Regional water footprint assessment for a semi-arid basin in India

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Abstract

Water footprint assessment enables us to pinpoint the impacts and limitations of the current systems. Identifying vulnerabilities across various regions and times helps us prepare for suitable actions for improving water productivity and promoting sustainable water use. This study aims to provide a comprehensive evaluation of the sector-wise water footprint in the Banas river basin from 2008-2020. The water footprint of the Banas river basin was estimated as 20.2 BCM/yr from all sectors. Water footprint has increased over the year with the increase in population, the number of industries, and crop production demand. The average annual water footprint of crop production varied from 11.4 - 23.1 BCM/yr (Mean 19.3 BCM/yr) during the study period. Results indicate that the water footprint has nearly doubled in the past decade. Wheat, Bajra, Maize, and Rapeseed & Mustard make up 67.4 % of crop production's total average annual water footprint. Suitable measures should be implemented in the basin to improve water productivity and promote sustainable water use in agriculture, which accounts for nearly 95.5 % of the total WF of the Banas basin. The outcomes of the study provide a reference point for further research and planning of appropriate actions to combat water scarcity challenges in the Banas basin.

Index of Notations and Abbreviations

Abbreviation/ Notations		Description
%	:	Percentage
$\propto$	:	Leaching runoff fraction
$\approx$	:	Approximately equal to
$^{\circ}$		Degree
AESR	:	Agro-ecological Sub Region
APSIM	:	Agricultural Production Systems Simulator
BCM	:	Billion cubic meters
BRB	:	Banas River Basin
CWU	:	Crop water use
DSSAT		Decision Support System for Agrotechnology Transfer
ET	:	Evapo-transpiration
ET_o	:	Reference evapo-transpiration
GOI	:	Government of India
Ha	:	Hectare
IMD	:	India Meteorological Department
LU	:	Land units
LULC	:	Land use land cover
MCM	:	Million cubic meters
Mha	:	Million hectares
PIB	:	Press Information Bureau
WEAP	:	Water Evaluation and Planning
WF	:	Water footprint
WFA	:	Water footprint assessment
WF_{blue}	:	Blue water footprint
WF_{green}	:	Green water footprint
WF_{grey}	:	Grey water footprint
WFN		Water Footprint Network
WOFOST		World Food Studies
WRD	:	Water Resource Department
Yr	:	Year

35

36

Introduction

38 India is the second most populous country in the world. It supports nearly 17.1 % of the world's
39 population (≈ 1.3 billion) and 20 % of the world's livestock population (≈ 500 million), resulting
40 in increased stress on limited freshwater resources (Jain, 2019). Efficient use of available water
41 resources is vital for a nation like India, where the agriculture sector is the leading consumer of
42 water. Over time average annual per capita water availability has declined from 1816 in 2001 to
43 1545 cubic meters in the year 2011, and it is projected to further go down to 1486 cubic meters
44 by the year 2021. It will be 1367 cubic meters by 2031 (PIB, 2020). Water availability and
45 allocation have become critical issues worldwide, particularly in arid and semi-arid regions.
46 Water security is essential for social and economic development, enhancing health, well-being,
47 and economic progress, particularly in developing countries (Mekonnen & Hoekstra, 2013).
48 Nearly two-thirds of the world's population currently faces water scarcity for at least one month
49 per year (Mekonnen & Hoekstra, 2016). Irrigation water use is essential, especially in the current
50 scenario where water scarcity and climate change are becoming significant threats worldwide.
51 The functionality of irrigation is not limited to providing sufficient water for crops to achieve
52 better production outcomes (Tesema et al., 2011). Technology and management practices play an
53 essential role in reducing inessential water use. Certain challenges are being posed by climate
54 change, water scarcity, and growing demand from other sectors. Thus, promoting efficient and
55 sustainable water use with better planning has become imperative (Hoekstra, 2017). There is a
56 need to develop better water management policies to meet our current and future demands,
57 ensuring food security and fulfilling domestic and industrial needs. Also, suitable measures
58 should be taken to increase water use efficiency and reduce the water demands of agricultural
59 production.

60 Water footprint (WF) is a broad concept that indicates water consumption within a region for a
61 product, commodity, process, or service (Hoekstra *et al.*, 2009). Calculated by summing the
62 volume of direct and indirect water used for a product, commodity, process, or service. Several
63 WF studies have been conducted worldwide at various scales (Hoekstra, 2017). Planning and
64 managing water resources at the river basin scale is essential for increasing water availability and
65 improving water quality while ensuring long-term sustainability. WF assessment helps
66 understand the importance of sustainable water utilization and forms a basis for global
67 freshwater management efforts (Chukalla, Krol & Hoekstra, 2015; Mekonnen & Hoekstra,

68 2016). Water scarcity assessment faces the challenges of incorporating green water, water

69 quality, environmental flow requirements, globalization, and virtual water trade-related issues

70 (Liu et al., 2017). Different crop models like Aqua crop, DSSAT, APSIM, and WOFOST (yield

71 gap) have been used earlier to study the effect of soil moisture stress, deficit irrigation, nutrient

72 stress, sowing date, and impact of climate change on crop growth and productivity (Tenreiro et

73 al., 2020). Various factors affecting water use efficiency include poor agricultural practices,

74 inefficient irrigation systems technology, and water pricing. Mitigating water scarcity has

75 become a significant concern globally, and numerous studies have been conducted on this

76 (Wada, Wisser & Bierkens, 2014; Kummu et al., 2016; Zhuo et al., 2016). WFs had been

77 quantified at high spatial and temporal resolution (Mekonnen & Hoekstra, 2011a, 2014; Hoekstra

78 & Mekonnen, 2012). Inter- and intra-annual variability of water availability and trends in WFs

79 have been studied (Zhuo et al., 2016; Liu et al., 2017).

80 River basins have seen a decline in per capita water availability all over India due to continuous

81 population pressures, agriculture, and industrial expansion (Dhawan, 2017). Freshwater

82 availability for agricultural purposes in India is less than required owing to the high WF and poor

83 farming practices (Kampman, Hoekstra & Krol, 2008). To ensure sustainability at a river basin

84 scale, capping/limiting the consumptive and degradative water use per river basin was proposed

85 so that water use stays within maximum sustainable levels (Hoekstra, 2014). At the river basin

86 scale, WF analysis can address certain policy and water management-related issues to facilitate a

87 more efficient allocation and use of water resources, providing a framework for policy

88 formulation (Mali et al., 2018; Nouri et al., 2019; Khan et al., 2021). WF modelling enables us to

89 pinpoint the impacts and limitations of the current crop production system. Assessing

90 vulnerabilities across agricultural management systems across various regions and times helps us

91 prepare for suitable actions for improving water productivity and promoting sustainable water

92 use.

93 The current literature provides crop WF for various areas worldwide and a global average for

94 comparison, but most use global or national statistics. WF can vary significantly spatially and

95 temporally, even within the basin. Water allocation strategies and crop planning for efficient

96 water use should be done considering a long-term perspective and local conditions. The findings

97 from this paper will benefit the farmers and water resource planners in the basin. This research

98 will also assist decision-makers in implementing proper agricultural governance and measures

99   that will help in ensuring global food and water security without endangering the environment.

100   Outcomes provide baseline information for further research and will provide imperative insights

101   into the current situation in the basin. This will assist in planning appropriate measures to

102   overcome water scarcity challenges and reduce the water footprint in the basin. This study

103   integrates local data and robust modeling capabilities of the AquaCrop model to more precisely

104   assess the WFs of major crops of the basin alongside estimates from other important sectors

105   which are generally not considered. Considering all these points, this study was undertaken with

106   the aim of evaluating the sector-wise water footprint in the Banas river basin.

Materials & Methods

Study Area

109   Banas River Basin (BRB) lies between 24°15'-27°20' latitudes and 73°25'-77°00' longitudes

110   (Figure 1). It has a catchment area of 47,060 km^2 (4.7 Mha) within Rajasthan (WRD, 2014a).

111   This study aims to determine the sector-wise water footprint at the basin level from 2008 to

112   2020. Basin also bears the impact of climate change, especially in regions with limited water

113   resources (Rani et al., 2022). The agriculture sector is the primary user of water in the basin.

114   Thus, a more comprehensive approach was taken to assess the WF of major crops in the basin.

115   Sixteen major crops cultivated in the basin were selected for the study based on their total

116   cultivated and irrigated area. They account for 94.0 % of the total cultivated and 89.6 % of

117   irrigated area annually.

Methodology

119   Water footprint was estimated using the AquaCrop model spatially over the study period

120   following the Water Footprint Network guidelines (Hoekstra et al., 2011). AquaCrop is a robust

121   crop water productivity model developed by FAO's land and water division. It simulates soil

122   water balance, crop growth, and yield response to water using a relatively small number of

123   explicit and mostly-intuitive parameters and input variables. This model was calibrated and

124   validated for various crops under different conditions. It has been utilized for determining WF at

125   different levels (field scale, basin, and regional).

126   AquaCrop model requires the daily rainfall, minimum and maximum temperatures, reference

127   evapotranspiration (ET$_o$), and the mean annual atmospheric carbon dioxide concentration as

128   input climatic data to run (Steduto et al., 2009). Daily gridded datasets of precipitation and

129   temperature for the study period were obtained from the India Meteorological Department

130   (IMD). Daily wind speed, relative humidity, and solar radiation data were obtained from the

131   Modern Era Retrospective-Analysis for Research and Applications (MERRA-2) assimilation

132   model dataset. Daily gridded datasets are rescaled to 0.5^{o} x 0.5^{o} spatial resolution to keep

133   consistency. After quality checks and processing, daily ET_o was calculated using the FAO

134   Penman-Monteith equation. Major data used in this study and their sources are given in Table 1.

135   The basin area was divided into homogenous land units based on land use, soil, and agro-

136   climatological characteristic to account for spatial variations while reducing the number of

137   simulations required (Mali *et al.*, 2015, 2019). Different thematic layers, namely soil, AESR,

138   LULC, basin boundary, and district boundaries, were overlaid, and LU polygons were formed

139   for each district using intersect feature in ArcGIS.

140   The plug-in version of the AquaCrop model was used in this study to assess crop WF over the

141   basin because of its flexibility and ease of use for multiple simulations (Raes *et al.*, 2018). For

142   simulating various crops, parameterization and calibration guidelines provided by the FAO were

143   followed (Steduto *et al.*, 2012). As per their recommendation, crop parameters derived from the

144   available literature were used for the first simulations, and outputs were compared with observed

145   values, then adjusting the parameters and rerunning the simulation. This approach was repeated

146   until the simulation findings roughly matched the observed data. The initial simulation

147   parameters were derived from the AquaCrop user manual (Raes *et al.*, 2018). Water fluxes are

148   divided into a crop's green and blue water footprint by following the post-processing of soil

149   water balances (Chukalla, Krol & Hoekstra, 2015). Grey water footprint and leaching runoff

150   fractions were determined using the Tier-1 approach recommended by WFN (Hoekstra et al.,

151   2011; Franke, Boyacioglu & Hoekstra, 2013).

152   Green and blue WF were obtained by dividing the respective crop water use (CWU) with the

153   yield (Y) over the season.

$$WF_{green} = \frac{CWU_{green}}{y} \qquad (1)$$

$$WF_{blue} = \frac{CWU_{blue}}{y} \qquad (2)$$

156   Where,

157   CWU_{green}: Green water consumption (m^3)

158   CWU_{blue}: Blue water consumption (m^3)

159   WF_{green}: Green WF (m^3/ton)

160   WF_{blue} : Blue WF (m³/ton)

161   Y   : Yield (ton)

162   The grey water footprint (WF_{grey}, m³/ton) refers to the quantity of water required to assimilate

163   pollutants load as per the ambient water quality standards (generally refers to the maximum and

164   permissible water quality standards). It is given by the equation,

165
$$WF_{grey} = \frac{(\propto \times AR)/(c_{max} - c_{nat})}{Y}$$
(3)

166   Where,

167   AR: application rate of fertilizers to the field per hectare (kg/ha)

168    $\propto$: leaching runoff fraction (%)

169   c_{max}: maximum acceptable concentration (kg/m³)

170   c_{nat}: natural concentration for the pollutant (kg/m³)

171   Y: crop yield (ton/ha)

172   The water footprint of crop production (blue, green, and grey) was estimated by multiplying the

173   crop WF with the production statistics of the crop and is presented as million cubic meters per

174   year. Besides agriculture, other sectors are equally crucial for the development and sustenance of

175   humankind. We adopted the WF of domestic, livestock, energy, wildlife, forests, and industries

176   sectors from the district-wise water demand of various sectors (WRD, 2014b). This data was

177   developed by adopting standard procedures and local datasets using Water Evaluation and

178   Planning (WEAP) model. Water demand and availability are intended to be included in a useful

179   tool for water resource planning by using the WEAP system. WEAP stands out for its flexible

180   strategy and integrated approach to modelling water systems. The WEAP puts the supply side of

181   the equation—streamflow, groundwater, reservoirs, and water transfers on an even footing with

182   the demand side, which includes diverse water consumption and its patterns, equipment

183   efficiency, and allocation. District-wise WFs of domestic, livestock, energy, wildlife, forests and

184   industries sectors were estimated using simple linear interpolation for the study period and

185   distributed proportionately based on the area of a district within the basin. These estimates are

186   based on the data of the census population of 1961, 1971, 1981, 1991, 2001, and 2011 future

187   population has been projected up to the year 2060 for the State as a whole for the total, rural and

188   urban population. The district-wise population projections have been made by the ratio method.

189   For the livestock sector, the available data from the livestock census was used. Further details of

190   the methodology used for water demand estimation for other sectors can be obtained from the

191   report (WRD, 2014b). The methodology of WF assessment at the basin scale is illustrated in

192   Figure 2.

193   Results

194   Water footprint of crop production

195   The WF was multiplied with crop statistics to estimate WFs of crop production in million cubic

196   meters (MCM) per year. The total annual WF of major crops in the basin was 19254.5 MCM/yr.

197   Wheat, Bajra, Maize, and Rapeseed & Mustard make up 67.4 % of the total average annual WF of

198   crop production in the Banas basin (20.2, 18.3, 15.8, and 13.1 %, respectively). The annual blue

199   WF of crop production was 3942.1 (MCM/yr). Wheat, and Rapeseed & Mustard make up almost

200   87.0 % of the average annual blue WF (66.7 and 20.3 %, respectively). The largest total WF in the

201   basin was found in Wheat (3890.5 MCM/yr), followed by Bajra (3532.7 MCM/yr), and then Maize

202   (3040.5 MCM/yr). Green WF was highest in Bajra (3213.5 MCM/yr), Maize (2776.1 MCM/yr),

203   and Rapeseed & Mustard (1371.2 MCM/yr). Blue WF of Wheat was highest (2629.8 MCM/yr),

204   followed by Rapeseed & Mustard (799.9 MCM/yr) and Barley (209.8 MCM/yr). The largest grey

205   WF was seen in Rapeseed & Mustard (348.0 MCM/yr), Bajra (306.2 MCM/yr), and Wheat (295.5

206   MCM/yr), respectively. Large WF is directly linked with the crop's average WF and the crop's

207   production in the basin. Crop with high production has higher WF in general. The average annual

208   WF of major crops produced in the Banas basin is shown in Figure 3.

209   The average annual WF of crop production during the study period is depicted in Figure 4. The

210   total WF for crop production was found to be highest at 23131.5 MCM/yr in 2019-20 and the

211   lowest at 11365.8 MCM/yr in 2009-10, respectively. Spatial variation of blue, green, grey, and

212   total WF of agriculture production for major crops in the Banas basin is presented in Figure 5.

213   The blue WF of crop production varies between 82.2-668.5 MCM/yr (Mean 328.5 MCM/yr) in

214   the districts of the basin. Similarly, green WF ranges between 232.3-2625.5 MCM/yr (Mean

215   1129.9 MCM/yr) in the basin districts. Grey WF of crop production varies between 30.8-303.8

216   MCM/yr (Mean 146.1 MCM/yr). The highest total WF in the basin was seen in the Jaipur district

217   (3557.1 MCM/yr), followed by Chittaurgarh (2860.6 MCM/yr). The lowest total WF in the basin

218   was found in Pratapgarh (408.6 MCM/yr), followed by the Bundi district (427.1 MCM/yr). The

219   WF of agriculture is directly linked with crop production, cultivated area, and yield. Hence,

220   districts with a smaller area in the basin have lower annual WF.

221 **Water footprint of Banas river basin**

222 The water footprint of domestic, livestock, energy, wildlife, forests, and industries sector were

223 derived from the district-wise water demand of various sectors from results from the WEAP

224 model from a study conducted by the Water Resource Department, Rajasthan (WRD, 2014b).

225 District-wise water demand data for various sectors from this report was interpolated using

226 simple linear interpolation for the study period. District-wise, WFs were distributed

227 proportionately based on the area of the district within the basin. The total WF of the Banas river

228 basin from all sectors was 20238.3 MCM/yr. The average annual WF in the various sector was in

229 the order Agriculture (19254.5MCM/yr), Domestic (631.4 MCM/yr), Livestock (146.8

230 MCM/yr), Industries (123.7 MCM/yr), Energy (79.1 MCM/yr), Forests (1.7 MCM/yr) and

231 Wildlife (1.1 MCM/yr). Spatial variation of sector-wise WF over the Banas river basin is

232 presented in Figure 6.

233 The agriculture sector accounted for nearly 95.5 % total WF of the Banas basin, which was

234 followed by the Domestic (3.0%), Livestock (0.8%), and Industry (0.5%) sectors, respectively.

235 WF in the Banas basin was found to be highest at 24337.5 MCM/yr in 2019-20 and the lowest at

236 12167.7 MCM/yr in 2009-10, respectively. WF has increased over the year with the increase in

237 population, rise of industries, and increased demand for crop production in the basin region.

238 Sector-wise WF during the study period is shown in Figure 7.

239 **Discussion**

240 Among the various crops highest total WF was found in Sesame, followed by Urad and Moong

241 under both irrigated (16203.6, 11892.1, and 11043.9 m^3/ton, respectively) and rainfed conditions

242 (14261.4, 10359.1 and 9655.1 m^3/ton, respectively). As we know, WF is directly proportional to

243 crop water use (CWU) and inversely proportional to crop yield. The average productivity of these

244 three crops was among the lowest and is the major reason for high WF. CWU in rainfed crops was

245 lower in comparison with the irrigated crop. Total WF was found lowest in Barley, followed by

246 Wheat, then Rapeseed & Mustard under both irrigated (1498.6, 1824.1, and 3200.6 m^3/ton,

247 respectively) and rainfed conditions (1241.3, 1508.3, and 2465.4 m^3/ton, respectively). These

248 crops had a higher yield which could be the main factor in the lower WF. It should be noted that

249 higher or lower WF does not mean higher or lower water use per hectare. Most crops have a lower

250 WF under rainfed conditions mainly because crop yields do not necessarily decrease directly with

251 water stress, as the duration and timing of water stress is also a critical factor. Also, rainfed
252 agriculture is largely practiced in the *kharif* season, where rainfall is plentiful. Significant spatial
253 and temporal variation was seen in WFs in the basin over the study period. For example, the overall
254 WF of the Wheat crop under irrigated condition varied between 1682.8-2133.2 m^3/ton (Mean
255 1824.1 m^3/ton) over the basin. Spatial variation of blue WF during the study period ranged between
256 1092.6-1451.2 m^3/ton (Mean 1242.7 m^3/ton). Blue WF was 68.1% of total WF on average.
257 Average green WF varied in the range of 407.8-510.4 m^3/ton (Mean 451.1 m^3/ton) during the
258 simulation period. Similarly, grey WF varied between 44.5-213.1 m^3/ton (Mean 130.4 m^3/ton).
259 Similarly, the total WF of the Wheat crop under rainfed condition varied between 1336.5-1716.8
260 m^3/ton (Mean 1508.3 m^3/ton) over the basin on average during the 2008-2020 period. Spatial
261 variation of green WF varied in the range of 1227.1-1529.5 m^3/ton (Mean 1361.3 m^3/ton) during
262 the simulation period. Similarly, grey WF varied between 47.1-247.7 m^3/ton (Mean 147.0 m^3/ton).

263 WF of major crops in the Banas basin under irrigated and rainfed conditions is presented in Figures
264 8 and 9.

265   A comparison between the outcomes of this study and earlier research work is given in
266 Table 2. Our study results are in line with previous studies. In the present study, the AquaCrop
267 model was used to estimate WF spatially over time using local data. The reference
268 evapotranspiration was calculated according to the Penman-Monteith equation, which is the most
269 widely used technique (Allen et al., 1998). The WF of most crops in the Banas basin was higher
270 in comparison with the global averages (Mekonnen & Hoekstra, 2011b). This is basically due to
271 lower yield and climatic variation. Several WF studies have been conducted on different crops at
272 different spatial scales and geographical locations. Only a few studies have been conducted in
273 India, and most use global or national statistics (Kampman, Hoekstra & Krol, 2008; Suhail, 2017).
274 Then there are global WF studies of crops and derived crop products which also include India
275 (Chapagain & Hoekstra, 2008; Mekonnen & Hoekstra, 2011b). Previous basin-level studies
276 conducted in India used simple computation methods using the CROPWAT model (Mali et al.,
277 2018; Rao, Hardaha & Vora, 2019). Some recent studies have used the AquaCrop model in
278 different regions/basins of the world for WF assessment (Zhuo & Hoekstra, 2017; Nouri et al.,
279 2019; Khan et al., 2021). The primary reason for differences in computed WFs could be the
280 variances in the methodology adopted, the technique used for ET estimation, input data, the model
281 used, the scale, and the scope of the studies. Best efforts were made to parameterize and run the

282 model using locally available data to capture the variation of water footprint adequately. We note

283 that AquaCrop has inherent limitations in modelling crop yield spatially (Chukalla, Krol &

284 Hoekstra, 2015; Berhane, 2018). A modified default crop file was used to simulate crops when the

285 standard crop file was unavailable in AquaCrop. Still, these results can provide a valuable

286 reference for similar future studies.

287 On average, the WF of crop production was 69.7 % green, 20.8 % blue, and 9.5 % grey in the

288 basin. Rainfed agriculture is prominent in the Banas river basin and is the reason for higher green

289 WF. In general, the WF of crop production is increasing as more area comes under cultivation of

290 crops, high-yielding varieties of crops are being developed, improved irrigation technologies

291 become available, and more water storage structures are being constructed. These results are in

292 line with previous results from similar studies. The blue WF accounted for 47.3% and 43.6% of

293 the total WF of Gomti and Betwa basins, respectively, while the share of grey WF was about

294 9.1% and 10.9% of total WF (Mali et al., 2018, 2019). Studies have shown that 78 % of the

295 global agricultural WF is green, 12 % is blue, and 10 % is grey WF (Mekonnen and Hoekstra,

296 2013).

297 The agriculture sector accounted for nearly 95.5 % total WF of the Banas basin, which was

298 followed by the Domestic (3.0%), Livestock (0.8%), and Industry (0.5%) sectors, respectively.

299 This is similar to one study from India, where crop production accounted for nearly 95.5% and

300 96.4% of the WF in the Gomti and Betwa basins, respectively (Mali et al., 2017, 2018, 2019). In

301 China, a study estimated the WF of the yellow river basin to be 1768 MCM, 96 % of which was

302 from agriculture (92 % for crop production and 4 % for livestock) and the rest 4 % from

303 industrial and domestic sectors, respectively (Zeng et al., 2012). Crop statistics, population,

304 livestock, and water demand data for other sectors are not available at the river basin level. So,

305 we had to calculate it based on district-level estimates and the area of districts within the basin.

306 This inherent limitation leads to errors in the calculation as statistics within the district are

307 assumed to be distributed equally, which may not be accurate in most cases. Many other

308 previous studies on data availability or planning of resources are done on administrative scales

309 instead of the basin. For proper management of water resources, there is a need to implement

310 basin-scale planning and databases. While more focus was put on the agriculture sector for this

311 WF assessment as it is the primary consumer of water in the basin. Evaluation of water demands

312 of other sectors was made based on data reported by the water resource department which was

313   comprehensive but somewhat outdated, and the distinction between the blue, green, and grey

314   components of WF couldn't be made for them. Future studies on various components of WF for

315   other sectors will also be instrumental. Even with their minor contribution to overall WF in the

316   basin, other sectors may significantly contribute blue and grey degenerative WF, which can be

317   crucial for sustainable water use planning.

318   Agriculture makes up a considerable part of the basin water footprint, and it is necessary to

319   reduce it to sustainable levels. Numerous studies have concluded that WF can be reduced by

320   adopting strategies, methods, and technologies to reduce non-beneficial consumptive water use

321   (Jovanovic et al., 2020). Some practices can upgrade the water management in agricultural fields

322   by implementing precision irrigation methods(Smith, 2011; Abioye et al., 2020), improving

323   irrigation efficiency (Evans & Sadler, 2008; Greenwood et al., 2010), and irrigation scheduling

324   (Hinton and Consulting, 2001; Tesema *et al.*, 2011; Wen *et al.*, 2017), adopting better

325   agricultural practices like drip irrigation and mulching (Chukalla *et al.*, 2015; Nouri *et al.*, 2019;

326   Scardigno, 2020; Ding *et al.*, 2021) and augmenting water productivity (Igbadun *et al.*, 2012;

327   Muhammad *et al.*, 2017; Mubvuma *et al.*, 2021). Agronomics practices and in-situ water

328   conservation can significantly reduce local water scarcity(Kumar et al., 2021; Sharma et al.,

329   2021; Singh et al., 2021). Reducing food wastage(Sun *et al.*, 2018; Kashyap and Agarwal, 2020)

330   and focusing on changing diets (Harris et al., 2017; Green et al., 2018) can also help decrease

331   water consumption.

332 Conclusions

333   This study provides a comprehensive estimate of the water footprint of various sectors. The

334   water footprint of major crops was estimated using the AquaCrop model spatially over the study

335   period (2008-2020). The water footprint of crop production (blue, green, and grey) was estimated

336   by multiplying the crop water footprint with district-wise production statistics. The water

337   footprint of domestic, livestock, energy, wildlife, forests, and industries sector were derived from

338   the district-wise water demand of various sectors. The water footprint of crop production in the

339   basin was 19.3 BCM/yr. Wheat, Bajra, Maize, and Rapeseed & Mustard make up 67.4 % of crop

340   production's total average annual water footprint. The larger water footprint is directly linked to

341   the cultivated area and production of the crop in the basin. Water footprint of the Banas river

342   basin was estimated as 20.2 BCM/yr from all sectors. The agriculture sector accounted for nearly

343 95.5 % total water footprint of the Banas basin. Water footprint has increased over the year with

344 the increase in population, the number of industries, and crop production demand. The results of

345 this study provide helpful insights into the current situation in the basin. Appropriate measures

346 are required to develop adaptation approaches to overcome water scarcity challenges in the

347 basin. Outcomes provide baseline information for further research to advance sustainable

348 production and planning. Suitable actions should be taken for improving water productivity and

349 promoting sustainable water use. There is a need to promote practices like changing crop

350 patterns, mulching, and micro irrigation to reduce water use in Agriculture.

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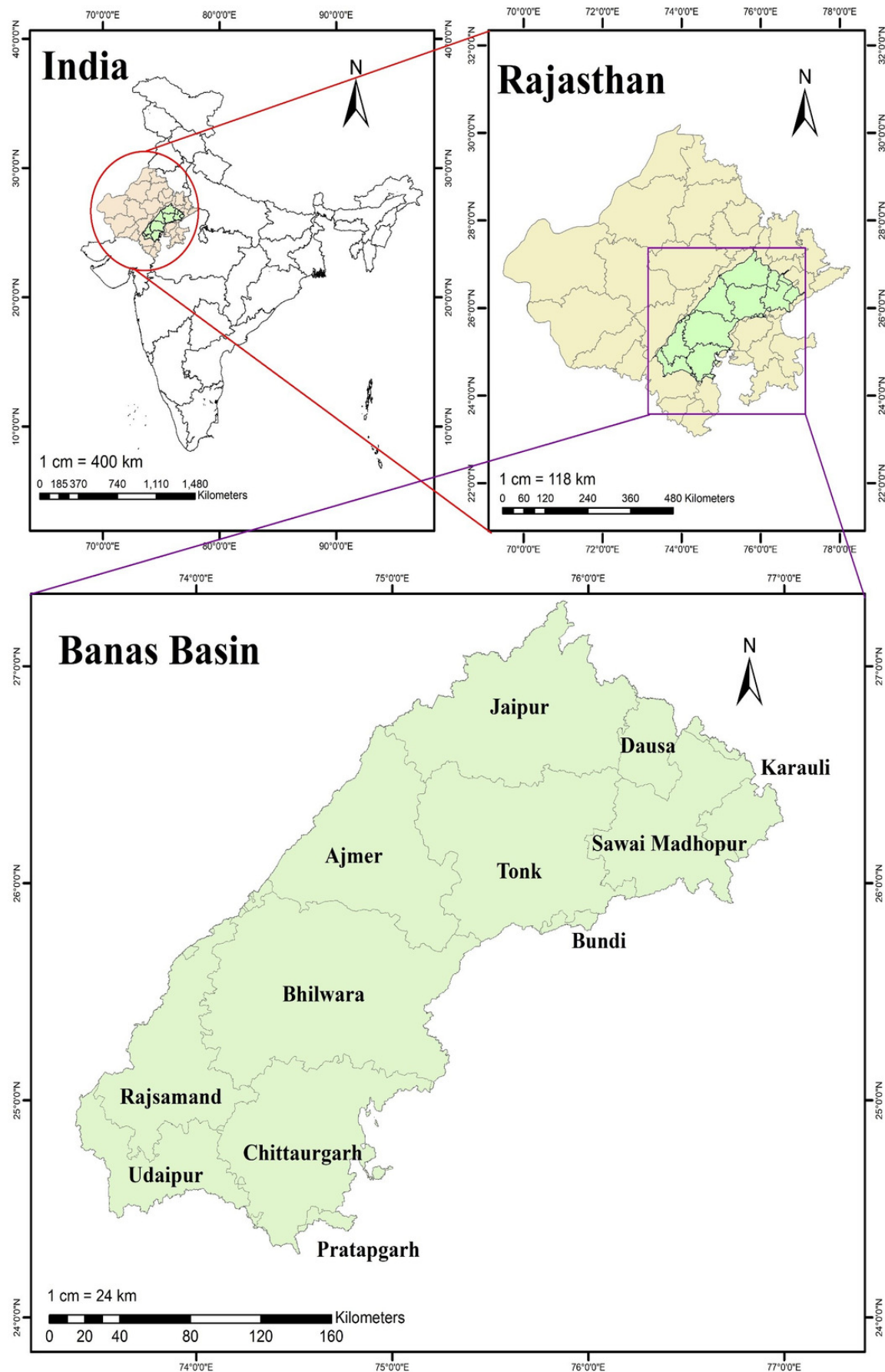
Figure 1

Location of Banas river basin

Datasets used and their sources

S.No	Type of data	Source
1.	Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM)	SRTM DEM, National Aeronautics and Space Administration (https://earthexplorer.usgs.gov/).
2.	Agro-Ecological Regions map	National Bureau of Soil Survey & Land Use Planning, Indian Council of Agricultural Research (http://geoportal.icar.gov.in/)
3.	Soil properties	Harmonised world soil database v1.2 (http://www.fao.org/)
4.	Land use land cover map	Bhuvan, National Remote Sensing Centre, Indian Space Research Organisation (https://bhuvan.nrsc.gov.in/)
5.	District-wise cropped area and agriculture statistics	Agriculture Statistics Handbook, Directorate of Economics & Statistics, Department of Planning, Government of Rajasthan (https://agriculture.rajasthan.gov.in/) and Agriculture Statistics at Glance, Minister of Agriculture & Farmers Welfare, Government of India (https://agricoop.nic.in/)
6.	Metrological Data	India Meteorological Department (IMD), Ministry of Earth Sciences, Government of India (GOI). (http://www.imdpune.gov.in/) and Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), NASA (https://power.larc.nasa.gov/)

Figure 2

Water footprint assessment methodology at basin scale

Soil Map	LULC	AESR	Basin and District boundary

Initialization and parameterization

Land Unit (LU)

Soil

Crop

Climate

Management

Fertiliser application rates

Aqua Crop

WF_grey

WF_blue

WF_green

Crop Statistics

WF_agriculture

WF_livestock

WF_domestic

WF_industry

WF_forestry

WF_wildlife

WF_energy

WF_basin

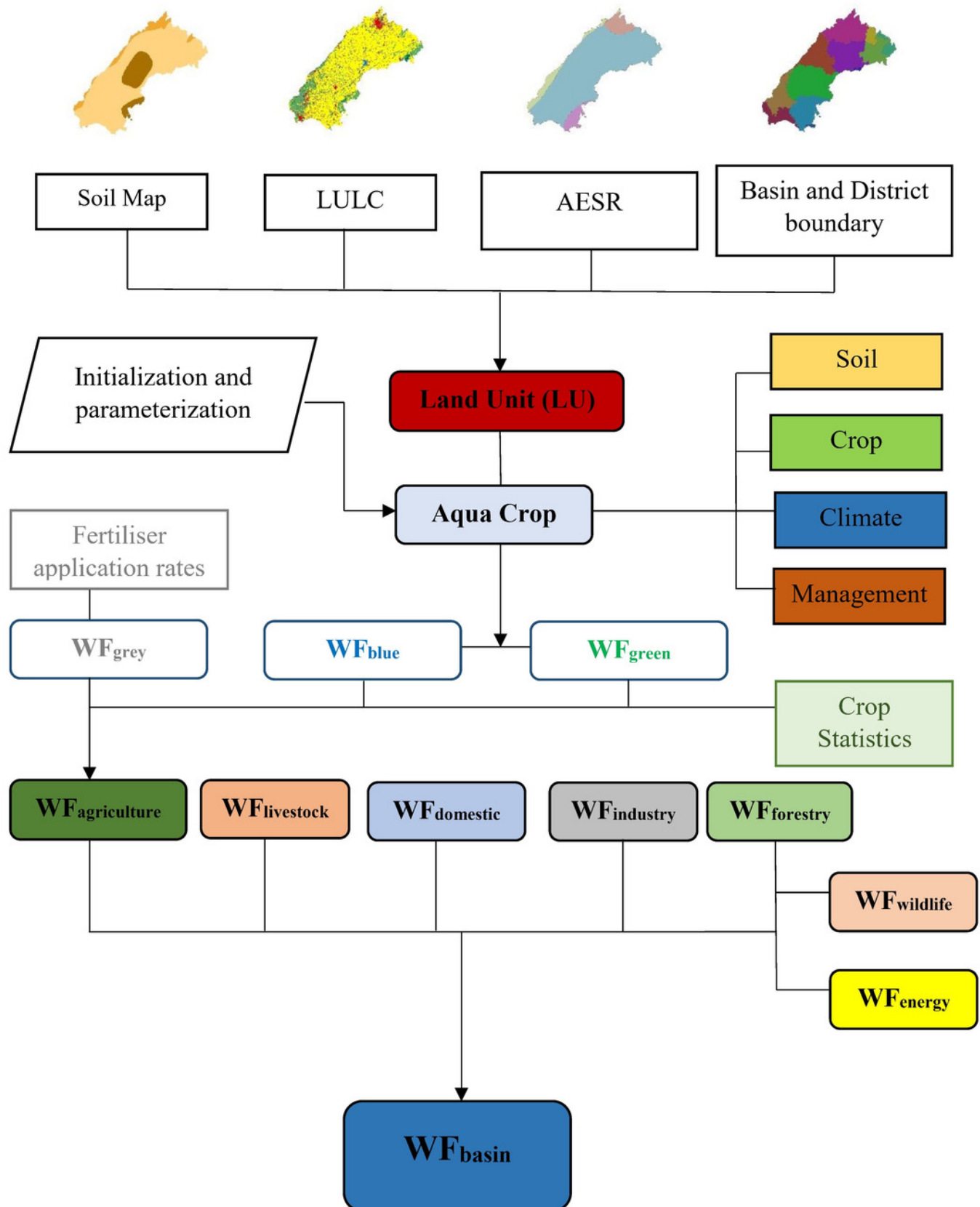



Figure 3

Average annual water footprint of major crops in basin

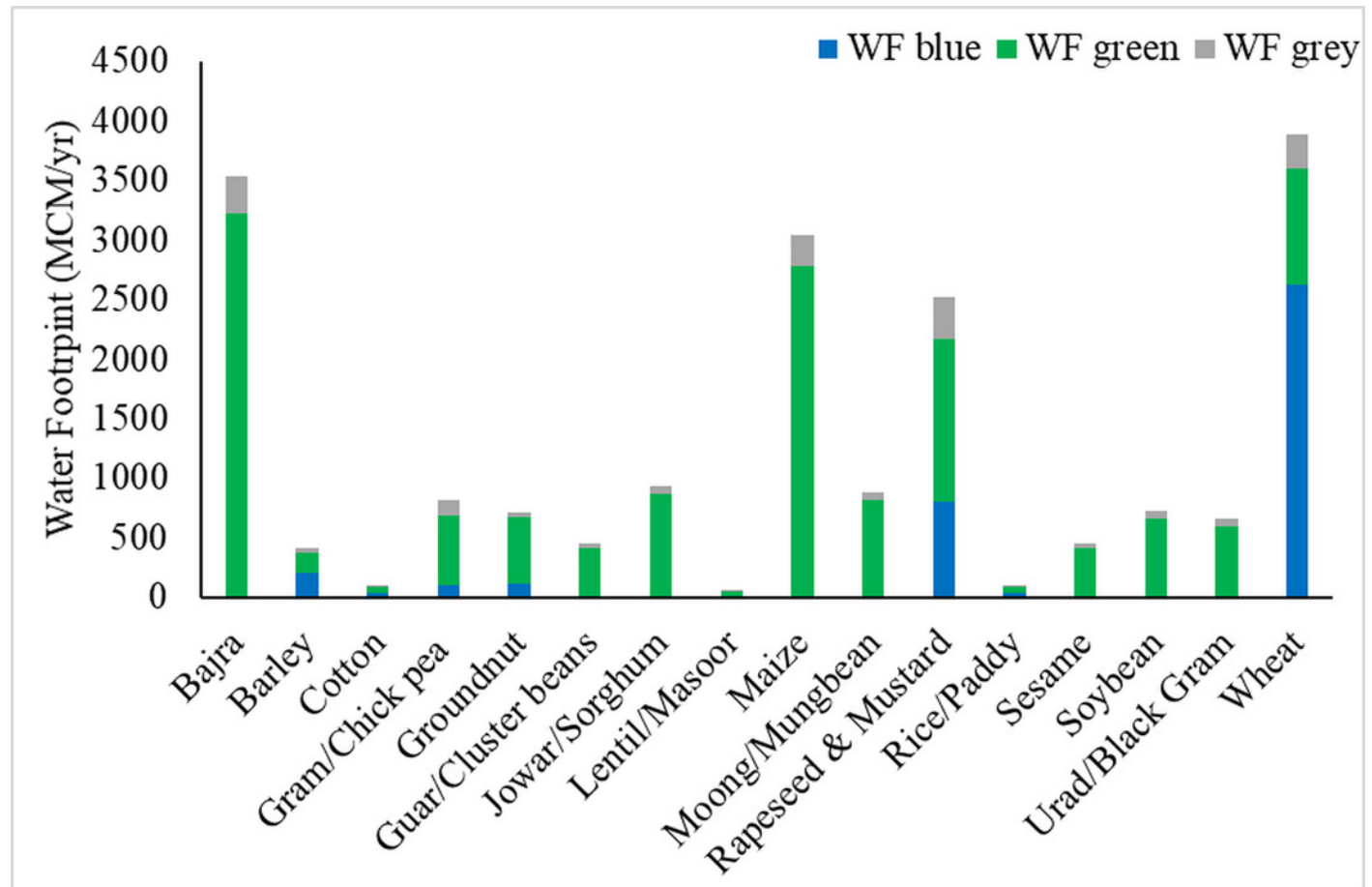



Figure 4

Average annual water footprint of crop production during 2008-2020

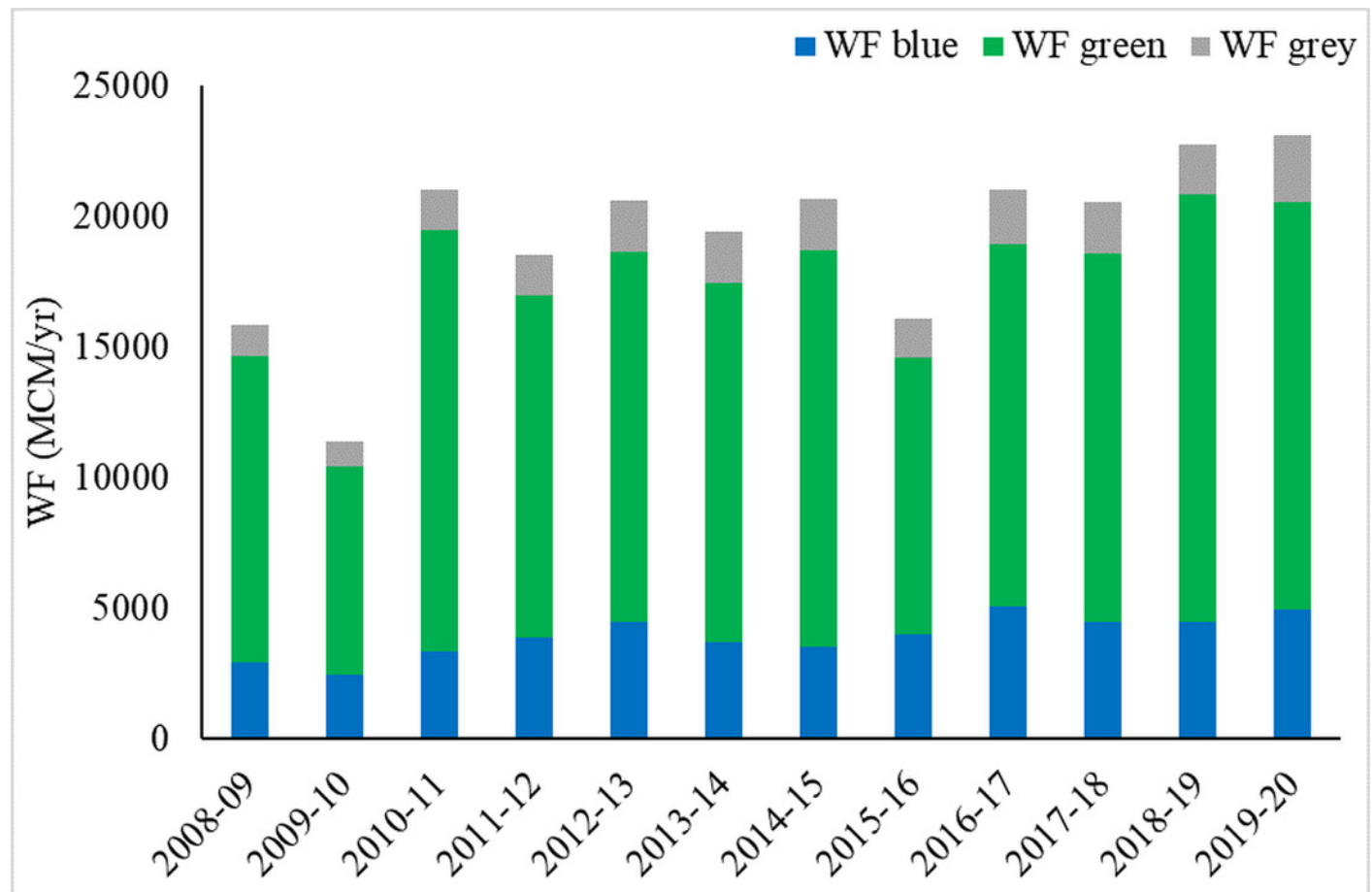



Figure 5

Spatial variation of blue, green, grey and total water footprint in Banas river basin

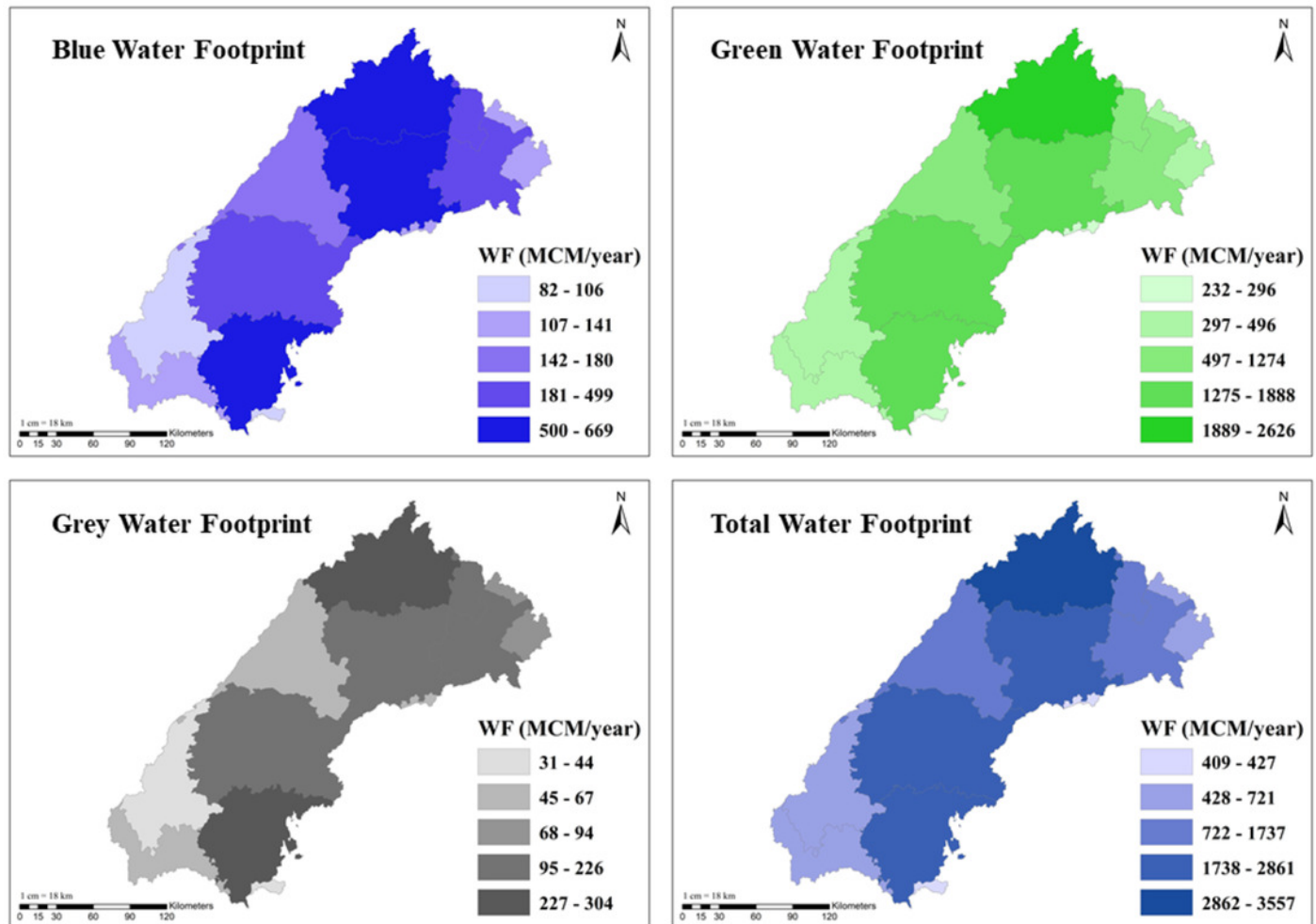



Figure 6

Spatial variation of sector-wise water footprint over the Banas river basin

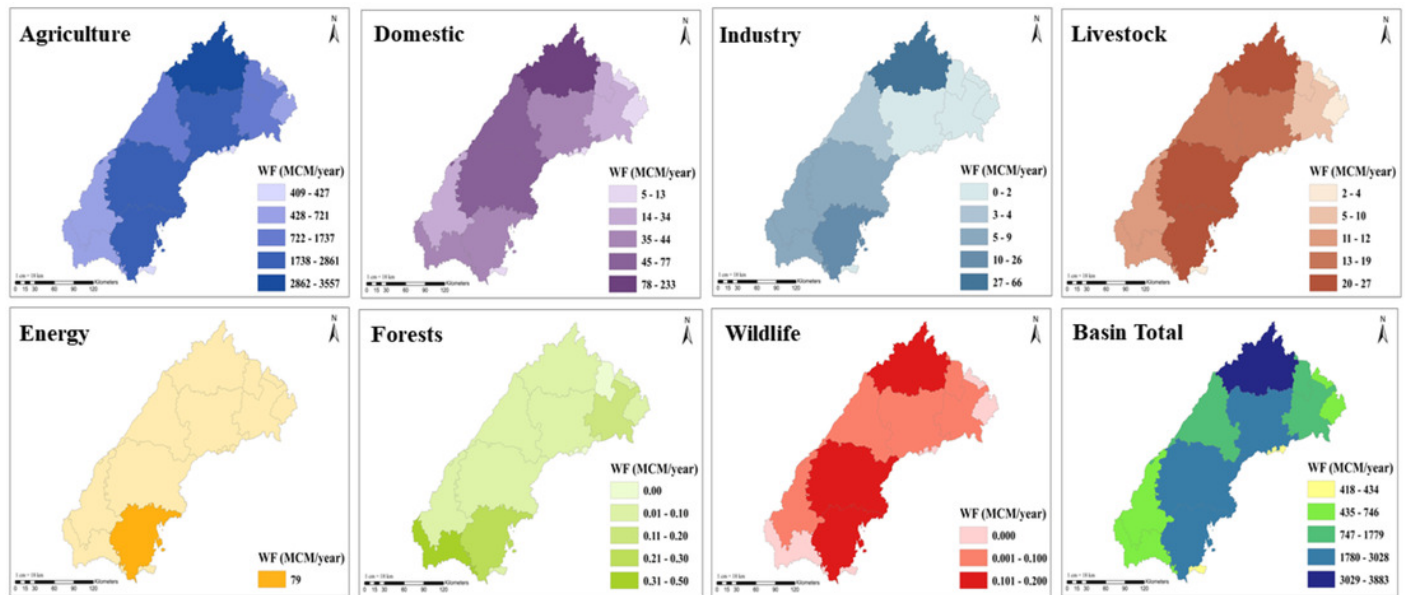



Figure 7

Sector-wise water footprint during the study period

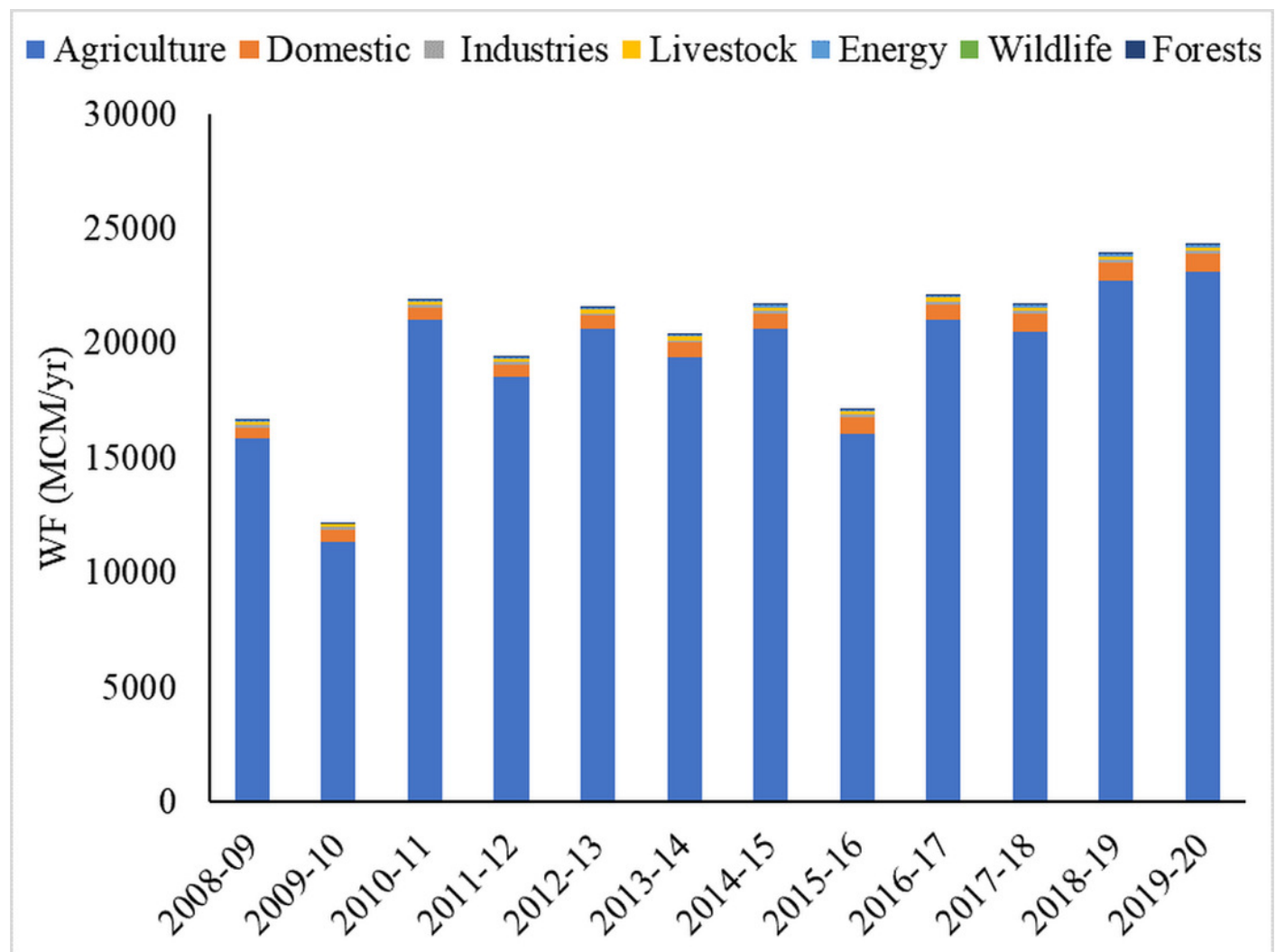



Figure 8

Water footprints of major crops in Banas river basin under irrigated condition

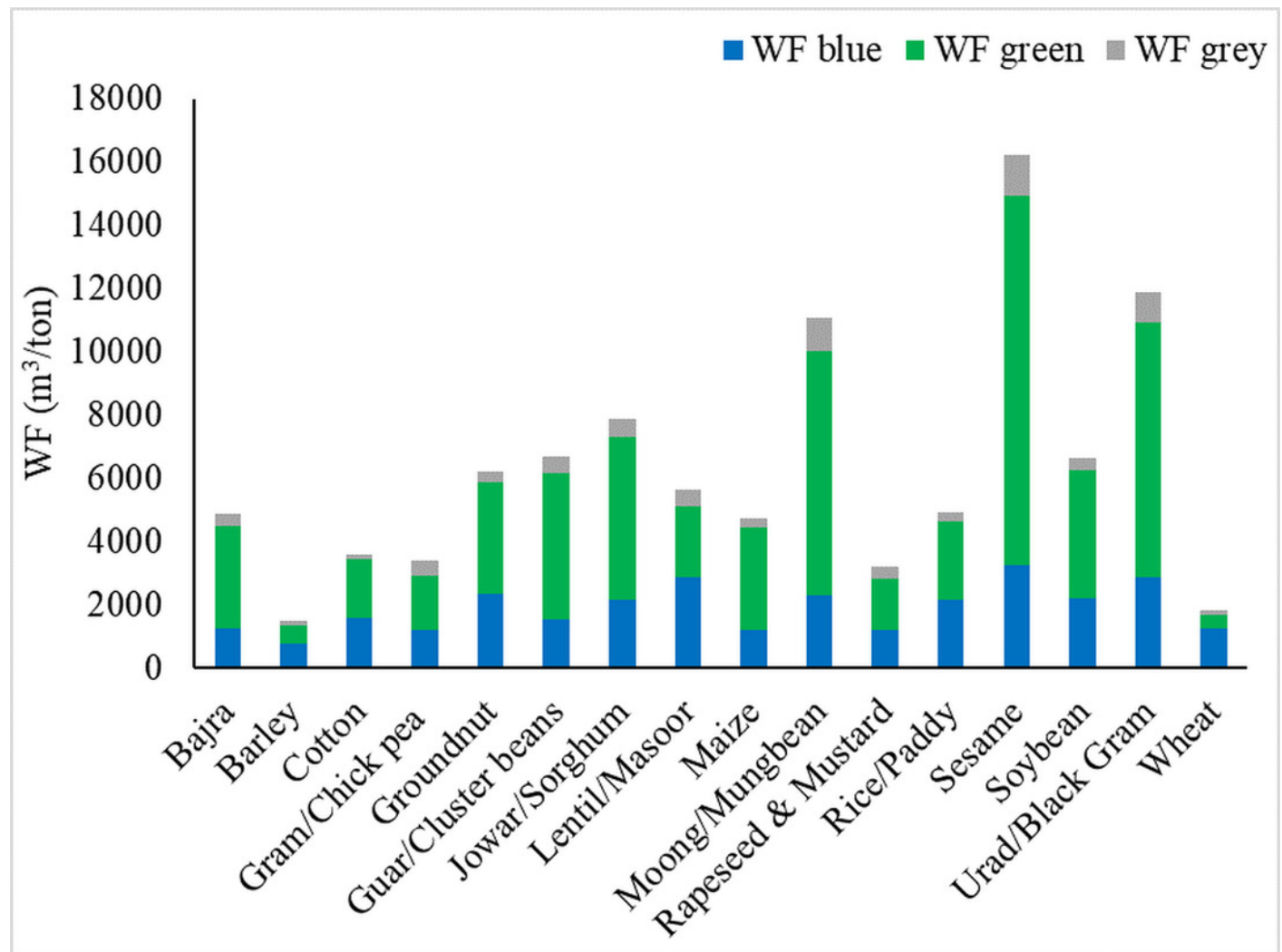
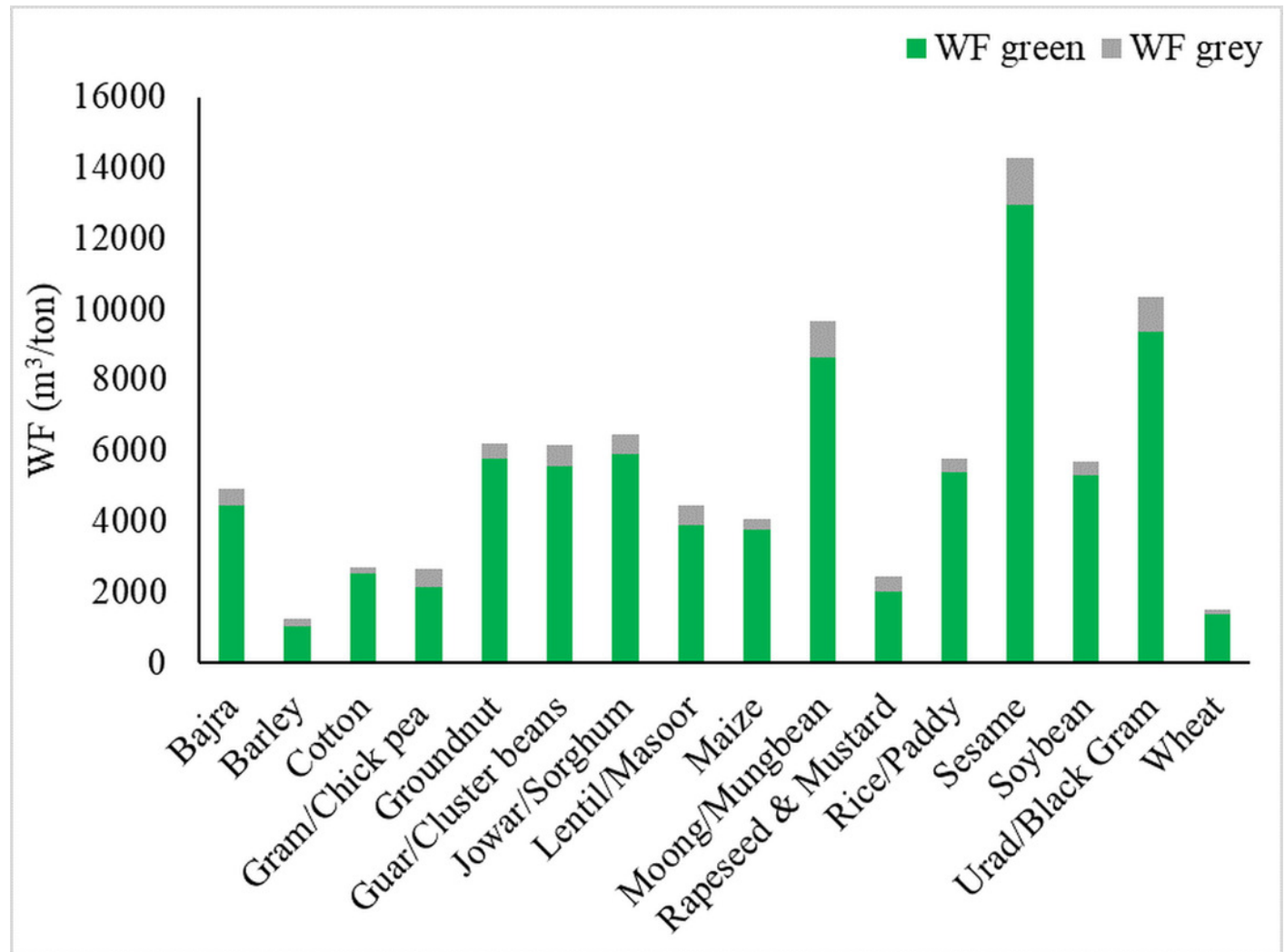



Figure 9

Water footprints of major crops in Banas river basin under rainfed condition

Water footprints of major crops in Banas river basin under rainfed condition

Comparison of present results with previous work

	Chapagain and Hoekstra, (2008)	Kampman, (2008)	Mali *et al.*, (2019)	Rao, (2019)	Suhail, (2017)	Mekonnen and Hoekstra, (2011)	Current Study	
							Irrigated	Rainfed
Bajra	3269	4222			4029	4478	4854	4908
Barley					2124	1423	1499	1241
Cotton	8264	10633				4029	3584	2713
Gram/Chickpea	2712	2071		9663		4177	3382	2649
Groundnut	3420	4372		4085		2782	6213	6205
Guar							6699	6148
Jowar/Sorghum	4053	3589		3739	6026	3048	7855	6463
Lentil/Masoor			5860			5874	5626	4432
Maize	1937	2399	1818	2886	2537	1222	4717	4066
Moong/Mungbean							11044	9655
Rapeseed & Mustard	2618	3972				2809	3201	2465
Rice/Paddy	4113	4073		7848	2070	1673	4897	5767
Sesame			8956			9371	16204	14261
Soybean	4124	3526		3060	4410	2145	6635	5711
Urad/Black Gram							11892	10359
Wheat	1654	1412	2473	5417	2100	1828	1824	1508
Study Period	1997-2001	1997-2001	2011	2000-2013	1999-2006	1996–2005	2008-2020	
Scale	Global	National	Regional	Regional	National	Global	Regional	
Location	India	India	Gomati Basin	Banjar Watershed	India	Global	Banas Basin, Rajasthan	
Method	CROPWAT	CROPWAT	CROPWAT	CROPWAT	CROPWAT	CROPWAT	AquaCrop	