A watershed level framework to assess the self-sufficiency and sustainability of water and food resources for the consumption and production in the current and future climate change scenarios

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Submission Date : 18-Aug-2023

PROPOSAL DETAILS

(PDF/2023/003985)

Principal Investigator	Mentor & Host Institution
Dr. DAGANI KOTESWARA RAO koteswararaodagani@gmail.com Post-Doctoral Fellow(Civil Engineering) **Contact No** : +919966709029 **Date of Birth** : 25-Aug-1991 **Name of Father/Spouse :** Raghavendra Rao	**V V Srinivas** vvs@iisc.ac.in Professor(Civil Engineering) **Indian Institute of Science** Cv raman rd, bengaluru, Bangalore urban district, Karnataka-560012 **Contact No.** : +919483888090 **Registrar Email** : registrar@iisc.ac.in **No. of PHD Scholars** : 11 **No. Post-Doctoral Fellow** : 0

Details of Post Doctorate

Ph.D. (Hydraulics and Water Resources Engineering)[Degree Awarded on : 20-Aug-2022]

Water footprint assessment of an urban agglomeration in developing economy: A case study of Hyderabad Metro Development Authority (HMDA) region.

Research Supervisor/Guide & Institution :

Dr. Satish Kumar Regonda

Indian Institute of Technology Hyderabad

Brief details of Thesis work :

Propagating the effect of imported water scarcity in the urban regions to the surroundings, due to virtual water imports in food trade, produced from the regional and global scarce water resources is a critical issue. It needs to be addressed by fairly quantifying the dependency of urban regions on external waters, so that sourced regions won't leave with inadequate water and be forced to rely on external sources. Also, it helps to redefine the water and food policies for the self-sufficiency of the regions and to secure water-centered resources. For the kind of studies in urban regions, hindered with availability of city level data, conceptualizing a framework is crucial. Here, a framework has been proposed by adopting a consumer centric approach to quantify dependency of the regions from consumption and production perspectives using water footprint (WF)s. Also, it's demonstrated by quantifying the dependency of Hyderabad Metro Development Authority (HMDA) region on external waters using consumer level consumption, agricultural production information available on open data platforms. From the results, it observed that, the Consumption WF (CWF) of HMDA region is 9386 MCM and it is 2 times the agricultural production WF (PWF) of volume 4572 MCM. Since that, the study found nearly half of HMDA's CWF is imported from external water resources only. Similar observations are found on comparing the CWF, PWFs of volumes, 6836, 4426 MCM, i.e., in the total food CWF, 35% of it comes from external waters only. The study region has more deficit WF in agricultural products and surplus in livestock WF, since it is importing an external WF of 3495 MCM in agricultural products and exporting an internal WF of 1085 MCM in livestock. Also, the study quantified the green, blue, and grey WFs and categorized the water-intensive products based on consumption quantity, standard WFs.

Technical Details :

Research Area : Earth & Atmospheric Sciences (Earth & Atmospheric Sciences)

Project Summary :

The recent emergence of El Niño has highlighted its detrimental effects on India's southwest monsoon and agricultural sector, which makes a substantial contribution to the Indian economy through agricultural exports. In light of this, India must undertake a comprehensive examination of its water resource dynamics, encompassing agriculture and other trade sectors, including agriculture itself. Furthermore, it is imperative to scrutinize the nation's reliance on external water sources at the watershed level. In order to comprehend the availability of regional water resources and the extent of a region's reliance on external water sources within India, particularly in light of current and future conditions of food consumption and production under evolving climate scenarios, a framework has been proposed. The framework aims to assess the self-sufficiency of regions in terms of food consumption and production. This assessment involves analyzing dietary practices and agricultural practices to determine the region's deficit or surplus in food production. The findings will guide the development of food trade policies to maintain food security and promote self-sufficiency. Additionally, the framework evaluates the sustainability of the region's water resources at the watershed level. It compares regional water availability with agricultural water consumption to determine if the region's water resources are sustainable in relation to food production. If deficits are identified in food consumption, production practices, and regional water resources, the framework analyses the underlying reasons through an investigation of current practices. The ultimate goal is to provide policy recommendations to decision-makers to address these challenges to achieve regional self-sufficiency, and security of water-food resources to achieve sustainable development goals by addressing the food systems, effectively.

Objectives :

• Developing a watershed-level framework to draft coherent policies for water and food resources between consumption and production regions.
• The self-sufficiency of the region's food and water resources will be assessed at different spatial scales, by comparing the number of calories produced and consumed from the food products and their relative volume of water utilized in food production and consumption.
• Sustainability of regional water resources will be assessed, by comparing the regional water availability with the amount of water utilized for food consumption and production.
• Draft the water and food policies between the wet and dry regions to maintain regional self-sufficiency and for the security of water and food resources.

Keywords :
self-sufficiency, sustainability, dependency, water and food security, water-energy-food nexus,

Expected Output and Outcome of the proposal :

- The regions of agricultural, hydrological, and socioeconomic-food drought will be identified by comparing the regional water availability with the current agricultural production and dietary practices in food consumption in the current and future climatic scenarios. - Regional food trade strategies (that are interconnected with the water-energy-ecologic-socioeconomic-nexus) will be suggested with respect to the regional water availability in the consumption and production regions to maintain self-sufficiency and security resources; also to draft the water-food at regional scales. - In addition to the above, 2 to 3 research publications will be the outcomes of the proposed research work. The tentative titles of the publications are as below: (i). Sustainability and self-sufficiency of regional water resources for the current state of food consumption and production at the multi-spatial level; (ii) A multi-spatial scale framework to develop regional-level water and food policies at the watershed scale;

Reference Details :

S.No	Reference Details
1	**Dr. Satish Regonda** **Department of Civil Engineering, IIT Hyderabad, Kandi Village, Sangareddy[+9581118374]** satishr@ce.iith.ac.in
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Title: A Watershed level framework to assess the self-sufficiency and sustainability of water and food resources for consumption and production in the current and future climate change scenarios.

Study background and Importance of current research:
India, as an agricultural nation, benefits from the southwest monsoon and exporting a substantial volume of virtual water of volume, 95 billion cubic meters, annually, in the form of agricultural products. Notably, India consumes only one-fourth of the virtual water it exports, surpassing the efforts of developed nations equipped with advanced technology. This exports significantly contributes to India's national economy. The recent onset of the El Nino effect has raised concerns among various global agencies and the Indian meteorological department (IMD) regarding its potential impact on the Indian monsoon and, consequently, the agricultural food systems. As a crucial player in the global economy in the food systems, India faces the necessity to position itself as a global leader in current and future climatic scenarios. This requires the country to ensure self-sufficiency of water-centred resources, primarily, food, energy, and water. In this context, it is imperative for India to closely monitor the flow of its water resources, particularly in the form of food and other trades. Additionally, the country must urgently address its dependency on external resources for water, food, and energy. A thorough investigation into these dependencies is essential to ensure long-term sustainability and resilience in the face of changing climatic conditions.

1. Introduction

Importance of food systems research:
The food systems have become more vulnerable with the geopolitical war and socioeconomic situations around the world due to post-pandemic crises (Charis M, 2023); and food systems are more prone to propagate the imported water risk to the surrounding regions through the food imports/trade (Hoekstra & Mekonnen, 2016). The regions around the world are importing food through the trade to reach their food needs, at the risk of consequences from the food emissions (GHG) (Pradhan et al., 2013) and water risks in water scarce producing regions [5]. Although food trade is common, but still many regions are facing the effect of malnutrition in combination with regional water scarcity (Pradhan et al., 2014), that is effecting the socio-economic conditions (Athare et al., 2020). This is due to (i) not monitoring the self-sufficiency and dependency of regions on external resources, where the maximum share of imports comes in the form of food products and (ii) lack of coherence in food and water policies between the source, importing regions at different spatial scales; and (iii) lack of mechanism that gauges the intersectoral fluxes on a common platform that elevates and resolves the socioeconomic, geopolitical, and transboundary conflict paradigms. These are crucial things that needs to be addressed with proper attention, since, globally more than 70% of the water resources are invested in food systems only, where water, energy and food resources are interconnected (Gerten et al., 2020). Thus, self-sufficiency of the regions in water, energy and food resources is given higher priority (Weil et al., 2020). In this context, food systems must be probed from the multi-interdisciplinary perspectives by integrating the regional water availability with the food consumption and production.

Available literature and research gaps:
From the literature, many studies addressed the food systems from the consumption or production perspectives but in most of the studies, water, energy, and food resources are considered as silos. There are various studies from regional to global scale on different perspectives for the security of water, energy (Gupta, 2019) and food, but less studies focused on the assessing of the self-sufficiency of the regions from the perspective of food to reach the nutrition deficiency, regional water and energy availability. However, some studies assessed the self-sufficiency of regions in food consumption and malnutrition from regional to global scale from the dietary practices of the regions (Kriewald et al., 2019; Pradhan et al., 2014). But these studies could not perform much research on self-sufficiency of regions by integrating the sustainability of regional water resources for food systems in consumption and production. Because food systems are interconnected with other sectors and it is difficult to integrate, where water, energy and food resources meet together and interdependent one on another. Therefore, understanding the food systems are very crucial to address the sustainability issues under the common platform. In this aspect water-energy-food nexus conceptualisation is proven approach to address these issues (Fader et al., 2018). This proposal focuses on exploring the dependency of the regions on external resources to investigate the regions self-sufficiency in food systems at different spatial scales, which are depended on water-centred resources and controls one another.

2. Objectives

The overall goal of this work is to develop a watershed level framework for analysing the interaction between the water and food systems between the consumption and productions regions. The specific objectives are given below.

i. Assessment of the Self-sufficiency of the regions in water and food resources at different spatial scales.
   a. The food consumption water for relative calorific consumption will be assessed from the consumption perspective.
   b. The crop calorie production, relative water and the regional water availability will be estimated using a crop growth and hydrological models in the production perspective.
   c. The consumption and production calories and relative water will be compared at different spatial scales to assess the self-sufficiency.
   d. The water intensive products will be identified from the consumption and production.
ii. Assessment of the sustainability of regional water resources for consumption and production.
   a. The consumption and production water will be compared with regional water resources availability.
iii. A watershed level framework will be developed to draft the coherent policies for water and food resources between consumption and production regions.

Possible scope of interest: In the current proposal is to "Integrate the food systems with the regional water availability based on the food consumption and production at the river basins scale under the varied climate scenarios" which helps not only to balance the supply and demand between the stakeholders, also helps to maintaining the food and water security at river basin scale by interlinking the foodsheds rather than watersheds/river basins.

3. Methodology

The overall methodology is divided into three components, i.e., consumption perspective, production perspective and dependency of the region on the external water resources. The specific methodology for each of the three components is given in following sub-sections.

A. Consumption Perspective:

In the consumption perspective, the food consumption of the regions will be assessed at river basin scale. As part of that, the per capita food consumption quantities of population (urban and rural) in the study region will be considered from primary or secondary datasets (example: from food balance sheet from FAO at global level or National Sample Survey Organization of India for national scale). The monthly per capita consumption quantities of different regions (states/districts) with in the river basin are considered based on the spread or stretch of river basin. The food quantities may include with agricultural and non-agricultural products. Considering the non-agricultural products, helps to assess the production WF of livestock feed in the study region.

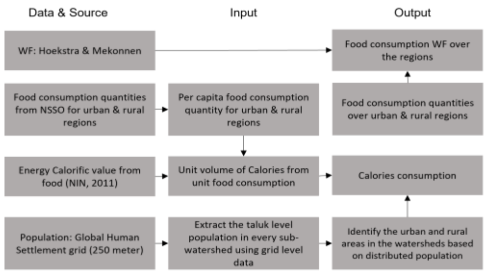


Figure 1: Flow chart detailing the methodology for assessing the food consumption calories.

The total food consumption quantity over the population in the study region will be quantified by considering the population data. To quantify the food consumption over the study region, the urban and rural population data will be considered; the average population density for urban, rural regions will be defined (based on population density statics of India) to quantify the total food consumption quantities over the study region. The total food consumption quantities will be coupled with standard WF of food products corresponding to the study region, which will be considered from data from the past research studies (Mekonnen & Hoekstra, 2010, 2011). Estimation of carbon emissions and calories consumption: The calorie consumption and carbon emissions will be estimated from the food consumption, using the standard calorific energy requirements for per capita given by the WHO for global regions or National Institute of Nutrition, India and carbon emission from each food product from the food consumption (Athare et al., 2020). So that, the volume of consumption calories, water, food, and carbon emission quantities will be estimated in the consumption perspective. Water-Food Nexus will be estimated using the consumption WF. The total consumption food consumption quantities, embedded water constants, standard WF of the products and per capita consumption WFs will be compared (Koteswara Rao et al., 2021) to identify the water intensive food products in the consumption.

<u>Significance of the study</u>: the study helps to understand which products are consumed more in the study region based on the dietary habits of population. Also, highlights the water intensive food products in the dietary habits of the study region.

B. Production perspective:

The production quantities of agricultural products are estimated from the following tasks (i) the crop water requirements will be estimated for the crops grown in study region using CROPWAT, (ii) the crop production will be estimated using the crop yield data, cropping area, (iii) the production WF of crop products in study region will be estimated from the crop production and estimated crop water requirements i.e., ET (green water), irrigation (blue water) or the crop production quantities in the study region at watershed level will be assessed using any hydrological model (for example: SWAT) which requires the inputs, land use land cover, soil type, cropping areas and crop pattern information. (iii) To know the regional water availability from the local climatic conditions, a hydrological study will be conducted over the study region.

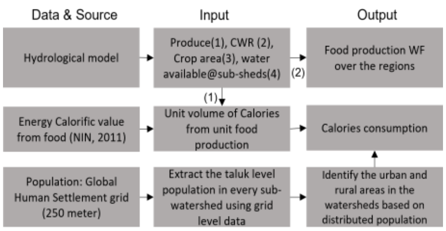


Figure 2: Flowchart detailing the methodology for assessing the production calories.

The crop production WF will be estimated from crop production and yield statistics information developed from the crop growth or hydrological models. Estimation of carbon emissions and calories production: In the production perspective, the carbon emission and calorie production values will be estimated using the standard per capita calorific energy (National Institute of Nutrition, India, 2011) and unit carbon emission values (Thushar et al., 2022). Estimation of water intensive crop products: Likewise, Water-Food nexus in consumption perspective, in the production perspective also estimated the production WF. The total production quantities, embedded water content in the production, standard WF volumes in the production and per capita production quantities will be analysed to identify the water intensive products in the production. The estimated crop WFs will be compared with regional water availability at every watershed or sub-watershed estimated from the hydrological study from the process based hydrological model.

Significance of the study: the study helps to understand, production WF of agricultural crops in the study region. Also, it helps to understand which regions may have water stress due to producing water intensive food products by comparing production WF and regional water availability.

C. Dependency of the regions on external water resources (External Water Footprint of food consumption):

To quantify the dependency of region on external water for food the consumption and production calories and the relative water consumption volumes of the study regions will be compared at different administrative/watershed levels, from lower to high scales. If the production calories and water volumes are more than the consumption, then the region is self-sufficient, and the analysis will be repeated at higher spatial scale (Pradhan et al., 2014).

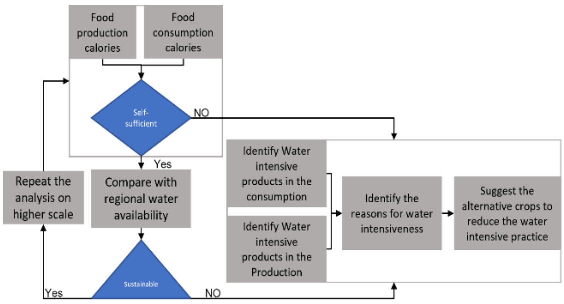
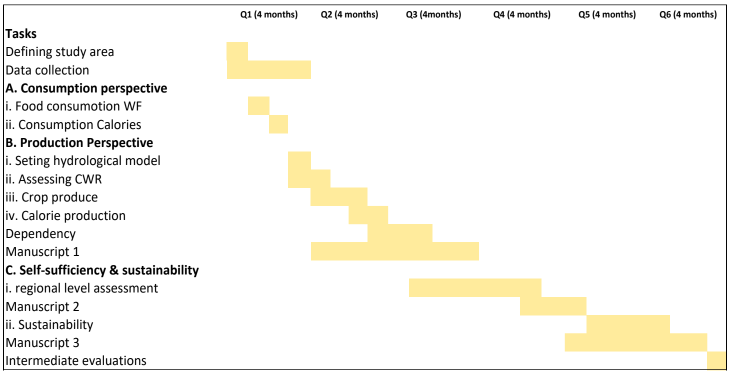


Figure 3: Flowchart detailing the methodology adopted to assess the self-sufficiency and sustainability of regional water resources with the food consumption and production.

Sustainability of regional water resources with consumption/production: After assessing the self-sufficiency of the regions, for suppose if the production calories and related water consumption is more than the consumption then it (at the considered spatial scale) considered as self-sufficient, and it will be compared with regional water availability that comes from a hydrological study. Comparing with regional water availability helps to understand, whether the self-sufficient region is sustainable with regionally available water resources or not. If the region is not sustainable with the regional water availability, the water intensive food products in the consumption and production will be compared to identify the water intensive products and analysed the reasons for water intensiveness of the products, based on total embedded water contents, consumption quantities, standard WF volume of products and per capita consumption in the study region. It helps to take food policy decisions by comparing the food consumption, production, and regional water availability, which confirms the sustainability of the regional water resources available with the food consumption and production at the considered scale. So that, the framework helps to have coherence between food and water policies between source and producing regions at different spatial scales.

4. Outcomes from the current study and timeline:

The proposed research to develop a framework to assess, self-sufficiency of regions and sustainability of regional water resources for the food consumption and production can be done in the two years of span and following chart shows the detailed work plan with the timeline.



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<u>**PROFORMA FOR BIO-DATA (to be uploaded)**</u>

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3. Institution: Indian Institute of Technology Hyderabad

4. Date of Birth: 25 August 1991

5. Gender (M/F/T): Male

6. Category Gen/SC/ST/OBC: SC

7. Whether differently abled (Yes/No): No

8. Academic Qualification (Undergraduate Onwards)

	Degree	Year	Subject	University/Institution	% of marks
1.	B-Tech	2012	Civil Engineering	PVP Siddhartha Institute of Technology (Affiliated to JNTUK)	66.78
2.	M-Tech	2014	Water Resources Engineering	National Institute of Technology (NIT) Warangal	6.94 CGPA
3.	Ph. D	2022	Hydraulics and Water Resources Engineering	Indian Institute of Technology (IIT) Hyderabad	6.83 CGPA

9. Ph. D thesis title, Guide's Name, Institute/Organization/University, Year of Award.

Title: Water footprint assessment of an urban agglomeration in developing economy: A case study of Hyderabad Metro Development Authority (HMDA) region.

Guide Name: Dr. Satish Kumar Regonda (Associate Professor)

Institute: Indian Institute of Technology (IIT) Hyderabad

Year of Award: August 2022.

10. Work experience (in chronological order).

S.No.	Positions held	Name of theInstitute	From	To	Pay Scale
1.	Research Associate	National Institute of Technology Warangal	April 2023	Till now	Consolidated
2.	Research Fellow	International Crop Research Institute for Semi-Arid Tropics (ICRISAT)	August 2022	November 2022	Consolidated
3.	Assistant Professor	PVP Siddhartha Institute of Technology	July 2014	December 2014	6th pay scale

11. Professional Recognition/ Award/ Prize/ Certificate, Fellowship received by the applicant.

S.No	Name of Award	Awarding Agency	Year
1.	Best Ph. D Award: Industry sponsored best PhD in water resources and allied areas by MEIL in department of Civil Engineering	IIT Hyderabad and MEIL	2022
2.	Research Scholars Travel Grant	MHRD	2019
3.	Research Scholars fellowship	MHRD	2015 to 2019
4.	Best Paper (Undergraduate level)	JNTU Ananthapur	2010

12. Publications *(List of papers published in SCI Journals, in year wise descending order).*

S.No.	Author(s)	Title	Name of Journal	Volume	Page	Year
1.	Koteswara Rao. D; S. K. Regonda; Chandrasekharam Dornadula.	Water and food nexus: Role of socioeconomic status on water-food nexus in an urban agglomeration Hyderabad, India using consumption water footprints	Water-MDPI	13	637	2021
2.	Koteswara Rao .D; Chandrasekharam Dornadula.	Quantifying the water footprint of an urban agglomeration in developing economy	Sustainable Cities and Society	50	101686	2019

13. Detail of patents.

S.No	Patent Title	Name of Applicant(s)	Patent No.	Award Date	Agency/Country	Status

14. Books/Reports/Chapters/General articles etc.

S.No	Title	Author's Name	Publisher	Year of Publication

15. Any other Information (maximum 500 words)

Undertaking by the Principal Investigator

To

The Secretary
SERB, New Delhi

Sir

I Dagani Koteswara Rao herby certify that the research proposal titled **A watershed level framework to assess the self-sufficiency and sustainability of water and food resources for consumption and production in the current and future climate change scenarios** submitted for possible funding by SERB, New Delhi is my original idea and has not been copied/taken verbatim from anyone or from any other sources. I further certify that this proposal has been checked for plagiarism through a plagiarism detection tool i.e. **Grammarly** Institute and the contents are original and not copied/taken from any one or many other sources. I am aware of the UGCs Regulations on prevention of Plagiarism i.e. University Grant Commission (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulation, 2018. I also declare that there are no plagiarism charges established or pending against me in the last five years. If the funding agency notices any plagiarism or any other discrepancies in the above proposal of mine, I would abide by whatsoever action taken against me by SERB, as deemed necessary.

D. K Rao

14 Aug 2023

Signature of PI with date

Name: Dr. Koteswara Rao Dagani

CEJ5RESCH01001

భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

भारतीय प्रौद्योगिकी संस्थान हैदराबाद

अभिषद की अनुशंसा पर सभी निर्धारित अपेक्षाओं को पूरा करने तथा
दि. 16 जून, 2022 को शोध–प्रबंध, शीर्षक:

**वाटर फुटप्रिंट एस्सेसमेंट आफ एन अर्बन अगलोमिरेशन इन ए डेवलपिंग एकोनोमि:
ए केस स्टडी आफ द हैदराबाद मेट्रो डेवलोपमेंट अथोरिटि (हेच एम डि ए) रीजियन**

के सफल पक्षपोषण के उपरांत:

विद्या वाचस्पति

की उपाधि

दगानी कोटेश्वर राव

को अपने सभी अधिकारों, विशेषाधिकारों तथा उत्तरदायित्वों के साथ एतद्वारा प्रदान करता है।
दिनांक बीस अगस्त दो हजार बाईस को संस्थान की मुद्रा अंकित यह उपाधि दी गई।

Indian Institute of Technology Hyderabad

Upon the recommendation of the Senate, hereby confers the degree of

Doctor of Philosophy

for fulfilling all prescribed requirements for the degree and
successfully defending the thesis on 16 June, 2022, titled:

Water Footprint Assessment of an Urban Agglomeration in a Developing Economy: A Case Study of the Hyderabad Metro Development Authority (HMDA) Region

on

Dagani Koteswara Rao

with all its rights, privileges, and responsibilities.
Granted under the seal of the Institute on
the Twentieth day of August,
Two Thousand and Twenty Two.

कुलसचिव Registrar	निदेशक Director	अध्यक्ष, अभिशासक परिषद Chairman, Board of Governors

MANDAL REVENUE OFFICE - VIJAYAWADA URBAN

KRISHNA DISTRICT, A.P - 520 003

SSID : 0617-8403-7097-7801 **Appl. No:** 2008 1798 **Date:** 25-07-2008

COMMUNITY, NATIVITY AND DATE OF BIRTH CERTIFICATE

1) This is to certify that Sri/Smt/Kum -DAGANI KOTESWARA RAO*****
Son / daughter of Sri -D. RAGHAVENDRA RAO***** of Village/Town
-WARD-37 (H.No. 35-9-4)***** Mandal -VIJAYAWADA URBAN*****
District -KRISHNA***** of the state of Andhra Pradesh belongs to
-MALA***** Community which is recognised
as -SCC***** under

The Constitution (Scheduled Castes) Order 1950
The Constitution (Scheduled Tribes) Order 1950

G.O.Ms. No. 1793, Education, dated 25 - 9 - 1970 as amended from time to time (B.Cs) S.Cs , S.Ts , list (Modification) Order, 1956 S.Cs and S.Ts (Amendment) Act. 1976

2) It is certified that Sri/Smt/Kum -DAGANI KOTESWARA RAO*****
is a native of -WARD-37***** Village/Town
-VIJAYAWADA URBAN***** Mandal -KRISHNA***** District
of Andhra Pradesh.

3) It is certified that the place of birth of Sri / Smt / Kum
-DAGANI KOTESWARA RAO***** is -WARD-37*****
Village/Town -VIJAYAWADA URBAN***** Mandal
-KRISHNA***** District of Andhra Pradesh.

4) It is certified that the date of birth of Sri/ Smt/ Kum
-DAGANI KOTESWARA RAO***** is
Day -25***** Month - 8***** Year - 1991*****
(in words)- Two Five***** -August***** - One Nine Nine One*****
as per declaration given by his/her father/mother/guardian and as entered in the school records where he/she studied.

Signature: G. [signature]

Date: 26/7/08

(Seal)

Name: TAHSILDAR VIJAYAWADA URBAN

Designation:

TAHSILDAR ★ Vijayawada Urban Krishna Dt. A.P ★

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Quantifying the water footprint of an urban agglomeration in developing economy

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ABSTRACT

Sustainable conservation of natural resources has become a primary concern for urban cities, globally as they are centers of consumption and economy. Due to population growth, cities depend more on imports of food, energy, water, and services from all over the globe, and consume more virtual water than direct water, because of their food habits and lifestyle. Most of the imported goods are water intensive and pose challenges in tracing the source of virtual water. The goal of this research is to develop a general framework to assess the water footprint (WF) of a typical city in India using existing databases. A consumer-centric approach has been adopted for assessing WF in Hyderabad Metro Development Area (HMDA). The variation of the WF across economic classes of consumers is also analyzed. The WF is estimated based on four broad categories: 1) food consumption, 2) fossil fuels based energy, 3) electric power, and 4) direct water. Average WF of HMDA region is 1041 m^3/cap/year (2852 LPCD), in which 70% (1986 LPCD) of WF was consumed by food, 25% (744 LPCD) by electric power, only 4% (121 LPCD) is from direct water consumption and surprisingly the contribution from fossil fuel WF to total per capita WF of HMDA area is less than 1%.

1. Introduction

Virtual water (VW) concept was initiated in the 1990s (Allan, 1998) and took several decades to gain focus from researchers. Chapagain and Hoekstra (Chapagain & Hoekstra, 2004; Hoekstra & Hung, 2002) initiated the concept of WF by accounting the VW content and VW trade for 172 agriculture crops in 210 countries over the globe. They assessed WF and VW by considering national average climatic variables without considering the spatial variations. Later, Siebert and others (Siebert, Doell, Siebert, & Döll, 2010) accounted for green, blue VWF of crops globally, by considering the spatial variations in climatic conditions. Based on these data, Mekonnen and others accounted green, blue and grey WF of crops, crop-derived products, and farm animals, animal products, this is a global scale study (Mekonnen & Hoekstra, 2010, 2011; Mekonnen & Hoekstra, 2012). Also, there are several studies at the national, regional level, and river basin scales to address WF (Vanham and Bidoglio, 2014b), but there is no much research on WF at the city scale concerning socio-economic aspects of consumers. Fulton and Gleick (Fulton & Gleick, 2012) assessed the WF of California based on the top-down approach, while Feng and Klaus (Feng, Siu, Guan, & Hubacek, 2012) assessed the regional WF of yellow river basin using multi-regional input-output (MRIO) assessment.

In past studies of city level WF assessment, previous authors talked about WF of agricultural products imported into the cities, considering the cities from developed (Berlin from Germany), developing (Delhi from India) and underdeveloped countries (Lagos from Nigeria) (Vanham, 2013a; 2013b; Vanham, Gawlik, & Bidoglio, 2017; Zhao, He, & Zhang, 2015). Vanham and others (Vanham & Bidoglio, 2014a; Vanham et al., 2017) assessed the WF of Milan, Hong Kong and suggested diet to conserve embedded water in food efficiently and this study was done not only at the city scale but also at regional levels (Vanham, Comero, Gawlik, & Bidoglio, 2018; Vanham, Comero, Gawlik, & Bidoglio, 2018). Zhao (Zhao et al., 2015) addressed the WF of Leshan city (3326 m^3/cap/year) in China and concluded that this city

Abbreviations: WF, water footprint; VWF, virtual water footprint; VW, virtual water; LPCD, liters per capita per day; MGD, million gallons per day; MCM, million cubic meters; MPCE, monthly per capita expenditure; LPG, liquid petroleum gas; HMDA, Hyderabad Metro Development Authority; GHMC, Greater Hyderabad Municipal Corporation; HMWSSB, Hyderabad Metro Water Supply and Sewerage Board; RWSS, rural water supply and sewerage; NSSO, National Sample Survey Organization

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targeted to export water-intensive products to other cities since it is rich in water resources. McCallum (McCallum and Shanafield, 2016) assessed the direct WF in 33 cities, indirect WF in 74 cities of United Staes and found that average direct WF (600 lit/cap/d) of urban cities dominated by average indirect WF (13,877 lit/cap/d) of the United States. These studies follow the approach of Hoekstra and others (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011) by considering FAO STAT food balance sheet data, census data and regional statistics from government departments.

Most of the studies indicated that urban cities are consuming 20 times more VW than physical water (McCallum and Shanafield, 2016). The water embedded food, agricultural, energy, and commercial products were imported from all over the globe and from both water scarce and water-rich regions (McCallum and Shanafield, 2016). These imports are building pressure on water resources in the source regions. In this scenario, there is a necessity for strict water policies and constructive water governance infrastructure for virtual and physical water quantification. Generally, when framing the water policies or riparian rights of riverfront waters, only physical water alone considered in demand and VW is not included. However, humans are consuming more virtual water than physical water. Due to this ignorance, only regionally available water has given importance and the volume of VW floating between the regions is not considered in water budgeting. Due to this, the source regions becoming arid and arid with rigorous pumping of water for goods production. This practice leads to putting local water resources under pressure and pushes regional and national water resources under crises (Vanham, Hoekstra et al., 2018). This disparity between local and national water resources will trigger global unsustainability.

In the literature, most of the studies, constructed on a top-down approach and also there are studies based on the bottom-up approach using regional and multi-regional input and output method. These approaches require massive trade data at the city level, which is not possible for every sector of a city. There has been much research on managing the direct WF of cities at global, national boundaries and also for India (George, Malano, Khan, Gaur, & Davidson, 2009; Manzardo, Loss, Fialkiewicz, Rauch, & Scipioni, 2016; Rathnayaka et al., 2016; Shaban & Sharma, 2007a). However, there are significant gaps in our understanding of cities' indirect WF and its management for Indian cities, in particular. A major hindrance in this regard is the lack of adequate trade data. To apply the methodology, suggested by Hoff et al (Hoff et al., 2014), data on imported goods are essential, but it cannot be applied here, due to lack of enough trade data at city scale. This issue seeks the attention of researchers and policymakers to focus not only on physical water management but also on VW trade management.

In this study, we mainly tried to address this issue by showing some alternatives for data other than city level trade data and developed a framework using this alternative dataset and these datasets are generally available on public forums. Here we followed a consumption-based approach in this study and presented a protocol for assessing the WF of a typical Indian city. Besides that, the authors also focused on WF across economic classes, which has not explored earlier. Previous studies have not tried to understand the gaps between WF of different economic strata, except for the study of Vanham and others (Vanham, Comero, Comero et al., 2018). Considering economic levels is likely an essential source of information for policy purposes.

This protocoled framework in this study helps in monitoring and managing VW, and to know how cities are dependent on external water resources by accounting and balancing consumption WF and production WF. Consumption WF is the amount of direct and indirect/virtual water consumed by the consumers of a region. Production WF is the volume of water from local or domestic resources used for the production of goods, which is used by consumers anywhere in the world. In previous studies, authors considered only trade data without considering the economic gradients of consumers. City level trade (import/exports) data may have leakages, which means that this trade may go out of cities as exports to another region. These leakages lead to inaccuracy of WF assessment. However, in the present study, we focused on consumer level consumption data of food, energy (fossil fuels and electric power) and direct water. This study is specific to consumers' consumption and their economic status. Also, assessed green, blue and grey WFs of food consumption and blue WF of energy and direct water consumption. Green WF is the amount of water comes from precipitation and water stored in soil moisture, blue WF is the amount of water in surface water bodies and aquifers, grey WF is the amount of fresh water required to dissimilate the polluted water (Hoekstra et al., 2011).

In this study consumption WF is assessed based on the consumer level trade data concerning their economic status, which has taken from consumer expenditure survey report provided by the National Sample Survey Organization (NSSO & MSPI, 2012). Production WF will be assessed using process-based assessment methods/tools. Difference between these production and consumption WF shows the importing and exporting status of the region/study area. If the difference is negative, then the region or city is net VW exporter. If it is positive, then the city is net VW importer. We applied this framework to agriculture products only. This framework can be applied to any sector, whether it is food, energy, agriculture, or to any water sector to know the import/export status of virtual water. The authors have limited the study only up to consumption WF of urban agglomeration for economic gradients of consumers.

The scope of this work is to plan strategies for reducing WFs by understanding how purchasing power, consumption behavior of consumers will influence the WF of urban cities, which is not shown in previous researches except the study of Vanham (Vanham, Comero, Comero et al., 2018). In the context of mission smart cities (Anand, Sreevatsan, & Taraporevala, 2018), this framework helps in water governance, planning and design of sustainable water infrastructure in cities that can sustain for future water crisis (Fialkiewicz et al., 2018; Haie, Rodrigues Freitas, & Castro Pereira, 2018). Also, it helps policymakers to understand and account environmental footprints to maintain balance in ecology. The proposed framework in this study is unique and helps policymakers and researchers to understand the WF of urban cities concerning change in economic growth and to plan the strategies for reducing the WF of different commodities groups and sectors in urban cities.

2. Study area

In this work, our study area is Hyderabad Metro Development Authority (HMDA) region (Fig. 1). HMDA is a cosmopolitan city and it is a combination of five districts, i.e., Hyderabad, Rangareddy, Medak, Mahabubnagar and Nalgonda districts and 54 mandals before the reorganization of Telangana state (Telangana social development report (TSDR - 2017)). In the earliest, Hyderabad is only up to the boundary of erstwhile Hyderabad, with the rapid growth of the migrated population, it encroached up to the boundaries of Greater Hyderabad municipal corporation (GHMC). Hyderabad is the central hub for cyber and manufacturing infrastructure, pharmaceutical, textile, food processing industries, commercial complexes and business centers with the massive demand for water for their production process and services. HMDA is an amalgamation of urban, surrounding rural regions and Hyderabad is a part of HMDA region, which has a population of 9.4 Million. HMDA is the 6^{th} populous urban agglomeration in India and it is going to reach 12.7 Million by the year 2030, according to world population review 2017 (Fig. 2). The annual average rainfall of Hyderabad region is 961 mm, with an annual maximum temperature of 45^0 C and annual minimum temperature of 6^0 C with hot and wet tropical climatic conditions.

With the industrial and infrastructural development, Greater Hyderabad extended beyond the boundaries of GHMC and combined with the rural areas nearby to form HMDA region. The total spread of HMDA is 7257 sq. Km (Boundaries of Hyderabad, GHMC, and parts of

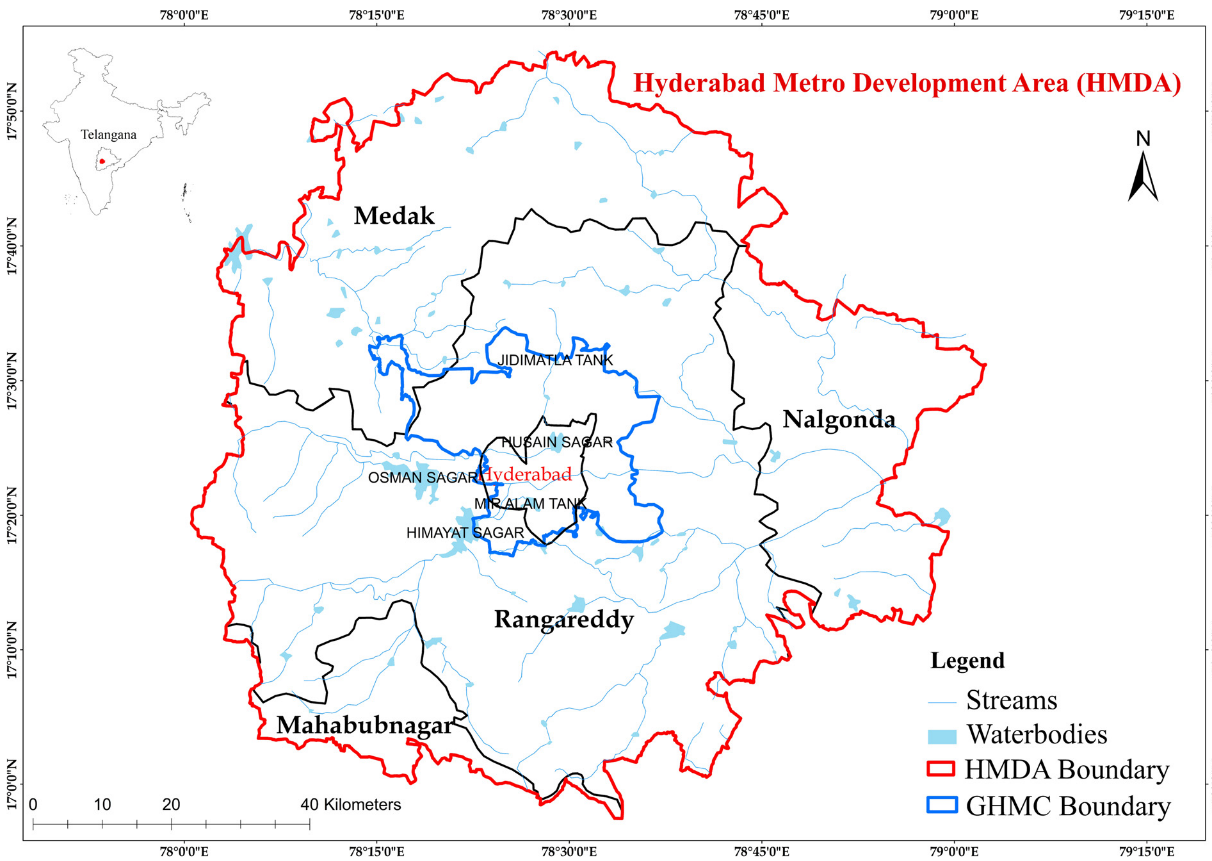

Fig. 1. Jurisdictions of HMDA region, boundaries of GHMC and parts of five districts Hyderabad, Rangareddy, Nalgonda, Medak, Mahabubnagar included in study area.

the five districts included in HMDA region are mentioned in Fig. 1). From the collected data (source: HMWS & SB) domestic water supply up to GHMC within the boundary of HMDA is 272 MGD (GHMC boundary shown in Fig. 1), commercial and industrial water demands of Hyderabad is 68 MGD. These demand quantities are only up to the boundary of GHMC and we have not mentioned the total water consumption of HMDA. HMWS & SB supplies drinking water up to GHMC only. For drinking water supply, HMDA initially depended on Osman Sagar and Himayath Sagar. Due to the rapid growth of population, water supply from the local watershed (Musi) is dominated by water supply from Krishna and Godavari basins, and they are major water sources for HMDA region. In the HMDA region, water supply is controlled by the Hyderabad Water Supply & Sewerage Board (HMWSSB) up to GHMC. For the rural areas outside the GHMC, water supply is regulated by the Rural Water Supply and Sanitation department (RWSS), for the areas nearer to the district headquarters, the respective municipalities will regulate water supply.

3. Methodology and material

WF methodology demands more data. The accuracy of WF results depends on the quality and quantity of data available. WF assessment can be done using either bottom-up or top-down approaches (Feng, Chapagain, Suh, Pfister, & Hubacek, 2011). As mentioned in the introduction, in this study, we proposed a framework to assess net/actual WF of HMDA region. Net/actual WF of a city is the total amount of fresh water consumed directly and indirectly by the habitants of the region (Fig. 3) (Dagani, Singh, & Dornadula, 2018). This framework supports

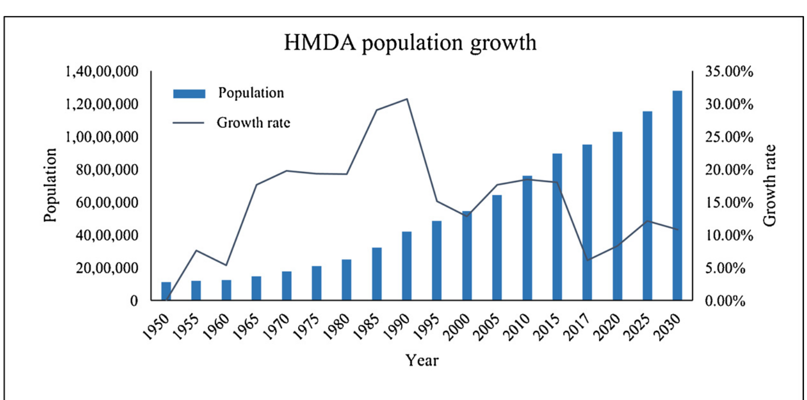

Fig. 2. Urban population growth of Hyderabad(reference:World population review-2017).

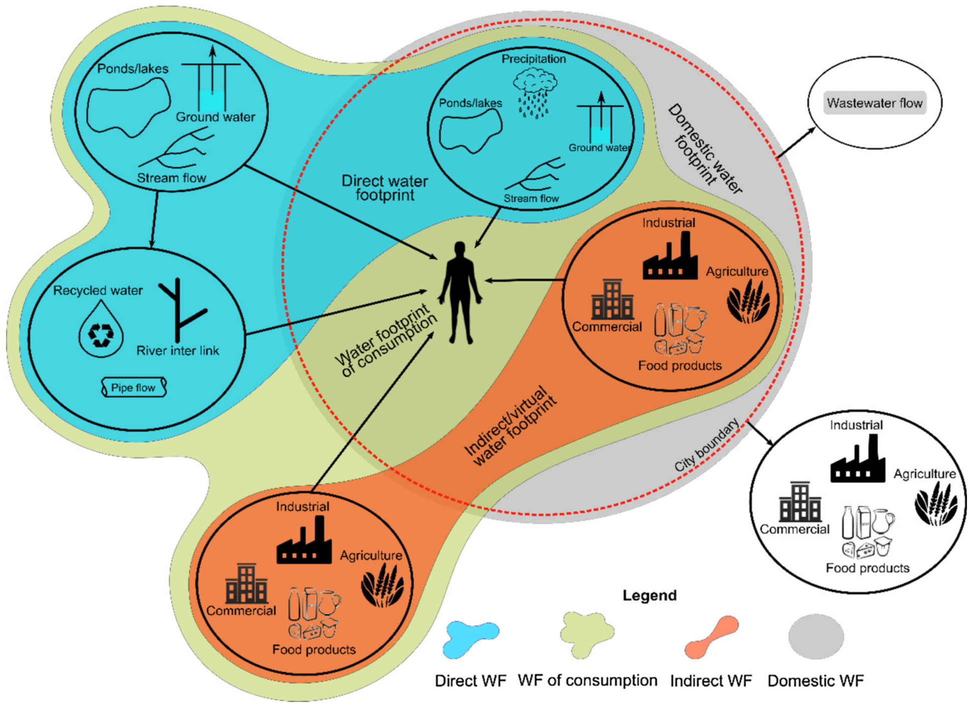

Fig. 3. Conceptual figure showing components of city WF, virtual water (red layer), direct water (blue layer), consumption footprint (green layer) and domestic WF (grey layer) with in city boundary.

policymakers to know the dependency of urban cities on external water resources by quantifying the difference between consumption WF and production WF. However, in this study, we presented a methodology to assess the consumption only, which includes food, energy (electric power, fossil fuels: petrol, diesel, kerosene, LPG, and coal) and direct water.

In general urban cities consume more resources like food, energy, commodities, etc. besides water. When we are talking about the WF of urban cities, there are two faces for this coin. One is consumption WF (domestic), the other one is production WF. A city can have the upper hand in any one of the WF or both. HMDA region is giving its huge contribution to global industrial production through different sectors - pharmaceutical, infrastructural, apparel, electronics, etc.

3.1. Water footprint of food, energy and physical water

To assess WF of any urban city, commodity-trading data is important. This data gives some information about the dependency of urban cities on external sources. However, at the city level (a small spatial scale), it is not easy to get the trade information. City level trade data contains many leakages; it may not be accurate. In this study, monthly per capita consumption expenditure is considered, as an alternative for city-level trade data of every economic class and their ranges of consumption expenditure from NSSO (MPCE ranges of every economic class was presented in Table 1 in supporting information). MPCE data provides information on quantity (in kgs) of food and non-food commodities consumed by consumers in all urban and rural regions in India based on the economic class of consumers(quantity of food commodities consumed by every fractile class is presented in supporting information Table 2). Table 1 shows the list of commodities considered for WF assessment in the present study. Here we have considered MPCE data from the 68th round of survey report, which was published by the NSSO in the year 2014. More information on survey procedure and methodology is given in 68th round survey report of NSSO(Appendix-B), detailing of NSSO survey methodology and procedure is out of the scope of this work.

MPCE data with respect to their economic classes from NSSO and census data of HMDA (HMDA, 2012), coupled with distribution of population in every economic class (Table 1 in supporting information), and WF of crops and crop derived products considered from the study of Mekonnen and Hoekstra (Mekonnen & Hoekstra, 2011, 2012)(Table 2 represents the data used in WFassessment and their sources).

To assess the WF of energy we followed the approach proposed by Mekonnen (Mekonnen et al., 2015) and production WF of energy is considered from the study of Peter Gleick (Gleick, 1994). In the energy category, we have electric power (from hydro and thermal generations), fossil fuel-based energy: petrol, diesel, kerosene, LPG, and coal also. In the Indian energy sector, production and usage of thermal power are very prominent. In this study, we assumed that 80% of

Table 1
List of commodities considered for assessment of WF(Reference: NSSO, 2012).

Food commodity group	Energy commodity group
1 Cereal grains	1 Electric power: hydro & thermal
2 Pulses	2 Coal
3 Sugar & jaggery	3 Kerosene
4 Milk & milk products	4 Diesel
5 Fats & oils	5 Liquid petroleum gas
6 Vegetables	6 Petrol
7 Fruits	
8 Animal products: meat & eggs	
9 Beverages: coffee & tea	

Table 2
Data used for WF assessment and their references.

Data Used	Reference
WF of crops & crop-derived products	Mekonnen & Hoekstra, 2011
WF of livestock	Mekonnen & Hoekstra, 2012
WF of energy products	Gleick, 1994
Consumers commodity data	NSSO & MSPI, 2012
Consumers economic class data	NSSO & MSPI, 2012
Census data of HMDA region	HMDA, 2012
Population distribution of every economic class	NSSO & MSPI, 2012

domestic power produced by thermal power plants. Eq. (1) is developed to calculate the WF of food consumption in every economic class.

$$WF_{U\_C} = \sum_{p=1}^{n} \sum_{ec=1}^{12} ((Q_p^{ec} * WF_p)_{ct} * (D_p * p)) \tag{1}$$

where, WF_{U_C} will be WF of urban consumption, 'Q_p^{ec}', quantity of food product(p) consumed by every economic class(ec) consumer, 'WF_p' water consumed for the production of every product, 'ct' is commodity type(ct) consumed by the consumer(Food, Energy, and Water), 'D_p' distribution of population in every class and 'p' population.

Domestic WF of GHMC is quantified using daily water supply data and population of GHMC. For areas other than GHMC direct WF is assessed based on information provided by RWSS engineers in personal interviews. Based on unpublished daily water supply data in GHMC (272 MGD) provided by HMWSSB for the year 2012, and population data of GHMC from census 2011, the per capita direct WF in GHMC was assessed. Direct WF of GHMC and areas other than GHMC are assessed separately and considered the average of these two regions, as direct WF of HMDA.

4. Results

The total per capita WF of HMDA region is 1041 m^3/cap/year, out of which 70% contribution is from food consumption and 25% is from electric power, 0.09% is from fossil fuels (petrol, diesel, kerosene, LPG, and coal) and only 5% is from direct consumption of water for daily activities.

4.1. Water footprint of food

Here we assessed WF of per capita at individual economic classes and total WF volume over the HMDA region after coupling with the population. Fig. 4(a) shows the per capita WF volume that every individual food group contributed to total WF of every economic class. It ranges from 493 to 952 m^3/cap/year from lower to higher economic classes, respectively. Fig. 4(b) shows total WF volume over the HMDA region after including the population. It ranges from 65 to 1029 MCM/year. From this figure, we can see WF of food consumption and the influence of consumer's economic status on the WF of urban dwellers. Per capita and absolute values of food consumption in the HMDA region has presented in Table 3 of supporting information.

In HMDA region, per capita WF of food consumption is 725 m^3/cap/year. It is contributing 70% of WF to the total WF of HMDA. However, in Fig. 4(b), WF over the HMDA region is changing its trend from lower to higher economic classes. Tenth and eight economic classes are at the top of the list with maximum WF of 1029 and 960 MCM/year. From Fig. 4 (a)&(b) WF of cereals, milk & milk products, eggs & meat products are following the same trend in contributing maximum to the total WF. In the HMDA region, cereals are primary food in their diet. WF of cereals are in the top of the list with a volume of 2973 MCM/year. Milk & milk products, eggs & meat products are next to the cereals with the volumes of 1387 MCM/year and 633 MCM/year. Moreover, we can observe that half of the food consumption WF of every economic class filled with cereals contributing 43% of WF to the total WF in HMDA region. WF of milk & milk products, eggs & meats are contributing 20%, and 9% of WF to the total food consumption WF, respectively and the WF contribution of pulses, vegetables, fruits, sugars is 453, 411, 319, 229, 82 MCM/year, respectively. This evaluation shows the influence of consumers purchasing power/economic class and population density on WF volumes in cities.

4.2. Water footprint of energy

After WF of food consumption, energy consumption WF takes the major portion in total WF of HMDA region. Annual WF of energy consumption is 2550 MCM/year and only 10 MCM/year in total energy WF is from fossil fuels: petrol, diesel, kerosene, LPG and coal. In energy WF, maximum part is occupied with WF of electric power. In WF of electric power, maximum weight is given to thermal power, because in this region, thermal power production is more dominant than hydropower. So, we assumed that 80% of electric power comes from thermal power production and 20% is from hydropower. WF of thermal power and hydropower per unit of production is 0.0017 and 4.09 m^3/Kwh. WF of energy in urban areas in HMDA region is, nearly 1900 MCM/year and 640 MCM/Year in rural areas. Which means that urban area is consuming nearly three times the WF than the rural areas lying outside GHMC.

In Fig. 5(a), (b) we see per capita, absolute WFs of electric power (Hydro and Thermal), kerosene on bar plots and WF of coal, LPG, petrol, and diesel in line plots with primary and secondary axes. This trend shows the potential impact of the socio-economic status of consumers on the WF of electric power. WF of electric power is high in 8^{th} and 10^{th} economic class for both thermal, hydropower consumption; it ranges between 8.23 MCM /year to 485 MCM/year for hydropower and 0.013 MCM/year to 0.8 MCM/year for thermal power. WF of petrol and diesel are also following the same trend. However, WF of petrol is high. In WF of kerosene and LPG, they are low in higher economic classes, and WF of kerosene is high in 4^{th} and 6^{th} economic classes. WF of LPG is following the same trend as electric power, petrol, and diesel, but it is decreasing in higher economic class. WF of coal is almost negligible in higher economic classes and a minimal amount of coal WF contributed from lower economic classes.

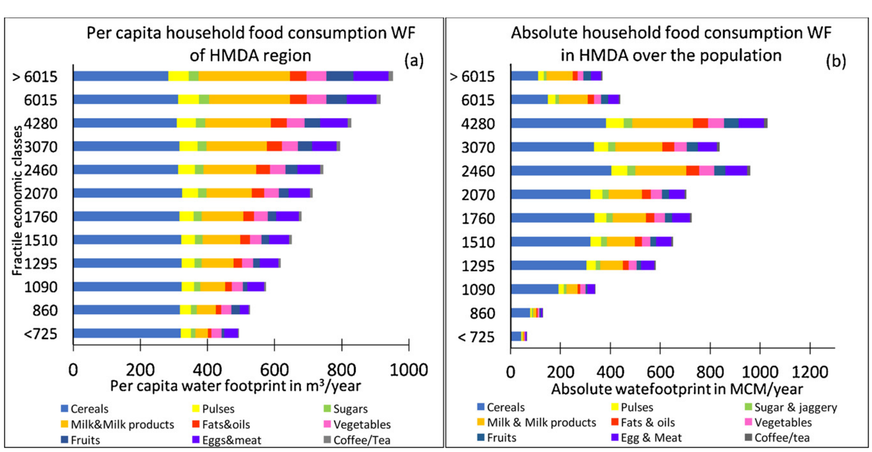

Fig. 4. Plots showing annual per capita consumption WF of HMDA region (in cubic meters (left panel)) and absolute WF over HMDA region in million cubic meters (right panel) with quantity of wf on x-axis and consumer economic class on y-axis.

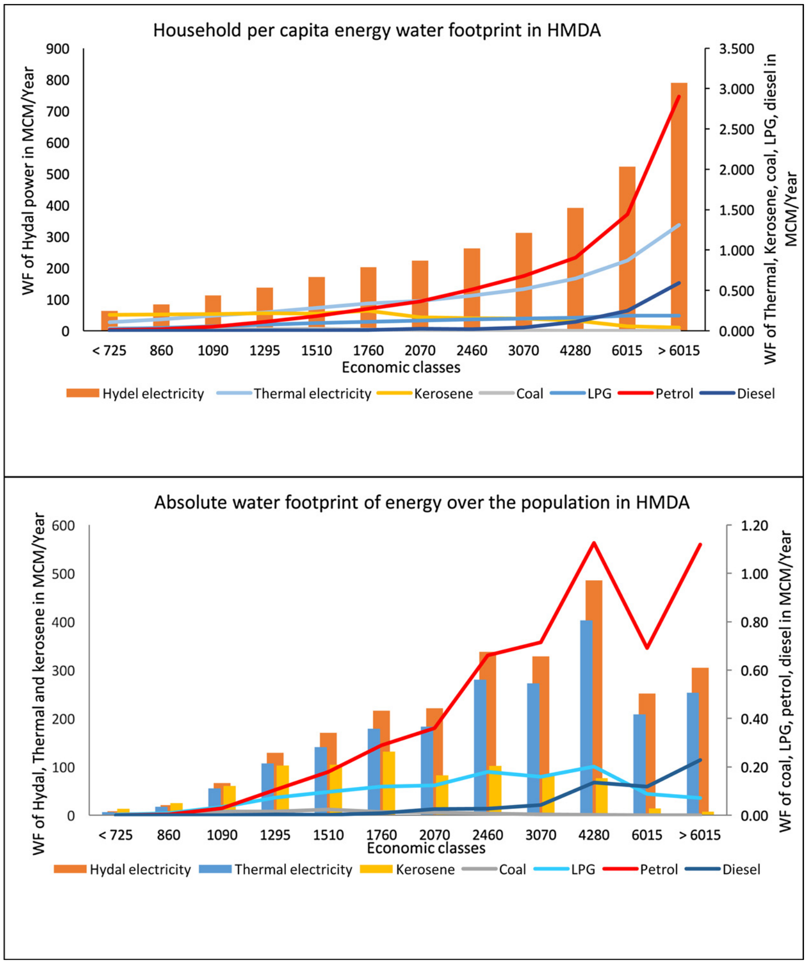

Fig. 5. (a): Per capita WF of electric power(hydel) in bar plot with quantities on primary axis at left side of plot and thermal power, kerosene, coal, LPG, petrol and diesel (all together considered as energy) on secondary axis at right side of the plot and with economic class MPCE (in rupees) details on x-axis. (b): This absolute WF of electric power(hydro and thermal), kerosene in bar plot with quantities on primary axis at left side of plot and WF volume of coal, LPG, petrol and diesel (all together considered as energy) on secondary axis at right side of the plot and with economic class details on x-axis.

All together per capita, WF consumption of energy in HMDA region is more than 270 m^3/cap/year. Per capita and total amounts of energy WF values were presented in supporting information in Table 4 (a), (b).

4.3. Water footprint of direct water

Most of the urban cities depend on ground and external surface water resources for its drinking and habitation needs. However, here we have considered direct WF of HMDA from surface water resources only, we have not considered WF of groundwater. To assess the direct WF of HMDA, we adopted a simple averaging method over the total population in HMDA because it is hard to get the direct water consumption details based on the economic classes of the consumers. As per the Bureau of Indian Standards, IS:1172-1993, a minimum quantity of 200 LPCD should be provided for domestic consumption in cities with a full flushing system. The ninth five-year plan advocated that water requirement in urban areas as 125 LPCD with the planned sewerage system, 70 LPCD for cities without planned sewerage system and 40 LPCD for those collecting water from public stand posts. To lead a hygienic existence, National Commission on Urbanization has recommended to have 90–100 LPCD of water. However, many municipal corporations are fixing their own value of demand requirements based on industrial and commercial developments as water requirements will vary in cities and towns with variation in industrial and commercial developments. Direct WF in urban areas of HMDA region is 375 MCM/Year, and per capita consumption WF is 53 m^3/cap/year. In rural areas, consumption WF of direct water is 41 MCM/Year, and per capita consumption WF is 17 m^3/year. Total per capita consumption WF of HMDA region is 97 lit/day, i.e., we are in the recommended quantity of supply of 90–100 LPCD by National Commission of Urbanization.

5. Discussion

5.1. Key findings from HMDA WF assessment

India is an agricultural nation; most of its agriculture practices depend on green water. Green water is a form of water, sourced from precipitation and stored as soil moisture. HMDA region is a metropolitan city from India. In HMDA's food consumption, 67% is occupied by green WF, 23% by blue WF, and only 10% by grey WF.

In 8th and 10th affluent classes have maximum WF because the maximum population of HMDA lies in these classes. In Indian diet, the major part is occupied with cereals, and it consumes maximum water and causes environmental stress with maximum WF (Green et al., 2018; Harris et al., 2017). Cereals also occupy the major part of HMDA's food consumption WF. WF of milk products, livestock, pulses, vegetables, oils &fats, fruits, sugars, coffee/tea are next to the cereals, respectively. This trend can be seen in every economic class. Therefore, food consumption WF pattern of every food group is also similar in all classes.

Coming to green, blue and grey WF, consumption trend shown in Fig. 6 (a), (b), (c) is changing for every food group and the pattern of food consumption WF remains same in all classes as in Fig. 4(b).

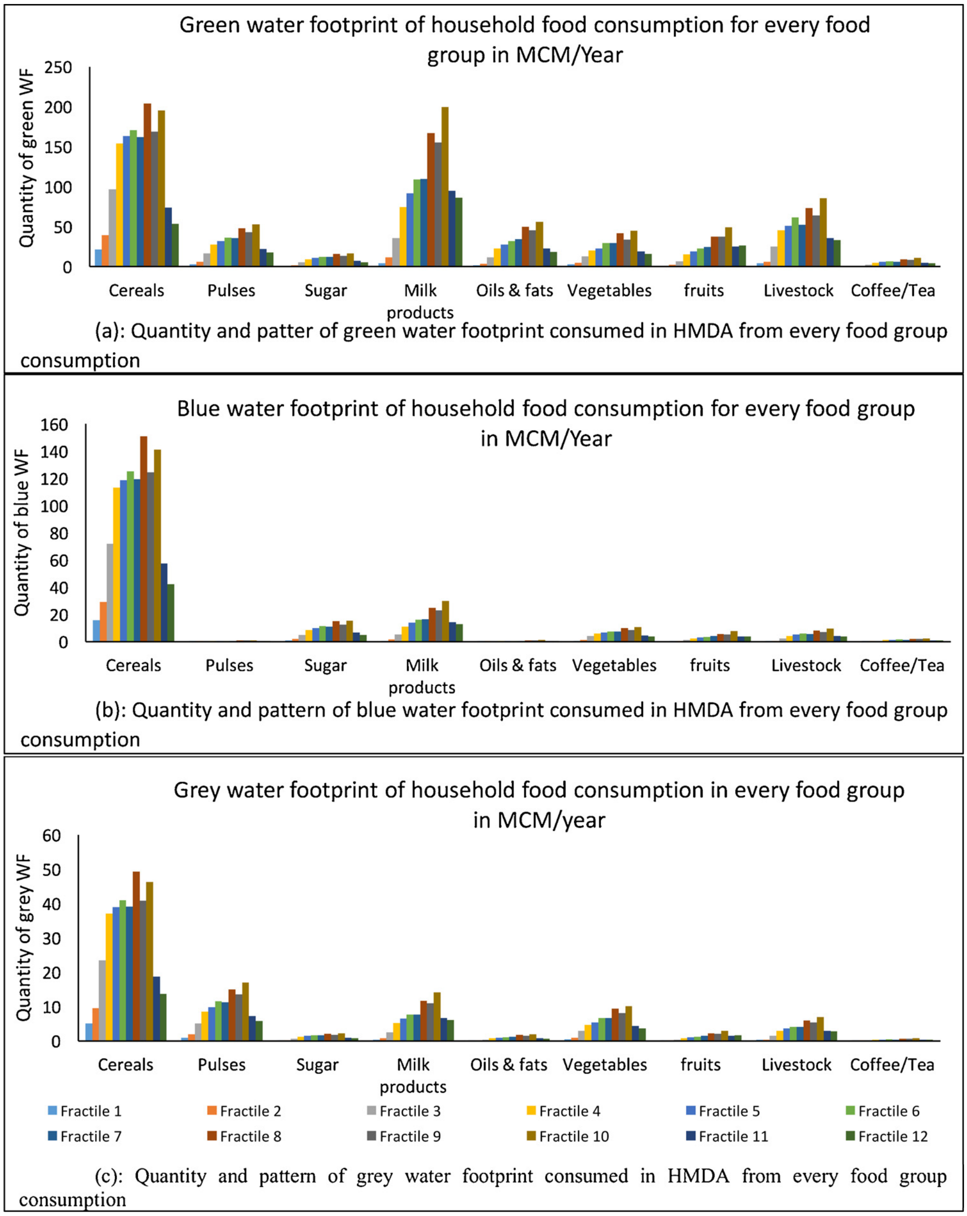

Fig. 6. (a): Quantity and patter of green water footprint consumed in HMDA from every food group consumption. (b): Quantity and pattern of blue water footprint consumed in HMDA from every food group consumption. (c): Quantity and pattern of grey water footprint consumed in HMDA from every food group consumption.

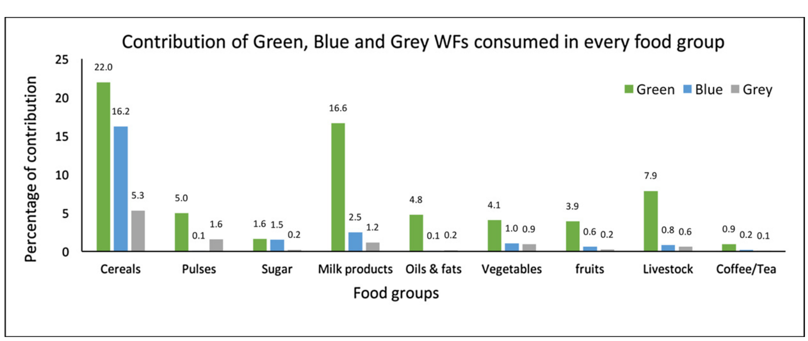

Fig. 7. Percentage of green, blue and grey water footprint consumed in every food group.

Contribution of green WF is high in all food groups. Blue, grey WFs are next in order (Fig. 7). In total WF, cereals (green 22%, blue 16%, grey 5%) and milk products (green 17%, blue 2%, grey 1%) are consuming maximum percentage of green WF. Blue and green WF of oils & fats (0.1%, 0.2%) and livestock products (0.8%, 0.6%) are negligible. However, 8th & 10th economic classes have maximum green, blue and grey WFs.

This study emphasizes WF of HMDA region in two different directions. First, it is showing food consumption WF of different economic classes, based on consumer purchasing capacity. Moreover, it is also depicting the impact of food consumption behavior and dietary habits of urban cities on WFs. WF assessment based on the economic status of fractile classes gives scope to plan VW trade strategies to import water-intensive products, by considering the regional water availability. It is necessary for governments to have an account on domestic consumption WF and dependency of cities on external water resources. Second, it emphasizes the status of green, blue and grey water extraction/consumption from its natural resources and its impact on ecology because of giving higher priority to particular food groups in dietary habits(also for producing) of urban cities.

Coming to energy WF, only the blue WF of energy for every class is assessed. In energy WF, maximum part contributed by electric power consumption (270 m^3/cap/year) and WF of fossil fuels is only 1 m^3/cap/year. In the HMDA region after electric power, WF of kerosene is high in below middle-class groups (6th, 5^{th,} and 4th classes). WF of diesel is gradually increasing from lower to upper economic classes. Surprisingly, WF of LPG is decreasing in upper economic classes, which tells that upper economic classes depend less on homemade food. Consumption WF of coal is negligible in HMDA region.

When coming to direct WF, it contributes only 4% (45 m^3/cap/year) to the total WF of HMDA. In 4% of direct WF 90% (40.5 m^3/cap/year) is concentrated in urban areas and only 10% (4.5 m^3/cap/year) is concentrated in rural areas. Here a simple averaging method was considered (based on the daily demand and supply of domestic water in HMDA region) over the population to assess the direct WF. However, we have not assessed direct WF based on purchasing power due to lack of data for every economic class.

Understanding regional/city level WF in different sectors helps in planning water requirement of urban cities. For cities under severe water crisis, VW trade strategies between wet and dry regions can release from water stress. VW transfer can resolve the transboundary issues on sharing water virtually. It needs quantification and balancing of consumption WF and production WF at a region level/water basin level (Wu et al., 2019). Moreover, water stewardship and cooperation between governments is essential to achieve sustainable water consumption through VW trade policies, with mutual cooperation.

In HMDA's WF, 95% is contributed to virtual water (VW) in the form of food and energy. This VWF is more than 20 times the direct WF. This evidence, again shows that urban cities consume 20 times more virtual water than direct water, which is supported by previous researches (Hoff et al., 2014; McCallum & Shanafield, 2016).

5.2. Comparing WF of HMDA with other cities

Cities from developed nations have high WF (Blas, Garrido, & Willaarts, 2018; Hoff et al., 2014; McCallum & Shanafield, 2016; Vanham & Bidoglio, 2014a). In this section, the difference between WF of HMDA and cities from developed, developing and under-developed nations is compared. The data for these cities were taken from past researches (Hoff et al., 2014; Vanham & Bidoglio, 2014a), and reasons for WF difference were mentioned in Table 3. In this comparison, we considered cereals and pulses as primary food products for comparison because these are common food products in these cities.

Hoff (Hoff et al., 2014) accounted only imported agricultural WF of Delhi, Berlin and Lagos cities(not included livestock products). HMDA's food consumption WF included WF of livestock, coffee/tea, and sugars products (725 m^3/cap/year). Here, we compared only agricultural WF of HMDA with Delhi, Berlin and Lagos cities. After excluding the coffee/tea, sugars, milk products, and livestock (for the similarity in products comparison between the cities), WF of HMDA is 391 m^3/cap/year. However, Delhi (434 m^3/cap/year) has higher WF than HMDA. Reason for the difference between Delhi and Hyderabad WF is, the average per capita cereals and pulses consumption of Hyderabad and Delhi are 56, 66 Kg/year with average VW content of 3530 and 2400 L/Kg (Hoff et al., 2014). Delhi's per capita consumption of cereals and pulses is higher than Hyderabad. In most of Hyderabadi's diet, rice consumption is higher than wheat. Due to much population weight for wheat consumption in Delhi, its food consumption WF is high, even though wheat has very less production WF than rice. Fig. 8 represents the primary food products in cities considered for this comparison, such as cereals, pulses, oils and fats, cassava, sorghum, soya, coffee are primary food products. In Hyderabad and Delhi's food consumption maximum part is occupied with cereals and pulses because they are primary food in their diet but not in the case of other cities.

Milan (Vanham and Bidoglio, 2014a) is a Europian city with high WF. Milan's food diet consists of more cereals, coffee, and less quantity of crop oils, fats. However, annual WF of crop oils and fats are at the top of the list even though they are consumed in very less quantity, because of its high VW content.

Lagos (Hoff et al., 2014) food diet consists of more cassava, sorghum, and soy products and less amount of imported rice. It's food diet consist of a good amount of livestock which is fed with sorghum and soya. Soya and sorghum are water intensive and imported. As an underdeveloped nation, where technology is not used in farming practices, its agricultural productivity is low, and most of the food products to Nigeria are imported from surrounding countries (Mekonnen & Hoekstra, 2014).

Berlin's (Hoff et al., 2014) food diet is occupied with more wheat, soya, and coffee. Most of the Europian cities food diet consists of more livestock products and to feed this livestock, soya will be imported from the surrounding regions in Europe (Hoff et al., 2014; Vanham, Mekonnen, & Hoekstra, 2013). Most of the cities food diet mentioned above depends on their regional availability and priority. In Indian food diet cereals, pulses are more in quantity, some of these are water intensive. However, in city diets of western nations, these quantities are substituted with regionally available products.

From the overall observation, Hyderabad's WF is 60% of Berlin, 32% of Lagos and 20% of Milan. Based on local climatic conditions and food availability, priority is given to their food diet in cities (Fig. 8). Hyderabad and Delhi's food diet contains water-intensive products. These cities are from the agricultural nation (India) whose climatic conditions are suitable to produce water-intensive products, and these cities get food products from surrounding agricultural regions. It is different for Lagos and Berlin; they are low in water productivity and imports products (soya, sorghum) from larger distances. However, Cassava is primary food in Lagos diet because of its low VW content. Coffee and cocoa are also common stimulants in European city's diet (Berlin and Milan), which are high in VW content (Fig. 8) (Hoff et al., 2014). Moreover, population density with water-intensive dietary habits also adds up to the reasons for more WF in these cities.

From the above comparison, it is clear that food consumption the local climatic conditions influence WF of cities, availability of food, and dietary habits. Consumption of less water-intensive products can contribute more weight to the conservation of water resources, and urban cities should depend more on locally available products.

In this study, we assessed WF of domestic power only, not considered the commercial and industrial WF of power consumption. Average consumption WF of energy in HMDA is 270 m^3/cap/year and WF of fuel(petrol, diesel, kerosene, LPG, coal) is 0.9 m^3/cap/year. WF of LPG consumption is less in higher classes which means that consumers of the higher economic class depend more on processed food products or ready-made products, which may be another reason for high per capita food consumption WF in higher classes. WF for coal based thermal energy is negligible in HMDA region. Whereas, WF of kerosene and coal consumption is higher in below middle classes and less in higher classes. WF of petrol consumption is high when compared with the WF of diesel, it is increased from the lower to higher economic class.

In the HMDA region, VWF is dominating direct WF, and these results show that physical water consumption is negligible when

Table 3
Comparing agricultural WF of urban cities (Berlin, Delhi, Lagos, Milan,) with WF of Hyderabad Metro Development region (after excluding livestock.

Study area	WF in m^3/cap/y	WF in L/cap/d	Reason for the difference in consumption WF
HMDA region	725	1986	Hyderabad's average per capita WF is 391 m^3/year, after excluding livestock products. It is doubled to actual WF 725 m^3/cap/y, which includes meat, milk & milk products in total footprint and average per capita consumption of cereals, pulses is 56 Kg/Year with an average virtual water content of 3530 L/Kg. Rice is the primary product in cereals consumption of Hyderabad. (Reference: Present study)
Delhi	434	1189	Delhi's average per capita consumption WF is 434 m^3/year without livestock products average per capita consumption of cereals and pulses is 66 Kg/year, with average virtual water content of 2400 L/Kg. it is more than Hyderabad's average cereals and pulses consumption (56 Kg/year) and total consumption footprint (391 CUM/year) but less in rice consumption. Reference: (Hoff et al., 2014)
Berlin	643	1761	Berlin's average per capita consumption footprint is 643 CUM/year, which is more than 63% consumption WF of Hyderabad and Delhi's on average. Berlin's average per capita cereals and pulses consumption is 108 Kg/year with a maximum consumption of wheat, soya which is produced locally with an average virtual water content of 1122 L/Kg in advantageous climatic conditions but this virtual water consumption is more than Delhi and Hyderabad. (Hoff et al., 2014)
Lagos	1210	3315	Lago's average per capita consumption WF is 1210 CUM/year, with average cereals, pulses consumption of 30 Kg/year with an average virtual water content of 5433 L/kg because of low water productivity of neighboring countries. With more virtual water consumption of soya(6800 L/Kg) in Lago's than Berlin(1755 L/Kg) and cassava is very common food in this region contributing more virtual WF of 983 L/kg with per capita consumption of 227 Kg/cap which is 7 times to the cereals and pulses consumption. (Hoff et al., 2014)
Milan	1878	5150	Milan's average per capita WF consumption is 1878 CUM/year which is more than doubled to the Hyderabad's WF in which 54% (1024 CUM/year) is WF from meat and milk, milk products which is nearly equal to the Lago's WF. The average WF of Milan by excluding meat, milk and milk products is 854 CUM/year with average cereals, pulses consumption of 77 Kg/year with a virtual water content of 1095 L/Kg. (Reference: /Kg. (Reference: Vanham and Bidoglio, 2014a).

Hyderabad(391 M3/Y)	Kg/Year	Liters/Kg	M3/Year
Cereals	102	2840	290
Pulses	11	4220	46
Vegetables	21	930	20
Fats & Oils	7	4330	30

Milan(1878 M3/Y)	Kg/Year	Liters/Kg	M3/Year
Cereals	130	1440	187
Pulses	20	2730	55
Oils & Fats	40	18250	730
Coffee	230	1260	290

Lagos(1210 M3/Y)	Kg/Year	Liters/Kg	M3/Year
Cassava	227	983	223
Sorghum	50	5700	285
Rice	33	3800	125
Soya	3	6800	20

Delhi(434 M3/Y)	Kg/Year	Liters/Kg	M3/Year
Rice	122	1900	232
Wheat	66	2100	139
Pulses	12	3200	38
Soya	5	4200	21

Berlin(643 M3/Y)	Kg/Year	Liters/Kg	M3/Year
Wheat	164	498	82
Soya	53	1755	93
Coffee	9	15000	135
Cocao	3	20000	60

Fig. 8. The annual consumption quantities (in Kg/Year) of primary food products, along with the VW (in Liters/Kg) content embedded and total WF of product (in m^3/year) of cities Hyderabad (HMDA), Milan, Lagos, Delhi, and Berlin.

compared with virtual water embedded in food and energy. Direct WF of Hyderabad is less than the European cities and cities in the United States. Average direct WF of Milan is 529 L/cap/day, average direct WF of United State urban cities are 600 L/cap/day (Vanham and Bidoglio, 2014a; McCallum and Shanafield, 2016). Whereas direct WF of HMDA is 120 L/cap/day, it is only 5% in HMDA's footprint. However, while assessing the direct WF, we have not assessed based on the economic gradients of consumers, due to data limitation of direct water consumption with respect to economic gradients of consumers, as in HMDA region for drinking water, consumers depend on several sources including groundwater, municipal water, and private water distribution sector. Assessing direct WF based on economic gradients alone is laborious and requires more data. It requires an enormous amount of effort and time. For now, we assessed using general averaging method over the population, and the obtained value of direct WF in urban is nearer to the values published from previous researches (Shaban & Sharma, 2007b; Shaban, 2008). Above results illustrate how the purchasing power of consumer can influence the WF of urban cities and it is demanding consciousness in consuming urban utilities.

6. Conclusion

We assessed WF of HMDA region based on economic classes using a consumer-centric approach. It helps to understand the consumption behavior of the different economic class population and to monitor products/goods consumption, which is more consumed by the affluent and non-affluent population. These assessments were required, to assess and plan foreign (out of HMDA boundary) VW, trade policies for water intensive and high consumables from water abundant regions. In addition, this approach helps to policymakers to plan strategies to reduce VWF of these goods (highly consuming goods) in the production phase, if they are importing from within the national territories.

Securing regional water resources alone will not fulfill the sustainability of water resources; it is the duty of all nations and regions.

Cooperation between the nations/regions with strong water stewardship is essential to satisfy the water needs between transboundary regions. Exporting/importing of water-intensive goods between water abundant and dry regions through VW trade can help to resolve transboundary water conflicts and release pressure on water scarce regions. Assessing WF of one city will not serve the purpose of water resources sustainability; it demands this kind of assessment for more cities to achieve future water resources sustainability.

In this study, we have quantified the HMDA region's WF at the consumer level by considering economic gradients of consumers. Out of total WF consumption, 95 percentage (997 m^3/cap/year) is from indirect WF, only 5% (44 m^3/cap/year) is from direct WF. In the HMDA region's WF, virtual WF dominated the direct WF. Here, we have not included the industrial, commercial WFs and temporal variations these WFs, which requires an enormous amount of information on commodity trades and its consumption WFs, this can be the future scope of this work.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.scs.2019.101686.

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Water and Food Nexus: Role of Socio-Economic Status on Water–Food Nexus in an Urban Agglomeration Hyderabad, India Using Consumption Water Footprint

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Abstract: Cities are complex and evolving systems with various factors playing key roles, e.g., population increase, the migration of population, the availability of resources, and the flexibility of policies. Consumers' socioeconomic status is also an important aspect that needs to be studied in the context of a self-reliant urban city in its resource consumption. In this regard, the association between water–food and socio-economic attributes was analyzed based on the consumer-centric approach for the Hyderabad Metro Development Authority (HMDA) region, India. In this study, the embedded water content in food consumption was estimated and analyzed for nine food groups and twelve economic classes of the HMDA region. The middle economic classes were found to correspond to ~80% of embedded water content in the HMDA region, followed by the upper and lower economic classes. Except for cereals, per capita, the water consumption of all food groups increased with the spending power of the economic class. The green, blue, and grey consumption water footprints (WFs) suggested that much of the water that is being consumed in the HMDA region is precipitation-driven, followed by surface and groundwater resources. Limited water resources, water resource variability, climate change consequences including future climate projections, uncertainty in data, WF estimates, and region's future growth imply a detailed study in drafting policies to become a self-reliant region.

Keywords: embedded water content; water footprint; water–food nexus; socio-economic status; food consumption; virtual water; spending capacity

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1. Introduction

Drafting globalized policies for the sustainable consumption of resources in urban regions is necessary. The increase in the role of urban regions by hosting significant population as well as providing various opportunities is reflected in its contribution to the national economy and, thereby, the global economy. As per the European Commission, urban regions (or urban cities) hosted 75% of the global population in 2015, and the population has risen relatively quickly in recent times [1]. Additionally, significant changes in land use and land cover have been observed. Importantly, agricultural land in peri-urban regions, which plays a crucial role in cities' food supplies [2,3], has shrunk [4]. Increases in population and decreases in resourceful land in combination with cities' growing requirements further add more stress to available resources including water, which is limited in quantity and variable with time.

Water is the key resource used by all elements of an urban region, and food is an entity that consumes a significant amount of water [5]. Food imports imply the importation of water from both near and faraway places; however, only a few studies have explored water movement across different sectors, particularly in the context of food consumption and its impacts on regional water balance at the city scale [6–8]. This has led to a poor understanding of water and food association at the urban and regional scales. Note that the unavailability of data and gaps in data are also limiting factors for the perusal of systematic efforts [6,8]. Nevertheless, both rapid economic growth and lifestyle changes have introduced new food habits that consist of more processed foods that are water-intensive in production [9–11]. These situations lead cities to be hotspots for the higher consumption of direct and indirect water resource utilization, increasing further water stress in a region [12,13]. Direct and indirect water resource computation and its movement across different regions and sectors is complex and requires systematic study. The nexus approach offers a practical solution, including for transboundary conflicts [5].

The nexus approach got its first attention in the world economic forum conference in 2011 [14]. The approach measures the interdependencies between water–energy–food (WEF) resources by accounting for the water used in various tasks, including production, transportation, and regional consumption. Thus, the information from the nexus approach can be used for governance and planning, as well as to evaluate trade-offs between WEF resources [5,15]. The nexus approach can be applied to the city, river basin, and continental scales from different perspectives of the water footprint [5,8,16,17]. The water–energy–food nexus approach suggests localized solutions specific to a region. Note that nexus studies have been pursued from different perspectives like food [18,19], energy [20,21], and climate [22–24] for regions of different areas. Additionally, an integrated tool to assess the WEF nexus was also developed [25]. Urban regions are hotspots for consumption; indeed, they consume more virtual water that is approximately 20 times more than direct water consumption [26], and it highlights the need to quantify the water and food nexus at the city scale. However, the application of the nexus approach to the city scale is relatively more complex compared to regions of a large spatial scale, e.g., river basins or continents. This is mainly due to the transboundary nature of resource consumption in urban cities [6,27,28], and only a few studies have addressed the water–food nexus at the city scale.

The food consumption of urban cities involves long supply chains with production, processing, and mobilization stages, and water is the central element in every stage [29,30]. These long supply chains increase water, energy, and food footprints in the pre-consumption of food, the post-consumption of food, and greenhouse gas (GHG) emissions [29,30]. Among the consequences of various socio-economic–environment elements, increased pressure on water resources is the most notable. Despite being the primary element in determining the water footprint, human consumption of water and food remains sparsely examined in the context of the urban food systems in various cities [29,31–38].

Many studies have analyzed the nexus between water-centered resources in high-income economic regions that are data-rich and use regional trade [18,19,39,40]. A few studies have considered commodity survey data [29,30], which is a coarse representation of the nexus of urban food systems, and consumers' socio-economic status has not been considered. Consumers' socioeconomic status is an important representational aspect in an urban system, and its role has further increased as urban regions have grown and differences in economic classes have widened [41]. Only a few studies have pursued the nexus by integrating consumers' socio-economic information for cities in Europe [37,42]. The fact that the changes vary significantly among urban dwellers of different economic classes emphasizes the need to have detailed data; however, data unavailability is common for many urban regions across the world. In this regard, the consumer-centric approach [43–46] is a reasonable solution to overcome the data-related issues for nexus studies.

In recent times, particularly during Coronavirus disease-2019 (COVID-19)-driven lockdowns, self-reliance on food and water resources has become a primary concern for many urban regions. The biggest importers have faced challenges because of COVID-19-driven lockdown restrictions on exports, and uncertainties in removing or easing lockdown restrictions increased difficulties further [47–49]. Covarrubias and Boas [6] analyzed the accessibility of proximity of food in the context of reducing food miles, energy utilization, and carbon emissions to understand how the city of Barcelona could be self-reliant for food consumption. Similarly, climate change consequences have the potential to bring the notion of self-reliance to cities. Climate change effects include a range of consequences, and in the context of food systems, changes in rainfall and temperature have important roles.

Changes in rainfall patterns on both small and large space and time scales have resulted in hydroclimate extremes such as floods and droughts at the city and river basin scales [50]. Additionally, temperature changes might produce other extremes such as heatwaves [51]. As it has been seen, these effects disrupt food system elements, and cities are relatively more vulnerable because these elements are highly dependent on peri-urban and regions elsewhere.

Most of the food products consumed in India are produced within the domestic boundaries; therefore, the impact of India's imported food trade is less significant on any part of the world in terms of the water footprint [29,52,53]. However, India is a source for water-intensive food trade, exporting 95.4 billion cubic meters/year of virtual water in the food trade, which is four times what India is consuming [54,55]. A high consumption of unevenly distributed water resources for exports is a primary reason for water stress conditions in the major cities of India [54]. In this context, India, including its urban regions, needs to cautiously monitor and secure its water-centered resources. In particular, India's smart cities mission further emphasizes this need, as more cities are planned to be developed shortly [56].

Ramaswami et al. [28] analyzed and quantified the impact of climate on the water, energy, and food nexus of Delhi city, India, for urban food systems [28]. This study revealed the transboundary interactions and interdependency of resources for the provision of water, energy, and food needs. Boyer addressed sustainability and environmental impacts by analyzing the unique food systems of nine Indian cities [29,30]. The authors also compared the food system characteristics of cities from India and United States, and they found differences in the food supply chain distance in the cities of both counties. They found relatively long food supply chain distances in Indian cities, this along with the increased consumption of water and energy, and the GHG emissions impacted the environment. The study also observed a large amount of pre-consumer food waste, though this was slightly higher in cities of the USA than in Indian cities. Typically, planning trade strategies and drafting water policies at the regional and national levels only consider available water resources, and the accountability of socio-material flow (embedded water in the supply chain) between transboundary regions is not given much importance [6–8]. This may be due to the lack of a common platform to deal with the nexus between water-centered resources. Regional food resiliency is frequently disturbed with floods and droughts, and it builds a competitive trade-off in allocating water resources between food production and domestic needs, thus leading to various transboundary conflicts [5,57].

While India's smart city mission facilitates the development of a systematic urban database in the near future, the evolution of cities into further complex systems poses challenges and difficulties in finding optimal solutions. The notion of becoming a self-reliant city drives sustainable city policies for various reasons including climate change, and it is important to understand the water footprint from various angles, including socio-economic status for the aforementioned reasons. In this regard, the main objective of the study was to understand the association between socio-economic attributes, including purchasing power, food consumption, and embedded waters in the Hyderabad Metro Development Authority (HMDA) region. Thus, the study can assist policymakers of local and national governments in providing information on water-intensive and water-friendly food products, as well as in developing trade strategies with water-rich regions so that the consumption of water in urban and peri-urban regions will eventually decrease. The information may play a role in drafting city-level food policies for the sustainable consumption of food and water resources to build sustainable and smart cities, which is part of the second, sixth, and eleventh goals of the United Nations' Sustainable Development Goals that were established in 2015 [58]. The trade strategies emphasize the revisiting of the water allocation trade-offs between food production and other domestic purposes, so regional water balance accounting export and import of virtual water is achieved.

2. Study Area

The study region, HMDA, includes Hyderabad, which is one of the most well-known cosmopolitan cities in India. Hyderabad city is capital of the relatively newly formed state Telangana, and the selected region, HMDA, has a wide variety of food cultures because people in the region are from different parts of the country. Approximately 70% of the HMDA's water footprint (WF) is due to food consumption [46], and the region's produce depends on food products from surrounding regions, particularly it's peri-urban region; the key role of the peri-urban region in agriculture products is evident in HMDA's food supply [2]. The agriculture and domestic water needs of these peri-urban regions are compromised to satisfy the water needs of the HMDA region, thus leading the peri-urban regions to have water conflict [59].

Initially, Hyderabad only up reached the boundaries of erstwhile Hyderabad (see Hyderabad part in Figure 1) with an area of 217 km^2, and rapid economic activity mainly led by information technology services resulted in exponential population growth and changes in land use. Consequently, the city expanded to 7257 km^2 and parts of surrounding districts—Ranga Reddy, Medak, Nalgonda, and Mahabubnagar—became the city's peri-urban regions [60]. The total population of the HMDA region is 9.4 million, and Hyderabad is the fourth most populous urban agglomeration in India [61]. Hyderabad is located on one of the riverbanks of River Musi, which is the tributary of River Krishna; however, another part of the study region is in another major river catchment, the Godavari river basin. The region gets most of its rainfall during the monsoon season, and the average annual rainfall of the Hyderabad region is 810 mm. The city consumes 1030 and 257 million liters per day for domestic and industrial purposes, respectively, and most of its water come from reservoirs, which range from within city limits to as far as 300 km away from the city (from annual reports of Hyderabad Metro Water Supply and Sewerage Board, 2016). Both the growing city's requirements and industry-driven, pollution-related issues on the city's water resources have compelled the region to depend on water resources far from the city limits [62].

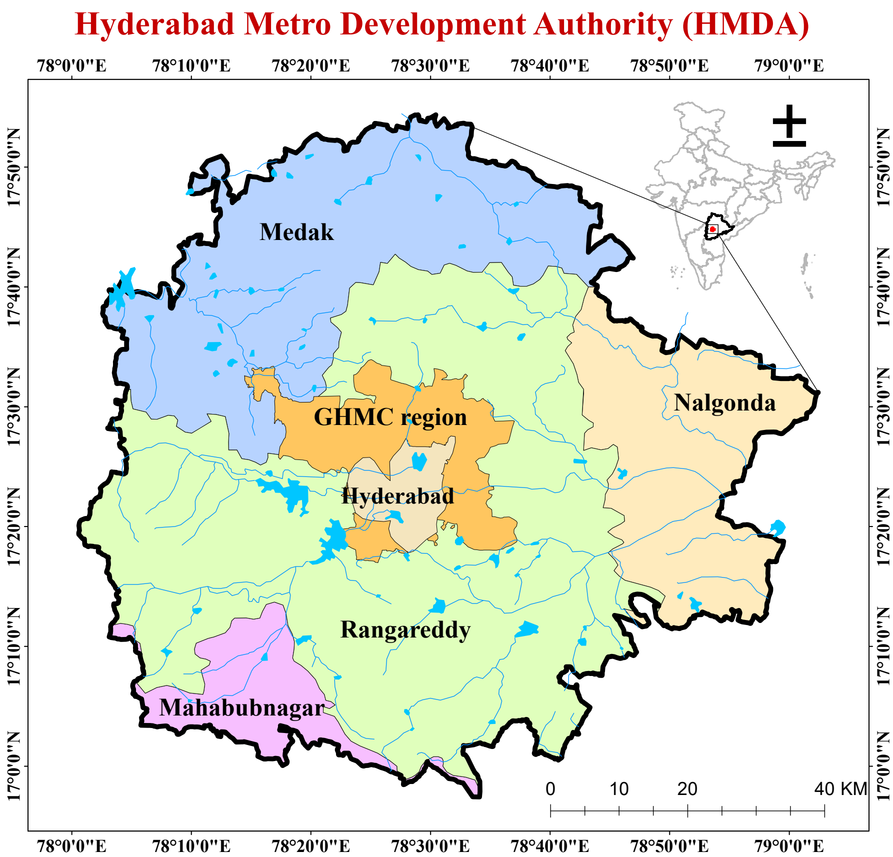

Figure 1. Jurisdictions of Hyderabad Metropolitan Development Authority (HMDA) region showing the boundaries of Greater Hyderabad Municipal Corporation (GHMC) and five districts, i.e., Hyderabad, Ranga Reddy, Nalgonda, Medak and Mahabubnagar.

3. Materials and Methods

3.1. Data

The data that were considered in this study are as follows: consumed food quantities, population, and water production footprint. Additionally, the commodity consumption data from the 68th consumer expenditure survey were used. The survey was conducted in 2012 by the National Sample Survey Organization (NSSO) [63], and the data consisted of consumed quantities for 88 food products for each of twelve economic classes for the HMDA region. The economic classes (ECs) were formed based on the monthly per capita consumption expenditure (MPCE) [63]. The food products were grouped into 9 food groups, namely cereals, fruits, livestock, coffee and tea, milk products, oils and fats, pulses, sugars, and vegetables, as per dietary guidelines of National Institute of Nutrition India [64]. Population data for each economic class for the HMDA region were obtained from the comprehensive transport survey of the HMDA [60]. The water production footprint, including green, blue, and grey water footprints for all individual food products, was taken from a well-known database [65,66].

3.2. Method

The study used a consumer-centric approach to quantify the water and food nexus for the study region in the context of socioeconomic status, and it adopted the framework developed by [46]. As shown in Figure 2, the study calculated the total amount of consumed food, and then it calculated the embedded water for each food commodity for and economic class. The embedded waters were used to analyze the water and food nexus for food groups, economic classes, and the HMDA region. Figure 3 shows the finer details of data and the calculation procedure. The below-mentioned steps detail the calculations and assist in the interpretation of results.

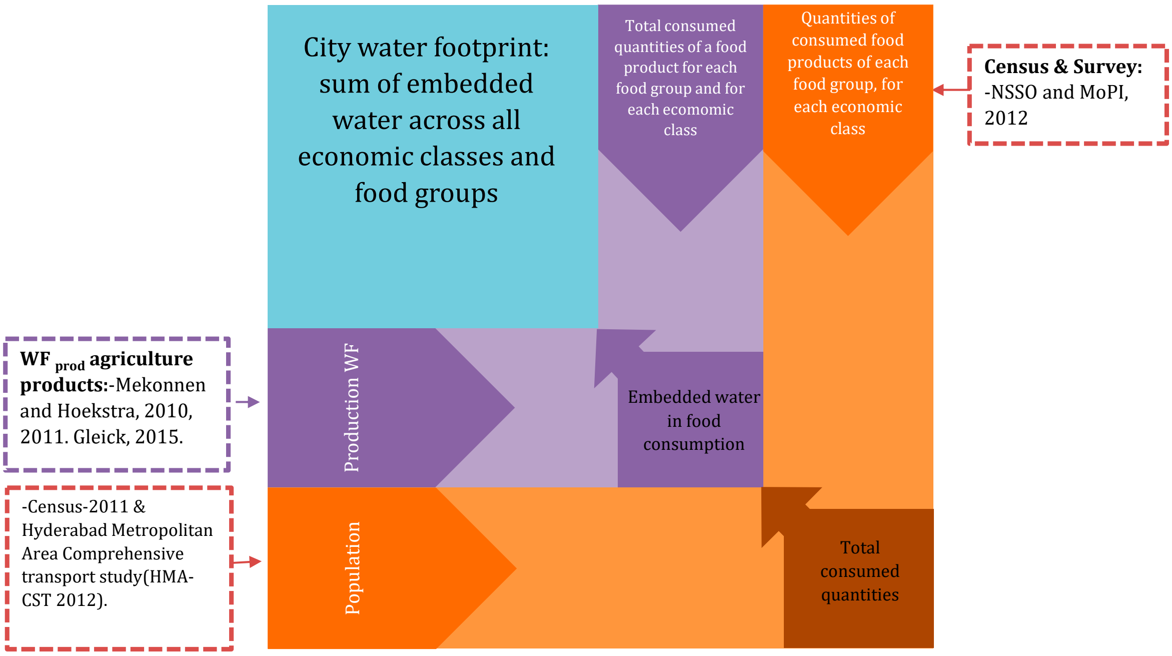

Figure 2. The framework to account for water footprint and the data used to assess the water, food, and economic nexus of Hyderabad. The arrows indicate the direction of their multiplier to quantify the central elements: total food consumption quantities of a food product for each economic class, the embedded water content in food consumption for each food product and each economic class, and city-level embedded water contents in food consumption. WF: water footprint; NSSO: National Sample Survey Organization.

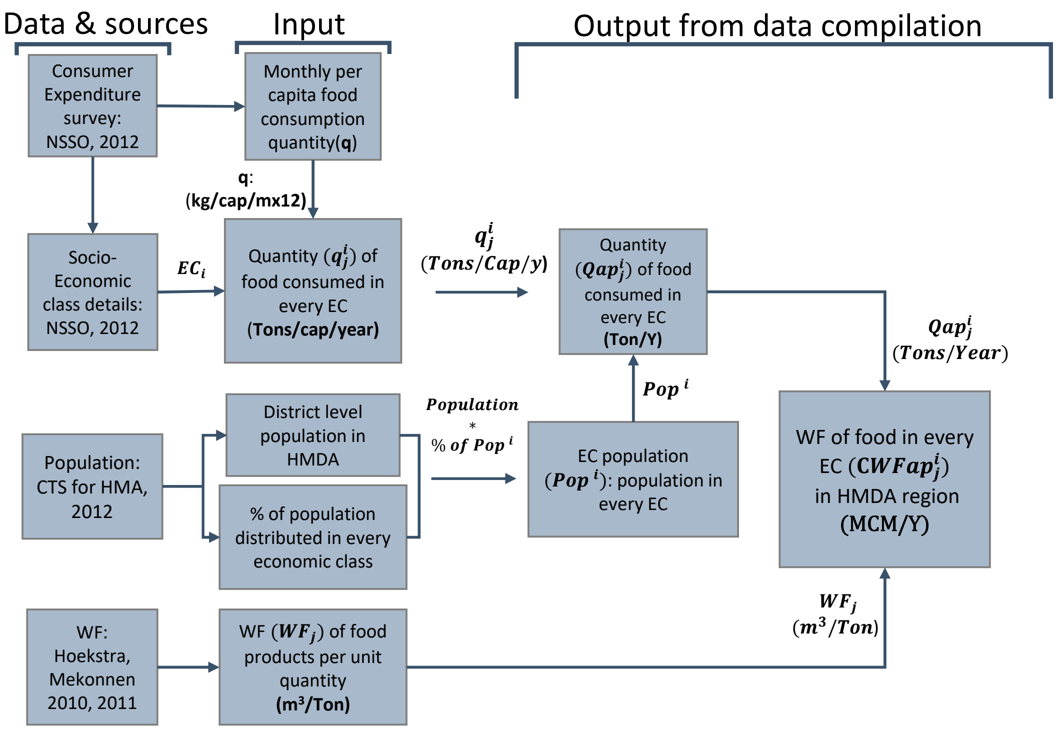

Figure 3. Calculation procedure to quantify embedded water content in food consumption for each food product and each economic class, and city-level embedded water contents in food consumption. EC: economic class.

Stepwise calculation procedure:

Step 1: Calculate food consumption quantities in tons per capita per year $\left(q_j^i\right)$ for all food products (j) and each economic class (i) using monthly per capita consumption quantities (q).

Step 2: Calculate the population for each economic class $\left(\mathrm{Pop}^{\mathrm{i}}\right)$ using the percentage of the population in each EC and the total population in the HMDA region.

Step 3: Calculate the total consumed quantities $\left(\mathrm{Qtotal}_{\mathrm{j}}^{\mathrm{i}}\right)$ for all food products (j) and each economic class (i) using information from steps (1) and (2).

$$\mathrm{Qtotal}_{\mathrm{j}}^{\mathrm{i}}\ (\mathrm{Tons/year}) = \mathrm{q}_{\mathrm{j}}^{\mathrm{i}}\ (\mathrm{Tons/cap/year}) \times \mathrm{Pop}^{\mathrm{i}} \tag{1}$$

Step 4: Calculate embedded waters, i.e., consumption WF $(\mathrm{CWF}_{\mathrm{j}}^{\mathrm{i}})$, for each economic class and each food product using the corresponding water production footprint $(\mathrm{WF}_{\mathrm{j}})$ and total consumed quantity $(Qtotal_j^i)$.

$$\mathrm{CWF}_{\mathrm{j}}^{\mathrm{i}}\ (\mathrm{MCM/y}) = \mathrm{Qtotal}_{\mathrm{j}}^{\mathrm{i}}\ (\mathrm{Tons/y}) \times \mathrm{WF}_{\mathrm{j}}\ \left(\mathrm{m}^3/\mathrm{Tons}\right) \tag{2}$$

This step is repeated for all three green, blue, and grey production WFs, and the sum of the three individual embedded waters yields the total embedded waters.

Step 5: Calculate the embedded waters for each economic class (i) and for each of the nine food groups (J) by summing embedded waters of corresponding food products.

$$\mathrm{CWF}_{\mathrm{j}}^{\mathrm{i}}(\mathrm{MCM/year}) = \sum_{\mathrm{j}=1}^{\mathrm{Jj}} \mathrm{CWF}_{\mathrm{i}}(\mathrm{MCM/year}) \tag{3}$$

where Jj is the number of food products in the food group J.

The embedded water of the HMDA region was calculated as shown below.

$$\mathrm{CWF}_{\mathrm{HMDA}}(\mathrm{MCM/year}) = \sum_{\mathrm{i}=1}^{12} \sum_{\mathrm{J}}^{9} \mathrm{CWF}_{\mathrm{j}}^{\mathrm{i}}(\mathrm{MCM/year}) \tag{4}$$

In addition, the per capital consumption quantity, total consumed food quantities' percentage equivalent concerning food groups, total embedded water's percentage equivalent concerning food groups, and production WF (which corresponds to consumed water during production of a food product) for each food group were calculated. The production WF was calculated as the sum of production WF of all food products of a food group. The percentage equivalent calculations reflected the contribution from every food group.

Food groups were categorized as water-intensive, water-neutral, or water-friendly based on the difference between the percentage equivalent of embedded waters and the percentage equivalent of food consumption. If the value of the difference, i.e., percentage point difference, was positive and greater than 2, then the corresponding food group was treated as water-intensive. If the value of the difference was negative and smaller than −2, then the food group was treated as water-friendly. If the values were between −2 and +2, then the food groups were treated as water-neutral. The threshold of '2' was used to account for the errors in the uncertainties, and it was subjective.

4. Results and Discussion

4.1. Water and Food Nexus in HMDA Region

Table 1 lists the total consumed food quantities and embedded water, i.e., water consumption footprint and production WF, for each of the nine food groups and for the HMDA region, which includes all 12 economic classes. The table also has percentage equivalents for total consumed food quantity (column 3) and embedded waters (column 5), as well as the percentage point difference of these two quantities (column 8). The total embedded water in food consumption was found to be 6833 MCM/year, and it was more than 20 times the HMDA region's direct water use, i.e., 375 MCM/year [46]. Among all the food groups, cereals, milk products, and livestock together contributed 73% (i.e., 4995 MCM/year) of the total embedded water, and the remaining six food groups, i.e., pulses, vegetables, fruits, oils and fats, sugars, and coffee and tea corresponded to 27% (column 5, Table 1). However, in terms of the total consumed food quantity, cereals, vegetables, and milk products contributed 79% of food consumed in the HMDA region. While cereals and milk products were found to be the highest contributing food groups in terms of both embedded water and consumed food quantity, livestock and vegetables also significantly contributed to embedded water and consumed food quantity, respectively. We defined a water-intensive food group as a group with a positive difference between the percentage equivalent of embedded water content and the percentage equivalent of food consumption categorizes cereals; as such, pulses and livestock were found to be water-intensive food groups. Cereals were the most water-intensive of the food groups, with a difference of 11% between the percent of embedded water and food consumption. Therefore, this can be treated as the most water-intensive food group, whereas livestock and pulses differed by 6 and 4%, respectively, in their proportion of embedded water content and their respective food consumption quantities. Therefore, these products can be treated as less water-intensive food groups. Due to their small values and uncertainty in the data, the fats and oils, coffee and tea, sugars, and milk product groups can be treated as water-neutral food groups. Unlike the above-mentioned products, vegetables and fruits were found to have lesser proportions of percent equivalents of embedded water content than their respective percent equivalent of food consumption, i.e., 18 and 4%, respectively. This implies that there is a relatively smaller percentage of consumed water than that of consumed food quantities at the city level, hence vegetables and fruits can be treated as water-friendly food groups.

It is interesting to note that cereals, vegetables, and milk products were found to be the most highly consumed food products in the HMDA region at 1.04, 0.75, and 0.69 tons/year, respectively. However, the corresponding total embedded waters by each of these food groups at the city level differed by significant amounts. Therefore, these food groups were labelled as water intensive, water-friendly, and water-neutral, respectively. The water production footprint of cereals (i.e., the embedded water content in production) was of medium value compared to the other products (see Table 1). However, its relatively high consumed quantities, i.e., 33% of the total food consumed across the HMDA, made the food group more water-intensive. Meanwhile, vegetables and milk products consumed approximately the same amount, i.e., 0.75 and 0.69 tons/year, respectively, but their production WF was greatly different at 2011 and 543 liters/kg, respectively. Hence they were treated as water-friendly and water-neutral food groups, respectively, for the HMDA region. Livestock and pulses consumed small quantities, i.e., ~0.1 tons/year (3% of total quantity), but their high production WF made them moderate water-intensive food groups. The sugars group and the oils and fats group consumed similar quantities, i.e., ~0.1 tons/year, but their relatively low production WF made them water-neutral. The group of coffee and tea had the highest production WF, but its relatively very small consumption quantity of ~0.01 tons/year corresponded to relatively similar low embedded waters at the city level. Consequently, this food group was treated as water-neutral food. As discussed, the food groups differed in their quantity, production WF, and, consequently, their embedded water quantities at the city level. However, after learning that these consumed quantities varied in each economic class, it was important to analyze them more for a better understanding of the water–food nexus at the sub-city level.

Table 1. Details of total food consumption and its percentage equivalent, total embedded water and its percentage equivalent, per capita food consumption, water production footprint, and category of food groups for the HMDA region (MCM: million cubic meters).

Food Group	Total Food Consumption (million tons/year)	Percentage Equivalent of Total Food Consumption	Total Embedded Water (MCM/year)	Percent Equivalent of Total Embedded Water	Per Capita Consumption (Kg/year)	Production WF (Liters/Kg)	Difference between Percent Equivalent of Total Embedded Water and Percent Equivalent of Total Food Consumption	Category
Cereals	1.04	33	2973	44	111.21	2839	11	Water-intensive
Pulses	0.1	3	453	7	11.2	4300	4	Water-intensive
Sugars	0.1	3	229	3	10.56	2255	0	Water-neutral
Milk products	0.69	22	1387	20	73.29	2011	−2	Water-neutral
Fats and oils	0.1	3	341	5	10.67	3399	2	Water-neutral
Vegetables	0.75	24	411	6	80.52	543	−18	Water-friendly
Fruits	0.27	9	319	5	29.52	1159	−4	Water-friendly
Livestock	0.09	3	633	9	10.56	6376	6	Water-intensive
Coffee and tea	0.01	0	82	1	1.25	6997	1	Water-neutral

4.2. Influence of Socio-Economic Status on Water and Food Nexus

The total embedded waters in food consumption for the HMDA region were analyzed for twelve different ECs, i.e., EC1–12; high numbers corresponded to high consumption power. As one would expect, the per capita food consumption increased with increase in spending power (Figure S1); in particular, the per capita consumption values increased linearly until EC7, and then an exponential increase was observed for middle and upper economic classes beyond EC7 (Table 2). Meanwhile, the population increased from the lower to middle economic classes (EC1–6), it appeared to be random in the middle economic classes (EC7–9), and that was followed by decreases in the upper economic classes (EC10–12); a relatively low population was observed for upper economic classes (Table 2). Thus, the twelve economic classes were found to be unique and implicitly indicated the corresponding population's spending power and lifestyle including food that could be afforded and consumed.

The embedded water in each economic class across all the food groups increased for the first six economic classes and was followed by no systematic pattern in the middle economic classes (EC6–10) with decreased amounts in the upper economic classes (EC11 and EC12) (Table 2)—a similar pattern was observed for population distribution for all ECs. The middle economic classes had a high total embedded waters, i.e., EC10 with the highest embedded water contents (1031 MCM/year) followed by EC8 and EC9. As one would expect, the lowest embedded water contents were observed in the lower economic classes and could be attributed to small population numbers and a small total consumed quantity. However, it is important to note relatively low embedded waters were also observed in the upper economic classes (EC11 and EC12). EC11 and EC12 had the highest spending power, but their relatively decreased population numbers produced relatively low embedded water levels (Table 2). In contrast, high embedded waters were observed in the middle economic classes regardless of their relatively low per capita consumption compared to upper economic classes. This was because of the large population in middle economic classes. Unlike the total embedded water, the per capita embedded waters increased with increased spending power, thus suggesting a larger consumption water footprint for a person with more spending power (Table 2).

Table 2. Details of spending capacity, population, per capita embedded water, and total embedded water for all twelve economic classes.

Economic Class	Spending Capacity (Rupees/Capita/Month)	Population	Per capita Embedded Water Content (Cubic Meters/Capita/Year)	Total Embedded Water (MCM/year)
1	<725	131806	493	65
2	860	244783	515	126
3	1090	593128	574	341
4	1295	941472	619	582
5	1510	997961	652	650
6	1760	1063864	683	727
7	2070	988546	713	705
8	2460	1289817	745	961
9	3070	1054449	795	838
10	4280	1242744	830	1032
11	6015	480151	917	440
12	>6015	386004	955	369

A plot of the total embedded water of food groups and economic classes suggested four-clusters of food groups and three clusters of economic classes (Figure 4). The food groups were as follows: cereals, milk products, livestock, pulses, vegetables, oils and fats, and fruits, as well as a cluster of sugars, coffee, and tea. Similarly, the three economic classes were as follows: EC4–10; these together corresponded to ~80% of the embedded water content in the HMDA region, including upper economic classes EC11 and EC12 (~12%) and lower economic classes EC1–3 (~8%). Note that population distribution across economic classes exhibited a similar pattern except that upper and lower economic classes corresponded to similar percentage equivalents of 9% and 8%, respectively. As mentioned in the previous section, cereals, a water-intensive food group, held a large volume of embedded water for the HMDA region, which was seen in all economic classes (Figure 4a). The volume of embedded water of the milk products, which held the second most embedded water content of the HMDA region, greatly differed compared to cereals, except for in the upper economic classes. The decreased volumes of embedded waters and approximately similar volumes for the upper economic classes (EC11 and EC12) for both cereals and milk products indicated changes in food habits compared to the other economic classes (Figure 4a).

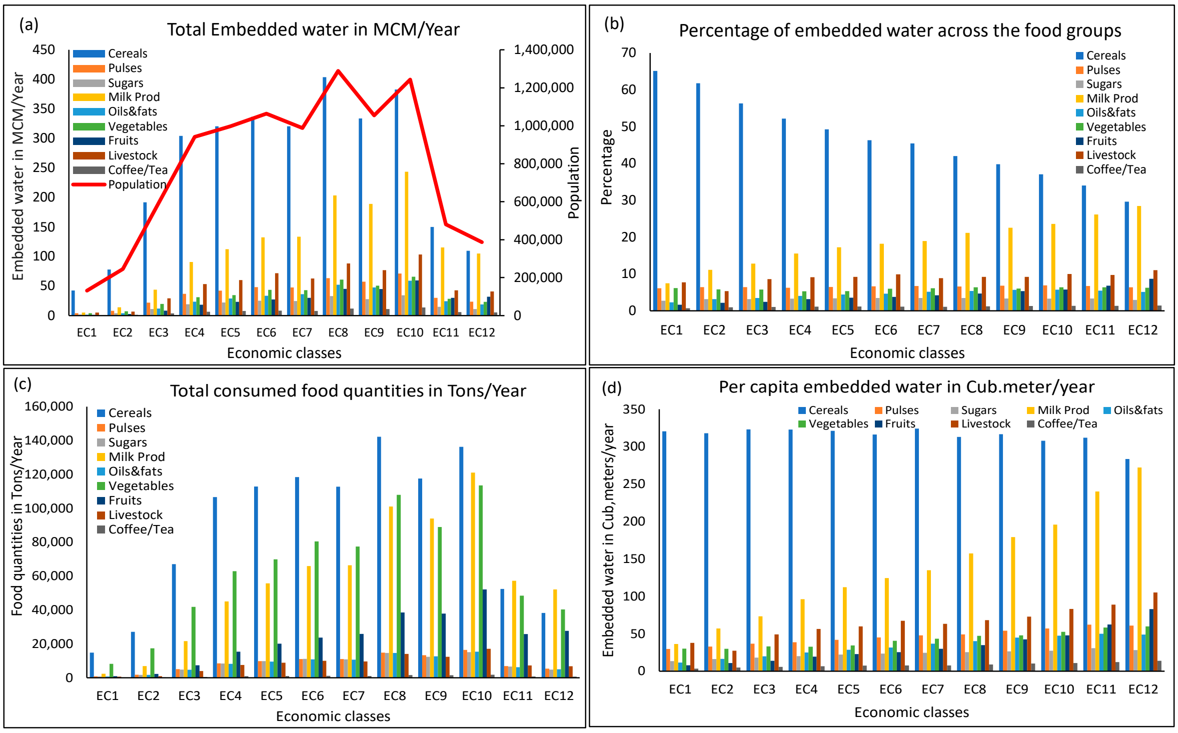

Figure 4. Total embedded water for each food group and each economic class, the plots also have population information on the right side of y-axis (**a**); similar to (**a**), but for the percentage equivalent of embedded water (**b**); similar to (**a**), but for total consumed food quantities (**c**); and similar to (**a**), but for per capita embedded water (**d**).

The food group of fruits held the second-lowest embedded water content in EC1–4. With the increase in spending power, the fruit group held more and more embedded water, and it was the food group with the fourth-highest embedded water content for EC11 and EC12. Fruits corresponded to a relatively low production WF, but their large total consumed quantities (ranked fourth) resulted in steep increases in its percentage equivalents; the high per capita consumed water footprint explained its increased total embedded water content for EC11 and EC12 (Figure 4b).

Livestock dominated as the third highest food group in terms of the HMDA region's water consumption footprint but corresponded to low food consumed quantities (ranked approximately sixth) in all economic classes, thus making it a water-intensive food group (Figure 4a,c); a similar observation was made in earlier sections. However, note that the percent equivalent was slightly on the rise in the low and high economic classes (Figure 4b).

Pulses, another water-intensive food group, held approximately similar proportions of embedded water across all economic classes (Figure 4b) but consumed less than livestock (Figure 4c). Consequently, the pulses group had a relatively low embedded water content compared to livestock (Figure 4a). In contrast, vegetables, as observed in Figure 4a, comprised the second most-consumed food group for all economic classes but held a low embedded water content because it had the lowest production WF. Hence, it was designated as a water-friendly group. Its percent equivalent, i.e., the proportion of the total food in an economic class, was approximately same across all economic classes (~6%) and was smaller than percent equivalent of livestock (~10%). While sugars held more embedded water than fruits in the lower economic classes, it is important to note that the quantities of both embedded waters and total consumed quantities were relatively small (Figure 4a,c). The percent equivalents of the sugars group and the coffee and tea group, i.e., 4 and 1.5%, respectively, were approximately constant across all economic classes. Being water-neutral groups, their roles in the embedded waters of the HMDA regions are small. A low embedded water amount consequently led to smaller proportions of the percent equivalent of total embedded waters of the HMDA region of lower economic classes, thus indicating its smaller role in consumption WF, e.g., the cereals percent equivalent was very high for the lower economic classes but its total embedded water was small. In general, total embedded waters and total consumed quantities followed the pattern of the population distribution of each economic class, and the combination of embedded waters and total consumed quantities highlighted the dietary habits of the economic classes (Figure 4a,c).

Total embedded water per capita suggests, in general, the volume of water consumption associated with a food product by an economic class. Being independent of population, these values reflect the potential water consumption of each economic class, and the values associated with each food group were found to vary across economic classes (Figure 4d). Except for cereals, the per capita water consumption of all food groups increased with the spending power of the economic class; approximately similar values for cereals for all economic classes suggested no role of an increased population in an economic class. Meanwhile, in the case of the milk products, the values exhibited a steep rate of changes and high values in middle and upper economic classes. This indicated milk products' potential roles in the region's consumption WF. Th other food products because of its small values, regardless of its moderate- (livestock), mild- (pulses, vegetables, oil and fats, and fruits), and flat-rate (sugars and coffee/tea) changes across economic classes, indicated its lesser role concerning population changes. Note that multiplication of per capita embedded water with population did not yield the total embedded water as the total embedded waters calculated from individual food products. In this regard, the consumption WF by each of the food products was analyzed (Table S1).

The three food products entitled rice–other sources, wheat/atta–other sources, and milk–liquid corresponded to approximately 55% of the total embedded water in an economic class (Figure S2). Meanwhile, two other products, i.e., rice–public distribution system and wheat/atta–public distribution system accounted for approximately 10–20% for the lower economic classes, and the percentage equivalent decreased for the middle and upper economic classes. The economic classes with higher spending power are excluded from benefitting the supply of food products from the public distribution system. Therefore, they corresponded to smaller percentage equivalents of total embedded water. Nevertheless, the combination of rice, wheat/atta, and milk–liquid in each economic class held approximately 63–78% of total embedded water with low- and high-percentage equivalents in upper and lower economic classes, respectively. Despite most of the proportion was from the water-intensive food group, being staple foods the opportunity to decrease the consumption WF is minimal. Only a few products in some economic classes had a percentage equivalent between 2 and 6; otherwise, many individual food products had smaller proportions and did not assist in decreasing the total embedded water of the region

4.3. Potential Policy Interventions with Nexus Approach for Water Conservation

The total amount of consumption of water footprint for the HMDA region was found to be 6836 MCM per year, and of which green, blue, and grey water corresponded to 67, 23, and 10%, respectively (Figure 5a, last column). The values suggested that much of the water that is being consumed in the HMDA region is precipitation-driven, followed by surface and groundwater resources. The grey WF percentage equivalent, ~10%, implied non-negligible pollutant loads as a result of food consumption. A similar inference could be derived from the values of percentage equivalent of the individual food groups, i.e., green WF percentage equivalent followed by the blue WF and grey WF percentage equivalents (Figure 5a). The green WF percentage equivalent ranged from approximately 50 to 95, and the food group of oils and fats group had the highest proportion, thus indicates its dependency on precipitation-driven water sources (Figure 5a). The sugars and cereals food groups corresponded to the first two highest percentage equivalent blue water sources, i.e., 45 and 37%, respectively (Figure 5a). Among all food groups, pulses corresponded to the highest greywater percentage equivalent, ~23%. However, note that the mentioned food groups, except for cereals, held small amounts of the embedded waters of the HMDA region regardless of their high percentage equivalents (see Table 1).

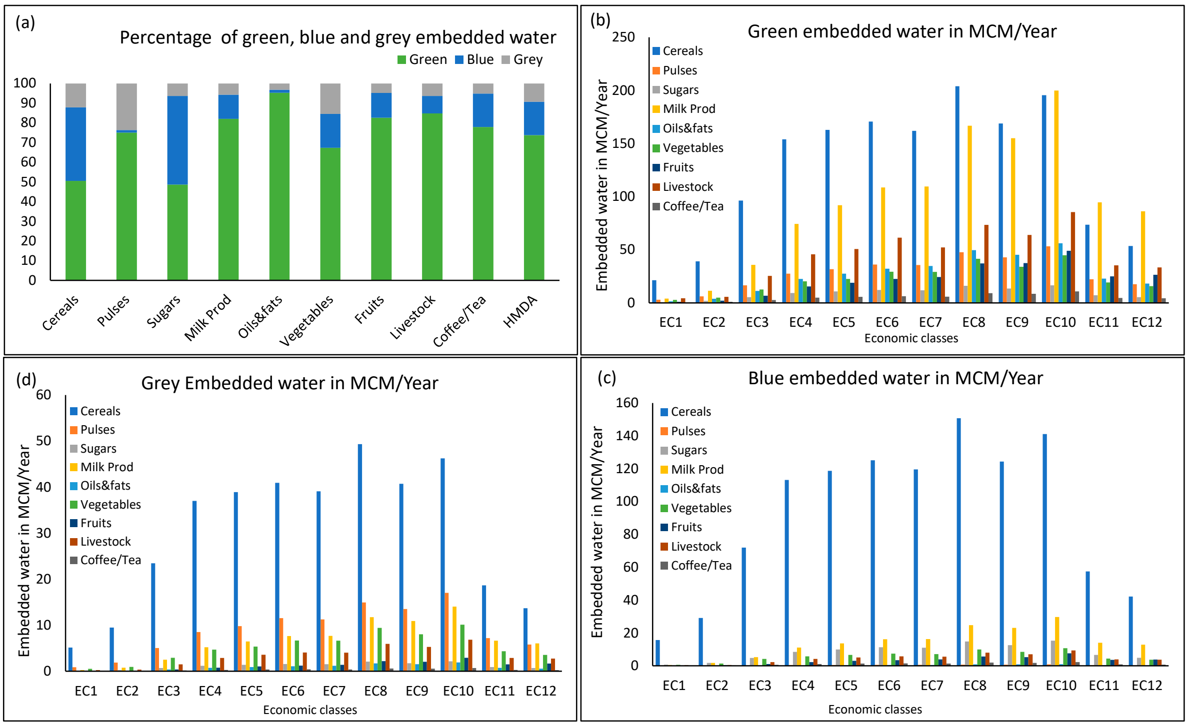

Figure 5. Percentage of green, blue and grey embedded water for each food group and the HMDA region (**a**), as well as the amount of green (**b**), blue (**c**), and grey (**d**) embedded water contents for each food group and each economic class.

The patterns of the consumption green, blue, and grey WFs concerning the economic classes were not much different from total consumption WF, which was the weighted sum of all three individual water footprints (Figure 5b–d vs. Figure 4a). Cereals and milk products corresponded to high consumption WF values, and their corresponding green, blue, and grey embedded waters were also relatively high. A high consumption WF, as discussed, is mainly driven by large quantities of total consumed food and high values of water production footprint. Relatively, sugars and pulses corresponded to small consumed food quantities, though they nevertheless corresponded to third and second highest embedded waters for blue and grey waters, respectively (Figure 5c,d). The volume of blue and grey embedded water in the city's consumption for many products was small, but cereals and milk product's blue embedded water and cereal's grey embedded water values were higher than a few products' green embedded water. The values for the food products entitled milk–liquid, rice–other sources, wheat/atta–other sources, chicken, and oils and fats accounted for a significant amount of individual waters; note that some of their percentage equivalents were small, and corresponding food groups were ranked as the highest contributors of the city's consumption WF (Table S1). In this regard, the blue and grey embedded water may have a potential role in the HMDA region's consumption water footprint.

In general, the values suggested the importance of rainfall (source for green water) followed by the surface and groundwater resources (source for blue water) of the HMDA region's consumption WF. Grey water is the amount of water that negates the influence of pollutants, so it also dependent on water resources. The fact that consumption WF is dependent on natural resources that are limited in quantity and, importantly, have variability highlights the importance of setting up guidelines and policies to make urban regions self-reliant. Curtailing exports during the recent pandemic hit the headlines in countries giving priority to food, water, and energy security for their self-sufficiency [48,49], but similar situation could happen under adverse climatic conditions. Consequently, food-importing regions have faced severe problems for food and water needs. Thus, policy drafting should account for the above-mentioned and future increases in consumption WF.

The entire process involves great efforts including the consideration of the uncertainties associated with the estimates and the overcoming of the limitations of the current study, as discussed below. Uncertainties in consumption WF estimates resulted from multiple sources including errors in the data that were obtained based on surveys. The data that were used in the current study were derived over one year and thus did not necessarily reflect the dynamics in recent years and future projections of urban development, e.g., the conversion of peri-urban agriculture and fertile croplands elsewhere to urban lands [4,67,68]. Additionally, note that the production WF varies regionally, but the regional water footprint for peri-urban of the HMDA region was not available and, hence, not considered. Similarly, the water footprint is not available for transportation or approximated for consumption WF calculations. These issues highlight the importance of the collection of additional data including the data of more food products from other than basic food groups. The future estimates should consider changes in dietary habits across different economic classes. Changes in dietary habits are inevitable for the migration of more and more people to the HMDA region for better livelihoods, the promotion of large-scale initiatives for alternate cereal products (e.g., maize, finger millet, and sorghum) that use less blue water resources [69,70], and changes in population distribution across economic classes because of the projected economic growth in the region [71].

Apart from all the above factors including proposed economic growth, climate will have a significant role in drafting policy. There is literature suggesting changes in rainfall patterns, e.g., an increased number of rainfall events with a high intensity and decreased duration is on the rise [72,73] and its effects will not necessarily be limited to urban, peri-urban, and rural regions. The adverse effect of climate change on both green or blue water resources may lead to additional stress for water resources and, in combination with the unsustainable consumption of water for irrigation [74], further increase the effects of limited water resources. In particular, urban heat islands effects need to be studied [75,76]. The study region received a significant amount of rainfall that led to floods this year [77], but decreased ground and reservoir water levels, as well as the possibility of not meeting the region's demands, were highly discussed topics a few years ago [78]. Multiple reservoirs of moderate-to-large sizes (stores of ~80 MCM of water per month) [79] and water distribution systems may dampen the climate change effects for a short period, but available water resources in the context of climate change's impacts on irrigation in the peri-urban region need to be analyzed and integrated into water footprint-based policies.

5. Conclusions

This study calculated the total amount of consumed food quantities and embedded water for different food product groups and economic classes. Embedded waters were used to analyze the water and food nexus for food groups among the economic classes in the HMDA region. Thus, the consumption water footprint of various food products associated with the socio-economic status of the region was interpreted. The food products were grouped into nine food groups, namely cereals, fruits, livestock, coffee and tea, milk products, oils and fats, pulses, sugars, and vegetables, and then the food groups categorized into water-intensive, water-neutral, and water-friendly groups based on their percent equivalent of consumed food and embedded waters. Cereals, vegetables, and milk products were the highly consumed food products, and, based on the associated embedded waters, these were categorized as water-intensive, water-friendly, and water-neutral food groups, respectively. While livestock was consumed relatively less in all economic classes, it has been treated as water-intensive food group because it holds significant amounts of embedded waters. The total embedded waters increased for the first six economic classes, followed by no systematic pattern in the middle economic classes, and finally ending with decreased amounts for the upper economic classes. The middle economic classes together corresponded to ~80% of total embedded water content in the HMDA region, followed by the upper economic classes EC11 and EC12 (~12%), and then the lower economic classes EC1–3 (~8%). Decreased volumes of embedded waters in combination with approximately similar volumes for both cereals and milk products indicated changes in food habits for the upper economic class as compared to the other economic classes, e.g., fruits ranked as the fourth in terms of embedded waters for EC11 and EC12. Largely, embedded waters and total consumed quantities followed the pattern of the population distribution of each economic class. Unlike total embedded water, the per capita embedded waters, except for cereals, increased with an increase in spending power that suggested a larger consumption water footprint for a person with more spending power. However, for cereals, all economic classes exhibited a similar potential consumption water footprint. While most of the proportion of total embedded water comes from a few groups, of which cereals are water-intensive, the fact is that these staple foods did not allow for the opportunity to decrease the consumption WF. That total consumption WF of the region was dominated by green WF, followed by blue and grey WF, suggests the role of precipitation, surface, and ground water resources. In this regard and as the region is expected to grow, a detailed study to make the region self-reliant is suggested.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4441/13/5/637/s1. Figure S1: Per capita food consumption in tons/capita/year for all nine food groups and for twelve economic classes; Figure S2: Percentage equivalent of total embedded water of Milk liquid, wheat, rice from other sources (**a**); percentage equivalent of total embedded water for rice and wheat from PDS (**b**); Table S1: Green, blue and grey water for individual food products over the HMDA region, MCM-Million Cubic Meters.

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Quantifying the water footprint of an urban agglomeration in developing economy

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A R T I C L E I N F O

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Consumption footprint
Trade policy

A B S T R A C T

Sustainable conservation of natural resources has become a primary concern for urban cities, globally as they are centers of consumption and economy. Due to population growth, cities depend more on imports of food, energy, water, and services from all over the globe, and consume more virtual water than direct water, because of their food habits and lifestyle. Most of the imported goods are water intensive and pose challenges in tracing the source of virtual water. The goal of this research is to develop a general framework to assess the water footprint (WF) of a typical city in India using existing databases. A consumer-centric approach has been adopted for assessing WF in Hyderabad Metro Development Area (HMDA). The variation of the WF across economic classes of consumers is also analyzed. The WF is estimated based on four broad categories: 1) food consumption, 2) fossil fuels based energy, 3) electric power, and 4) direct water. Average WF of HMDA region is 1041 m^3/cap/year (2852 LPCD), in which 70% (1986 LPCD) of WF was consumed by food, 25% (744 LPCD) by electric power, only 4% (121 LPCD) is from direct water consumption and surprisingly the contribution from fossil fuel WF to total per capita WF of HMDA area is less than 1%.

1. Introduction

Virtual water (VW) concept was initiated in the 1990s (Allan, 1998) and took several decades to gain focus from researchers. Chapagain and Hoekstra (Chapagain & Hoekstra, 2004; Hoekstra & Hung, 2002) initiated the concept of WF by accounting the VW content and VW trade for 172 agriculture crops in 210 countries over the globe. They assessed WF and VW by considering national average climatic variables without considering the spatial variations. Later, Siebert and others (Siebert, Doell, Siebert, & Döll, 2010) accounted for green, blue VWF of crops globally, by considering the spatial variations in climatic conditions. Based on these data, Mekonnen and others accounted green, blue and grey WF of crops, crop-derived products, and farm animals, animal products, this is a global scale study (Mekonnen & Hoekstra, 2010, 2011; Mekonnen & Hoekstra, 2012). Also, there are several studies at the national, regional level, and river basin scales to address WF (Vanham and Bidoglio, 2014b), but there is no much research on WF at the city scale concerning socio-economic aspects of consumers. Fulton and Gleick (Fulton & Gleick, 2012) assessed the WF of California based on the top-down approach, while Feng and Klaus (Feng, Siu, Guan, & Hubacek, 2012) assessed the regional WF of yellow river basin using multi-regional input-output (MRIO) assessment.

In past studies of city level WF assessment, previous authors talked about WF of agricultural products imported into the cities, considering the cities from developed (Berlin from Germany), developing (Delhi from India) and underdeveloped countries (Lagos from Nigeria) (Vanham, 2013a; 2013b; Vanham, Gawlik, & Bidoglio, 2017; Zhao, He, & Zhang, 2015). Vanham and others (Vanham & Bidoglio, 2014a; Vanham et al., 2017) assessed the WF of Milan, Hong Kong and suggested diet to conserve embedded water in food efficiently and this study was done not only at the city scale but also at regional levels (Vanham, Comero, Gawlik, & Bidoglio, 2018; Vanham, Comero, Gawlik, & Bidoglio, 2018). Zhao (Zhao et al., 2015) addressed the WF of Leshan city (3326 m^3/cap/year) in China and concluded that this city

Abbreviations: WF, water footprint; VWF, virtual water footprint; VW, virtual water; LPCD, liters per capita per day; MGD, million gallons per day; MCM, million cubic meters; MPCE, monthly per capita expenditure; LPG, liquid petroleum gas; HMDA, Hyderabad Metro Development Authority; GHMC, Greater Hyderabad Municipal Corporation; HMWSSB, Hyderabad Metro Water Supply and Sewerage Board; RWSS, rural water supply and sewerage; NSSO, National Sample Survey Organization

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13. PHOTOGRAPH

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bearing Roll No **1300597**

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has appeared and PASSED at the SSC EXAMINATION held in MARCH 2006 in FIRST

Division with TELUGU as the medium of instruction.

DATE OF BIRTH	25/08/1991	DAY	MONTH	YEAR
		TWO FIVE	AUGUST	ONE NINE NINE ONE

THE CANDIDATE SECURED THE FOLLOWING PERCENTAGE OF MARKS

SUBJECT		Marks Secured (in figures)	Marks Secured (in words)
FIRST LANGUAGE	: (TELUGU)	75	SEVEN FIVE
THIRD LANGUAGE	: ENGLISH	72	SEVEN TWO
MATHEMATICS	:	84	EIGHT FOUR
GENERAL SCIENCE	:	75	SEVEN FIVE
SOCIAL STUDIES	:	79	SEVEN NINE
TOTAL	:	385	THREE EIGHT FIVE
SECOND LANGUAGE	: (HINDI)	66	SIX SIX
GRAND TOTAL	: 451	451	FOUR FIVE ONE

Life Skills Education : GRADE SECURED :

Marks of Identification :
1. A mole on the right foot thumb
2. A mole on the right hand

Head of Institution with School Stamp — A. Janaki 14.6.06 HEADMISTRESS Bala Bharathi Childrens' High School

Date of issue : 04-05-2006 VIJAYAWADA

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1. Life skills Education The Grade shall be incorporated by the respective Head of the Institution before delivery of the certificate to the candidates.
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Undertaking by the Fellow

I, **Dagani Koteswara Rao**, Son/~~Daughter~~/~~Wife~~ of Shri **Dagani Raghavendra Rao**, resident of **Ho. No. 35-9-4, GPN Colony, Md. Ismayeal street, Vijayawada-10, Andhra Pradesh** have been awarded SERB N-PDF . I accept the award and undertake that:

1. I shall abide by the rules and regulations of SERB during the entire tenure of the fellowship.
2. I shall also abide by the rules, discipline of the institution where I will be implementing my fellowship
3. I shall devote full time to research work during the tenure of the fellowship
4. I shall prepare the progress report at the end of each year and communicate the same to SERB through the mentor
5. I shall send two copies of the consolidated progress report at the end of the fellowship period.
6. I further state that I shall have no claim whatsoever for regular/permanent absorption on expiry of the fellowship.

D. K Rao

Date: 14 Aug 2023 **Signature**

V. V. Srinivas

PhD (IIT Madras), 2001

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Research Areas:
Stochastic hydrology; Regionalization of watersheds and hydrometric networks; Regional frequency analysis for prediction of extreme rainfall, floods, and droughts in ungauged/sparsely-gauged locations; Impact assessment of climate and land-use/land-cover changes on the hydrology of river basins; Forecasting flows in rivers; Dam break analysis, Urban hydrology and hydraulics.

Professional Experience

Period	Position	Name of the Institute
Aug. 2001 - Jul.2002	Post-doctoral Research Associate	Purdue University, USA
Jul. 2002 - Jun.2008	Assistant Professor	IISc Bangalore
May 2007 - Nov.2007	Visiting Scholar	Purdue University, USA
Jul. 2008 – Jun.2014	Associate Professor	IISc Bangalore
Jul. 2014 – Date	Professor	IISc Bangalore

Selected Publications:

Masanta, S. K. and Srinivas, V. V. (2022), Proposal and Evaluation of Nonstationary versions of SPEI and SDDI based on Climate Covariates for Regional Drought Analysis, Journal of Hydrology, 610, 127808.

Kiran, K. G., and Srinivas V. V. (2021), Fuzzy ensemble clustering approach to address regionalization uncertainties in flood frequency analysis. Water Resources Research, 57(3), e2020WR028412.

Kiran K. G. and Srinivas V. V. (2021), A Mahalanobis distance based automatic threshold selection method for Peaks Over Threshold (POT) model. Water Resources Research, 57(1), e2020WR027534.

Basu, B., and Srinivas, V. V. (2015), Analytical approach to quantile estimation in regional frequency analysis based on fuzzy framework. Journal of Hydrology, 524 (1-4), 30-43.

Basu, B., and Srinivas, V. V. (2013), Formulation of a mathematical approach to regional frequency analysis. Water Resources Research, 49(10), 6810-6833.

Significant Research Contributions: Developed novel approaches in conventional/fuzzy frameworks for risk analysis of extreme rainfall, floods, and droughts at data-sparse locations. In addition, approaches are contributed for downscaling Global Climate Model (GCM) simulations to local-scale hydrometeorological variables, simulating flows in river basins, and tracking low-pressure systems for risk mitigation.

Awards and recognition (Selective)

- INAE Young Engineer Award - 2006, Indian National Academy of Engineering, New Delhi.
- Distinguished Alumni Professional Achievement Award, NIT, Warangal, November 2016.
- Eminent Alumnus, Osmania University, Hyderabad, December 2017.
- Fellow of A.P. Akademi of Sciences (November 2017)
- Associate Editor of Journals: Stochastic Environmental Research and Risk Assessment (2022-date), Current Science (2018 –2022), and Earth System Science (2008-2014), Springer.
- Jacques W. Delleur Award - 2002, Purdue University, West Lafayette, USA.

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Regr(CiE)/SERB NPDF-59/2023 17th August 2023

Endorsement Certificate from the Mentor & Host Institute

This is to certify that:

I. The applicant, Dr. Dagani Koteswara Rao, will assume full responsibility for implementing the project.

II. The fellowship will start from the date on which the fellow joins University/Institute where he/she implements the fellowship. The mentor will send the joining report to the SERB. SERB will release the funds on receipt of the joining report.

III. The applicant, if selected as SERB-N PDF, will be governed by the rules and regulations of the University/ Institute and will be under administrative control of the University/ Institute for the duration of the Fellowship.

IV. The grant-in-aid by the Science & Engineering Research Board (SERB) will be used to meet the expenditure on the project and for the period for which the project has been sanctioned as indicated in the sanction letter/ order.

V. No administrative or other liability will be attached to the Science & Engineering Research Board (SERB) at the end of the Fellowship.

VI. The University/ Institute will provide basic infrastructure and other required facilities to the fellow for undertaking the research objectives.

VII. The University/ Institute will take into its books all assets received under this sanction and its disposal would be at the discretion of Science & Engineering Research Board (SERB).

VIII. University/ Institute assume to undertake the financial and other management responsibilities of the project.

IX. The University/ Institute shall settle the financial accounts to the SERB as per the prescribed guidelines within three months from the date of termination of the Fellowship.

Dated: 14-08-2023

Signature of the Mentor: V.V.

Name & Designation: Dr. V. V. Srinivas. Professor
Department of Civil Engineering
Indian Institute of Science, Bangalore

Capt Sridhar Warrier (Retd) (Aug 17, 2023 17:34 GMT+5.5)

Seal of the Institution

Signature of the Head of Institute

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Capt. Sridhar Warrier (Retd.)
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