methodology for defining spatial resolution, four distinct spatial resolution units were identified in each basin.

In a recent study, the spatial resolution for ET_c estimation was based on arbitrary division of basin into upper, middle and lower regions based on water resources, economic structure, and household incomes and consumption patterns (Feng *et al.*, 2012). In another study, ET_c estimates at provincial level were assumed to be applicable at basin level (Aldaya and Llamas, 2008). However, in present study, concept of APUs for defining the spatial resolution can be considered as an improvement over other approaches. APU's retain original administrative structure while delineating the homogeneous units.

It was observed that WF assessment studies at river basin level are limited in the literature, which may be largely due to the lack of data availability. In many WF studies at river basin scale, authors were either silent or provided limited details on how administrative level data was downscaled or up scaled to basin level (Dumont *et al.*, 2013) or just superimposed the watershed over the administrative boundaries at the county level (Feng *et al.*, 2012). Since, majority of data are not available at a river basin level, (Zeng *et al.*, 2012) the data for administrative boundaries (*i.e.* a county or a city) are either downscaled or up scaled to obtain the information at the river basin level, which would result in a crude approximation of data at basin level. In present study, proportionality factor based approach was proposed to disaggregate administrative level datasets to a desired spatial resolution within the river basin. Proportionality factors were derived using the district level statistics on cropped areas, irrigated areas and humans and animal population. The proposed methodology is a step towards improving accuracy in WF assessments and is flexible enough to be extended to other river basins in India.

Research area II: Assessment of virtual water content of crops and water footprint

The basin level average VWC of crops estimated in this study slightly differ from the state level average values estimated by Kampman (2008). The difference may be due to the difference in the crop productivity and site specific ET_c estimates. Kampman (2008) used the state level average crop productivity values while in present study district specific values were used. The climatic condition is one important reason for the higher VWC values in the selected river basins.

The WF analysis revealed that the WF of Gomti and Betwa was about 12773 and 9186 million m³. Large share of agricultural WF (96.1% and 97.8% for Gomti and Betwa basins, respectively) indicated that agriculture is the dominant water consuming sector within these basins. Many researchers (Savenije, 2000; Liu *et al.*, 2009) have proposed to increase the green WF to relieve the pressure on blue water resource. The farm level practices such as mulching and land levelling can be practiced to make the effective use of rainwater. Domestic and industrial sector contributed about 38.3% and 17.9% to total grey WF within the Gomti and Betwa indicating that the water pollution resulting from these sectors was also responsible for water scarcity problem in these basins.

Virtual water balance estimation showed that about 2110 million m³ water is being exported in virtual form from the Gomti basin. Betwa basin, which is already a water scarce semi-arid basin, also exports about 2905 million m³ of water in virtual form which might add further to water scarcity in the basin. Water scarcity can be reduced if regional trade is taken into account (Feng *et al.*, 2012) and exports of water intensive crops are reduced. Overall, both basins were assessed as net VW importers, *i.e.* more VW is imported than the export, which is an undesirable trait of integrated river basin management.

Blue WF was also analysed from economic perspective. As compared to Betwa, the economic productivity (EWP) of blue water was higher in Gomti basin mainly because of higher productivity of crops in Gomti. The concept of EWP was useful in identifying low value water intensive crops, which was also applied in previous studies (Aldaya and Llamas, 2008). Following the present cropping pattern, considerable part of blue WF comes from low value water intensive crops *viz.* chickpea, mustard and pearl millet. In order to increase the economy of blue water use these crops should be cultivated under rainfed conditions.

Water allocation in canal irrigated areas of India is based on per hectare basis, without due consideration to the type crop being cultivated. Although, farmers are interested in crops having higher profits per hectare, however, from the WF perspective, selecting crops having higher economic productivity of blue water is desirable. It is proposed that cropped areas should be allocated on the basis of crop WFs such that the total WF of the basin is reduced.

Higher leaching of nitrates adds to grey WF. In view of significant grey WF within the basins, use of modern irrigation systems and fertigation technologies needs to be promoted. Also there is need to educate farmers on judicious fertilizer management pertaining to fertilizer doses and split applications for different crops.

Research area III: Sustainability assessment and optimal cropping patterns to reduce crop water footprints

Sustainability of blue and grey WFs of Gomti and Betwa basins was assessed at monthly time step. It was observed that human consumption of freshwater has raised the concern over sustainability of WFs due to violation of rule related to environmental flows and/or deteriorating water quality. Throughout the year, water pollution level (WPL) in Gomti basin was within acceptable limits, where as in Betwa, it was very high (>350%) during January and February indicating unsustainability of grey WF. Zeng *et al.* (2012) observed that blue WF was 31% of the total surface runoff indicating that runoff in the Heihe river basin was significantly modified by anthropogenic activities, exceeding the sustainability level. In Betwa basin, surface runoff was not sufficient to meet even the environmental flow requirements for the period from January to June. This type of situation leads to unsustainable water use, causing severe ecological degradation in terms of drying-up of rivers and death of riparian vegetation (Kang *et al.*, 2007).

As a strategy to reduce the blue WF of basins, optimal cropping patterns were developed. Two scenarios a) minimization of blue water footprint (Scenario 1) and b) minimization of green water footprint of rainfed areas (Scenario 2) were considered in this study. Major emphasis of the scenario 1 was to reduce the use of blue water resources within the basins by reducing blue WF without affecting the present levels of crop production. Reallocation of cropped areas from high WF to low WF areas resulted in savings of about 196.0 and 213.5 million m³ of blue water in Gomti and Betwa basins, respectively. In optimal plan, for Gomti basin, the area under paddy and sugarcane was decreased and the saved water was allocated to maize, groundnut, black gram and sesame. This type of reallocation showed possible opportunities in reducing water scarcity within basins.

Results revealed that optimal cropping pattern to reduce blue WF decreased the irrigated areas under sugarcane, paddy and mustard in Gomti basin and soybean, pea, wheat and groundnut in Betwa basin without altering the prevailing production. This resulted in reduction of about 196.0 and 213.5 million m³ in blue WF of Gomti and Betwa basins respectively. Optimal cropping pattern for dry year resulted in reduction of about 314.8 and 1065.2 million m³ in green WF of the basins. Results indicated that increasing the crop yields under drip or sprinkler irrigation (as per suitability of crops) up to the achievable level can reduce the WF of wheat, sugarcane and potato in Gomti basin by 38.6, 62.7 and 42.7 % respectively, whereas in Betwa basin it would reduce by 52.9% in wheat, 36.6 %in chickpea and 21.5% in groundnut. Laser levelling of irrigated lands would reduce the WF in Gomti and Betwa basins by 710.0 and 276.4 million m³. In order to ensure sustainability of WF in the basin, farmers should be encouraged to adopt optimal cropping pattern and improved irrigation practices.

SUMMARY AND CONCLUSIONS

The study was undertaken to develop a methodology to assess the water footprint (WF) at river basin scale, assess the water footprints and virtual water flows and to develop and evaluate management strategies to reduce the WF of the Gomti and Betwa river basins. Major focus of the methodology development part was associated with defining appropriate spatial resolution for WF assessment and standardizing protocols to rescale the administrative level datasets to basin scale. Crop evapotranspiration (ET_c) was estimated for normal rainfall year using FAO CROPWAT model. An integrated approach using multivariate geostatistics and non-parametric clustering techniques was used to map the spatial variability of crop evapotranspiration (ET_c) and to delineate the spatial resolution units (SRUs). Data downscaling factors were estimated to obtain the basin level crop related area information required for assessment of agricultural WF. The green and blue virtual water content of crops cultivated within the basins was assessed at high spatial resolution. The study quantified the blue, green and grey WF of crop and livestock production and domestic and industrial uses in the basins. The study further estimates virtual water flows related to trade of agricultural goods. Sustainability of blue and grey WF was assessed at monthly time step using Blue Water Scarcity Index and Water Pollution Index, respectively, for the Gomti and Betwa river basins. A quantitative assessment of response of blue and green water footprints to different management alternatives were proposed for reduction of WF in the basins.

Major conclusions drawn from the study were:

1. Large spatial variation in crop evapotranspiration was observed within the basin and Agro Ecological Sub Regions (AESR), which necessitated WF assessment at SRU level. Therefore, assessment of WF of crop production considering entire basin as one unit might not be realistic. Hence, appropriate spatial resolution for ET_c estimation and WF assessment needs to be defined for each basin.

2. The methodology for estimation of WF suggested in this study considered the spatial variability of crop evapotranspiration within the basin.
3. Application of developed methodology can reduce the data and time requirement in assessment of crop water footprint of a basin. The developed methodology is flexible and can be replicated for other river basins in India.
4. The water footprint of Gomti and Betwa river basins during the year 2011 was about 12773 million m³ and 9186 million m³, respectively. The agricultural sector, (*i.e.* crop production and livestock), accounted for the largest share of freshwater consumption amounting to 96.1% and 97.8% of the total WF within Gomti and Betwa basins, respectively.
5. Production of crops having low economic water productivity can be limited to meet the consumption needs and the saved blue water may be used to cultivate other water efficient crops.
6. Sustainability analysis showed that Gomti basin experienced blue water scarcity in January, while in Betwa, the deficit was for five months (November, December and January to March) indicating that freshwater consumption in these basins is achieved at the cost of environmental flows. Also, water pollution level (WPL) in Gomti basin was within acceptable limits while in Betwa basin it exceeded permissible limits in two months, indicating unsustainability of water use pattern in the Betwa basin.
7. Optimal cropping pattern to reduce blue WF would result in reduction of about 196.0 and 213.5 million m³ in blue WF of Gomti and Betwa basins, respectively. Under this scenario, irrigated areas under sugarcane, paddy and mustard in Gomti basin and soybean, pea, wheat and groundnut in Betwa basin were reduced without altering the prevailing crop production.
8. Optimal cropping pattern for reducing green WF of rainfed areas would reduce the green WF of Gomti and Betwa basins by about 314.8 and 1065.2 million m³, respectively.

9. Results indicated that increasing the crop yields under drip or sprinkler irrigation up to the achievable level can reduce the WF of wheat, sugarcane and potato in Gomti basin by 38.6, 62.7 and 42.7 % and wheat, chickpea and groundnut in Betwa basin by 52.9, 36.6 and 21.5%, respectively.
10. Laser levelling in irrigated lands would reduce the WF in Gomti and Betwa basins by 710.0 and 276.4 million m³, respectively.
11. Laser levelling in irrigated lands and replacing flood irrigation by drip or sprinkler irrigation systems would reduce the WF of crop production in the basins which would result in reduction of net virtual water imports.

SUGGESTIONS FOR FUTURE WORK

A meticulous review of literature revealed that the estimation of water footprint (WF) of Indian River basin was not attempted earlier and hence an effort was made in this study with certain assumptions. The present investigation can be further strengthened by considering the following researchable issues:

- Due to non-availability of basin level import and export data, the study did not provide comprehensive information on internal and external WF. Future studies may be taken up to estimate the internal and external WF.
- Study can also be undertaken to investigate the impact of changing climate scenarios on water footprints at regional scales. Such investigation would provide information on import or export of virtual water under changing climate scenarios besides dry and wet years.
- A study may also be undertaken to assess the sustainability of green water footprint at basin or regional scales.

Crop Water Footprint Assessment for Sustainable Agriculture in Selected Sub-basins of River Ganga

ABSTRACT

Indian river basins are subject to increasing pressure in the form of consumptive water use and pollution. Quantitative assessment of the water footprint is considered as a key in understanding the pressure put on the freshwater resources in water scarce river basins. Blue, green and grey virtual water content (VWC) and water footprint (WF) of crop production and other water user sectors have been recognized as potentially useful concepts in water resource management at river basin scale. This study was undertaken to develop a comprehensive methodology for WF assessment at rivers basin scale with major emphasis on defining spatial resolution for WF assessment and its compliance with the structure of data availability in Indian context. Developed methodology was applied to assess the blue, green and grey virtual water content, water footprints and virtual water flows within the Gomti and Betwa river basins located in semi-arid regions of North and central India. The WF analysis was further extended to assess the sustainability of water footprints and formulate the alternate crop and water management strategies to reduce the water footprints.

Results showed that there is a considerable spatial variation in crop evapotranspiration (ET_c) within the basins indicating that assumption of river basin as a homogeneous unit for WF assessment is not appropriate and WF estimated at the river basin scale will be unrealistic. The appropriate spatial resolution for ET_c and WF assessment needs to be defined for each basin. A robust framework for defining spatial resolution for WF assessment is proposed in this study and can be replicated for other river basins in India. Water footprint analysis revealed that the water footprint of Gomti and Betwa river basins in the year 2011 was about 12773 million m³ and 9186 million m³, respectively. The agricultural sector (crop production and livestock) accounts for the largest share of freshwater consumption accounting for about 96.1% and 97.8% of the WF within Gomti and Betwa basins respectively. Paddy, wheat and sugarcane have the largest water footprints, together accounting for 88.3% of the total water footprint and 94.4 % of blue WF within Gomti basin. In Betwa basin, wheat, soybean and chickpea have the largest water footprints. These crops accounted for 75.3% of the total

water footprint and about 87.73 % of blue WF. In Gomti basin blue and grey WF was about 47.3% and 9.1% of the total WF while in Betwa their contribution was about 43.6% and 10.9% of total WF. Large share of green WF indicates that improving green water management and green water use efficiency is important for reducing the pressure on blue water resource. Share of domestic and industrial sector in grey WF was about 38.3% and 17.9% in WF of Gomti and Betwa basins, respectively. Considerable portion of available blue water is being used for the production crops having low economic blue water productivity. Under prevailing production and consumption pattern, about 2110 million m³ and 2905 million m³ of virtual water is being exported from Gomti and Betwa basins. Export of water may further add to the water scarcity in already water stressed Betwa basin. Despite of huge VW exports, both the basins were assessed as net virtual water importers with VW exports amounting to 5054 million m³ in Gomti basins and 3590 million m³ in Betwa basin. Sustainability analysis revealed that water consumption and pollution in Gomti basin are sustainable while in Betwa basin there is need for reduction of current water footprint to reduce the pressure on the environment and to improve water quality.

Impact of suggested management alternatives on WF of the basins revealed that reallocating cropped areas from areas of high water footprint to low water footprint would result in blue water savings of about 9.26% and 25.12% in Gomti and Betwa basins, respectively. At prevailing cropping pattern, adoption of drip and sprinkler irrigation systems will reduce the WF by about 28.4% and 45.0 % in Gomti and Betwa basins respectively. With the adoption of improved irrigation methods and laser land leveling it would be possible to reduce the WF of crops as well as virtual water imports to the basins and hence the dependence of these basins on water resources of other regions can be minimized.

गंगा नदी के चयनित उप-नदी क्षेत्रों में संपोषणीय कृषि के लिए फसल के पानी पदचिह्न का आँकलन

सार

भारतीय नदी क्षेत्रों पर पानी के बढ़ते उपयोग और प्रदूषण की वजह से दबाव बढ़ता जा रहा है। पानी के पदचिह्न का मात्रात्मक आकलन, कम पानी वाले नदी क्षेत्रों में स्वच्छ पानी की उपलब्धता पर बढ़ते दबाव को समझने में प्रमुख प्रक्रिया के रूप में माना जाने लगा है। नीले, हरे और भूरे आभासी पानी की मात्रा और फसल उत्पादन और अन्य क्षेत्रों के पानी पदचिह्न को नदी क्षेत्रों में जल प्रबंधन के लिए संभावित उपयोगी अवधारणाओं के रूप में माना जाने लगा है। इस अध्ययन में नदी क्षेत्रों में पानी पदचिह्न के आँकलन के लिए भारतीय संदर्भ आँकड़ों की उपलब्धता को ध्यान में रखते हुए स्पेशियल रिसोल्यूशन को परिभाषित करने पर विशेष ध्यान दिया गया है। इस अध्ययन में विकसित प्रणाली को उत्तर और मध्य भारत में स्थित गोमती और बेतवा नदी क्षेत्रों में नीले, हरे और भूरे आभासी पानी की मात्रा, पानी के पदचिह्नों और आभासी पानी के आयात-निर्यात के आँकलन में किया गया है। पानी पदचिह्न के विश्लेषण को पानी पदचिह्न की स्थिरता के आकलन और पानी पदचिह्न को कम करने के लिए वैकल्पिक फसल और जल प्रबंधन रणनीति तैयार करने के लिए भी किया गया है।

परिणामों से पता चलता है की, दोनों नदी क्षेत्रों में फसल बाष्पोत्सर्जन में काफी स्थानिक विभिन्नता है अतः पुरे नदी क्षेत्र को पानी पदचिह्न के आँकलन के लिए एक स्थानिक इकाई के रूप में लेना उपयुक्त नहि होगा। ऐसा करने पर पानी पदचिह्न का आँकलन अव्यवहारीक होगा। अतः पानी पदचिह्न आँकलन के लिए एक स्थानिय इकाई परिभाषित करना आवश्यक है। इस अध्ययन में पानी पदचिह्न आँकलन के लिए लिए एक स्थानिय इकाई को परिभाषित करने के लिए एक मजबूत ढांचा परिभाषित है जिसको भारत के अन्य नदी क्षेत्रों में भी दोहराया जा सकता है।

पानी पदचिह्न के आँकलन से पता चलता है की वर्ष २०११ में गोमती और बेतवा नदी क्षेत्रों में पानी का पदचिह्न क्रमशः १२७७३ मिलियन मी^३ और ९१८६ मिलियन मी^३ था। परिणामों से यह भी पता चलता है की कृषि क्षेत्र (फसल उत्पादन और पशुपालन) मिठे पानी का बड़ा हिस्सा उपयोग करते है। इस क्षेत्र का हिस्सा बेतवा और गोमती नदी क्षेत्रों के कुल पानी पदचिह्न में क्रमशः ९६.१ % और ९७.८% है। धान, गेहूं और गन्ने का पानी पदचिह्न सबसे ज्यादा है। इन फसलों का हिस्सा गोमती नदी क्षेत्र के कुल पानी पदचिह्न में ८८.३% और निले पानी पदचिह्न में ९४.४% है। बेतवा नदी क्षेत्र में गेहूं, सोयाबीन और चना का हिस्सा कुल पानी

पदचिह्न में ७५.३% और निले पानी पदचिह्न में ८७.७% हैं। गोमती नदी क्षेत्र में निले और भूरे पानी पदचिह्न का हिस्सा कुल पानी पदचिह्न में क्रमशः ४७.३% और ९.१% है। तथा बेटवा नदी क्षेत्र में इनका हिस्सा क्रमशः ४३.६% और १०.९% है। हरे पानी पदचिह्न का जादा होना यह दर्शाता है की इन नदी क्षेत्रों में हरे पानी के प्रबंधन से निले पानी पर पडने वाले दबाव को घटाया जा सकता है। गोमती और बेटवा नदी क्षेत्रों के भूरे पानी पदचिह्न में घरेलू और औद्योगिक क्षेत्र की हिस्सेदारी क्रमशः ३८.३% और १७.९% है। उपलब्ध नीले पानी का एक बड़ा हिस्सा कम आर्थिक पानी उत्पादकता वाली फसलों के उत्पादन में उपयोग होता है। अभी के उत्पादन और इस्तेमाल के हिसाब से गोमती और बेटवा नदी क्षेत्रों में क्रमशः २११० मिलियन मी^३ और २९०५ मिलियन मी^३ आभासी पानी का निर्यात हो रहा है। पानी की इस निर्यात से बेटवा नदी क्षेत्र में भविष्य में पानी की समस्या को और भी बिकट बना सकती है। भारी मात्रा में पानी की निर्यात के बावजूद, गोमती और बेटवा नदी क्षेत्रों में क्रमशः ५०५४ मिलियन मी^३ और बेटवा बेसिन में ३५९० मिलियन मी^३ आभासी पानी का आयात हो रहा है। इस हिसाब से दोनों नदी क्षेत्र परोक्ष रूप से पानी आयातक नदी क्षेत्र हैं। स्थिरता विश्लेषण से पता चलता है की बेटवा नदी क्षेत्र में पर्यावरण पर दबाव को राहत देने के लिए और पानी की गुणवत्ता में सुधार करने के लिए मौजूदा पानी पदचिह्न में कमी करने जरूरत है, जबकि गोमती नदी क्षेत्र में पानी की खपत और प्रदूषण पैटर्न टिकाऊ हैं।

नदी क्षेत्र में पानी पदचिह्न को कम करने के लिए दिये गये सुझावों से पता चलता है की गोमती और बेटवा नदी क्षेत्रों में फसल क्षेत्रों के पुनःनिर्धारण से पानी पदचिह्न में क्रमशः ९.२६% और २५.१२% की कमी लाई जा सकती है। अभी के फसल चक्र के अनुसार ड्रिप और स्प्रिंकलर सिंचाई पद्धति से गोमती और बेटवा नदी क्षेत्रों में पानी पदचिह्न को क्रमशः २८.४% और ४५.०% तक कम किया जा सकता है। बेहतर सिंचाई के तरीके और लेजर लैंड लेवलिंग के इस्तेमाल से पानी पदचिह्न और आगामी पानी के इस्तेमाल को और कम करने की संभावना है। ऐसा करने से इन नदी क्षेत्रों की पानी के लिए अन्य नदी क्षेत्रों पर निर्भरता को कम किया जा सकता है।

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APPENDICES

Appendix I

Evapotranspiration of selected crops (ETc, mm) in different agricultural production units (APUs) in Gomti basin under irrigated condition

APU No	Paddy	Pearl Millet	Maize	Wheat	Chickpea	Pigeon pea	Sugar-cane	Ground-nut	Sesame	Mustard	Potato	Peas	Sorghum	Black gram	Lentil
1	549.7	367.0	464.2	340.3	300.2	539.2	1520.2	502.8	365.3	296.6	360.6	283.5	312.7	441.5	346.0
2	546.7	359.2	459.1	350.2	307.3	537.1	1526.2	498.7	363.3	301.8	367.1	290.9	429.0	445.8	352.0
3	557.8	365.3	462.2	329.4	291.0	540.8	1495.5	501.8	370.2	291.2	349.7	275.5	437.6	445.8	335.8
4	557.8	365.3	462.2	329.4	291.0	540.8	1495.5	501.8	370.2	291.2	349.7	275.5	437.6	445.8	335.8
5	530.5	346.2	442.7	360.9	321.1	529.9	1503.1	482.3	349.8	305.7	379.4	297.1	415.6	440.9	358.1
6	531.0	346.7	443.2	360.9	321.2	530.1	1503.1	482.3	305.7	291.2	379.4	297.1	415.6	440.9	358.1
7	531.0	346.7	443.2	360.9	321.2	530.1	1503.1	482.3	305.7	291.2	379.4	297.1	415.6	440.9	358.1
8	531.0	346.7	443.2	360.9	321.2	530.1	1503.1	482.3	305.7	291.2	379.4	297.1	415.6	440.9	358.1
9	557.3	368.3	471.7	341.3	303.7	550.5	1532.4	508.0	372.2	297.2	360.7	284.6	440.3	444.5	347.0
10	557.3	368.3	471.7	341.3	303.7	550.5	1532.4	508.0	372.2	297.2	360.7	284.6	440.3	444.5	347.0
11	532.7	351.7	450.1	300.6	270.9	513.8	1406.9	481.3	357.5	264.3	318.7	252.0	419.3	402.2	305.6
12	542.9	358.9	459.1	359.8	318.8	544.4	1406.9	494.1	361.8	306.8	379.6	299.2	430.0	451.9	357.2
13	543.1	359.1	459.3	359.8	319.1	544.4	1538.1	497.5	361.8	306.8	379.6	299.2	430.0	451.9	357.2
14	553.9	367.0	466.2	350.3	307.3	545.3	1542.6	507.5	372.3	303.5	367.8	290.3	437.2	448.9	351.0
15	553.9	367.0	466.2	350.3	307.3	545.3	1542.6	507.5	372.3	303.5	367.8	290.3	437.2	448.9	351.0
16	539.2	357.4	452.3	312.5	280.8	529.8	1450.4	490.8	361.3	277.2	333.4	263.1	425.6	415.5	317.6
17	549.2	363.4	460.3	329.4	294.0	540.9	1491.4	500.8	368.3	287.4	349.8	275.7	433.5	432.5	334.7
18	549.0	361.4	465.4	351.3	314.1	544.6	1532.0	140.0	110.0	301.8	367.8	290.3	433.1	447.6	353.1
19	549.0	361.4	465.4	351.3	314.1	544.6	1532.0	140.0	110.0	301.8	367.8	290.3	433.1	447.6	353.1
20	562.4	372.3	476.0	344.2	308.0	557.8	1547.7	511.9	373.3	300.4	363.8	286.6	445.5	449.7	348.1
21	529.9	350.3	444.8	374.2	329.5	535.4	1506.8	483.4	351.8	314.8	390.1	304.9	417.1	436.8	370.4

Appendix II

Evapotranspiration of selected crops (ET_c, mm) in different agricultural production units (APUs) in Betwa basin under irrigated condition

APU No	Paddy	Wheat	Sorghum	Maize	Chickpea	Pigeon pea	Black Gram	Lentil	Peas	Ground-nut	Sesame	Rape-seed	Soybean
1	546.4	408.7	380.8	382.2	316.5	565.9	318.4	396.8	317.3	529.4	386.2	330.1	473.1
2	546.4	408.7	380.8	382.2	316.5	565.9	318.4	396.8	317.3	529.4	386.2	330.1	473.1
3	419.8	423.9	370.8	372.7	328.9	554.1	308.1	411.6	334.4	524.6	374.2	337.6	462.7
4	424.8	398.3	380.8	387.1	309.9	567.0	321.8	385.5	308.1	532.9	389.5	317.5	478.0
5	424.8	398.3	380.8	387.1	309.9	567.0	321.8	385.5	308.1	532.9	389.5	317.5	478.0
6	424.8	398.3	380.8	387.1	309.9	567.0	321.8	385.5	308.1	532.9	389.5	317.5	478.0
7	552.6	393.1	381.9	387.1	302.0	569.0	325.4	387.5	297.7	534.4	308.3	308.3	482.0
8	552.6	393.1	381.9	387.1	302.0	569.0	325.4	387.5	297.7	534.4	308.3	308.3	482.0
9	557.3	370.1	383.4	388.3	290.0	573.8	321.6	368.8	286.6	537.5	406.1	301.6	486.2
10	564.5	393.1	390.1	398.4	302.5	578.7	332.6	379.1	295.2	537.5	406.1	307.4	488.3
11	564.5	393.1	390.1	398.4	302.5	578.7	332.6	379.1	295.2	537.5	406.1	307.4	488.3
12	550.0	409.3	384.9	388.3	316.1	572.0	321.6	395.2	315.1	539.0	400.5	328.4	482.3
13	559.7	382.7	384.9	394.1	298.4	573.6	331.5	372.0	292.0	535.4	406.9	305.1	485.1
14	503.4	421.0	384.9	381.5	323.7	524.9	290.7	406.8	326.8	499.4	365.9	335.4	439.0
15	503.4	421.0	384.9	381.5	323.7	524.9	290.7	406.8	326.8	499.4	365.9	335.4	439.0
16	519.4	417.9	359.8	390.8	320.5	538.2	302.1	407.8	324.7	509.7	376.2	329.6	451.3
17	519.4	417.9	359.8	390.8	320.5	538.2	302.1	407.8	324.7	509.7	376.2	329.6	451.3
18	519.4	417.9	359.8	390.8	320.5	538.2	302.1	407.8	324.7	509.7	376.2	329.6	451.3
19	519.4	417.9	359.8	390.8	320.5	538.2	302.1	407.8	324.7	509.7	376.2	329.6	451.3
20	512.7	437.7	354.8	386.8	337.5	535.0	293.9	417.6	335.3	508.6	376.1	344.0	442.0
21	582.1	396.5	402.9	438.4	310.9	595.2	339.9	389.1	306.0	559.1	432.4	320.4	505.1
22	558.8	398.4	387.0	420.2	308.9	576.2	326.8	387.4	305.7	537.0	415.2	317.5	485.1
23	558.8	398.4	387.0	420.2	308.9	576.2	326.8	387.4	305.7	537.0	415.2	317.5	485.1
24	558.8	398.4	387.0	420.2	308.9	576.2	326.8	387.4	305.7	537.0	415.2	317.5	485.1
25	558.8	398.4	387.0	420.2	308.9	576.2	326.8	387.4	305.7	537.0	415.2	317.5	485.1
26	525.2	419.6	362.9	394.0	324.6	543.9	303.2	404.8	323.7	515.8	389.7	333.4	454.3
27	525.2	419.6	362.9	394.0	324.6	543.9	303.2	404.8	323.7	515.8	389.7	333.4	454.3

Appendix III

Spatial correlation between evapotranspiration of crops in Gomti basin

	PD	PM	MZ	PP	SO	GN	SS	SC	BG	WH	CP	MU	PT	PS	LT
PD	1.00														
PM	1.00	1.00													
MZ	0.99	0.99	1.00												
PP	0.81	0.84	0.86	1.00											
SO	1.00	1.00	1.00	0.85	1.00										
GN	0.97	0.98	0.99	0.92	0.99	1.00									
SS	1.00	1.00	0.98	0.79	0.99	0.96	1.00								
SC	0.42	0.45	0.52	0.84	0.49	0.63	0.38	1.00							
BG	0.25	0.28	0.37	0.72	0.32	0.48	0.21	0.98	1.00						
WH	-0.29	-0.24	-0.17	0.31	-0.20	-0.04	-0.32	0.75	0.84	1.00					
CP	-0.26	-0.22	-0.15	0.33	-0.18	-0.01	-0.29	0.76	0.85	1.00	1.00				
MU	-0.18	-0.13	-0.08	0.40	-0.10	0.06	-0.21	0.80	0.87	0.98	0.98	1.00			
PT	-0.25	-0.20	-0.14	0.34	-0.17	0.00	-0.28	0.77	0.85	1.00	1.00	0.98	1.00		
PS	-0.27	-0.23	-0.15	0.31	-0.18	-0.02	-0.30	0.76	0.86	0.99	0.99	0.97	0.99	1.00	
LT	-0.24	-0.19	-0.12	0.36	-0.16	0.01	-0.27	0.78	0.86	1.00	1.00	0.98	1.00	0.99	1.00

Spatial correlation between seasonal evapotranspiration of crops in Betwa basin

	PD	SO	MZ	PP	SS	SY	GN	WH	CP	LT	PS	MU
PD	1.00											
SO	1.00	1.00										
MZ	1.00	1.00	1.00									
PP	1.00	1.00	1.00	1.00								
SS	1.00	1.00	1.00	1.00	1.00							
SY	1.00	1.00	1.00	1.00	1.00	1.00						
GN	0.99	0.99	0.99	1.00	0.99	0.99	1.00					
WH	-0.89	-0.87	-0.89	-0.86	-0.89	-0.89	-0.83	1.00				
CP	-0.85	-0.82	-0.84	-0.81	-0.84	-0.84	-0.77	0.99	1.00			
LT	-0.86	-0.84	-0.86	-0.82	-0.86	-0.86	-0.79	1.00	0.99	1.00		
PS	-0.88	-0.86	-0.87	-0.85	-0.87	-0.87	-0.82	0.98	0.96	0.97	1.00	
MU	-0.86	-0.84	-0.85	-0.82	-0.86	-0.85	-0.78	1.00	0.99	1.00	0.97	1.00

Note: PD-paddy, SO-sorghum, MZ-maize, PP-pigeon pea, SS-sesame, SY-soybean, GN-groundnut, WH-wheat, CP-chickpea, LT-Lentil, PS-peas, MU-mustard, PT-Potato, PM-pearl millet, SC-sugarcane, BG-black gram.

Appendix IV

District wise geographical area, gross cultivated and gross irrigated areas and human population within the Gomti basin

District	Geographical area (ha)	Geographical area in basin (ha)	Gross cultivated area (ha)	Gross cultivated area within the basin (ha)	Gross irrigated area (ha)	Total irrigated area within the basin (ha)	District population	District population in the basin
Barabanki	443058	305759	488370	287880	443528	261447	3260699	2298180
Faizabad	209818	15158	267348	13933	242067	12615	2470996	159976
Hardoi	601035	368652	693329	345900	547251	273022	4092845	2586574
Jaunpur	403207	222388	464940	212972	382344	175138	4494204	2559653
Kheri	770949	215621	709400	207781	574267	168201	4021243	1115343
Lucknow	253908	253908	210027	208974	182709	181793	4589838	4589838
Pilibhit	359266	86334	402444	65346	386610	62775	2031007	450511
Pratapgarh	371298	293257	300556	279723	267435	248898	3209141	2553617
Raebareli	461823	359578	413331	325131	360737	283760	3405559	2693944
Shahjahanpur	465307	101524	608761	98178	539180	86957	3466382	680423
Sitapur	577975	320965	648863	309909	537224	256588	4483992	2385616
Sultanpur	441628	343012	436968	323093	371066	274365	3797117	2975107
Unnao	459757	186116	469279	173530	362940	134208	3108367	1186392
Varanasi	154945	51993	156802	49374	128555	40480	3676841	2185460

Appendix V

District wise geographical, gross cultivated and gross irrigated areas (ha) and human population within the Betwa basin

District	Geographical area (ha)	Geographical area in basin (ha)	Gross cultivated area (ha)	Gross cultivated area within the basin (ha)	Gross irrigated area (ha)	Total irrigated area within the basin (ha)	District population	District population in the basin
Ashoknagar	472642	295274	392764	201680	115553	59335	845071	476821
Bhopal	272374	215689	232021	173520	77415	57896	2371061	2270134
Chhatarpur	871134	262012	475945	170771	181018	64950	1762375	485706
Hamirpur	426211	241143	324439	210272	105220	68194	1104285	640190
Jalaun	457162	67098	420227	50507	162520	19533	1689974	239685
Jhansi	506656	400100	455474	355174	199191	155327	1998603	1693447
Lalitpur	504791	504791	426777	422861	189699	187959	1221592	1221592
Mahoba	283569	166038	283066	156844	103108	57131	875958	552363
Raisen	849815	322656	582681	242311	153985	64035	1331597	532973
Sagar	1025310	535466	810533	397023	166916	81760	2378458	1048804
Sehore	656863	18363	642235	16242	188092	4757	1311332	33608
Shivpuri	1043893	137990	537290	75364	180369	25300	1726050	204372
Tikamgarh	506691	506440	372972	374691	218020	219025	1445166	1444489
Vidisha	730667	639047	746786	616075	166241	137144	1458875	1295498

Appendix VI
Irrigated and rainfed areas under various crops in different SRUs of Gomti basin

Crops	Irrigated area (ha)				Rainfed area (ha)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	0	0	0	0	2609	42895	3472	19262
Groundnut	31	0	0	93	2571	7381	0	3686
Maize	476	1142	157	943	2824	18625	20758	26729
Pearl Millet	77	0	0	1	623	12265	4543	3455
Pigeon pea	2	23	0	1	365	21971	6190	2930
Paddy	106902	400532	77190	137272	7981	7415	118	2681
Sesame	20	3	0	11	2809	8461	324	16905
Sorghum	22	3	0	14	207	17181	2397	5132
Sugarcane	70092	16017	5208	67073	14370	937	0	5635
Chickpea	7	959	62	114	33	11100	3113	683
Lentil	0	0	0	0	9343	13739	133	16135
Mustard	8975	24169	1224	12459	3957	2721	246	3684
Peas	340	9225	3694	1850	0	0	0	0
Potato	1740	26857	5592	6438	241	3495	314	1760
Wheat	118613	617519	117225	274198	1905	3266	389	0

Appendix VII
Irrigated and rainfed areas under various crops in different SRUs of Betwa basin

Crops	Irrigated area (ha)				Rainfed area (ha)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	0	0	0	0	17545	22788	10537	99019
Groundnut	94	9	0	9139	17217	6114	3300	34682
Maize	5	1	0	0	32558	9	9404	3538
Pigeon pea	0	0	5	12	176	10433	12352	6741
Paddy	207	135	2	837	8462	1372	8079	30998
Sesame	0	0	1	0	4281	6098	1290	28322
Sorghum	0	0	0	0	12015	28439	9011	14031
Soybean	10	0	48	21600	42820	321	301498	35171
Chickpea	66694	19385	110553	47891	59097	93161	211271	81925
Lentil	0	0	0	0	45736	42266	122994	30581
Mustard	1405	792	45	3260	32833	4310	4888	979
Peas	34165	38289	11912	62092	0	0	0	0
Wheat	127358	88534	210636	254747	41662	17677	171825	15001

Appendix VIII
Crop productivity in different SRUs under irrigated and rainfed conditions in Gomti basin

Crops	Irrigated area productivity (kg/ha)				Rainfed area productivity (kg/ha)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	607	534	688	547	454	414	523	417
Groundnut	920	656	1000	830	920	656	1000	830
Maize	1143	1200	1470	1003	1143	1200	1470	1003
Pearl Millet	1167	1014	1318	1137	1167	1014	1318	1137
Pigeon pea	757	1179	770	907	626	946	613	741
Paddy	2230	2111	2073	2020	2230	2111	2073	2020
Sesame	187	186	200	207	163	177	200	207
Sorghum	930	933	1210	1103	930	933	1210	1103
Sugarcane	57450	51512	52888	52310	40233	35213	30841	37560
Chickpea	827	830	970	590	427	394	450	289
Lentil	850	845	773	863	371	330	287	347
Mustard	853	935	1200	923	569	574	719	587
Peas	1843	1190	1650	1190	0	0	0	0
Potato	18490	21328	15928	17903	3238	2754	1727	2472
Wheat	3600	2915	2838	3250	2598	1880	1744	2179

Appendix IX
Crop productivity in different SRUs under irrigated and rainfed conditions in Betwa basin

Crops	Irrigated area productivity (kg/ha)				Rainfed area productivity (kg/ha)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	355	243	390	365	266	206	250	298
Groundnut	1145	745	1066	1248	792	485	830	883
Maize	1697	1050	1960	1250	1367	748	1833	1036
Pigeon pea	1193	843	859	868	1026	684	820	765
Paddy	893	1175	570	692	604	703	453	487
Sesame	465	193	266	298	411	155	260	261
Sorghum	868	1075	1160	922	809	941	1155	870
Soybean	909	723	816	825	729	529	728	673
Chickpea	868	945	958	1357	279	308	340	458
Lentil	640	873	539	485	183	249	172	145
Mustard	725	677	611	607	339	244	251	230
Peas	611	1260	546	679	0	0	0	0
Wheat	1499	2365	1362	1982	583	259	679	821

Appendix X
All India averaged market prices of crops as on 11.6.2014

Crop	Market Price, Rs/q
Black Gram	5110
Groundnut	3320
Maize	1325
Pearl Millet	1225
Pigeon pea	4200
Paddy	1460
Sesame	9618
Sorghum	1790
Soybean	3570
Sugarcane	280*
Chickpea	3225
Lentil	4374
Mustard	3230
Peas	3200
Potato	1705
Wheat	1840

†Mandi Prices portal of Agmarknet, CRISIL, 2014

Appendix XI
Per capita consumption (kg/month) of crop and crop products in urban and rural areas of Madhya Pradesh and Uttar Pradesh

Crops	Crop Product	Consumption in Kg/month			
		Madhya Pradesh		Uttar Pradesh	
		Rural	Urban	Rural	Urban
Paddy	Rice-PDS	0.428	0.142	0.747	0.219
	Rise -Other Sources	1.702	1.578	3.491	2.576
	Chira/poha	0.034	0.124	0.018	0.014
	Khoi/lawa	0.002	0.005	0.005	0.003
	Muri	0.002	0.002	0.007	0.008
	Other rice Products	0.000	0.004	0.005	0.004
Wheat	Wheat/atta - PSD	1.761	0.956	0.512	0.526
	Wheat/atta - Other sources	6.307	6.315	7.028	6.417
	Maida	0.014	0.034	0.035	0.044
	Suji/Rawa	0.023	0.068	0.037	0.054
	Sewai	0.002	0.016	0.008	0.027
	Bread(bakery)	0.017	0.069	0.035	0.170
	Other wheat Products	0.002	0.002	0.001	0.002
Sorghum	Jowar & its Products	0.274	0.048	0.003	0.000
Pearl millet	Bajra & its Products	0.067	0.000	0.084	0.038
Maize	Maize & its Products	0.599	0.043	0.027	0.011
Pigeon pea	Arhar, tur	0.241	0.358	0.192	0.241
Chick pea	Gram: split	0.091	0.079	0.060	0.077
	Gram: whole	0.045	0.024	0.024	0.030
	Gram products	0.002	0.003	0.001	0.110
	Besan	0.067	0.095	0.052	3.250
Lentil	Masur	0.058	0.055	0.064	5.010
Black gram	Urd	0.073	0.037	0.087	4.990
Peas	Peas	0.018	0.010	0.241	2.490
Sugarcane	Sugar - PDS	0.108	0.054	0.045	0.016
	Sugar - Other Sources	0.658	0.851	0.602	0.754
	Gur/jaggery	0.037	0.025	0.059	0.030
Potato	Potato	1.138	1.186	2.814	2.577
Mustard	Mustard Oil	0.155	0.145	0.510	0.514
Groundnut	Groundnut Oil	0.004	0.033	0.002	0.004
	Groundnut	0.056	0.068	0.030	0.035
Soybean	Soybean Oil	0.147	0.213	0.105	0.124

Source: Report No 541, National Sample Survey Office, Ministry of Statistics and Programme Implementation (2012)

Appendix XII
Crop products considered in estimation of consumption of crops

Crop	Crop Product	Crop	Crop Product
Paddy	Paddy	Chickpea	Gram: split
	Chira/poha		Gram: whole
	Khoi/lawa		Gram products
	Muri		Besan
	Other rice products	Lentil	Lentil
Wheat	Wheat flour/atta	Black Gram	Black gram
	Maida	Peas	Peas
	Suji/Rawa	Sugarcane	Sugar - PDS
	Sewai		Sugar - Other sources
	Bread (bakery)		Gur/Jaggery
	Other wheat products	Potato	Potato
Sorghum	Sorghum & its products	Mustard	Mustard oil
Pearl millet	Pearl millet & its products	Groundnut	Groundnut oil
Maize	Maize & its products		Groundnut whole
Pigeon Pea	Arhar, tur	Soybean	Soybean oil

Appendix XIII
Product fractions used in estimation of consumption of crops

Primary Crop	Processed Product	Product Fraction	Primary Crop	Processed Product	Product Fraction
Rice	Rice-PDS	0.66	Pigeon Pea	Arhar, tur	1
	Rise -Other Sources	0.66	Chickpea	Gram: split	1
	Chira/poha	0.66		Gram: whole	1
	Khoi/lawa	0.66		Gram products	1
	Muri	0.66		Besan	1
	Other rice Products	0.66	Lentil	Lentil	1
Wheat	Wheat/atta - PSD	1	Black Gram	Black Gram	1
	Wheat/atta - Other sources	1	Peas	Peas	1
	Maida	1	Sugarcane	Sugar - PDS	0.105
	Suji/Rawa	1		Sugar - Other Sources	0.105
	Sewai	1		Gur/jaggery	0.105
	Bread(bakery)	1	Potato	Potato	1
	Other wheat Products	1	Mustard	Mustard Oil	0.36
Jowar	Jowar & its Products	1	Groundnut	Groundnut Oil	0.415
Bajra	Bajra & its Products	1		Groundnut - shelled	0.705
Maize	Maize & its Products	1	Soybean	Soybean Oil	0.18
Barley	Barley & its Products	1		Cake of Soybean	0.8
			Sesame	Sesame Oil	0.39

Source: FAO (2006); Kampman, (2008)

Appendix XIV

Blue component of evapotranspiration of crops (ETc blue, mm) in different APUs of Gomti basin under irrigated condition

APU No	Paddy	Pearl Millet	Maize	Wheat	Chickpea	Pigeon pea	Sugar-cane	Ground-nut	Sesame	Mustard	Potato	Peas	Sorghum	Black gram	Lentil
1	81.4	81.2	4.7	325.0	287.6	275.5	886.5	82.9	60.9	295.8	349.6	282.2	49.5	250.0	337.1
2	303.5	77.1	4.2	336.9	296.1	267.2	920.6	72.6	51.6	301.6	357.4	290.9	67.9	292.7	344.4
3	64.6	78.1	4.2	312.9	280.4	259.1	865.6	65.9	50.3	291.0	341.6	275.3	70.0	297.2	330.0
4	64.6	78.1	4.2	312.9	280.4	259.1	865.6	65.9	50.3	291.0	341.6	275.3	70.0	297.2	330.0
5	78.2	76.4	5.3	358.0	318.4	258.3	929.6	62.5	48.3	305.5	377.0	296.9	67.9	289.4	356.1
6	78.7	76.9	5.8	358.0	318.5	258.5	929.6	62.5	36.5	291.0	377.0	296.9	67.9	289.4	356.1
7	78.7	76.9	5.8	358.0	318.5	258.5	929.6	62.5	36.5	291.0	377.0	296.9	67.9	289.4	356.1
8	78.7	76.9	5.8	358.0	318.5	258.5	929.6	62.5	36.5	291.0	377.0	296.9	67.9	289.4	356.1
9	106.6	85.1	14.5	328.2	293.4	290.4	951.9	88.6	68.2	296.6	351.9	283.7	79.0	289.6	340.0
10	106.6	85.1	14.5	328.2	293.4	290.4	951.9	88.6	68.2	296.6	351.9	283.7	79.0	289.6	340.0
11	80.9	80.5	5.3	265.1	236.7	264.8	843.0	84.0	65.5	259.1	286.8	244.9	74.3	270.3	278.1
12	64.7	78.9	5.3	352.1	311.7	264.5	788.6	61.0	50.1	306.7	373.2	299.1	70.0	287.8	352.0
13	64.9	79.1	5.5	352.1	312.0	264.5	919.8	64.4	50.1	306.7	373.2	299.1	70.0	287.8	352.0
14	82.6	79.8	5.8	337.3	296.4	274.8	938.6	78.8	57.9	303.2	358.2	289.7	70.0	287.6	343.3
15	82.6	79.8	5.8	337.3	296.4	274.8	938.6	78.8	57.9	303.2	358.2	289.7	70.0	287.6	343.3
16	114.5	101.0	24.9	286.8	257.3	294.6	896.6	105.3	84.1	274.7	312.1	259.5	95.4	262.2	299.6
17	55.5	78.2	5.3	311.9	282.6	257.8	823.7	63.5	49.5	286.5	340.8	274.4	68.9	256.2	327.9
18	72.1	79.3	5.4	337.8	302.8	274.5	924.9	17.9	17.9	301.6	358.0	290.0	70.0	292.8	345.4
19	72.1	79.3	5.4	337.8	302.8	274.5	924.9	17.9	17.9	301.6	358.0	290.0	70.0	292.8	345.4
20	183.3	119.2	68.1	332.9	298.2	326.8	1044.4	139.8	102.4	299.3	355.1	285.1	124.0	297.8	340.9
21	69.0	78.4	5.4	372.5	328.1	262.7	922.4	62.5	48.3	314.5	388.9	304.6	67.9	282.9	369.4

Appendix XV
Blue component of evapotranspiration of crops (ETc blue, mm) in Betwa basin under irrigated condition

APU No	Paddy	Wheat	Sorghum	Maize	Chickpea	Pigeon pea	Black Gram	Lentil	Peas	Ground-nut	Sesame	Rape-seed	Soybean
1	284.1	408.2	215.2	227.0	306.5	328.1	154.6	380.5	316.8	350.4	209.9	301.6	274.9
2	284.1	408.2	215.2	227.0	306.5	328.1	154.6	380.5	316.8	350.4	209.9	301.6	274.9
3	115.4	420.9	148.5	167.4	307.7	250.0	108.1	378.0	332.0	293.4	141.5	296.5	202.5
4	139.7	396.8	196.8	214.5	297.4	309.4	141.9	367.4	306.4	334.9	195.2	286.8	259.3
5	139.7	396.8	196.8	214.5	297.4	309.4	141.9	367.4	306.4	334.9	195.2	286.8	259.3
6	139.7	396.8	196.8	214.5	297.4	309.4	141.9	367.4	306.4	334.9	195.2	286.8	259.3
7	301.9	380.3	231.4	243.9	293.1	347.5	168.5	302.5	295.1	371.1	141.2	284.0	297.3
8	301.9	380.3	231.4	243.9	293.1	347.5	168.5	302.5	295.1	371.1	141.2	284.0	297.3
9	414.1	385.5	293.7	303.5	296.9	411.7	226.2	361.2	285.3	438.4	243.1	286.4	362.8
10	297.2	376.3	225.6	242.6	290.7	341.5	165.4	361.9	291.8	360.0	229.3	281.4	288.3
11	297.2	376.3	225.6	242.6	290.7	341.5	165.4	361.9	291.8	360.0	229.3	281.4	288.3
12	291.2	409.0	226.8	233.0	312.7	346.2	151.0	389.6	314.9	369.9	229.1	317.4	290.0
13	354.0	378.8	259.0	275.7	287.2	375.6	199.9	356.0	288.0	396.1	268.3	277.8	323.7
14	187.9	420.1	153.3	172.4	309.9	228.2	87.3	384.4	326.1	284.4	141.8	301.1	181.0
15	187.9	420.1	153.3	172.4	309.9	228.2	87.3	384.4	326.1	284.4	141.8	301.1	181.0
16	214.9	413.4	154.6	186.2	308.4	255.4	92.1	389.0	322.6	301.1	153.3	320.4	205.9
17	214.9	413.4	154.6	186.2	308.4	255.4	92.1	389.0	322.6	301.1	153.3	320.4	205.9
18	214.9	413.4	154.6	186.2	308.4	255.4	92.1	389.0	322.6	301.1	153.3	320.4	205.9
19	214.9	413.4	154.6	186.2	308.4	255.4	92.1	389.0	322.6	301.1	153.3	320.4	205.9
20	232.9	436.5	165.5	211.7	319.8	267.8	120.0	389.1	334.0	311.1	166.9	305.2	216.6
21	306.8	395.6	233.4	274.5	304.6	353.2	162.4	379.0	305.4	376.9	250.2	300.8	299.8
22	278.9	396.5	206.3	248.9	299.3	323.2	144.8	372.4	304.2	343.9	224.2	291.5	270.9
23	278.9	396.5	206.3	248.9	299.3	323.2	144.8	372.4	304.2	343.9	224.2	291.5	270.9
24	278.9	396.5	206.3	248.9	299.3	323.2	144.8	372.4	304.2	343.9	224.2	291.5	270.9
25	278.9	396.5	206.3	248.9	299.3	323.2	144.8	372.4	304.2	343.9	224.2	291.5	270.9
26	226.6	417.9	162.2	201.5	309.7	264.2	108.8	381.1	322.5	309.0	173.3	297.8	215.2
27	226.6	417.9	162.2	201.5	309.7	264.2	108.8	381.1	322.5	309.0	173.3	297.8	215.2

Appendix XVI
Green component of evapotranspiration of crops (ET_c green, mm) in Gomti basin under irrigated condition

APU No	Paddy	Pearl Millet	Maize	Wheat	Chickpea	Pigeon pea	Sugar-cane	Ground-nut	Sesame	Mustard	Potato	Peas	Sorghum	Black gram	Lentil
1	468.3	285.8	459.5	15.3	12.6	263.7	633.7	419.9	304.4	0.8	11.0	1.3	263.2	191.5	8.9
2	243.2	282.1	454.9	13.3	11.2	269.9	605.6	426.1	311.7	0.2	9.7	0.0	361.1	153.1	7.6
3	493.2	287.2	458.0	16.5	10.6	281.7	629.9	435.9	319.9	0.2	8.1	0.2	367.6	148.6	5.8
4	493.2	287.2	458.0	16.5	10.6	281.7	629.9	435.9	319.9	0.2	8.1	0.2	367.6	148.6	5.8
5	452.3	269.8	437.4	2.9	2.7	271.6	573.5	419.8	301.5	0.2	2.4	0.2	347.7	151.5	2.0
6	452.3	269.8	437.4	2.9	2.7	271.6	573.5	419.8	269.2	0.2	2.4	0.2	347.7	151.5	2.0
7	452.3	269.8	437.4	2.9	2.7	271.6	573.5	419.8	269.2	0.2	2.4	0.2	347.7	151.5	2.0
8	452.3	269.8	437.4	2.9	2.7	271.6	573.5	419.8	269.2	0.2	2.4	0.2	347.7	151.5	2.0
9	450.7	283.2	457.2	13.1	10.3	260.1	580.5	419.4	304.0	0.6	8.8	0.9	361.3	154.9	7.0
10	450.7	283.2	457.2	13.1	10.3	260.1	580.5	419.4	304.0	0.6	8.8	0.9	361.3	154.9	7.0
11	451.8	271.2	444.8	35.5	34.2	249.0	563.9	397.3	292.0	5.2	31.9	7.1	345.0	131.9	27.5
12	478.2	280.0	453.8	7.7	7.1	279.9	618.3	433.1	311.7	0.1	6.4	0.1	360.0	164.1	5.2
13	478.2	280.0	453.8	7.7	7.1	279.9	618.3	433.1	311.7	0.1	6.4	0.1	360.0	164.1	5.2
14	471.3	287.2	460.4	13.0	10.9	270.5	604.0	428.7	314.4	0.3	9.6	0.6	367.2	161.3	7.7
15	471.3	287.2	460.4	13.0	10.9	270.5	604.0	428.7	314.4	0.3	9.6	0.6	367.2	161.3	7.7
16	424.7	256.4	427.4	25.7	23.5	235.2	553.8	385.5	277.2	2.5	21.3	3.6	330.2	153.3	18.0
17	493.7	285.2	455.0	17.5	11.4	283.1	667.7	437.3	318.8	0.9	9.0	1.3	364.6	176.3	6.8
18	476.9	282.1	460.0	13.5	11.3	270.1	607.1	122.1	92.1	0.2	9.8	0.3	363.1	154.8	7.7
19	476.9	282.1	460.0	13.5	11.3	270.1	607.1	122.1	92.1	0.2	9.8	0.3	363.1	154.8	7.7
20	379.1	253.1	407.9	11.3	9.8	231.0	503.3	372.1	270.9	1.1	8.7	1.5	321.5	151.9	7.2
21	460.9	271.9	439.4	1.7	1.4	272.7	584.4	420.9	303.5	0.3	1.2	0.3	349.2	153.9	1.0

Appendix XVII
Green component of evapotranspiration of crops (ET_c green, mm) in Betwa basin under irrigated condition

APU No	Paddy	Wheat	Sorghum	Maize	Chickpea	Pigeon pea	Black gram	Lentil	Peas	Ground-nut	Sesame	Rape-seed	Soybean
1	262.3	0.5	165.6	155.2	10.0	237.8	163.8	16.3	0.5	179.0	176.3	28.5	198.2
2	262.3	0.5	165.6	155.2	10.0	237.8	163.8	16.3	0.5	179.0	176.3	28.5	198.2
3	304.4	3.0	222.3	205.3	21.2	304.1	200.0	33.6	2.4	231.2	232.7	41.1	260.2
4	285.1	1.5	184.0	172.6	12.5	257.6	179.9	18.1	1.7	198.0	194.3	30.7	218.7
5	285.1	1.5	184.0	172.6	12.5	257.6	179.9	18.1	1.7	198.0	194.3	30.7	218.7
6	285.1	1.5	184.0	172.6	12.5	257.6	179.9	18.1	1.7	198.0	194.3	30.7	218.7
7	250.7	12.8	150.5	143.2	8.9	221.5	156.9	85.0	2.6	163.3	167.1	24.3	184.7
8	250.7	12.8	150.5	143.2	8.9	221.5	156.9	85.0	2.6	163.3	167.1	24.3	184.7
9	143.2	15.4	89.7	84.8	6.9	162.1	95.4	7.6	1.3	99.1	163.0	15.2	123.4
10	267.3	16.8	164.5	155.8	11.8	237.2	167.2	17.2	3.4	177.5	176.8	26.0	200.0
11	267.3	16.8	164.5	155.8	11.8	237.2	167.2	17.2	3.4	177.5	176.8	26.0	200.0
12	258.8	0.3	158.1	155.3	3.4	225.8	170.6	5.6	0.2	169.1	171.4	11.0	192.3
13	205.7	3.9	125.9	118.4	11.2	198.0	131.6	16.0	4.0	139.3	138.6	27.3	161.4
14	315.5	0.9	231.6	209.1	13.8	296.7	203.4	22.4	0.7	215.0	224.1	34.3	258.0
15	315.5	0.9	231.6	209.1	13.8	296.7	203.4	22.4	0.7	215.0	224.1	34.3	258.0
16	304.5	4.5	205.2	204.6	12.1	282.8	210.0	18.8	2.1	208.6	222.9	9.2	245.4
17	304.5	4.5	205.2	204.6	12.1	282.8	210.0	18.8	2.1	208.6	222.9	9.2	245.4
18	304.5	4.5	205.2	204.6	12.1	282.8	210.0	18.8	2.1	208.6	222.9	9.2	245.4
19	304.5	4.5	205.2	204.6	12.1	282.8	210.0	18.8	2.1	208.6	222.9	9.2	245.4
20	279.8	1.2	189.3	175.1	17.7	267.2	173.9	28.5	1.3	197.5	209.2	38.8	225.4
21	275.3	0.9	169.5	163.9	6.3	242.0	177.5	10.1	0.6	182.2	182.2	19.6	205.3
22	279.9	1.9	180.7	171.3	9.6	253.0	182.0	15.0	1.5	193.1	191.0	26.0	214.2
23	279.9	1.9	180.7	171.3	9.6	253.0	182.0	15.0	1.5	193.1	191.0	26.0	214.2
24	279.9	1.9	180.7	171.3	9.6	253.0	182.0	15.0	1.5	193.1	191.0	26.0	214.2
25	279.9	1.9	180.7	171.3	9.6	253.0	182.0	15.0	1.5	193.1	191.0	26.0	214.2
26	298.6	1.7	200.7	192.5	14.9	279.7	194.4	23.7	1.2	206.8	216.4	35.6	239.1
27	298.6	1.7	200.7	192.5	14.9	279.7	194.4	23.7	1.2	206.8	216.4	35.6	239.1

Appendix XVIII
Evapotranspiration of crops (ETc, mm) in Gomti basin under rainfed conditions

APU No	Paddy	Pearl Millet	Maize	Wheat	Chickpea	Pigeon pea	Sugar-cane	Ground-nut	Sesame	Mustard	Potato	Peas	Sorghum	Black gram	Lentil
1	350.0	363.3	380.4	205.9	116.5	486.3	1161.5	484.6	363.4	170.9	76.8	71.2	354.4	380.8	98.6
2	346.9	359.0	378.7	206.0	116.5	487.8	1133.2	489.6	359.1	171.3	75.8	71.0	349.8	337.6	97.7
3	350.1	363.0	378.2	202.7	115.8	489.4	1133.7	492.0	365.5	169.9	74.6	70.8	356.0	317.8	97.0
4	350.1	363.0	378.2	202.7	115.8	489.4	1133.7	492.0	365.5	169.9	74.6	70.8	356.0	317.8	97.0
5	331.1	349.1	363.4	192.6	109.6	464.6	953.3	472.3	346.2	161.9	68.4	66.6	337.7	333.1	90.2
6	332.4	346.9	363.4	203.7	116.7	480.9	968.3	472.3	346.2	171.8	73	71.1	337.7	338.2	96.4
7	332.4	346.9	363.4	203.7	116.7	480.9	968.3	472.3	346.2	171.8	73	71.1	337.7	338.2	96.4
8	342.6	354.4	370.3	208.5	116.9	475.4	1088.0	479.1	355.3	169.2	78.3	72.3	345.9	308.4	103.6
9	354.4	367.4	386.8	204.7	116.4	487.8	1136.9	499.2	367.3	170.9	75.6	71.1	358.2	336.6	97.8
10	354.4	367.4	386.8	204.7	116.4	487.8	1136.9	499.2	367.3	170.9	75.6	71.1	358.2	336.6	97.5
11	339.2	350.5	366.7	210.0	116.5	470.6	1055.7	474.4	352.4	168.0	87.5	72.2	342.6	292.0	105.4
12	344.4	358.5	377.6	194.3	109.6	471.1	1125.5	488.0	357.7	162.0	69.9	69.1	349.3	348.0	90.9
13	345.6	358.5	377.6	205.3	116.7	487.5	1143.1	488.0	357.7	171.9	74.5	71.1	349.3	353.2	97.1
14	352.6	366.8	383.9	205.8	116.6	491.5	1119.7	497.2	366.3	171.4	75.9	71.1	357.7	350.3	97.9
15	352.6	366.8	383.9	205.8	116.6	491.5	1119.7	497.2	366.3	171.4	75.9	71.1	357.7	350.3	97.9
16	343.3	357.4	370.0	206.8	116.2	470.4	1080.1	480.9	357.7	169.1	81.7	71.4	348.9	322.2	101.6
17	348.3	362.3	377.3	203.5	116.1	487.6	1164.1	489.9	362.5	170.1	75.5	71.0	353.5	349.7	97.8
18	348.7	361.4	380.7	206.1	116.5	489.1	1136.6	492.0	361.2	171.4	75.8	71.0	352.1	341.0	97.7
19	348.7	361.4	380.7	206.1	116.5	489.1	1136.6	492.0	361.2	171.4	75.8	71.0	352.1	341.0	97.7
20	356.2	370.5	388.6	205.2	116.8	478.5	1081	502.3	370.1	171.3	76.1	71.3	361.3	334.7	98.3
21	335.6	349.4	364.7	204.3	117.1	482.9	1005.2	473.8	348.8	172.6	75.5	66.7	340.3	331.3	89.9

Appendix XIX
Evapotranspiration of crops (ET_c, mm) in Betwa basin under rainfed conditions

APU No	Paddy	Wheat	Sorghum	Maize	Chickpea	Pigeon pea	Black gram	Lentil	Peas	Ground-nut	Sesame	Rape-seed	Soybean
1	316.3	127.8	343.1	315.5	68.6	466.7	266.4	63.8	36.3	276.5	327.1	104.1	355.3
2	341.4	151	364.6	341.1	82.4	506.5	290.5	75.7	44.9	303.5	352.5	123.9	383.6
3	374.7	175.8	366.8	350.2	93.3	532.3	306.7	94	46	349.2	363	141.6	403.8
4	336.3	130.5	350.5	324.4	70.6	477.9	276.4	66.6	37	289.2	336.4	106.4	366.8
5	368.1	160.4	373.9	355.3	88.6	526.5	306.7	82.3	48.4	324.3	366.6	132	402.3
6	336.6	130.5	350.5	324.4	70.6	477.9	276.4	66.6	37	289.2	336.4	106.4	366.8
7	293	120	342.3	310.7	66.8	457.1	265.1	60	37.9	270.9	325.3	99.1	348.8
8	293	120	342.3	310.7	66.8	457.1	265.1	60	37.9	270.9	325.3	99.1	348.8
9	247.5	113.9	309.1	267.2	63.4	404.8	221.4	55	36.8	225.1	283.1	94.4	292.6
10	311.9	124.5	352.4	320.6	68.7	471.7	275.2	63.6	38.1	285.5	335.8	102.3	361.9
11	311.9	124.5	352.4	320.6	68.7	471.7	275.2	63.6	38.1	285.5	335.8	102.3	361.9
12	306.8	113	346.9	321.1	62.5	463.2	274.1	53.2	36	269.6	333.4	93.7	358
13	279.2	122.7	330.2	290.6	68.5	434.9	247.2	62.7	38.9	256.3	307.5	101.2	320.9
14	338.5	160	346.5	339.9	86.2	508.8	302.6	82	45.1	336.7	349.1	130.4	392.8
15	363.3	160	346.5	339.9	86.2	508.8	302.6	82	45.1	336.7	349.1	130.4	392.8
16	340.6	127.1	349.5	330.3	68.9	482.1	289	64.5	36.7	305.3	341.6	103.8	375
17	341.3	150.4	357.2	348.1	82.8	512.9	308.3	76.2	45.4	331.1	357.3	123.7	398.6
18	364.3	150.4	357.2	348.1	82.8	512.9	308.3	76.2	45.4	331.1	357.3	123.7	398.6
19	340.6	127.1	349.5	330.3	68.9	482.1	289	64.5	36.7	305.3	341.6	103.8	375
20	346.5	169.2	351	328.6	90.2	501.5	283.4	88.6	45.6	317.4	341	137	375.3
21	322.6	118.3	361.8	330.7	64.8	480.6	285	57.4	36.2	285.7	345.6	97.4	371.2
22	329.3	124	3354	329.1	67.6	479	280.6	61.9	36.8	287	329.5	101.6	370.5
23	366.9	153.9	378.1	360.4	85.6	528.4	311.2	77.6	48.1	322.8	364.6	127.3	406.5
24	329.3	124	3354	329.1	67.6	479	280.6	61.9	36.8	287	329.5	101.6	370.5
25	329	124	3354	329.1	67.6	479	280.6	61.9	36.8	287	329.5	101.6	370.5
26	337	161.4	359.2	341.9	87.1	512.6	298.1	83.5	45.5	327	353.2	131.5	390.2
27	358.4	161.4	359.2	341.9	87.1	512.6	298.1	83.5	45.5	327	353.2	131.5	390.2

Appendix XX
Blue, green, and grey VWC of crops under irrigated conditions in different SRUs of Gomti basin

	Blue VWC (m ³ /t)				Green VWC (m ³ /t)				Grey VWC (m ³ /t)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	4411	5389	4186	5297	2435	3034	2213	2900	0.0	0.0	0.0	0.0
Groundnut	878	1560	625	786	4401	7281	4209	5272	109.1	175.5	100.0	120.8
Maize	162	131	36	48	4130	3949	2979	4696	566.9	524.6	408.2	616.9
Pearl Millet	778	849	587	706	2289	2840	2063	2588	265.6	314.6	236.5	280.1
Pigeon pea	3538	2845	3369	2914	3362	2686	3531	3176	0.0	0.0	0.0	0.0
Paddy	394	390	267	285	1824	2006	2054	2214	623.0	661.0	666.0	683.3
Sesame	3855	3388	2415	2422	20350	19899	15100	15469	0.0	0.0	0.0	0.0
Sorghum	844	853	561	632	3765	4008	2877	3326	0.0	0.0	0.0	0.0
Sugarcane	151	185	177	163	98	117	110	123	15.7	17.7	17.2	17.2
Chickpea	3297	3866	3307	4765	217	132	24	184	0.0	0.0	0.0	0.0
Lentil	3519	4077	4652	3821	195	85	23	71	0.0	0.0	0.0	0.0
Mustard	3167	3270	2555	3102	32	4	2	5	705.8	651.2	500.0	650.1
Peas	1508	2414	1811	2311	17	6	1	5	0.0	0.0	0.0	0.0
Potato	170	171	239	191	10	4	1	5	82.3	71.4	94.5	84.1
Wheat	798	1161	1275	963	58	42	9	52	417.4	516.7	528.7	462.3

Appendix XXI
Blue, green, and grey VWC of crops under irrigated conditions in different SRUs of Betwa basin

	Blue VWC (m ³ /t)				Green VWC (m ³ /t)				Grey VWC (m ³ /t)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	4576	5110	2463	4139	5170	3716	5448	5027	0.0	0.0	0.0	0.0
Groundnut	3553	5546	2969	3201	1714	2027	2079	1785	0.0	0.0	0.0	0.0
Maize	1496	2692	971	2113	987	1160	1045	1496	377.5	594.6	312.4	540.1
Pigeon pea	3432	4448	3137	3738	2384	2409	3563	2907	0.0	0.0	0.0	0.0
Paddy	3332	3132	3771	4036	3395	3183	3879	4127	792.3	632.1	1217.7	997.8
Sesame	7387	13152	6355	8928	5656	9396	9090	7668	0.0	0.0	0.0	0.0
Sorghum	2599	2500	1426	2466	1921	1299	1894	2078	0.0	0.0	0.0	0.0
Soybean	3185	4431	2552	3730	2212	2266	3099	2945	335.1	415.2	377.1	415.0
Chickpea	3613	3184	3301	2266	90	97	152	86	0.0	0.0	0.0	0.0
Lentil	6093	3433	7406	6508	191	1759	432	3474	0.0	0.0	0.0	0.0
Rapeseed	4252	4363	5382	5706	299	344	462	568	694.8	771.0	876.4	993.9
Peas	5338	2434	6201	6202	8	23	32	35	0.0	0.0	0.0	0.0
Wheat	2954	1692	3187	2059	4	40	23	21	872.7	533.4	915.7	627.9

Appendix-XXII
Green VWC of crops under rainfed conditions in Gomti and Betwa river basins

Crops	Green VWC (m ³ /t)- Gomti basin				Green VWC (m ³ /t)- Betwa basin			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	6845	8478	6411	7996	10370	9125	8681	9756
Groundnut	5218	8691	4738	5935	3998	5539	4154	3882
Maize	3490	3347	2474	3885	2547	4193	1897	3659
Pearl Millet	3049	3681	2656	3278	5604	6486	6614	6411
Pigeon pea	7565	6144	7787	6734	5455	4310	7776	6886
Paddy	1543	1679	1607	1730	12493	23519	14772	15981
Sesame	25051	24246	17343	17645	4441	3733	3255	13558
Sorghum	3772	4027	2796	3222	--	--	--	--
Soybean	--	--	--	--	5118	6194	5478	6353
Sugarcane	267	326	319	305	--	--	--	--
Chickpea	2883	3160	2557	4012	2539	2223	2499	1644
Lentil	2823	2955	3246	2811	3471	2529	4762	5230
Mustard	2977	3012	2356	2897	3533	4211	5357	5687
Peas	2209	3873	3120	3580	33465	29169	36393	31414
Wheat	805	1093	1153	933	2364	763	2455	1676

Appendix XXIII
Rainfall and runoff in different SRUs of Gomti basin for the year 2011

SRU1			SRU2			SRU3			SRU4		
Rainfall, mm	Runoff, mm	Runoff, MCM	Rainfall, mm	Runoff, mm	Runoff, MCM	Rainfall, mm	Runoff, mm	Runoff, MCM	Rainfall, mm	Runoff, mm	Runoff, MCM
7.6	0.0	0.0	22.0	0.3	5.5	7.6	0.0	0.0	80.7	29.1	200.7
54.4	1.0	3.9	26.5	1.0	18.0	54.4	1.0	2.7	22.2	4.7	32.3
50.6	23.5	94.8	10.3	0.2	4.1	50.6	23.0	63.1	50.7	0.8	5.6
32.3	10.2	41.0	18.9	2.8	49.5	32.3	9.8	27.0	21.8	4.5	30.9
45.5	19.5	78.8	51.5	0.6	11.4	45.5	19.1	52.4	11.2	0.5	3.3
22.5	4.5	18.0	13.8	1.0	17.5	22.5	4.3	11.7	45.5	20.4	140.4
42.8	6.2	24.8	12.7	0.7	12.4	42.8	5.8	16.0	41.6	17.4	119.8
16.0	1.7	6.8	11.7	0.5	8.4	16.0	1.6	4.3	23.8	5.5	38.2
44.2	6.7	27.2	16.5	1.9	32.8	44.2	6.4	17.5	28.5	8.3	57.2
29.7	8.5	34.4	25.0	5.8	102.1	29.7	8.2	22.6	19.7	3.5	23.8
12.0	0.5	2.2	55.5	27.5	483.1	12.0	0.5	1.3	9.6	0.2	1.3
72.1	41.5	167.3	58.2	29.7	522.0	72.1	40.8	112.0	41.2	6.1	42.1
11.8	0.5	2.0	49.7	22.8	401.4	11.8	0.4	1.2	8.4	0.1	0.4
25.0	5.8	23.3	7.9	0.0	0.2	25.0	5.6	15.2	15.1	1.6	10.8
50.1	23.1	93.2	47.8	0.3	5.4	50.1	22.6	62.1	12.8	0.9	5.9
8.9	0.1	0.3	14.9	1.3	23.2	8.9	0.0	0.1	11.4	0.5	3.6
12.6	0.7	2.7	35.4	12.3	215.5	12.6	0.6	1.7	78.6	27.6	190.6
51.6	10.2	41.2	7.3	0.0	0.0	51.6	9.7	26.8	21.7	0.4	2.7
17.8	2.3	9.5	7.8	0.0	0.1	17.8	2.2	6.1	13.2	1.0	6.7
21.1	0.2	0.9	7.7	0.0	0.1	21.1	0.2	0.4	36.0	13.3	91.7
29.2	8.2	33.1	70.9	40.5	711.3	29.2	7.9	21.8	11.3	0.5	3.4
10.6	0.3	1.1	10.6	0.3	4.9	10.6	0.2	0.6	11.3	0.5	3.4

Appendix-XXI...continued

23.4	4.9	19.9	21.1	3.8	66.9	23.4	4.7	12.9	120.8	59.7	411.5
11.1	0.4	1.4	11.3	0.4	7.1	11.1	0.3	0.9	16.9	2.2	15.4
16.9	2.0	8.1	50.9	0.6	10.3	16.9	1.9	5.1			
32.5	10.3	41.5	7.5	0.0	0.0	32.5	10.0	27.4			
9.2	0.1	0.4	25.4	6.0	105.9	9.2	0.1	0.2			
17.5	2.2	9.0	10.0	0.2	3.3	17.5	2.1	5.7			
			23.1	0.5	7.9						
			23.5	5.0	88.0						
			23.8	5.2	90.7						
			42.4	17.3	303.2						
			30.7	9.2	161.3						
			18.3	2.6	45.1						
			18.5	2.6	46.5						
			11.2	0.4	6.7						
			28.0	1.3	23.5						
			66.8	3.2	56.5						
			15.1	1.4	24.4						
			16.8	2.0	34.8						
			27.5	7.2	127.0						
779.0	195.0	786.9	1054.5	218.5	3838.0	779.0	189.1	518.8	754.0	209.1	1441.7

Appendix XXIV
Rainfall and runoff in different SRUs of Betwa basin for the year 2011

SRU1			SRU2			SRU3			SRU4		
Rainfall, mm	Runoff, mm	Runoff, MCM	Rainfall, mm	Runoff, mm	Runoff, MCM	Rainfall, mm	Runoff, mm	Runoff, MCM	Rainfall, mm	Runoff, mm	Runoff, MCM
32.2	8.0	74.6	46.6	7.1	33.8	28.5	3.6	61.4	36.9	9.7	116.6
76.1	38.1	357.3	159.1	114.1	540.9	111.7	80.5	1371.0	61.3	25.3	303.4
199.1	148.2	1390.4	42.7	15.2	71.9	83.6	54.7	930.4	160.8	109.5	1311.6
116.0	71.7	673.0	40.1	13.5	64.0	80.9	52.2	889.1	65.8	28.6	342.5
83.4	44.0	412.5	48.5	19.1	90.5	46.1	2.6	44.2	41.0	12.0	144.2
38.1	3.5	32.7	13.2	0.9	4.3	15.5	2.8	46.9	19.1	2.0	23.8
14.4	1.0	9.1	35.6	3.4	16.2	15.0	2.5	43.4	26.7	4.8	57.0
34.6	2.6	24.2	19.9	3.0	14.0	39.7	17.7	301.1	14.2	0.8	9.1
34.5	9.2	86.1	18.8	2.6	12.1	32.9	5.2	88.8	30.3	6.4	76.4
13.0	0.7	6.3	59.7	12.8	60.6	9.1	0.6	10.6	33.0	1.8	21.8
27.7	5.7	53.7	36.9	11.5	54.6	13.1	1.8	30.9	14.1	0.7	8.9
16.1	1.4	13.0	77.9	6.3	29.8	35.7	14.8	251.3	22.4	3.1	36.9
45.5	15.8	147.9	17.7	2.2	10.3	35.1	14.3	244.1			
						9.2	0.6	11.0			
						39.8	17.8	302.4			
						18.7	4.2	71.9			
						67.6	24.0	408.7			
						15.3	2.7	45.5			
						19.1	4.4	75.3			
						9.2	0.6	11.0			
730.7	349.7	3280.8	616.7	211.5	1003.2	725.8	307.8	5238.8	525.6	204.7	2452.2

Appendix XXV
Cropping pattern practiced in various SRUs of the study basins for the year 2011

Gomti basin

	Irrigated area (ha)				Rainfed area (ha)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	0	0	0	0	2609	42895	3472	19262
Groundnut	31	0	0	93	2571	7381	0	3686
Maize	476	1142	157	943	2824	18625	20758	26729
Pearl millet	77	0	0	1	623	12265	4543	3455
Pigeon pea	2	23	0	1	365	21971	6190	2930
Paddy	106902	400532	77190	137272	7981	7415	118	2681
Sesame	20	3	0	11	2809	8461	324	16905
Sorghum	22	3	0	14	207	17181	2397	5132
Sugarcane	70092	16017	5208	67073	14370	937	0	5635
Chickpea	7	959	62	114	33	11100	3113	683
Lentil	0	0	0	0	9343	13739	133	16135
Mustard	8975	24169	1224	12459	3957	2721	246	3684
Peas	340	9225	3694	1850	0	0	0	0
Potato	1740	26857	5592	6438	241	3495	314	1760
Wheat	118613	617519	117225	274198	1905	3266	389	0

Betwa basin

	Irrigated area (ha)				Rainfed area (ha)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	0	0	0	0	17545	22788	10537	99019
Groundnut	94	9	0	9139	17217	6114	3300	34682
Maize	5	1	0	0	32558	9	9404	3538
Pigeon pea	0	0	5	12	176	10433	12352	6741
Paddy	207	135	2	837	8462	1372	8079	30998
Sesame	0	0	1	0	4281	6098	1290	28322
Sorghum	0	0	0	0	12015	28439	9011	14031
Soybean	10	0	48	21600	42820	321	301498	35171
Chickpea	66694	19385	110553	47891	59097	93161	211271	81925
Lentil	0	0	0	0	45736	42266	122994	30581
Mustard	1405	792	45	3260	32833	4310	4888	979
Peas	34165	38289	11912	62092	0	0	0	0
Wheat	127358	88534	210636	254747	41662	17677	171825	15001

Appendix XXVI

Optimal cropping pattern of the SRUs to reduce the blue WF of irrigated areas in the basins

Gomti basin

	Irrigated area (ha)				Rainfed area (ha)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	0	0	0	0	0	0	37802	21004
Groundnut	0	0	11235	0	0	0	0	0
Maize	0	67134	0	0	0	0	0	0
Pearl millet	0	0	0	0	0	0	0	18111
Pigeon pea	0	0	0	0	0	30714	0	0
Paddy	10370	323604	71320	205409	13415	106416	0	25012
Sesame	0	26983	0	0	0	0	0	0
Sorghum	0	0	0	0	0	0	0	22289
Sugarcane	146404	0	0	0	20942	0	0	0
Chickpea	0	0	925	0	1829	13100	0	0
Lentil	0	0	0	0	1517	9935	0	27898
Mustard	0	0	36004	0	0	6414	4195	0
Peas	0	0	12026	0	0	0	0	0
Potato	0	37002	0	0	0	5810	0	0
Wheat	53363	657744	56492	362130	5561	0	0	0

Betwa basin

	Irrigated area (ha)				Rainfed area (ha)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	0	0	56	11969	0	0	0	144115
Groundnut	0	0	0	0	0	0	0	67956
Maize	0	0	0	0	0	0	29928	0
Pigeon pea	0	0	0	0	20553	0	0	0
Paddy	0	0	0	0	0	35047	0	0
Sesame	0	0	0	0	24834	0	0	0
Sorghum	0	0	0	0	0	40527	16335	0
Soybean	0	0	0	0	89686	0	309207	40433
Chickpea	0	0	257246	0	0	52155	393298	0
Lentil	0	0	0	0	114551	105259	0	0
Mustard	0	0	0	0	33983	0	0	0
Peas	0	113454	0	0	0	0	0	0
Wheat	229622	33546	35758	367991	0	0	117679	128487

Appendix XXVII
Optimal cropping pattern of the SRUs to reduce green WF of rainfed areas in the basins

Gomti basin

	Irrigated area (ha)				Rainfed area (ha)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	0	0	0	0	0	0	0	0
Groundnut	0	0	0	0	0	0	0	0
Maize	0	0	5866	0	0	0	0	0
Pearl millet	0	0	0	0	0	0	0	0
Pigeon pea	0	58667	0	0	0	0	0	0
Paddy	177622	359054	76689	205409	34357	125082	37802	0
Sesame	0	0	0	0	0	0	0	0
Sorghum	0	0	0	0	0	0	0	0
Sugarcane	0	0	0	0	0	0	0	0
Chickpea	0	251011	0	0	0	0	0	0
Lentil	0	0	0	0	0	0	0	0
Mustard	0	0	0	0	0	0	0	0
Peas	0	0	0	0	0	0	0	0
Potato	0	45374	0	0	0	0	0	0
Wheat	129675	382345	36592	295058	0	0	0	0

Betwa basin

	Irrigated area (ha)				Rainfed area (ha)			
	SRU1	SRU2	SRU3	SRU4	SRU1	SRU2	SRU3	SRU4
Black gram	0	0	0	0	0	0	0	0
Groundnut	0	0	0	0	0	0	0	0
Maize	0	0	0	0	0	0	23410	0
Pigeon pea	0	0	0	0	0	0	43435	0
Paddy	317	146	56	31587	135073	75575	288625	252503
Sesame	0	0	0	0	0	0	0	0
Sorghum	0	0	0	0	0	0	0	0
Soybean	0	0	0	0	0	0	0	0
Chickpea	0	0	0	96049	0	0	0	0
Lentil	0	0	0	0	0	0	0	0
Mustard	0	0	0	0	0	0	0	0
Peas	0	0	0	0	0	0	0	0
Wheat	229622	147000	333146	34726	0	0	0	0