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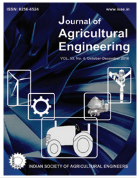

Assessment of Water Footprints in Betwa River Basin under Limited Data Availability

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ABSTRACT

In the context of intensive water consumption patterns emanating from urbanization and accelerated economic growth, water footprint (WF) has been recognized as comprehensive measure to promote efficient, equitable and sustainable use of water resources. In the present study, the WF of a river basin was assessed and blue, green and grey water footprints of major water-consuming sectors of agriculture, domestic and industry within the Betwa river basin were quantified. Sustainability of the blue and grey WFs were analysed to identify temporal hotspots wherein water consumption and pollution infringed upon environment flow requirements. Total annual WF of the Betwa river basin was estimated as 9186 Mm^3. Agricultural sector was the largest water consumer accounting for 96.4 % of the total WF, followed by the industrial and domestic sectors (2.2 %). The WF of rainfed and irrigated agriculture was 3868 and 4986 Mm^3, respectively. The comparable proportions of blue (45.5 %) and green (43.6 %) WFs in total WF highlighted equal dependence on rainfall, surface water and groundwater resources. The study demonstrated that consumption-based approach of WF provided more realistic estimates of the water uses at river basin scale. Higher values of sustainability indicators like Blue Water Scarcity Index (>400 during December, January and February) and Water Pollution Index (>135 during January and February) indicated that the pattern of human consumption of blue water and resultant pollution was encroaching into environmental flows within the Betwa river basin.

***Keywords*:** Virtual water content, water footprint, sustainability assessment, blue water scarcity index, water pollution index

Water footprint (WF) is a measure of human's appropriation of freshwater resources, which measures the 'water use' in terms of volume consumed or polluted per unit of time (Hoekstra *et al*., 2011). The concept of WF is being used by agricultural, commercial and industrial water users to measure and report their water consumption, assess the magnitude of environmental impact(s) arising from this consumption, and to identify opportunities for risk mitigation strategies that promote sustainable water use (Zeng *et al*., 2012; Dumont *et al*., 2013). The WF and Virtual Water Content (VWC) are the relatively new approaches used to promote efficient, equitable and sustainable use of water resources at different geographical scales such as river basin, state, and country (Hoekstra and Chapagain, 2007; Liu and Savenije, 2008; Hoekstra *et al*., 2011; Dumont *et al*., 2013). In addition, the WF also distinguishes between blue water (surface water and groundwater), green water (precipitation used as soil moisture) and grey water (freshwater required to assimilate pollution). The WF analysis involves a four-step process: (i) setting goal and scope of the WF accounting, (ii) assessment of WF, (iii) assessment of sustainability of WFs, and (iv) response formulation (Hoekstra *et al*., 2009).

Several studies covered the first two steps of the WF analysis (Feng *et al*., 2012; Zhao *et al*., 2015), and only a few extended it up to the third step of sustainability assessment (Zeng *et al*., 2012; Pellicer-Martínez and Martínez-Paz, 2016). Sustainability analysis compares blue WF with blue water availability to locate the spatial and temporal hotspots where the WF exceeds the water availability (Witmer and Cleij, 2012). Recent studies used WF based 'water scarcity indices' to identify hotspots of water scarcity (Jefferies *et al*., 2012; Zeng *et al*., 2013). Zeng *et al*. (2012) analysed the sustainability of WF within the Heihe River Basin (HRB) in northwest China and found that blue WF within the HRB exceeded blue water availability during eight months per year and also on annual basis. Hoekstra *et al*. (2012) quantified blue water scarcity in more than 400 river basins all over the world at a monthly time-step and found severe water scarcity in 201 river basins with 2.67 billion inhabitants during at least one month in the year.

It was revealed from the literature that studies dealing with assessment of water footprints mainly focused on large spatial scales such as the global, national and district levels. Very few studies reported assessment and sustainability of WFs for river basins. Therefore, the present study aimed at estimation of blue, green and grey WFs of agriculture, livestock, domestic and industrial sectors in Betwa river basin located in a semi-arid region of India. This study further assessed sustainability of water consumption patterns in the study area.

MATERIALS AND METHODS

Study Area Description

The present study was carried out at ICAR-Indian Agricultural Research Institute, New Delhi to assess the WF of Betwa river basin located in the semi-arid region of India (Fig. 1). The basin covers an area of 43,120 km^2, out of which 68 % is in Madhya Pradesh and 32 % is in Uttar Pradesh. The upper region of the basin is hot and dry sub-humid, while in lower reaches it is characterized as hot and moist semi-arid. The average annual rainfall and evaporation are 1,138 and 787 mm, respectively. The average annual temperature of the basin is 23.5 ^{o}C, and it ranges from 22 ^{o}C at upstream end to 25 ^{o}C at downstream end. Groundwater is the only reliable source of water for irrigation, domestic and industrial uses within the area (Nag and Kundu, 2018; Bisht *et al*., 2018). There is a substantial bias towards cultivation of wheat and chickpea crops as is evident from their higher share (56 %) in total cropped area in the basin (Table 1).

Data Collection

The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at 90 m spatial resolution was obtained from the website https://lpdaac.usgs.gov/ for delineating the basin boundary using ArcGIS. The land use/cover map for the year 2011 was obtained from the Bhuvan portal (http://bhuvan-noeda.nrsc.gov.in) of the Indian Space Research Organization (ISRO, 2012). The soil properties *viz.* sand, silt, clay percentages and bulk density were taken from the Harmonized World Soil Datasets, version 1.2 (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008) of the Food and Agriculture Organization (FAO), Rome, available at the website (https://eusoils.jrc.ec.europa.eu/). Other soil properties like field

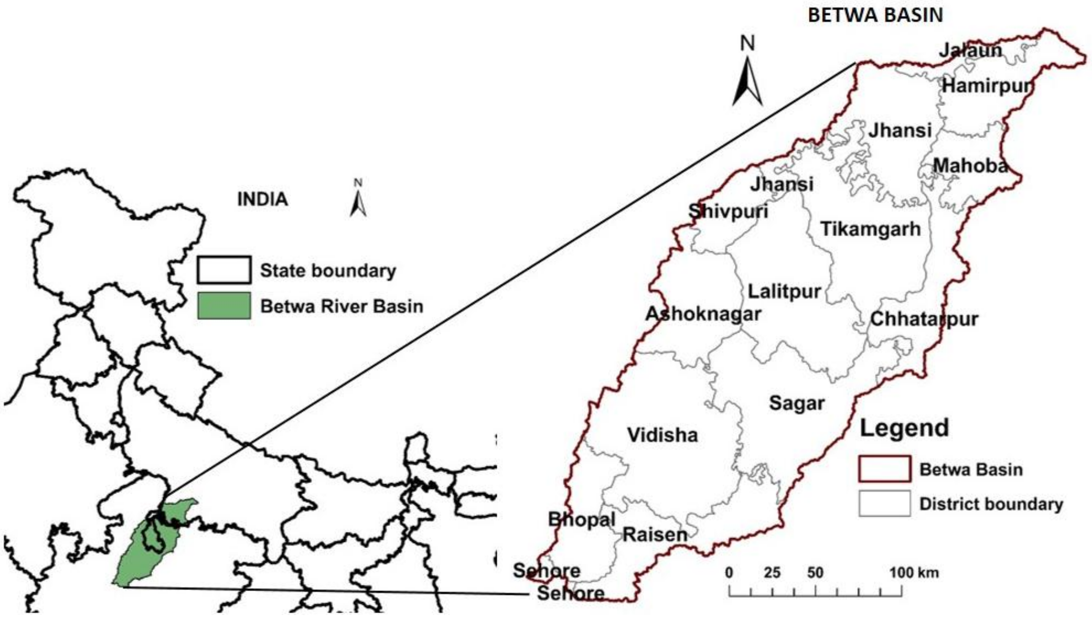

Fig. 1: Location of Betwa River basin showing administrative districts

Table 1. Water footprints (WFs) of crop production under irrigated and rainfed areas in Betwa river basin

Crop	Cropped area, ha		Water footprint of area, Mm^3					Total WF of crop
			Irrigated				Rainfed	
	Irrigated	Rainfed	Blue	Green	Grey	Total	Green	
Black gram	0	149889	0	0	0	0	414.8	414.8
Groundnut	244524	445454	31.8	17.8	0	49.6	174.2	223.8
Maize	9243	61314	0	0	0	0	149.4	149.4
Pigeon pea	0	241578	0.1	0	0	0.1	143.4	143.5
Paddy	6	45508	3.6	3.7	0.8	8.1	161.6	169.7
Sesame	5502	43010	0	0	0	0	133.3	133.3
Sorghum	1181	48912	0	0	0	0	273.8	273.8
Soybean	146459	0	58.6	46.4	6.5	111.5	1483.6	1595.1
Chickpea	17	29703	746.0	28.0	0	774.0	346.1	1120.1
Lentil	1	39990	0	0	0	0	171.8	171.8
Mustard	0	63496	16.0	1.5	2.8	20.3	42.5	62.8
Peas	21657	379809	442.3	3.1	0	445.4	0	445.4
Wheat	681275	246166	2727.3	32.8	817.5	3577.6	374.0	3951.6
Total Water Footprint			4025.7	133.3	827.6	4986.6	3868.5	8855.1
% share in total WF_c			45.5	1.5	9.3	56.4	43.7	100.0

capacity, wilting point and maximum infiltration were estimated using pedotransfer functions for the Indian soils developed by Adhikari *et al.* (2008). The agro-ecological map of the basin was digitized from the country level agro-eco region map available at the ICAR-National Bureau of Soil Survey and Land Use Planning (ICAR-NBSS & LUP), Nagpur. District-wise data of crop production and cropped areas were collected from the Department of Economics and Statistics, Government of India (http://eands.dacnet.nic.in). The crop parameters like sowing and harvesting dates were obtained from the Department of Economics and Statistics, Government of India (MOAFW, 2011) and Crop Science Division of the Indian Council of Agricultural Research, New Delhi. The crop coefficients (Kc) values for initial, mid-season, developmental and late-season stages of crop growth were obtained from Allen *et al.* (1998). The gridded (0.5°×0.5°) climate dataset of India Meteorological Department (IMD), Pune, available at website of National Innovations in Climate Resilient Agriculture (NICRA, 2012) were used to get the district-wise climatic data within the basin. District-wise annual utilizable ground water resource data were collected from the Central Ground Water Board (CGWB, 2011). District-wise livestock population data required in estimating WF of livestock were collected from the Department of Animal Husbandry and Fisheries of Uttar Pradesh and Madhya Pradesh states. Most of the datasets relating to cropped areas, crop production, water withdrawals, animal census and utilizable groundwater resources were available at district levels. Non-availability of the data at river basin scale was the major limitation of this study.

Delineating basin into homogenous spatial units

There is a large spatial variation in the crop evapotranspiration demand (Mali *et al.,* 2015) in the Betwa basin, and the assumption of uniform crop water requirements over entire basin may lead to non-realistic WF assessments. To improve the accuracy of WF estimation and to account for the spatial variability in the ETc, the study area was subdivided into homogeneous spatial units according to the district boundary, soil type and agro-ecological regions (Fig. 2) of the basin. The resulting polygons, called the agricultural production units (APUs), were homogeneous units in terms of soil and climate (Fig. 3a). The WF of a crop in each of the APU was assessed and summed to get the WF at basin level.

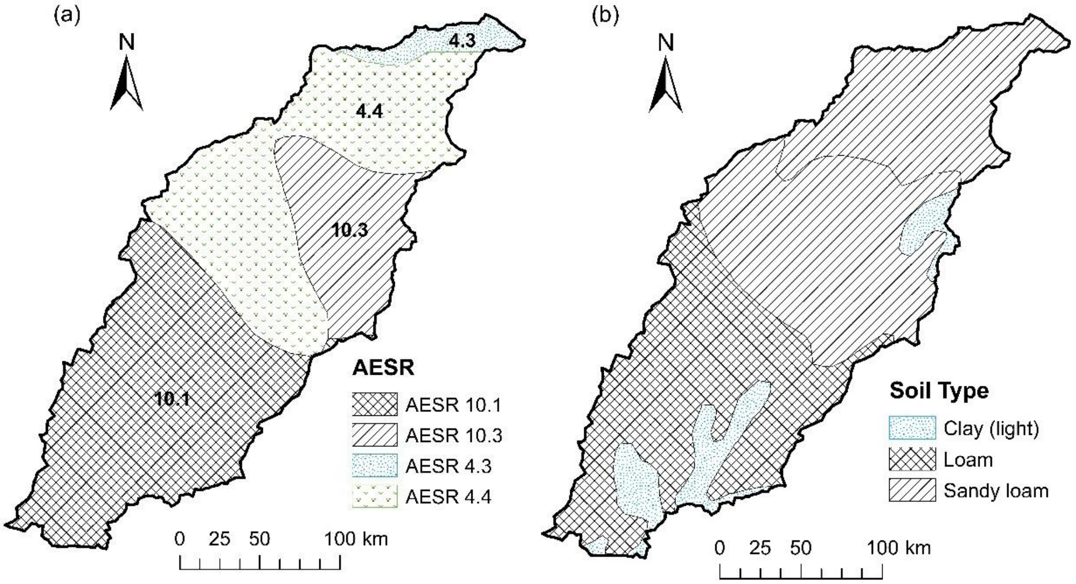

Fig. 2: Maps of (a) agro-ecological sub-regions and (b) soil type of study area

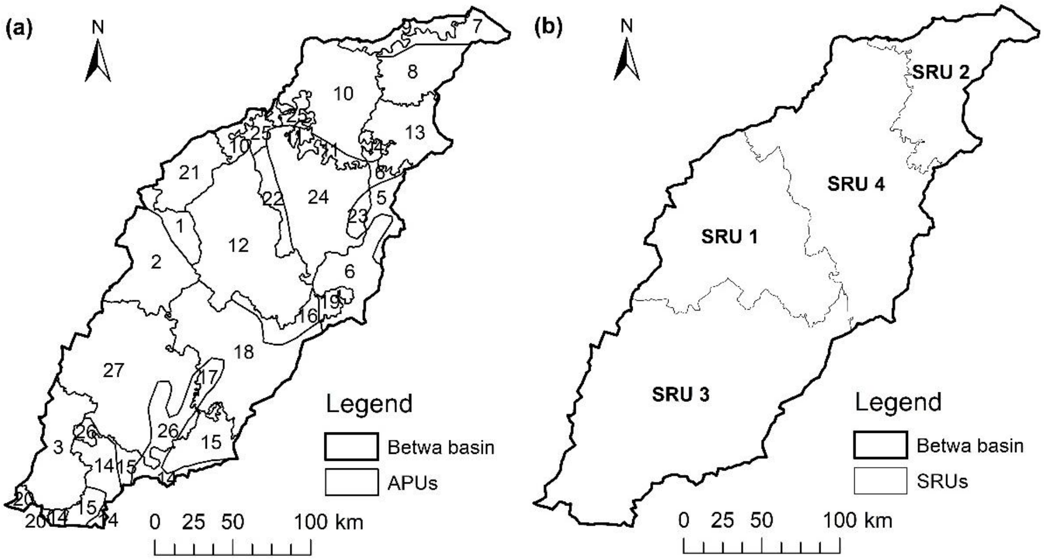

Fig. 3: Delineated agricultural production units (APUs) (a) and Spatial Resolution Units (SRUs) (b) in study area

Further, in order to assess the daily runoff, it was required to reduce the number of units of assessments (APUs) for reducing the computational load. Therefore, the delineated 27 APUs were grouped into four Spatial Resolution Units (SRUs) on the basis of crop ETc using statistical clustering approach (Yan *et al.,* 2001). This clustering was based on the evapotranspiration (ETc) values of 13 crops estimated for 27 APUs. The ETc values of 13 crops formed 13 dimensional vectors in statistical *k*-means clustering and the analysis led to formation of 4 SRUs in the Betwa basin (Fig. 3b). In present study, area weighted proportionality factors were used to downscale the data pertaining to cropped areas, water withdrawals and water resources to APU level. Further, the district level climatic parameters were reasonably assumed to be the same for all the APUs of that district.

Estimating Crop Water Requirements

Crop evapotranspiration (ETc) is a basic parameter that is required for the assessment of WF of crops. The ETc values of 13 major crops (wheat, paddy, black gram, maize, lentil, pigeon pea, sorghum, chickpea, sesame, peas, groundnut, mustard and soybean) considered in this study were estimated for each of the APUs. Due to non-availability of data pertaining to area and production, other minor crops like vegetables (tomato, brinjal, cow pea, cabbage, cauliflower, and okra), fruit crops (mango, guava, litchi, and banana) and crops like safflower, ragi, barley, sunflower, hay and pastures were not considered in this study. These crops share only 19 % of the gross cropped area in the study area.

The APU-wise soil and climate data were used in estimating the ETc of 13 crops using the original Penman-Monteith approach (Allen *et al*., 1998). Daily crop water requirements, in terms of blue crop water use (CWU_{blue}) and green crop water use (CWU_{green}), were estimated from planting to harvesting period using CROPWAT software for the year 2011 (Allen *et al*., 1998; FAO, 2012). The year 2011 was selected as that year was a normal year as per the criterion (annual rainfall ±19% of normal rainfall) given by India Meteorological Department (IMD, 2012).

The daily minimum and maximum temperature values were used as input to the CROPWAT software, and other climatic parameters such as relative humidity, wind velocity, sunshine hours and solar radiation were estimated using in-built functions available in the software. The software was also used for simulating soil water balance under both rainfed and irrigated conditions and irrigation scheduling at daily time step. The USDA effective rainfall method was used to assess the CWU_{green} (Dastane, 1974). The reduced crop yields under rainfed conditions were estimated using linear relationship between grain yield and evapotranspiration (Doorenbos and Kassam, 1979).

Estimating Dilution Water Requirement of Crops

The dilution water requirement (*DWRc*) of a crop is the volume of water required to dilute the amount of leached pollutant to an extent that meets the desired standard of drinking water quality. In the study area, intensification of agricultural and industrial activities has led to nitrate pollution of groundwater (Bijay *et al*., 1994; Srinivas Rao, 1998). Hence, the *DWRc* ($m^3.ha^{-1}$) in terms of grey water for crop production was estimated for nitrate leaching in this study using the following expression (Hoekstra *et al*., 2011):

$$DWR_c = \frac{NAR_c \times lf_c}{rl} \quad ...(1)$$

Where,

NAR_c = Crop-specific nitrogen application rate, $kg.ha^{-1}$,

lf_c = Crop-specific percentage of applied nitrogen leaching to groundwater, %, and

rl = Recommended level of nitrate into groundwater as per the drinking water quality standards, $mg.l^{-1}$.

The *DWRc* was multiplied with cultivated areas of the crop to obtain the crop-specific total grey WF for the study area. The NAR_c is the product of cultivated area (ha) of a crop within the basin and the recommended dose of nitrogen for that particular crop ($kg.ha^{-1}$). Due to limited spatial information on leaching percentages, a uniform leaching fraction was considered over entire river basin to estimate the grey WF. Chapagain and Hoekstra (2011), while analysing the WF of paddy production in 13 major paddy growing countries, considered 5 % of applied nitrogen as leaching and permissible nitrogen concentration limit as 50 $mg.l^{-1}$ to estimate the amount of *DWRc*. In this study, the same permissible nitrogen limit (50 $mg.l^{-1}$) was considered. Leaching fractions were taken from earlier studies reported under Indian conditions [3 % for pearl millet (Kapoor *et al*., 2011), 12 % for paddy (Pathak *et al*., 2006), 10 % for wheat (Mittal *et al*., 2007), 6 % for maize (Arora *et al.,* 1980), 10 % for potato (Behera and Panda, 2009) and 6.2 % for soybean (Mohanty *et al.,* 2016)]. Due to low nitrogen application rates and larger areas under rainfed conditions, the nitrogen leaching from chickpea, pigeon pea, groundnut, sesame, peas, sorghum, black gram and lentil was not considered while estimating grey WF in the study area.

Computing Virtual Water Content of Crops

Virtual Water Content (VWC) is the amount of water (m^3) needed during the entire crop duration to produce a unit quantity of produce (ton). In the present study, the main product was only considered in estimating the blue, green and grey WF of crop production. The blue, green and grey VWCs of crops in each APU were computed by dividing the blue (surface water and groundwater), green (effective rainfall) and grey (dilution water requirement) water use with the crop yields; and addition of these three components of the crop water uses led to the total VWC of a crop as shown below (Hoekstra *et al*., 2011):

$$VWC_{blue,c,k} = \frac{CWU_{blue,c,k}}{Y_{c,k}} \quad ...(2)$$

$$VWC_{green,c,k} = \frac{CWU_{green,c,k}}{Y_{c,k}} \qquad ...(3)$$

$$VWC_{grey,c,k} = \frac{DWR_{c,k}}{Y_{c,k}} \qquad ...(4)$$

$$VWC = VWC_{blue,c,k} + VWC_{green,c,k} + VWC_{grey,c,k} \qquad ...(5)$$

Where,

$VWC_{blue,c,k}$ = Blue virtual water content of crop *c* in k^{th} APU, $m^3.t^{-1}$,

$VWC_{green,c,k}$ = Green virtual water content of crop *c* in k^{th} APU, $m^3.t^{-1}$,

$VWC_{grey,c,k}$ = Grey virtual water content of crop *c* in k^{th} APU, $m^3.t^{-1}$,

$CWU_{blue,c,k}$ = Blue water use of crop *c* in k^{th} APU, $m^3.ha^{-1}$,

$CWU_{green,c,k}$ = Green water use of crop *c* in k^{th} APU, $m^3.ha^{-1}$,

k = Index for APU,

DWR_c = Dilution water requirement of crop *c* in k^{th} APU, $m^3.ha^{-1}$, and

$Y_{c,k}$ = Yield of crop *c* in k^{th} APU, $t.ha^{-1}$.

Estimating Water Footprint of Crop Production

The WF of crop production was estimated by multiplying VWC of each crop with its annual production (ton) within the APU and then summing up for all crops (Hoekstra *et al.*, 2011). The total WF of crop production (WF_{crop}) in the basin is the sum of blue, green and grey WF of that crop.

$$WF_{crop} = \sum_{c=1}^{n}\sum_{k=1}^{m}\{WF_{blue,c} + WF_{green,c} + WF_{grey,c}\} \qquad ...(6)$$

$$WF_{blue,c} = \sum_{c=1}^{n}\sum_{k=1}^{m} VWC_{blue,c,k} \times P_{c,k} \qquad ...(7)$$

$$WF_{green,c} = \sum_{c=1}^{n}\sum_{k=1}^{m} VWC_{green,c,k} \times P_{c,k} \qquad ...(8)$$

$$WF_{grey,c} = \sum_{c=1}^{n}\sum_{k=1}^{m} VWC_{grey,c,k} \times P_{c,k} \qquad ...(9)$$

Where,

WF_{crop} = Total WF of crop production within the basin, m^3,

$WF_{blue,c}$ = Blue WF of crop production within the basin, m^3,

$WF_{green,c}$ = Green WF of crop production within the basin, m^3,

$WF_{grey,c}$ = Grey WF of crop production within the basin, m^3,

c = Index for crop,

m = Total number of APUs within the basin (27 in this study),

k = Index for APU,

n = Total number of crops considered, and

$P_{c,k}$ = Production of a crop *c* in k^{th}APU, t.

Computing Water Footprint of Livestock

The consumptive use of water for livestock consists of three components: water required to produce animal feed, drinking and cleaning purposes (Mekonnen and Hoekstra, 2012). In the study area, the animal feed mostly comes from crop residues and other products of maize, sugarcane, sorghum and de-oiled cakes of soybean and groundnut. Thus, a major portion of feed water requirement (WF of animal feed) was already accounted in WF of crops; and hence, the same was not separately considered (Dumont *et al.*, 2013). Also, a major portion of water consumed in livestock cleaning returns to waterbodies; therefore, consumptive use of water in cleaning of livestock was neglected. Hence, the WF of livestock (WF_{ls}) mainly consists of drinking water requirement, which is mainly blue water use, as expressed below:

$$WF_{ls} = \sum_{k=1}^{m}\sum_{t=1}^{p}\sum_{g=1}^{q}\{APop[t,g,k] \times WR_d[t,g]\} \qquad ..(10)$$

Where,

WF_{ls} = WF of livestock, m^3,

$APop[t,g,k]$ = Population of animal type *t* in the *g* age group in k^{th}APU, number,

$WR_d\,[t,g]$ = Drinking water requirement of animal type *t* in the *g* age group, $m^3.yr^{-1}$,

p = Number of animal types, and

q = Index of age groups in an animal type *t*.

All the major animal types present in the study area, viz., cattle, buffalo, sheep, goat, horse, donkey and pig were considered in this study. District-level animal population densities and area of the APU within the district were used to get the animal population in each APU. The estimated WF_{ls} for the year 2011 was equally distributed over each month to derive the monthly WF_{ls}.

Estimating Water Footprint of Industrial and Domestic Sectors

Groundwater is the main source of industrial and domestic water uses in the study area. The WF of industrial and domestic sectors was estimated by multiplying water withdrawal with a water consumption ratio (*WCR*). Due to lack of information on pollutant load discharged in the area by industries, the grey WF resulting from discharge of pollutants in the waterbodies was not included.

$$WF[b]_{dom+ind} = \sum_{k=1}^{m} GWW[k]_{dom+ind} \times WCR \quad ...(11)$$

$$GWW[k]_{dom+ind} = GWW[d]_{dom+ind} \times \frac{Aapu_{k,d}}{A_{t,d}} \quad ...(12)$$

Where,

$WF[b]_{dom+Ind}$ = Water footprint of domestic and industrial sectors within the basin, m^3,

$GWW[k]_{dom+ind}$ = Groundwater withdrawal for domestic and industrial purposes in k^{th} APU, m^3,

$GWW[d]_{dom+ind}$ = Groundwater withdrawal for domestic and industrial purposes in district d, m^3,

WCR = Water consumption ratio, fraction,

$Aapu_{k,d}$ = Area of k^{th}APU within the district d, ha, and

$A_{t,d}$ = Total geographical area of district d, ha.

The WF estimated using the above equation does not include the WFs of livestock sector. In present study, WCR of 0.1 was considered while estimating the WF of domestic and industrial sectors. WCR values of 0.05-0.15 were reported in earlier studies (Hoekstra and Mekonnen, 2012; Herrebrugh, 2018).

Assessing Blue Water Availability

Sustainability assessment requires monthly values of blue and grey WF to be compared with blue water availability of the respective months. Due to lack of river discharge data for the study basin, the natural surface runoff in each SRU was assessed using NRCS CN method (USDA, 1986). Each SRU was divided into Hydrological Response Units (HRUs) on the basis of soil type and land use. Daily actual runoff was estimated for each HRU using the CN method, and daily runoff values were summed upto obtain monthly surface runoff) in each SRU. The quantity of surface water available for human consumption (SW_{blue}) is the natural runoff minus the environmental flow requirements (EFR). In previous WF studies (WWF, 2010; Hoekstra and Mekonnen, 2012; Zeng *et al*., 2012), the EFR was estimated using the "presumptive environmental flow standard" defined by Richter *et al*., (2011). In order to account for the temporal variability of natural runoff, the monthly environmental flow requirement ($EFR[t]$) of the study area was estimated using the Variable Flow Method (VFM) (Pastor *et al*., 2013), which takes into account intra-annual variability of runoff.

For a particular time, step [t], the surface water availability within the basin was estimated as the sum of the monthly surface water availability from all the SRUs ($SW_s[t]$).

$$SW[t] = \sum_{s=1}^{r} SW_s[t] \quad ...(13)$$

Where,

$SW[t]$ = Monthly surface water availability in the basin, m^3,

$SW_s[t]$ = Monthly surface water availability in a SRU, m^3,

s = Index for SRU, and

r = Number of SRUs in the basin.

The utilizable groundwater resource within the study area ($GW[b]$) was estimated using the following equation:

$$GW[b] = \sum_{k=1}^{m} UGW_d \times \frac{Aapu_{k,d}}{A_{t,d}} \quad ...(14)$$

Where, UGW_d = utilizable groundwater resource of the district as obtained from the CGWB.

Since CGWB provides utilizable groundwater resource data on annual basis, the estimated annual groundwater availability within the basin was equally distributed over 12 months (Zeng *et al.,* 2012) in order to obtain the monthly groundwater resource availability ($GW[t]$).

The blue water resources availability at time t ($WA_{blue}[t]$) within the study area was estimated as follows:

$$WA_{blue}[t] = SW[t] + GW[t] - EFR[t] \quad ...(15)$$

Where,

$WA_{blue}[t]$ = Monthly blue water availability, m^3, and

$EFR[t]$ = Monthly environmental flow requirement, m^3.

Assessing Sustainability of Blue and Grey Water Footprints

Sustainability of blue and grey WFs at monthly time step was assessed using 'Blue Water Scarcity Index' (BWSI) and 'Water Pollution Index' (WPI) criteria. During certain time step *t*, if blue WF (WF_{blue}) exceeds blue water availability (WA_{blue}), there is reason for sustainability concern (Hoekstra *et al.*, 2012). Also, if the value of WPI exceeds 100 %, there is concern about the sustainability of grey WF.

Mathematically, the BWSI and WPI are expressed as (Schmid *et al.*, 2009; Liu *et al.*, 2018):

$$BWSI[t] = \frac{WF_{blue}\,[t]}{WA_{blue}\,[t]} \times 100 \qquad ...(16)$$

$$WPI[t] = \frac{WF_{grey}\,[t]}{R_{act}\,[t]} \times 100 \qquad ...(17)$$

Where,

BWSI[t] = Blue water scarcity index, %,

WPI[t] = Water pollution index, %,

R_{act} [t] = Monthly natural runoff in the basin, m^3, and

t = Index for month of year (1 to 12).

RESULTS AND DISCUSSION

Virtual Water Content of Crops

The values of VWC_{blue} for *rabi* crops varied from 2473 m^3.t^{-1} (wheat) to 5860 m^3.t^{-1} (lentil). For *kharif* crops, it ranged from 1818 m^3.t^{-1} (maize) to 8956 m^3.t^{-1} (sesame). Maize being a short duration *kharif* crop had the lowest value of ; while because of its low productivity, sesame showed highest VWC_{blue} (Fig. 4). In a particular agro-climatic setup, low values of VWC indicates higher crop productivities or lower crop water requirements. The estimated value of VWC of the crops in this study were slightly higher than those reported in earlier study for Madhya Pradesh (Kampman *et al.*, 2008). This variation in the VWC values might be due to the difference in spatial scales in both the studies. The earlier study of Kampman *et al.* (2008) estimated state-level WF of crops for India, whereas the present study estimated the VWC of crops at higher spatial resolution of APU.

The proportion of blue water in the total VWC ranged from 43.9 % to 66.8 % for *kharif* crops, and from 76.5 % to 99.5 % for *rabi* crops. Shorter crop durations in *kharif* season and adequacy of rainfall to meet the crop water requirements resulted in lesser proportion of blue water in the total VWC of maize, paddy, black gram, groundnut, pigeon pea, sesame, sorghum and soybean. Black gram and pigeon pea had the highest value of VWC. Higher dose of fertilizer application at 120, 100 and 60 kg.ha^{-1} in case of wheat, mustard and paddy, respectively, (Dubey et al., 2015; Shekhawat et al., 2015) and combined with accelerated leaching of fertilizers resulted in higher proportions of grey VWC for wheat (22.8 %), mustard (13.5 %) and paddy (11.5 %). Compared to wheat, the lower percentage of grey VWC in case of rice was due to lower nitrogen application rate in this crop.

Water Footprint of Crop Production

Estimates of the water footprints of irrigated and rainfed crops are presented in Table 1. The annual WF of crops was estimated as 8855.1 Mm^3 in the area with irrigated agriculture accounting for 56.3% of the total WF of crops. A major portion of the WF from irrigated crops came from wheat (3577.6 Mm^3, 71.7%) and chickpea (774 Mm^3, 15.5 %). Water footprint of rainfed agriculture mainly came from the consumption of rainwater in the form of crop evapotranspiration. A major proportion (61.8 %) of the cultivated areas in the study area depended on rainfall. Rainfed agriculture accounted for 43.7 % (3868.5 Mm^3) of the WF of the crop production in the basin (Table 1). Black gram, soybean, sorghum, chickpea and wheat were the major crops that together accounted for 74.8 % of the WF of rainfed crop production. In case of irrigated agriculture, blue, green and grey WF accounted for 80.9 %, 2.7 % and 16.4 % of total WF of irrigated crops, respectively. Wheat, chickpea and peas were major contributors to blue WF under irrigated agriculture. Overall, grey WF accounted for 9.4 % (827.6 Mm^3) of the total WF of crop production in the area. A comparable share of green (45.2 %) and blue (45.5 %) water components in total WF of crops (irrigated + rainfed) highlighted that crop production in the study area was as equally dependent on irrigation (surface water and groundwater resources) as also on rainfall. Due to their larger area under cultivation, crops like wheat, soybean and chickpea accounted for a substantial portion of WF of the basin. At the national level, paddy, wheat, coarse

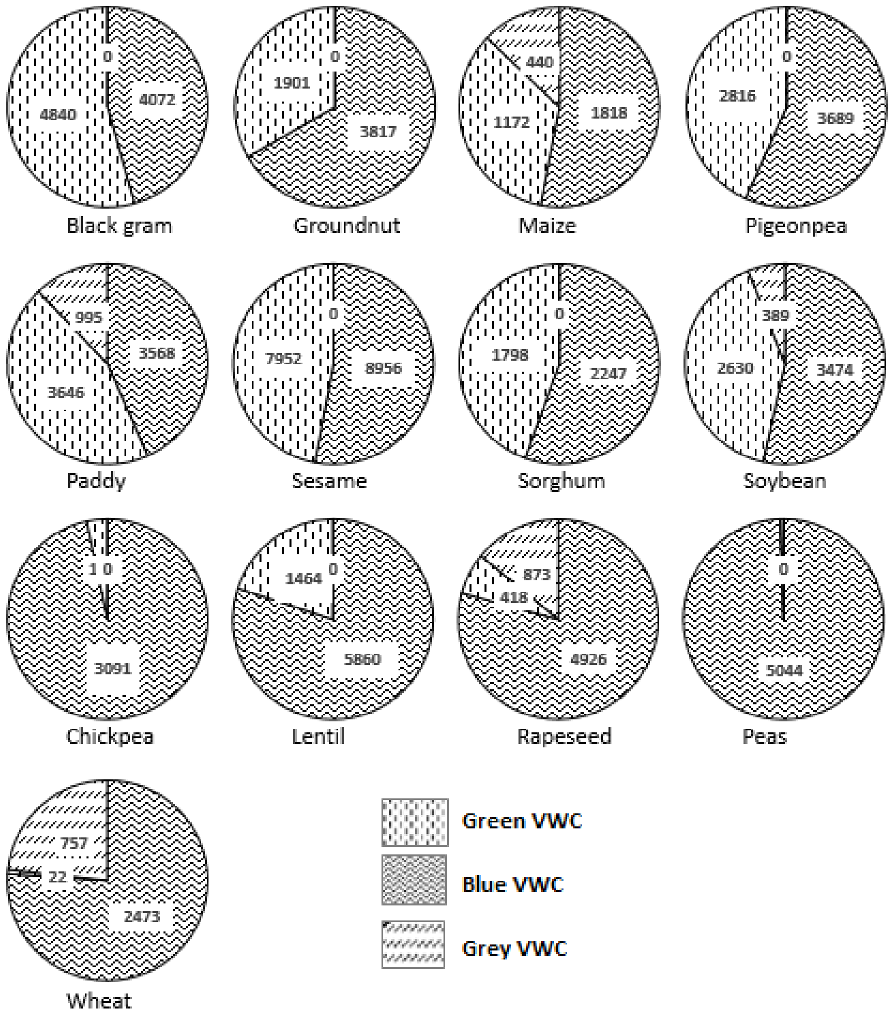

Fig. 4: **Average blue, green and grey virtual water content of crops ($m^3.t^{-1}$) under irrigated conditions in study area**

cereals and sugarcane were the major contributors to total WF (Kampman *et al.*, 2008).

Water Footprint of Livestock

Annual water footprint of livestock production) was 129.6 Mm^3 (Fig. 5). Cattle and buffalo accounted for more than 80 % of WFls in the study area, which was mainly due to large population of these animals. Pigs also contributed significant portion (17.6 %) to . However, horse, sheep and donkey showed a small share (0.32 %) in WFls. Livestock production accounted for 1.4 % of the total WF in the study area.

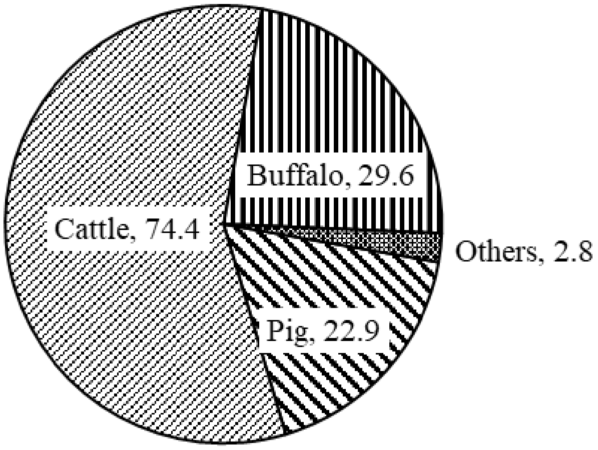

Fig. 5: **Percentage distribution of livestock water footprint(%) into animal types**

Water Footprint of Domestic and Industrial Sectors

The annual WF of domestic and industrial sectors was 201.2 Mm^3. The WF based analysis indicated that the share of domestic and industrial sectors in total WF was 2.2 %; whereas, the water withdrawal-based indicator showed that the domestic and industrial sectors consume 11% of the total water withdrawals in the country (MOWR RD & GR, 2014). It was observed that the values of WFs based on water consumption and withdrawal indicators differed considerably. At basin level, the part of the water withdrawn for industrial or domestic purposes returned to the groundwater or surface waterbodies within the basin from where it was abstracted. Because of this fact, the actual consumptive use of water in these sectors was far less than the water withdrawals. Therefore, the consumption-based approach of assessing the water use provides more realistic estimates of water use.

Total Water Footprints

The annual WF of the study area considering agricultural, livestock, domestic and industrial sectors was estimated at 9185.9 Mm^3 (Table 2). Overall, agriculture represented the largest WF, with 96.4 % share in the total WF; while livestock, domestic and industrial sectors jointly accounted for only 3.6 % of the total WF. Contribution of blue WF in total WF was 47.4% (4356.5 Mm^3), while share of grey WF was 9 % (827.6 Mm^3).

Table 2. Sector-wise and total water footprint WF (Mm^3) of the study area

Sector	Blue WF	Green WF	Grey WF	Total WF
Crop production	4025.7	4001.8	827.6	8855.1
Livestock	129.6	0	0	129.6
Domestic and industrial	201.2	0	0	201.2
Total water footprint	4356.5	4001.8	827.6	9185.9

Blue water availability

In the study area, monthly runoff availability was high from July to October due to higher amount of rainfall (885 mm) received during the monsoon months. During this period, the monthly runoff was in the range of 2379.5 Mm^3 to 6547.8 Mm^3, while the period from February to May was comparatively dry with monthly runoff values ranging from 0 to 46.3 Mm^3. Blue water availability as estimated after accounting for utilizable groundwater resource and the environmental flow requirements varied from 220.6 Mm^3 to 2844.3 Mm^3. Total annual blue water availability in the basin was estimated at 8685.5 Mm^3.

Sustainability of blue and grey water footprints

Comparison of the monthly WF_{blue} with monthly WA_{blue} (Table 3) showed that WF_{blue} exceeded WA_{blue} for the period from January to March, and November and December months. Hoekstra *et al.* (2012) classified BWSI into four levels: (i) low (<100 %), (ii) moderate (100-150 %), (iii) significant (150-200 %), and (iv) severe (>200 %). According to this classification, the months of March (112 %) and November (109 %) were in the category of 'moderate' BWSI. The months of January, February and December were characterized under the 'severe' BWSI (401-435 %) level, while rest of the seven months had BWSI in the 'low' category. Higher values of BWSI for five months in the year showed that runoff in the study area was significantly modified by human activities, and blue WF was partly met at a cost of environment flow requirements.

The *rabi* season (November-February) showed higher grey WF (819.5 Mm^3), as shown in Table 3. Due to lack of round-the-year irrigation facility and semiarid climatic conditions, the grey WF of the study area was very small during the months from March to November. Further, cultivation of crops on smaller areas and low fertilizer dose of crops were the primary reasons for low grey WF during this period. Cultivation of wheat crop with high fertilizer application (120 kg.ha^{-1}; Dubey *et al.*, 2015) had resulted in high grey WF in *rabi* season. Non-availability of utilizable runoff water combined with high WF_{grey} resulted in high WPI of 135 % and 588 % during January and February months, respectively, indicating that ambient water quality standards were not met during these months.

With indicators as monthly BWSI and WPI, it was possible to identify the temporal hotspots within which the blue and grey WFs exceeded the blue water availability. Hotspots occur where both water consumption and water scarcity are high (Jefferies *et al.*, 2012). Performing the analysis on a basin scale provides more realistic information than that is done at the country level, especially in large countries like India (Hoekstra *et al.*, 2011). In present study, the sustainability of blue water use was a concern during the non-monsoon period (October to June), during which river flows are significantly low. As an indicator, WPI allows the use of 'volumetric approach' in determining the extent of deterioration in total blue

Table 3. Monthly runoff, blue water availability, blue and grey water footprints (WFs) and sustainability indices for Betwa river basin

Month	Runoff, Mm^3	Blue water availability, Mm^3	WF of the basin, Mm^3		Sustainability index, %	
			Blue	Grey	Blue Water Scarcity Index	Water Pollution Index
January	202.7	284.1	1164.3	273.2	410	135
February	46.3	220.6	885.5	272.2	401	588
March	6.3	220.6	246.0	0.0	112	0
April	0.0	220.6	35.5	0.0	16	0
May	0.0	220.6	35.5	0.0	16	0
June	171.9	229.9	35.5	0.0	15	0
July	5194.7	2844.3	35.5	0.0	1	0
August	6547.8	1464.7	45.9	3.8	3	0
September	5018.1	1410.1	85.4	3.8	6	0
October	2379.5	798.2	92.2	0.5	12	0
November	1107.6	509.0	552.7	0.9	109	0
December	449.7	262.8	1142.5	273.2	435	61

water resources at river basin scale (Zonderland-Thomassen and Ledgard, 2012).

CONCLUSIONS

A case study of Betwa river basin located in semi-arid region was conducted for assessment of water footprint (WF) of the river basin under limited data availability conditions. Sector-wise comparison of WFs revealed that crop production activity had the largest share (96.4 %) in total WF of the basin. Green WF accounted for 45.2 % of total WF of crops. This highlighted the importance of managing green water and improving green water use efficiency for relieving the pressure on blue water resources. The concept of WF provided realistic estimates of the water use. Sustainability analysis showed that there was a serious concern over sustainability of blue WFs within the area, highlighting the need to reduce the blue and grey WFs to restore the environmental flows and improve water quality. Policy interventions are needed to raise awareness about the environmental consequences of basin's water consumption pattern and generate concrete actions that can result in more sustainable use of water resources at the river basin scale.

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