Assessing water footprints and virtual water flows in Gomti river basin of India

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This article analyses the blue, green and grey water footprints and virtual water flows within the Gomti river basin (GRB) in India. Assessments were made at spatial resolution of agricultural production units (APUs). An APU is a homogeneous spatial unit delineated on the basis of soil type, agro-ecological region and district boundaries. Water footprints of crop production and consumption were compared to arrive at virtual water balance within the GRB. Results show that water footprint of GRB was 12,773 million m^3 year^{-1}. Crop production was the largest water consumer accounting for 95.5% of water footprint within the basin. The higher proportion of blue water footprint (47.3%) indicates the dependence of GRB on irrigated agriculture. Contribution of rainfed agriculture to total water footprint was about 11.2%. Considerable portion of blue water is used in the production of low value water-intensive crops. The GRB was assessed as a net virtual water importer, indicating its dependence on the water resources of other river basins; it imports 2945 million m^3 virtual water annually. This scenario can be changed if the area allocated to different water-intensive crops is optimized and limited to the extent that meets the consumption needs within the basin, leading to reduction in production surplus of these crops.

Keywords: Economic water productivity, river basin, virtual water flow, water footprint.

FRESHWATER scarcity is a growing global concern. Increasing scarcity of this important resource is directly linked to human activities[1,2]. In India, the demand for this natural resource exceeds the supply by a great margin[3]. Sustainability of water resources use and food security calls for meticulous assessment of water supply and demand at river basin-scale. Virtual water content (VWC) and water footprint (WF) have emerged as indicators of water consumption and can help promote efficient, equitable and sustainable water uses[4,5]. WF is a consumption-based indicator and can be considered as the total volume of virtual water embodied in the final products consumed by people of a country or region[6]. Assessing WF at the river basin level is an important step to understand how human activities influence natural water cycles. It is the basis for integrated water resources management and sustainable water uses[7].

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[8]. Also, the recent National Water Policy (2012) of India emphasized on evolving water footprints and water auditing benchmarks on the use of water resources to promote efficient use of water[9]. Several studies have recognized the usefulness of the concept of virtual water for analysing production patterns and associated water flows[10]. Researchers have used the concept of WF to analyse the hydrologic and economic aspects of water footprint[11], water pollution levels in river basins across the globe[12], to know whether WF of human activities within the basin violates environmental flow requirements[7] and to assess the extent scarce water resources in the basin are allocated to low-value export crops[11].

Considering the opportunities offered by WF as a tool for water resources management, the present study analyses the blue, green and grey WF within the Gomti river basin (GRB) located in the Indo-Gangetic plains of India. Water footprint of crop production was analysed in the context of economy of blue water use by different crops. The study further presents the appraisal of virtual water flows within the basin. A comprehensive assessment of WF of crop production considering multiple types of water (e.g. green, blue and grey water) has not been done before for any river basin in India. The assessments made in the study will be useful in understanding the entire process of water consumption within the GRB, and identifying ways to improve water management.

Materials and methods

Study area

Located in the central part of Uttar Pradesh (UP), GRB is a sub-basin of River Ganga and is an important agricultural basin in India. River Gomti originates in the Pilibhit

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district of UP, flows through several districts of the state and joins River Ganga in Saidpur Kaithi near Varanasi (Figure 1). It travels about 940 km and drains about 31,240 sq. km area of the central part of UP. The cropping intensity within the basin is 155% (ref. 13). Efficiency of surface irrigation systems is 35%–45% (ref. 14), while that of groundwater irrigation is about 45%–93% (ref. 15).

Crop production and livestock population in Gomti river basin

District level cropped area, irrigated area and livestock population datasets were obtained from the Directorate of Economics and Statistics, Government of India[16]. Gross cropped area (GCA) of the part of the district within the basin boundary was estimated using land-use/land-cover maps obtained from Bhuvan Thematic Services, Indian Space Research Organization[17]. Percentage of irrigated and rainfed area of a crop in a district, as obtained from district-level datasets, was multiplied with GCA of the districts within the basin boundary to get the cultivated area of each crop within the GRB. The gross cropped area of Gomti is about 2.48 m ha. Irrigated agriculture constitutes about 85% of the gross cropped area within the GRB (Table 1). Animal population in the districts within the basin was estimated by multiplying the district-level population density with the geographical area of the district within the basin. The district-level live stock population data were obtained from online statistical database of India[18].

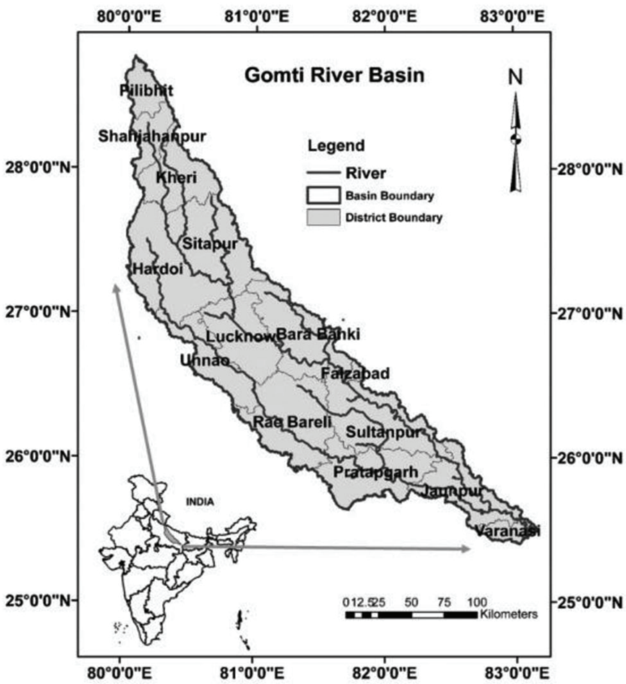

Figure 1. Location of the Gomti river basin in India.

Spatial resolution unit for water footprint assessment

Accuracy of WF depends on the resolution at which it is estimated. In the present study, the basin area was divided into homogeneous units (called agricultural production units, APUs) in terms of soil type, agro-ecological regions and district boundaries. The soil and climate of these delineated APUs can be assumed to be 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 spatial unit (highest resolution) for assessment of WF at river basin-scale. Figure 2 shows the delineated APUs of GRB. The detailed procedure for delineation of APUs is available in the literature[19].

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[20,21]. The 'Irrigation schedule' option in CROPWAT was used to estimate the green water use (CWU_{green}, m^3/ha) at daily time steps. Values of crop coefficient (K_c) were adopted from the literature[20]. The climatic data derived from gridded daily time series data of India Meteorological Department (IMD) obtained from the project on National Initiative on Climate Resilient Agriculture[22] were used in this study.

The green crop water use is the volume of total rainfall that is actually used for evapotranspiration by the crop over the complete growing period. It is estimated using the eq. (1)

Table 1. Irrigated and rainfed areas in Gomti river basin for 2011

Crop	Irrigated area (ha)	Rainfed area (ha)	Per cent irrigated
Wheat	1,127,555	5,561	99.5
Paddy	721,896	18,117	97.6
Sugarcane	158,390	19,812	88.9
Mustard	46,826	9,623	83.0
Black gram	0	54,227	0.0
Maize	2,718	49,063	5.2
Potato	40,628	4,142	90.7
Lentil	0	35,469	0.0
Pigeon pea	26	30,532	0.1
Sorghum	40	21,683	0.2
Pearl millet	79	18,819	0.4
Chickpea	1,143	14,667	7.2
Sesame	35	15,717	0.2
Peas	15,109	0	100.0
Groundnut	124	9,954	1.2

$$\mathrm{CWU}_{\mathrm{green}}[c,N]=10*\sum_{t=1}^{i}\mathrm{Min}(P_{\mathrm{eff}}[c,t,N],\,\mathrm{ET}_c[c,t,N]), \tag{1}$$

where $\mathrm{CWU}_{\mathrm{green}}[c, N]$ is the green water use of crop c in the Nth APU, P_{eff} $[c, t, N]$ the effective rainfall (mm) for crop c in the Nth APU and at time step t, ET_c $[c, t, N]$ the evapotranspiration (mm) of crop c in the Nth 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 is added to convert mm into $\mathrm{m^3/ha}$ and summation is done over the complete length of the growth period at daily time steps.

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 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 ($\mathrm{CWU}_{\mathrm{blue}}$, $\mathrm{m^3/ha}$) in crop production is obtained using eq. (2)

$$\mathrm{CWU}_{\mathrm{blue}}[c,N]=10*\sum_{t=1}^{i}\mathrm{ET}_c[c,t,N]-P_{\mathrm{eff}}[c,t,N]), \tag{2}$$

where $\mathrm{CWU}_{\mathrm{blue}}$ $[c, N]$ is the blue water use ($\mathrm{m^3/ha}$) of crop c in the Nth APU, ET_c $[c, \mathrm{t}, N]$, the evapotranspiration (mm) of crop c in the Nth APU at time step t and P_{eff} $[c, t, N]$ is the effective rainfall (mm) for crop c in the Nth APU and at time step t. The factor 10 is added to convert blue water use from mm to $\mathrm{m^3/ha}$, and summation is done over the complete length of the growth period at daily time steps.

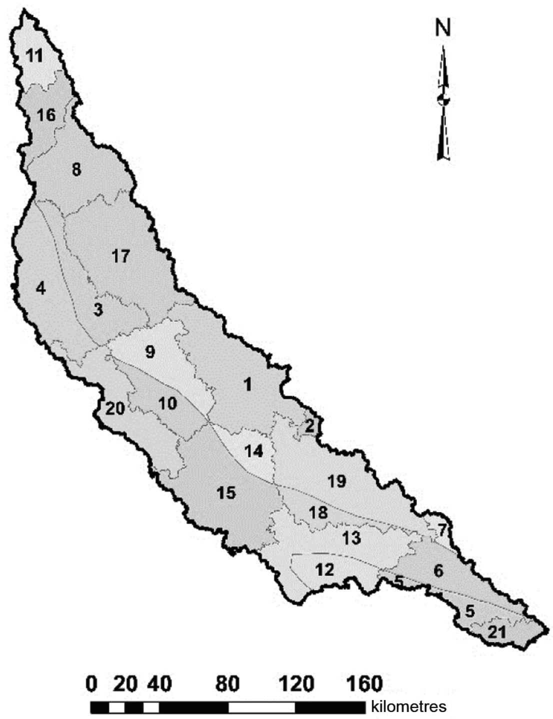

Figure 2. Delineated agricultural production units within GRB.

The grey water use of a crop ($\mathrm{CWU}_{\mathrm{grey}}$ $[c]$, $\mathrm{m^3/ha}$) is the volume of water that is required to dilute the nitrate leached to the groundwater to a desired level. It is estimated at basin level using eq. (3)

$$\mathrm{CWU}_{\mathrm{grey}}[c]=\frac{N_{\mathrm{app}}[c]*lf[c]}{rl}, \tag{3}$$

where N_{app} $[c]$ is the amount of nitrogen fertilizer applied (kg/ha) to the crop c throughout growing season, $lf\,[c]$ the nitrogen leaching fraction (ratio between N_{leach} and N_{app}) for a crop c and rl is the recommended level of nitrogen ($\mathrm{kg/m^3}$) according to water quality standards for drinking purpose. It is worth mentioning here that, due to lack of information on district-specific nitrogen leaching fractions, uniform lf is assumed for entire the GRB. Nitrogen leaching under rainfed conditions has not been considered in the present study.

The green, blue and grey VWC ($\mathrm{m^3/t}$) of a crop in an APU was estimated as the ratio of the respective water use by the crop yields (eqs (4)–(6))

$$\mathrm{VWC}_{\mathrm{green}}[c,N]=\frac{\mathrm{CWU}_{\mathrm{green}}[c,N]}{Y[c,\,N]}, \tag{4}$$

$$\mathrm{VWC}_{\mathrm{blue}}[c,N]=\frac{\mathrm{CWU}_{\mathrm{blue}}[c,N]}{Y[c,\,N]}, \tag{5}$$

$$\mathrm{VWC}_{\mathrm{grey}}[c,N]=\frac{\mathrm{CWU}_{\mathrm{grey}}[c]}{Y[c,\,N]}, \tag{6}$$

where $Y[c, N]$ is the yield (t/ha) of crop c in the Nth APU. The total VWC of a crop is estimated using eq. (7)

$$\mathrm{VWC}_{\mathrm{total}}[c,\,N]=\mathrm{VWC}_{\mathrm{green}}[c,\,N] +\mathrm{VWC}_{\mathrm{blue}}[c,\,N]+\mathrm{VWC}_{\mathrm{grey}}[c,\,N]. \tag{7}$$

WF of crops under rainfed and irrigated conditions was estimated separately. A linear relationship between yield and evapotranspiration was used to get crop yields under rainfed conditions[23].

WF of crop production is estimated using eq. (8)

$$\mathrm{WF}[c,\,rb]=\sum_{c=1}^{n}\sum_{N=1}^{N}\sum_{i=1}^{2}\{\mathrm{VWC}_{\mathrm{tot}}[c,\,N,\,i]*\mathrm{Prod}[c,\,N,\,i]\}, \tag{8}$$

where $\mathrm{WF}[c, rb]$ is the WF of crop production within the river basin, c the crop index, N the number of APUs and i is the type of agriculture (1 – irrigated, 2 – rainfed).

Economic water productivity of blue water for irrigated crops was obtained by dividing the gross returns (Rs) of the particular crop from the entire basin with its blue WF (m^3).

Virtual water export

Virtual water export from the basin 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 the quantity of export from the basin. Consumption of a crop within the basin includes human and animal consumption, seed and wastage at farm and market level. The state-level per capita consumption of agricultural commodities was obtained from NSSO[24]. 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. Processing of primary products into processed product involves some loss of weight of the primary crop. Consumption of primary products is calculated by dividing quantity of processed product consumed by the product fraction[8], as shown in eq. (9)

$$Q_{\text{cons}}[c, N] = \sum_{1}^{j} \frac{\begin{bmatrix} \text{Pop}_{\text{rural}}[N] * q_{\text{rural}}[p_j, c] + \\ \text{Pop}_{\text{urban}}[N] * q_{\text{urban}}[p_j, c] \end{bmatrix}}{pf_j}, \tag{9}$$

where $Q_{\text{cons}}[c, N]$ is the quantity of crop c consumed in the Nth APU; $\text{Pop}_{\text{urban}}$ and $\text{Pob}_{\text{rural}}$ are the urban and rural population respectively, of the Nth APU; q_{urban} $[p_j, c]$ and q_{rural} $[p_j, c]$ are the per capita consumption of a product p_j derived from crop c in urban and rural areas respectively, pf_j the product fraction for the jth 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. According to a study[25], the post-harvest losses of foodgrains in India are 7–10% of the total production from farm to market level and 4–5% at market and distribution level. In the present study, wastage at farm and market levels was estimated considering the loss of 10% of total production for all the crops.

The virtual water balance (VWB) for agricultural products is defined by eq. (10)

$$\text{VWB} = \text{WF}_{\text{cons}}[c] - \text{WF}_{\text{prod}}[c], \tag{10}$$

$$\text{WF}_{\text{cons}}[c] = \text{VWC}_{\text{blue+green}}[c] * Q_{\text{cons}}[c], \tag{11}$$

$$\text{WF}_{\text{prod}}[c] = \text{VWC}_{\text{blue+green}}[c] * Q_{\text{prod}}[c], \tag{12}$$

where $Q_{\text{cons}}[c]$ and $Q_{\text{prod}}[c]$ are the quantities of crop c consumed and produced within the basin respectively; $\text{WF}_{\text{prod}}[c]$ and $\text{WF}_{\text{cons}}[c]$ are the WF of production and consumption respectively. In order to estimate virtual water flow, it is assumed that the production of a crop in excess of consumption is exported out of the basin and the consumption deficit of a crop, if any, is met from import of that crop from other basins.

Result and discussion

Virtual water content of crops

Among other crops, sesame, black gram and groundnut showed higher VWC. Virtual water content of other cereals ranged from 1586 to 4555 m^3/tonnes (Table 2). High-productivity crops like sugarcane and potato exhibited low VWC. Against the common perception, the virtual water content of paddy and sugarcane was comparatively lower. High application of nitrogen resulted in highest grey VWC (660 m^3/tonnes) in paddy, followed by mustard and wheat. Maize being short duration *kharif* crop showed the lowest blue VWC of 94 m^3/tonnes (Figure 3). Blue water proportion (BWP) ranged from 14.2% to 66.8% for *kharif* crops, while it ranged from 80% to 99.7% in case of *rabi* crops. This indicates that green water makes significant contribution in the production of *kharif* crops.

Water footprint of crop production

The annual WF of crop production (WF_c) in the GRB was assessed at 12,196 million m^3 (Table 3). Wheat crop had the highest WF of 4263 million m^3, while chickpea showed the lowest (20.8 million m^3) WF. Share of blue WF in irrigated agriculture was about 56% (5908 million m^3). Rainfed agriculture showed significant contribution in total water used for crop production within the basin. Black gram, maize, pigeon pea and sugarcane were the major contributors (>64%) to WF of rainfed agriculture (Figure 4). Grey water use in irrigated agriculture accounted for 3.8% (718 million m^3). Contribution of cereal crops (paddy, wheat, maize and pearl millet) in WF_c was about 70%. Due to their large cultivation areas, paddy, wheat and sugarcane accounted for about 88% of WF_c.

Water footprint of livestock, domestic and industrial sectors

Annual WF of livestock (WF_l) in GRB was about 82.04 million m^3. Cattle and buffalo accounted for over 94% of WF_l (Figure 5). This is mainly due to the large population of these animals within the basin. Horse, sheep

Table 2. Virtual water content (VWC) of various crops under irrigated and rainfed conditions

Crop	Irrigated condition		VWC, rainfed condition
	Total VWC	Proportion of blue VWC	
Black gram	7,466	64.6	7,747
Groundnut	6,399	15.4	7,182
Maize	4,555	2.3	3,278
Pearl millet	3,459	23.0	3,294
Pigeon pea	6,355	49.8	6,744
Paddy	3,018	14.2	1,653
Sesame	20,724	14.6	22,103
Sorghum	4,217	17.1	3,641
Sugarcane	298	60.1	313
Chickpea	3,949	96.5	3,127
Lentil	4,110	97.7	2,971
Mustard	3,664	99.6	2,866
Peas	2,018	99.7	–
Potato	277	97.5	–
Wheat	1,586	96.3	1,040

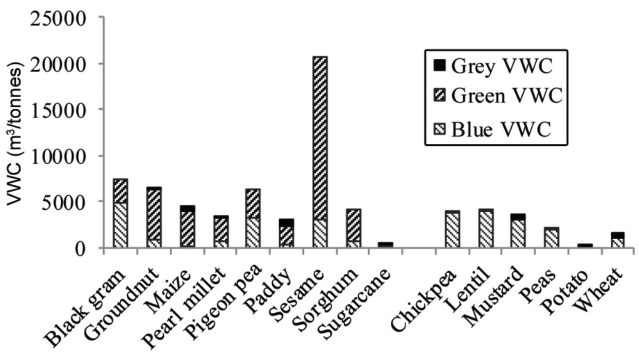

Figure 3. Blue, green and grey virtual water content of various crops under irrigated condition.

and donkey had a small share in WF_l. WF of domestic and industrial sector was 495.7 million m^3. High population density and presence of processing and manufacturing industries which consume and pollute large amounts of blue water resulted in high blue as well grey WF of these sectors in GRB. Industrial and domestic sector was responsible for pollution of huge quantities of water as the water required for assimilation of pollution from these sectors was estimated as 416.12 MCM.

Water footprint of river basins

The WF of river basin (WF_{rb}) was obtained as summation of WF of crop, livestock, domestic and industrial sectors. Annual WF of Gomti and Betwa basins was about 12,773 and 9186 million m^3 respectively. Large-scale cultivation of water-intensive crops like paddy, sugarcane and wheat resulted in higher WF in GRB. Two principal activities, crop and livestock production, accounted for about 95% and 0.6% in WF_{rb}, while the share of domestic and industrial sector was about 3.9%. Share of blue water in total WF of agriculture was about 97.8%. Further analysis revealed that the blue and grey WF accounted for 47.3% (6040 million m^3) and 9.1% (1165 million m^3) of total WF of GRB respectively. Three major crops, viz. rice, wheat and sugarcane contributed significantly to WF_c. Among all the animals, cattle and buffalo were the largest consumers of freshwater in GRB.

Economic productivity of blue water

Crops with higher productivity and economic value showed higher economic productivity of blue water (EWP) (Figure 6). Crops with comparatively lower blue VWC and higher economic value such as maize and potato resulted in higher economic water productivity of 107.0 and 93.3 Rs/m^3 respectively. Paddy (43.5 Rs/m^3) and groundnut (40.5 Rs/m^3) were the most profitable crops in terms of economy of blue water use. Despite their lower EWP, crops like sugarcane and mustard are cultivated on larger areas, mainly because they are more remunerative on per unit area basis.

Virtual water flow and virtual water balance

Sugarcane, wheat, maize and sorghum were produced in excess of their consumption needs within the basin. The WF of export was about 2110 million m^3, indicating huge amount of water being consumed to meet the food requirements of other regions through exports. Also, the net virtual water inflow through import of other crops was about 4970 million m^3, leading to a positive virtual water balance of 2860 million m^3 (Table 4). Sugarcane contributed 67.1% in total VW exports from the basin. Virtual water balance clearly indicated that GRB is a net virtual water importer.

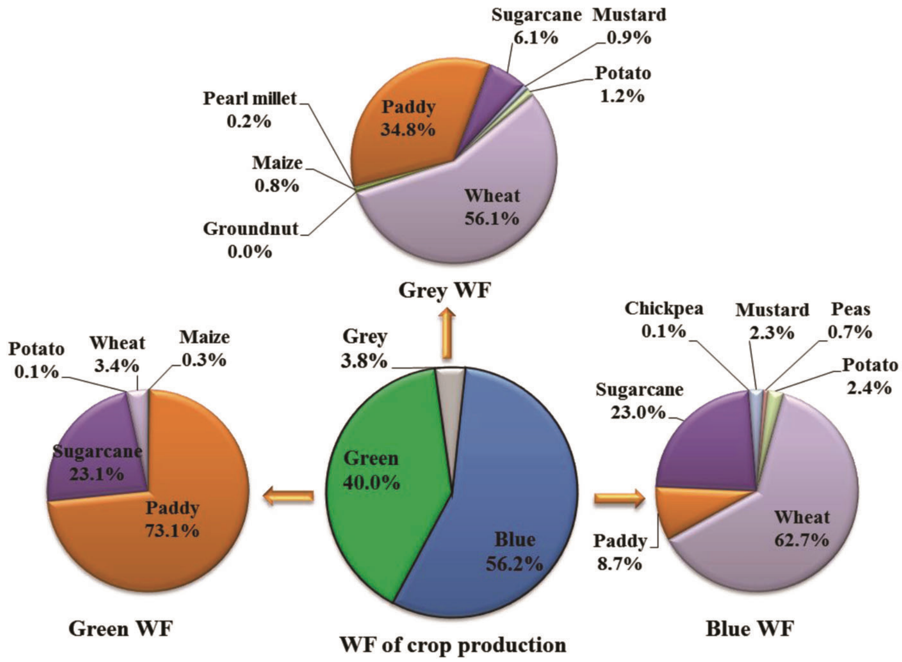

Figure 4. Crop wise share in green, blue and grey water footprint (WF) of crop production in the GRB (note: crops with <0.1% shares in WF are not shown).

Table 3. Water footprint of crop production in the GRB

Crop	Water footprint (million m^3) Irrigated area	Rainfed area
Black gram	0.0	233.3
Groundnut	0.8	66.9
Maize	18.3	258.7
Pearl millet	1.5	74.7
Pigeon pea	0.1	152.6
Paddy	3,839.2	63.3
Sesame	0.1	103.9
Sorghum	0.2	88.1
Sugarcane	2,373.3	231.8
Chickpea	3.5	17.3
Lentil	0.0	39.0
Mustard	143.1	18.0
Peas	43.7	0.0
Potato	156.7	4.4
Wheat	4,252.0	11.5
Total WF	10,832.5	1,363.5

Under the present cropping pattern considerable part of blue WF is 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 savings in blue water. In order to achieve higher EWP, cropping pattern should focus more on high value-low water intensive crops rather those with higher net returns per unit area. Implementation of *in situ* rainwater harvesting and soil moisture conservation practices along with promotion of crops that use green water more efficiently will also lead to reduction of blue WF, consequently resulting in saving of blue water resources. In the past decades, several studies concluded that green water management should be emphasized in addition to blue water[26,27]. Farm-level practices such as mulching and land levelling can be implemented for effective use of rainwater.

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 crops with higher economic productivity of blue water is more important from the perspective of water scarcity. Policy reforms are required to limit the farmers' choice of crops, such that total blue water use within the basin is minimized. Large spatial variation of ET_c among the APUs suggests that allocation of crops from high to low blue WF areas can result in significant savings in surface and groundwater resources. This calls for optimization of cropping pattern to achieve more sustainable water use.

VWB showed an export of 2110 million m^3 of water in virtual form. Export of huge amounts of water in virtual form may lead to water scarcity. Instead of exporting water-intensive crops, an optimum crop production, import and export plan can be worked out to make WF of the basin more sustainable.

Since agricultural activities are probably the most significant anthropogenic source of nitrate contamination[28], devising more efficient fertilizer management practices is essential to reduce the grey WF. In general, most of the farmers apply fertilizers as single basal dose or in 2–3

Table 4. Crop production, consumption and virtual water (VW) flow in GRB

Crops	Production (tonnes)	Consumption (tonnes)	Crop export/import (tonnes)	VW flow (million m^3)
Black gram	28,531	34,201	5,670	+44
Groundnut	11,235	20,247	9,011	+40
Maize	80,560	18,112	–62,448	–206†
Pearl millet	20,586	29,152	8,566	+34
Pigeon pea	29,056	72,709	43,653	+246
Paddy	1,574,035	2,326,497	752,462	+2905
Sesame	5,029	5,674	646	+13
Sorghum	24,592	3,658	–20,934	–76
Sugarcane	9,253,473	4,384,189	–4,869,284	–1417
Chickpea	6,834	52,021	45,187	+79
Lentil	13,510	24,605	11,095	+46
Mustard	49,905	498,766	448,861	+1431
Peas	19,843	86,004	66,161	+142
Potato	805,184	1,187,575	382,390	+74
Wheat	3,460,801	3,103,350	–357,451	–411
Virtual water balance				+2945

‘+’ indicates VW import and ‘–’ indicates VW export.

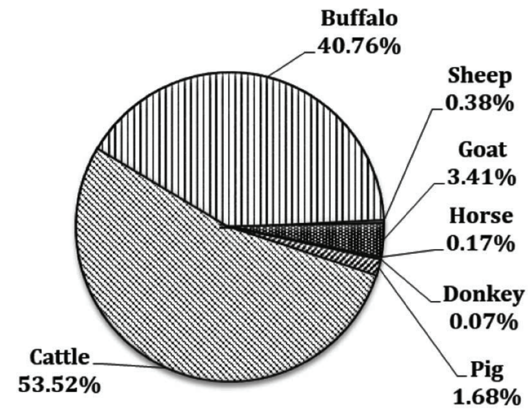

Figure 5. Water footprint of livestock.

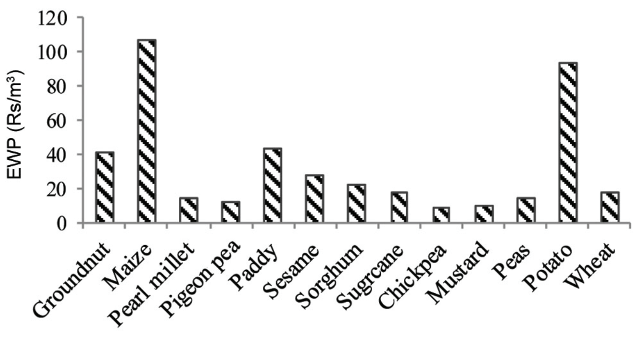

Figure 6. Economic productivity of blue water.

splits during the cropping season. Studies have shown that splitting of N application (120 kg N/ha) into three parts resulted in leaching of about 20–30% of applied N (ref. 29). In view of significant grey WF within the basin, use of modern irrigation systems and fertigation technologies needs to be promoted. This study analyses WF and virtual water flow for any Indian river basin. Further analysis can focus on assessing the sustainability of WF within the basin.

Conclusion

This study presents an assessment of water footprint of crop and livestock production, and industrial and domestic uses in the GRB of northern India. In the present cropping pattern, considerable agricultural land is allocated to few crops (paddy, sugarcane and wheat), which contribute 97% in the total WF of irrigated area. Although there is considerable virtual water outflow through export of these crops, import of other essential crops assesses the GRB as a net virtual water importer. Further, considerable amount of blue water is being used to produce crops with low EWP. In view of economy of water use, allocation of agriculture land to various crops on the basis of EWP can ensure better utilization of available water resources. The GRB shows potential to produce crops that can be exported to other basins, reducing water scarcity in the importing basins. Improving efficiency of rainwater use and reallocation of cropping patterns can be potential solutions to reduce blue water use in the basins. Large amounts of freshwater would be required to assimilate the pollution occurring in the basin. Relocation of crops from high WF to low WF areas can be seen as a better management alternative for reducing WF within the GRB.

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