Assessment of sustainable water use and water stress in India using census-based statistical data

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European Geosciences Union
General Assembly 2018
Vienna | Austria | 8-13 April 2018

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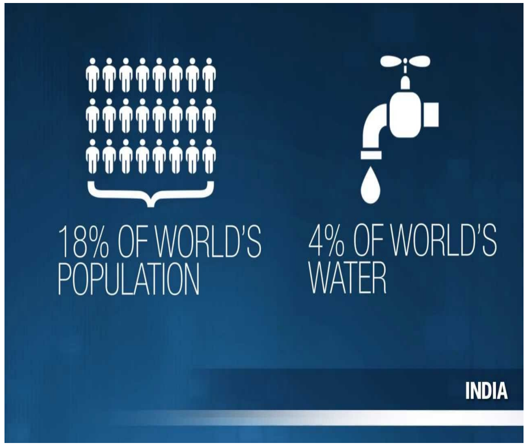
Motivation for research



Critical GW depletion in north-western parts of India
(Wada *et al.*, 2011)

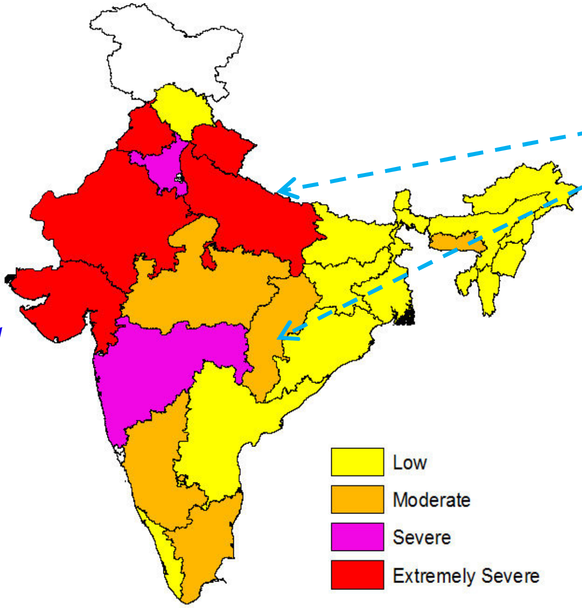


Figure 1. Annual average water stress in India

40% of population experiences moderate to extremely severe water stress

Year	Available water (m^3/year)
1950	5177
2010	**1588**

(CWC, 2010)

RESEARCH ARTICLE | SUSTAINABILITY

Four billion people facing severe water scarcity

Mesfin M. Mekonnen* and Arjen Y. Hoekstra
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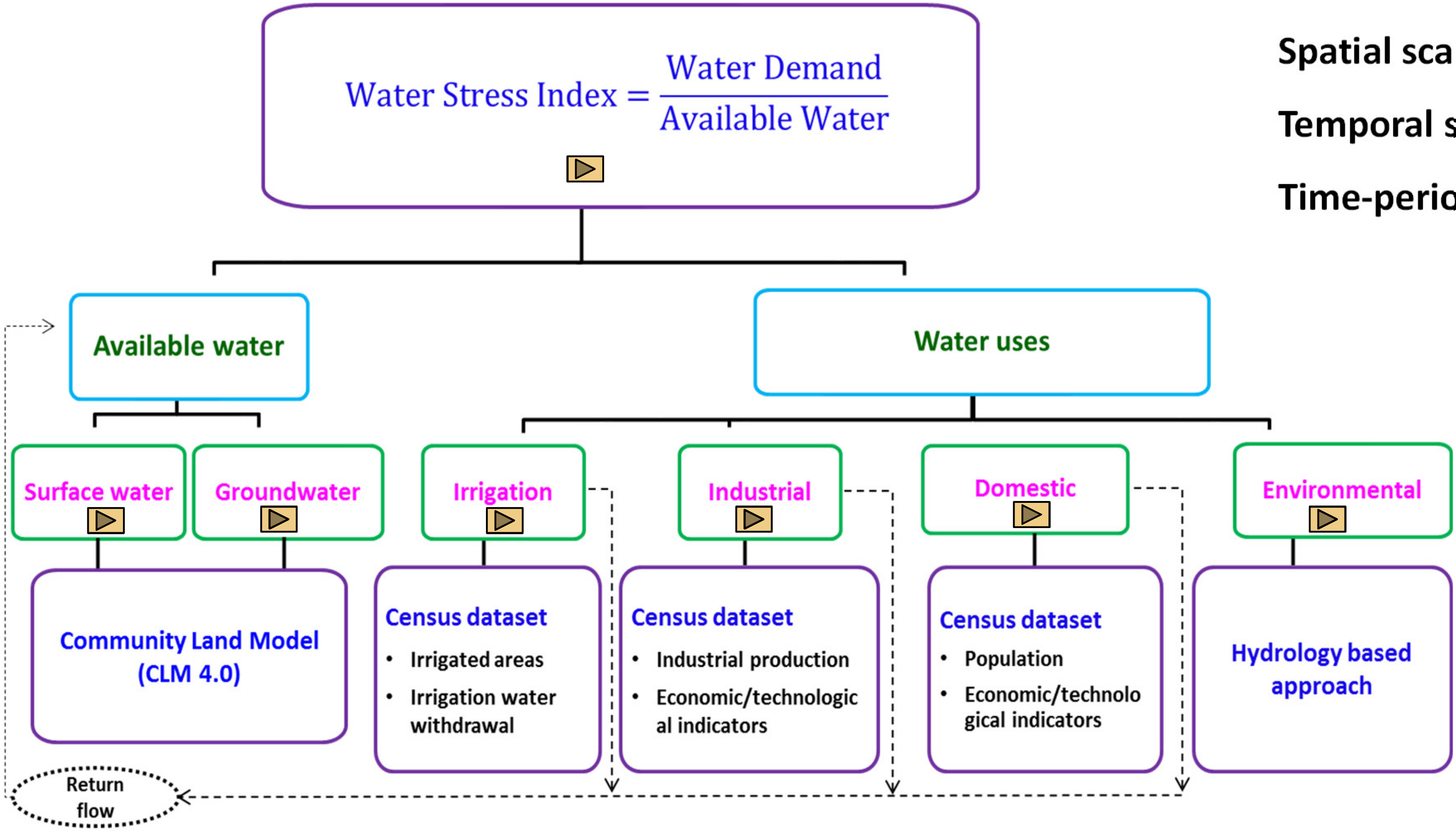
1 billion from India

Modelling framework



Spatial scale – State

Temporal scale – Monthly

Time-period – 1991 – 1999

Quantification of surface water

Model: **CLM 4.0** – Developed by National Centre for Atmospheric Research (NCAR) (*Oleson et al., 2010*)

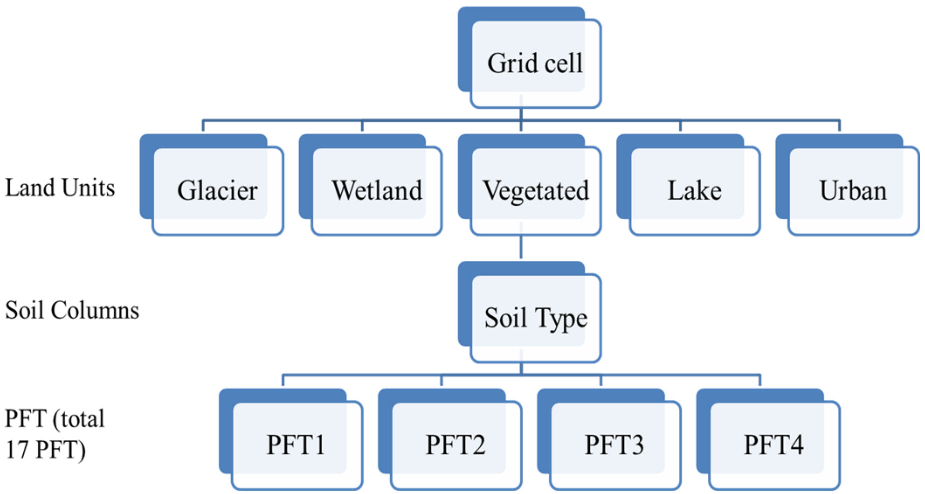


Figure 2. CLM sub grid hierarchy

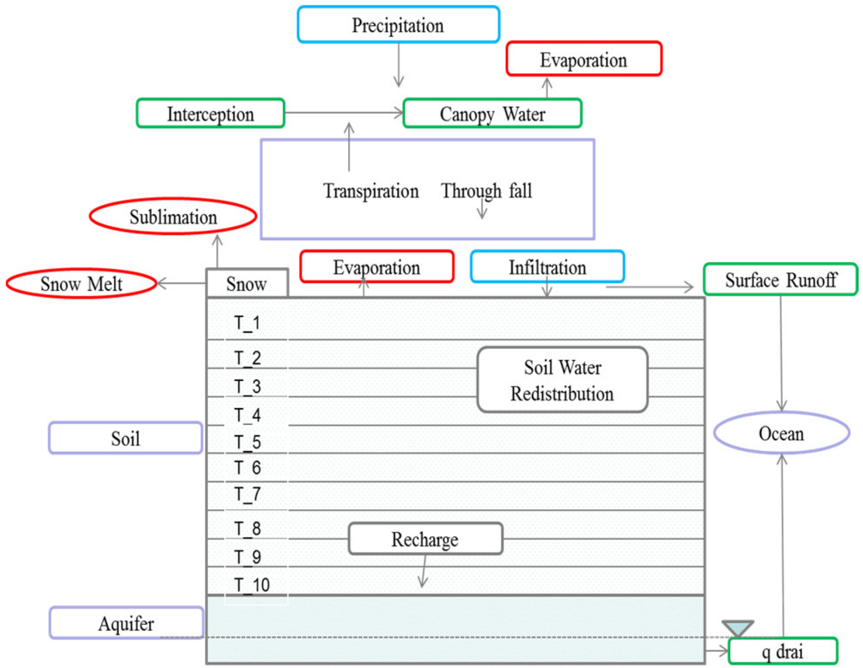
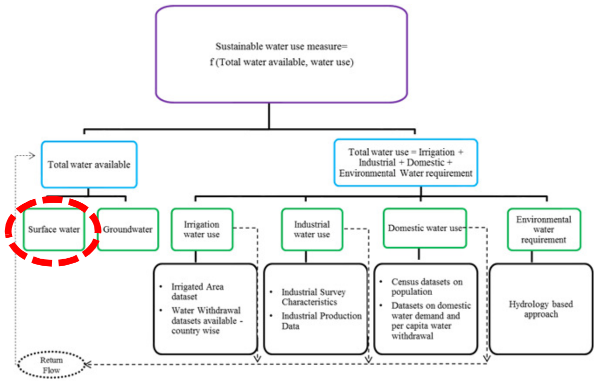


Figure 3. CLM Water Balance

__CLM__ – Community Land Surface Model, __PFT__ – Plant Functional Type, __qdrai__ – Sub-surface runoff

Discharge data collected



East flowing river

Godavari River

Gauge location - Polavaram

Data period:

1990 – 91 to 2000 – 01

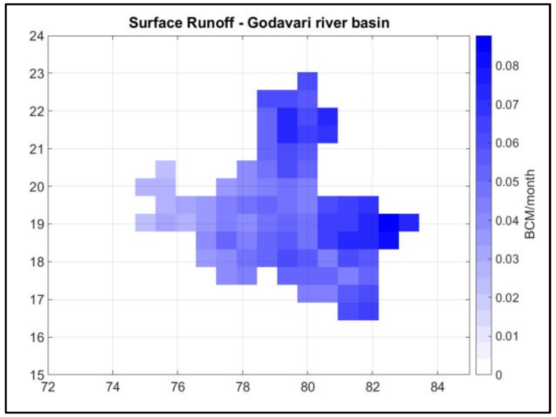
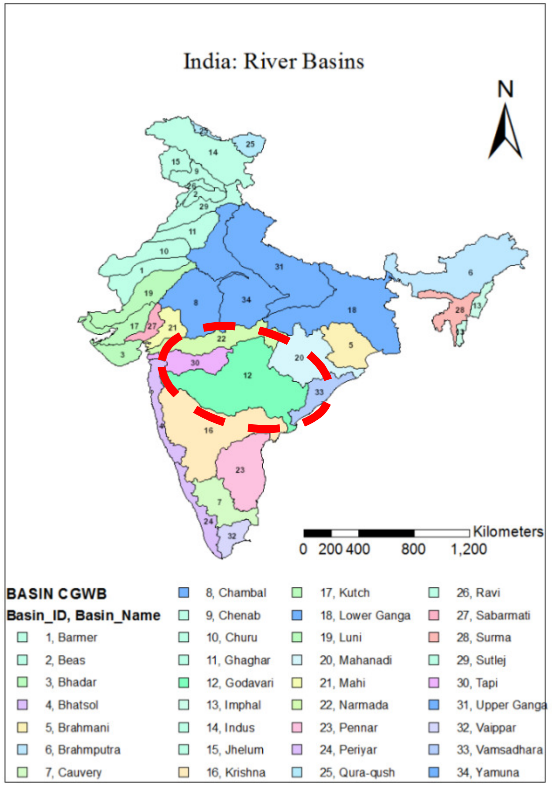


Figure 4. Average surface runoff



Annual Runoff – Godavari basin

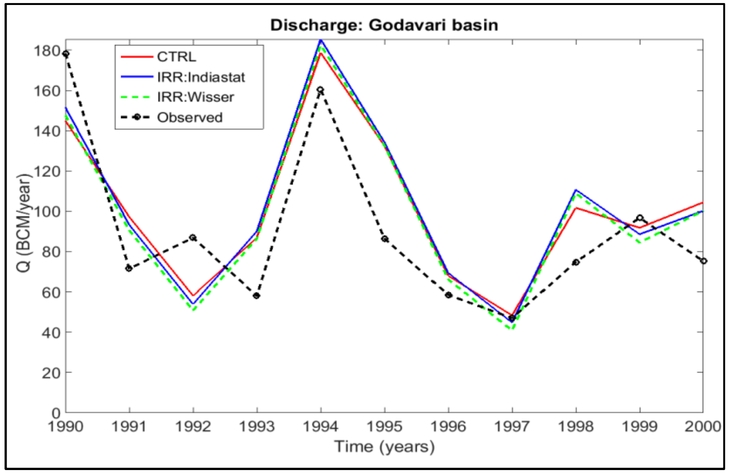


Figure 5. Modelled and observed runoff vs time

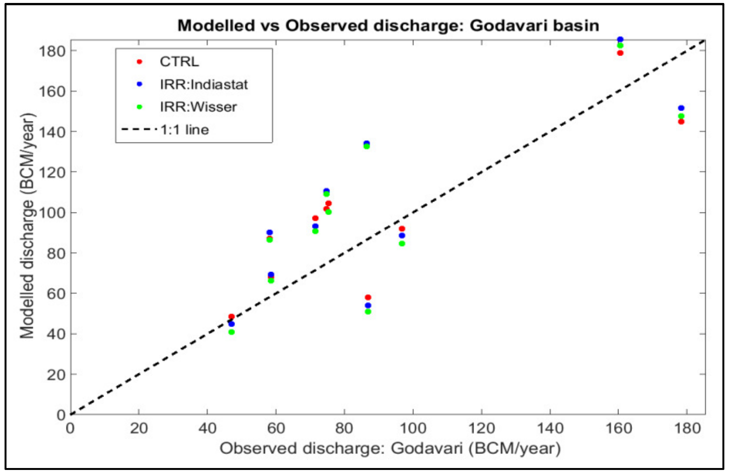


Figure 6. Modelled vs Observed runoff

Q	Control	IRR: Indiastat	IRR :Wisser
R-squared	0.81	0.81	0.80
RMSE	26.26	27.51	27.12
NSE	0.57	0.52	0.54

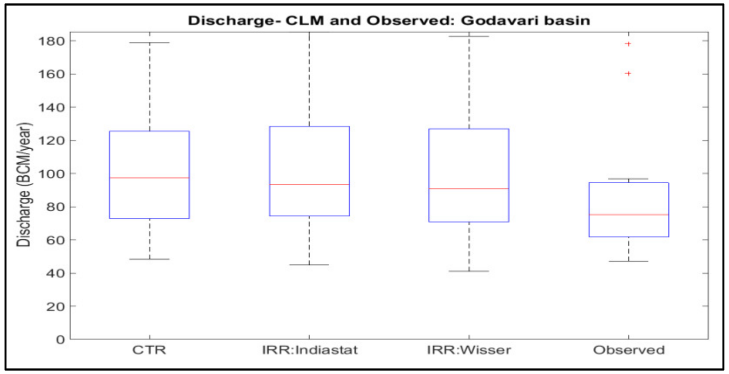
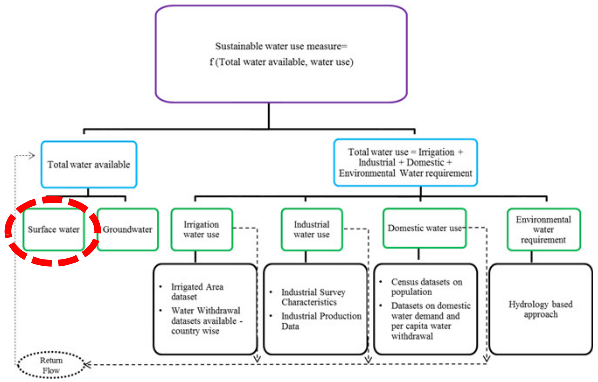


Figure 7. Monthly runoff box plot

Discharge data collected



West flowing river

Narmada River

Gauge location - Gurudeshwar

Data period:

1990 – 91 to 1996 – 97

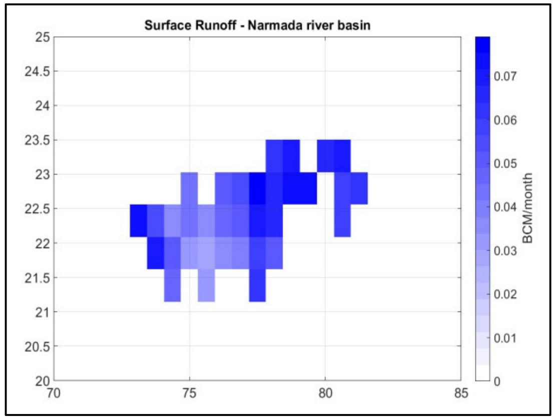
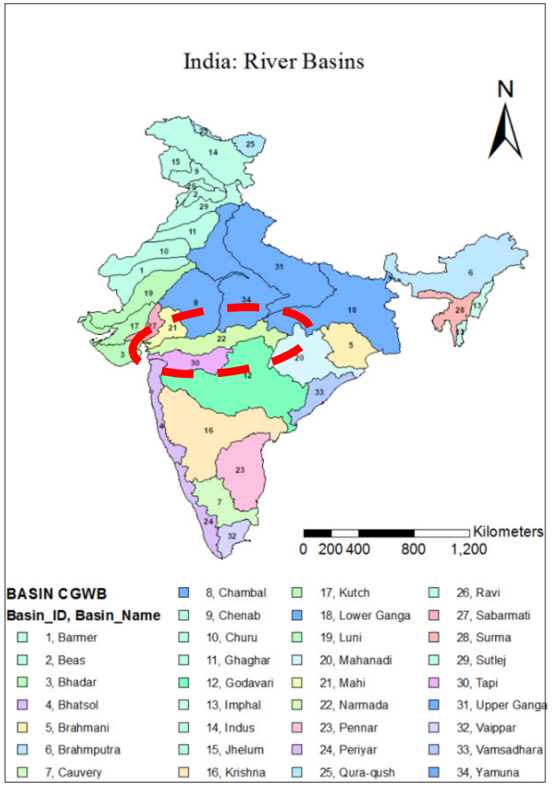


Figure 8. Average surface runoff



Annual Runoff – Narmada basin

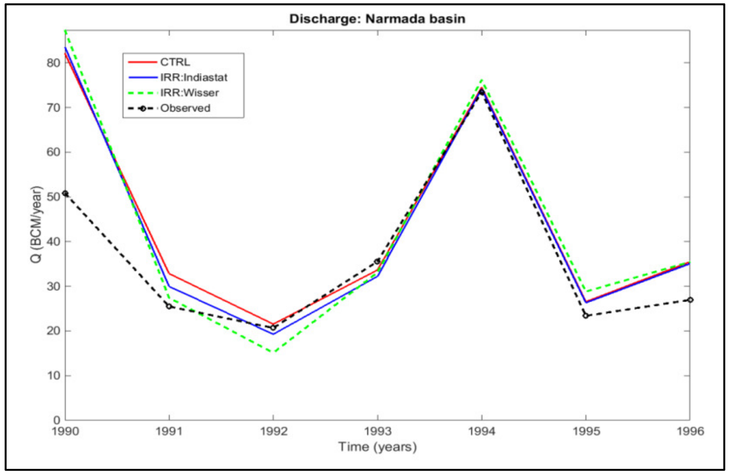


Figure 9. Modelled and observed runoff vs time

Q	Control	IRR: Indiastat	IRR :Wisser
R-squared	0.89	0.88	0.88
RMSE	12.65	12.98	14.54
NSE	0.49	0.47	0.33

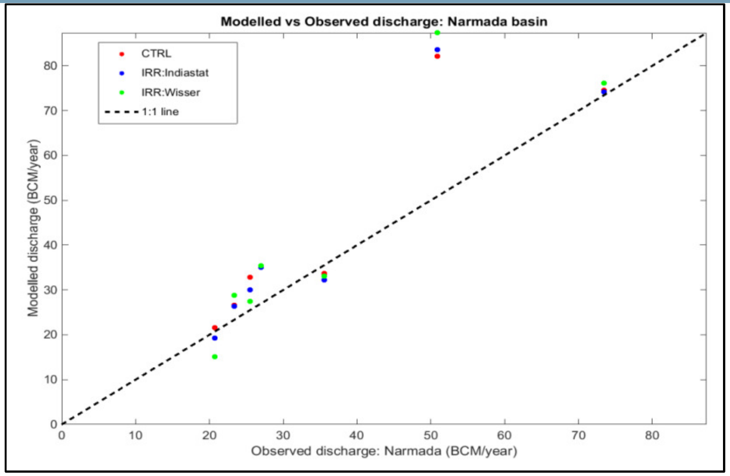


Figure 10. Modelled vs Observed runoff

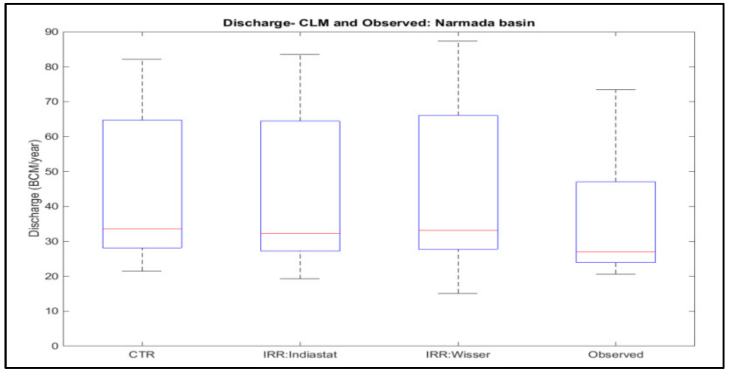


Figure 11. Monthly runoff box plot

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Irrigation water use

- Data: state-wise source-wise net irrigated area (NIA) – 2000 to 2011 (*Source: INDIASTAT*)
- For surface water,

$$R_{SW-i} = \frac{\frac{NIA_{SW-i-2000}}{NIA_{SW-India-2000}} + \cdots + \frac{NIA_{SW-i-2011}}{NIA_{SW-India-2011}}}{12}$$

$$V_{T-SW-NIA-base\ year} = V_{SW-i-base\ year} \times \frac{NIA_{T-i-base\ year}}{NIA_{SW-i-base\ year}}$$

Where R_{SW-i}: $Average\ fraction\ of\ surface\ water\ NIA\ in\ state\ i\ during\ year\ 2000\ to\ 2011$

$NIA_{SW-i-2000}$: $Surface\ water\ NIA\ of\ state\ i\ in\ 2000 (Thousand\ Hectares)$

$NIA_{SW-India-2000}$: $Surface\ water\ NIA\ of\ the\ entire\ India\ in\ year\ 2000\ (Thousand\ Hectares)$

$V_{T-SW-NIA-base\ year}$: $Irrigation\ Water\ volume\ estimated\ from\ NIA\ in\ base\ year\ (MCM)$

$V_{SW-i-base\ year}$: $Irrigation\ Water\ Volume\ from\ surface\ water\ in\ state\ i\ in\ base\ year\ (MCM)$

$NIA_{T-i-base\ year}$: $Total\ NIA\ in\ state\ i\ in\ base\ year\ (Thousand\ Hectares)$

$NIA_{SW-i-base\ year}$: $NIA\ of\ surface\ water\ in\ state\ i\ in\ base\ year\ (Thousand\ Hectares)$

Irrigation water use (Contd.)

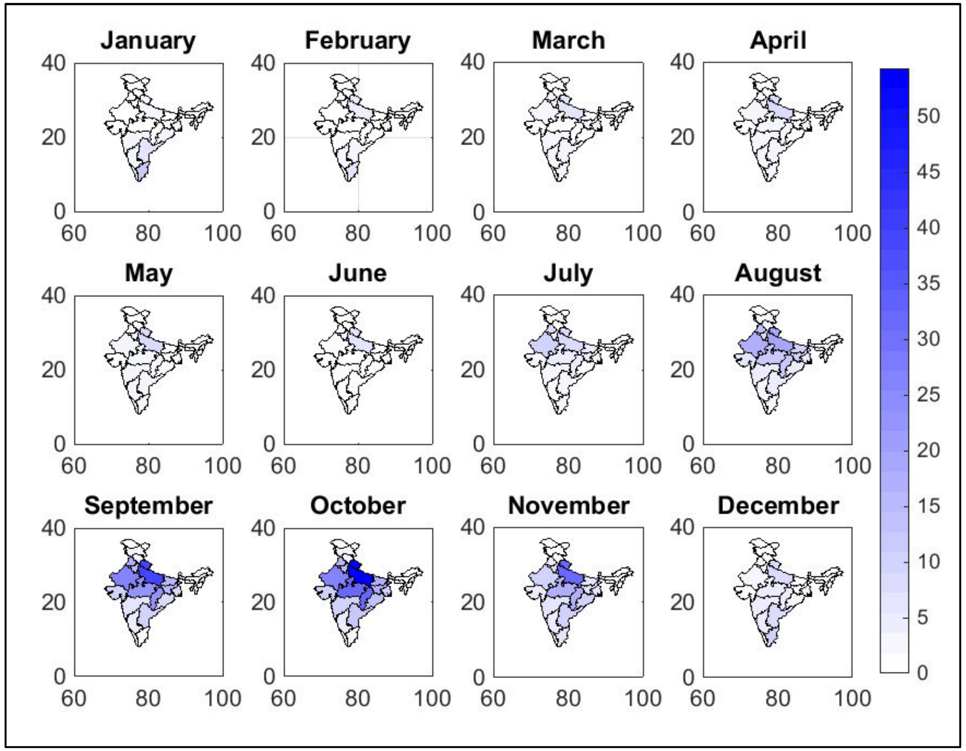


Figure 12. Average monthly irrigation water withdrawal – 1991 to 1999

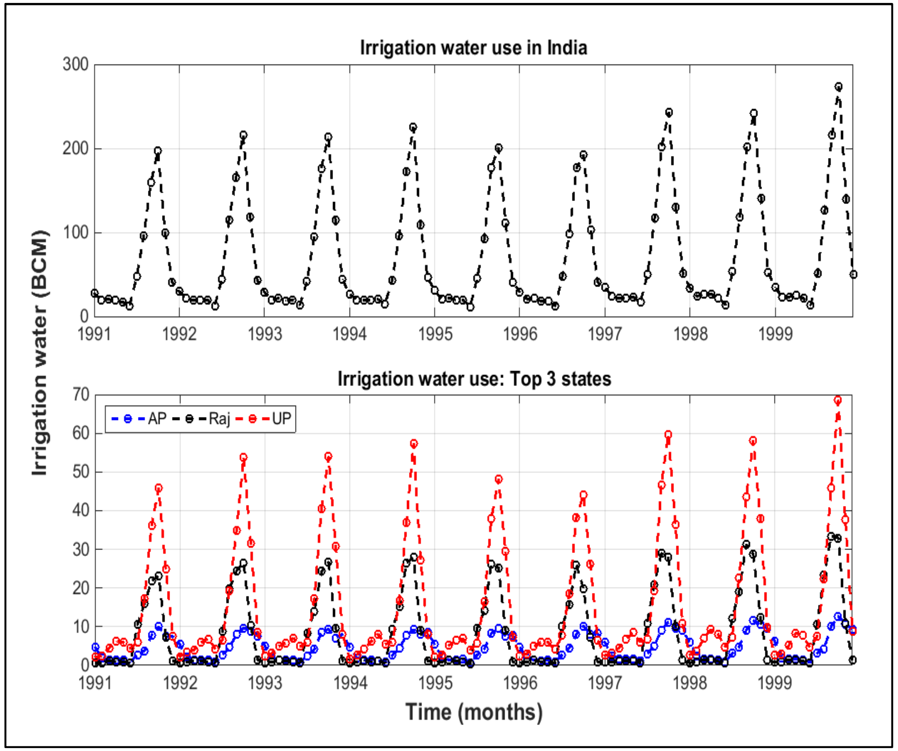
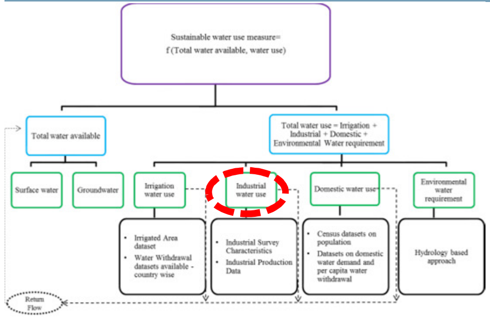


Figure 13. Monthly time-series of irrigation water – 1991 to 1999

Industrial water use



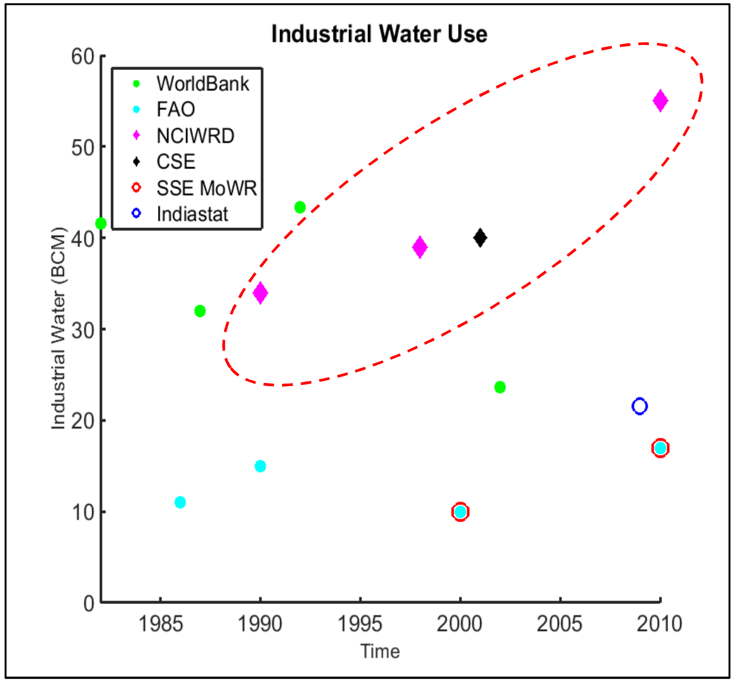


Figure 14. Industrial water use data comparison

- The present study uses census data-sets
  - Industrial production (52)
  - Industrial survey components (29)
  - Economic indicators (3)
- Cross correlated variables → Principal component analysis (PCA)

FAO – Food and Agriculture Organisation
NCIWRD – National Commission of Integrated Water Resources Development
CSE – Centre for Science and Environment
SSE MoWR – Standing Sub Committee of Ministry of Water Resources

Modelling and Correlation check

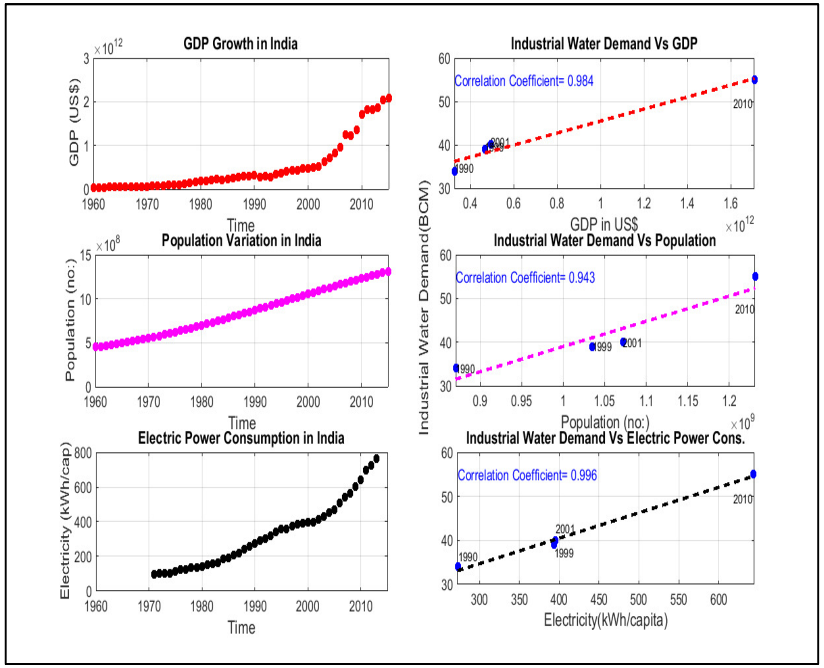


Figure 15. Correlation of Industrial Water Demand with Economic Development Indicators

Table 1. Cross Correlation Matrix

Correlation	GDP	Population	Electricity
GDP	1	0.86	0.91
Population	0.86	1	0.98
Electricity	0.91	0.98	1

- High correlation with the economic development indicators
- Additional variables – Industrial production and survey components
- Method to reduce the large no: of highly correlated variables – PC analysis

Principal Component Analysis

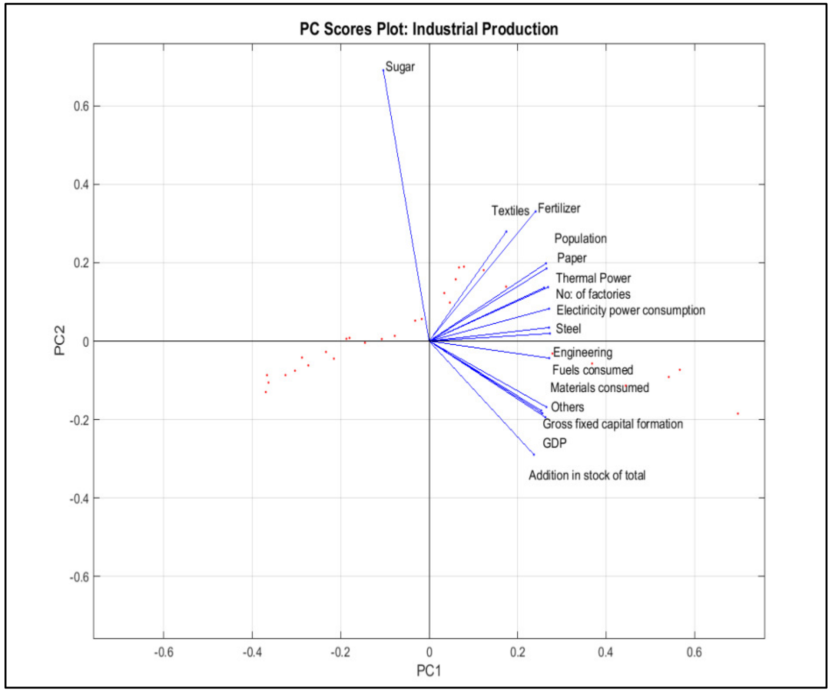


Figure 16. PC scores plot

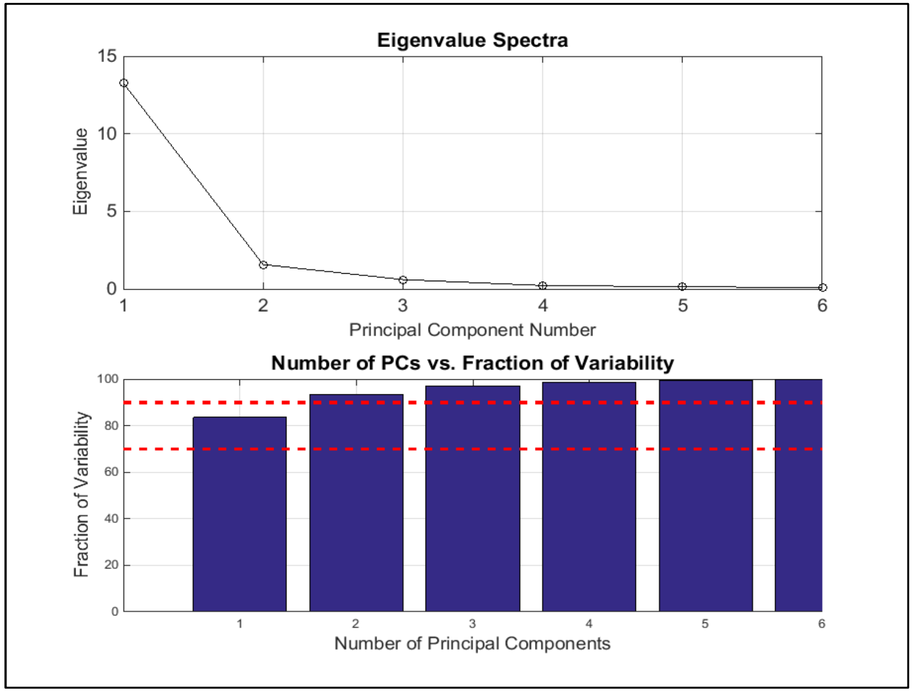


Figure 17. Eigen Value Spectra and Fraction of Variability

Industrial water use (contd.)

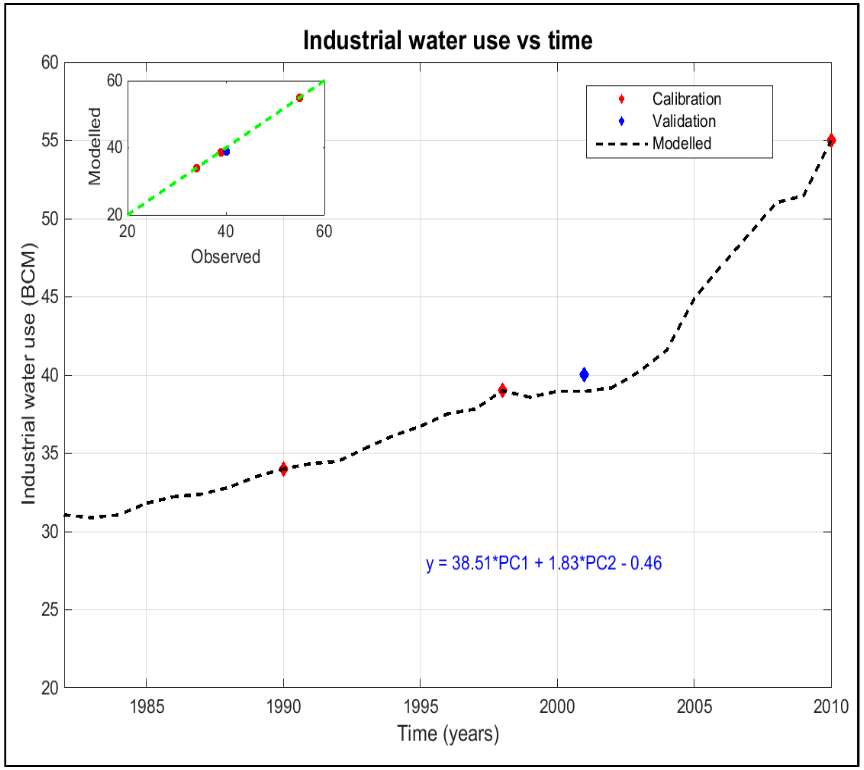


Figure 18. Modelled industrial water use

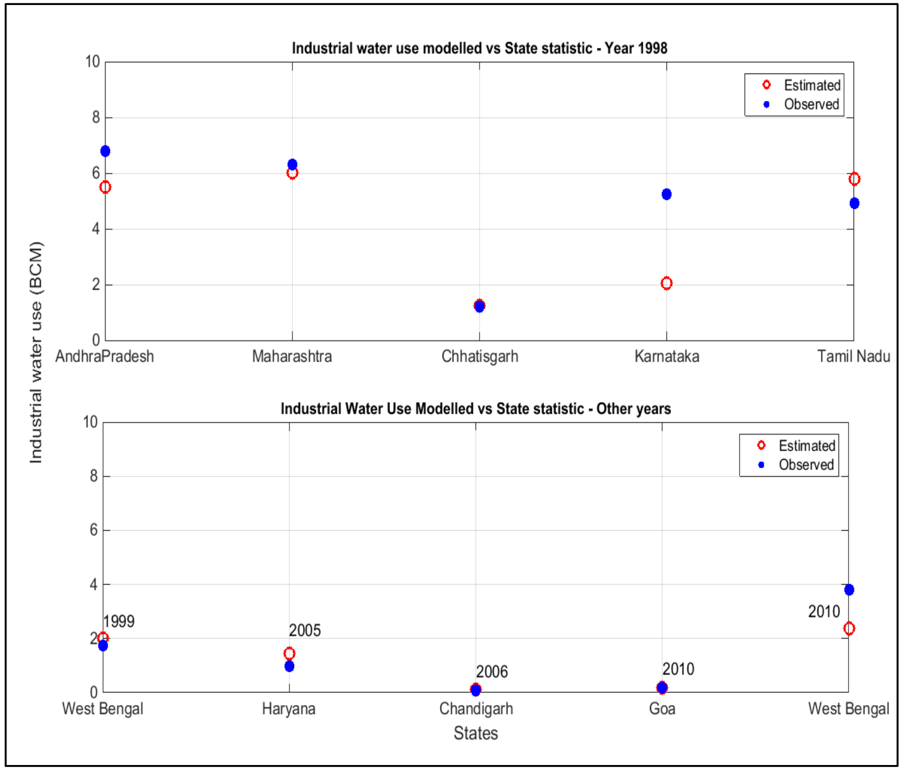
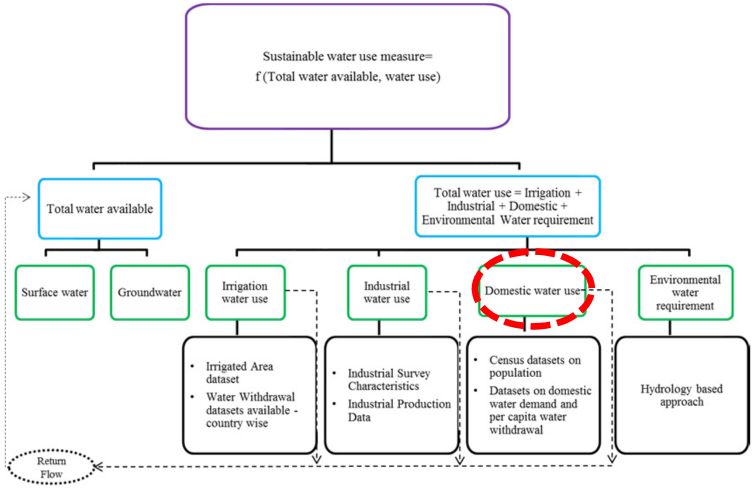


Figure 19. Model validation at state-level

Domestic water use modelling in India



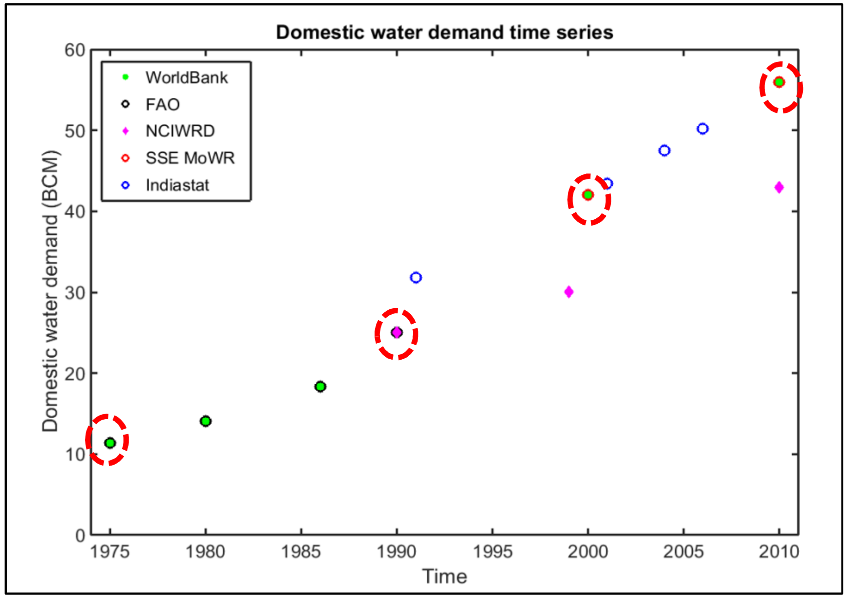


Figure 20. Comparison of domestic water use statistics

Additional datasets:

- GDP – 1960 to 2015
- Population – 1960 to 2015
- Electricity consumption – 1971 to 2013

FAO – Food and Agriculture Organisation
NCIWRD – National Commission on Integrated Water Resources Development, India
SSE MoWR – Standing Sub-committee of Ministry of Water Resources, India

Domestic water use modelling (Contd.)

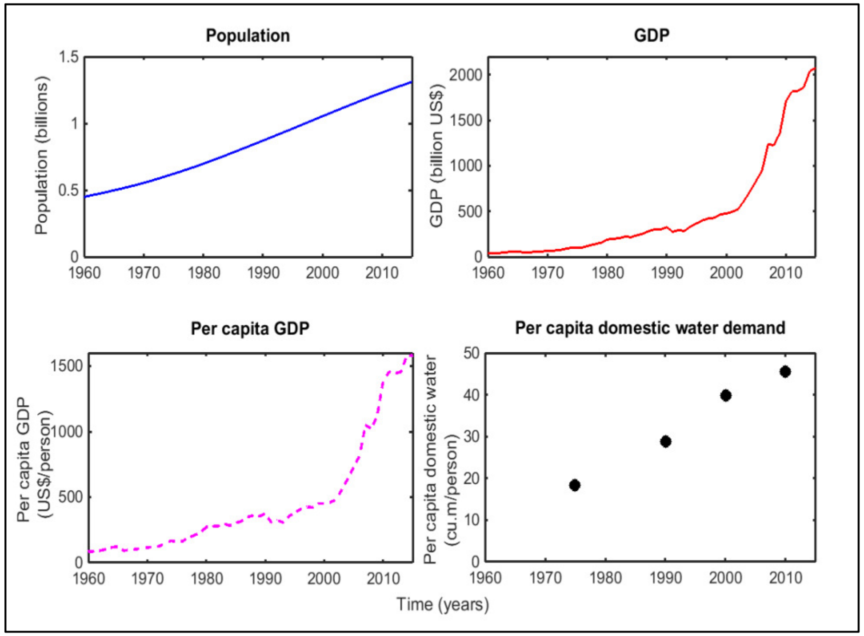


Figure 21. Time series of Population, GDP, Per-capita GDP and Per-capita domestic water demand

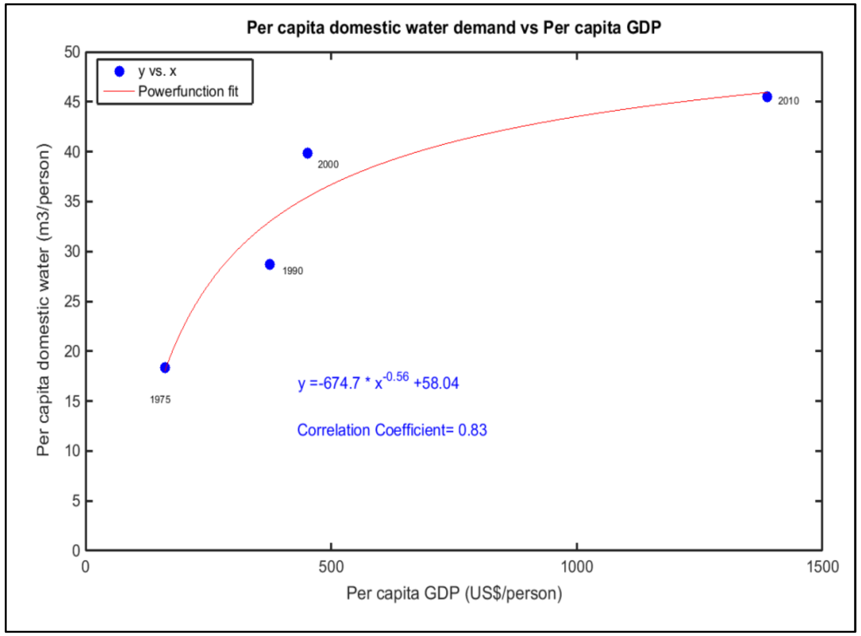


Figure 22. Per capita domestic water demand vs. per capita GDP

Model for per-capita domestic water demand with per-capita GDP

(Literature support: Oki and Kanae, (2006))

Domestic water use validation

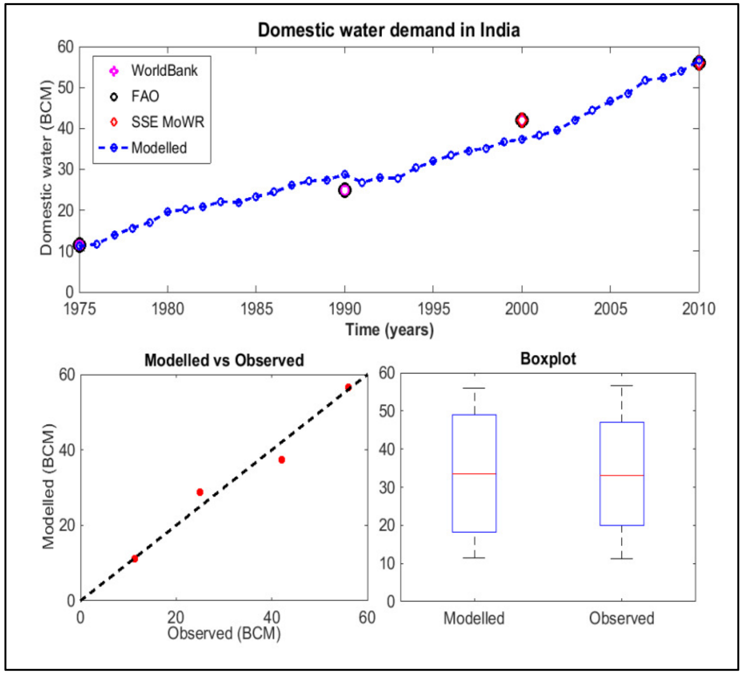


Figure 23. Time series of domestic water demand modelled and observed

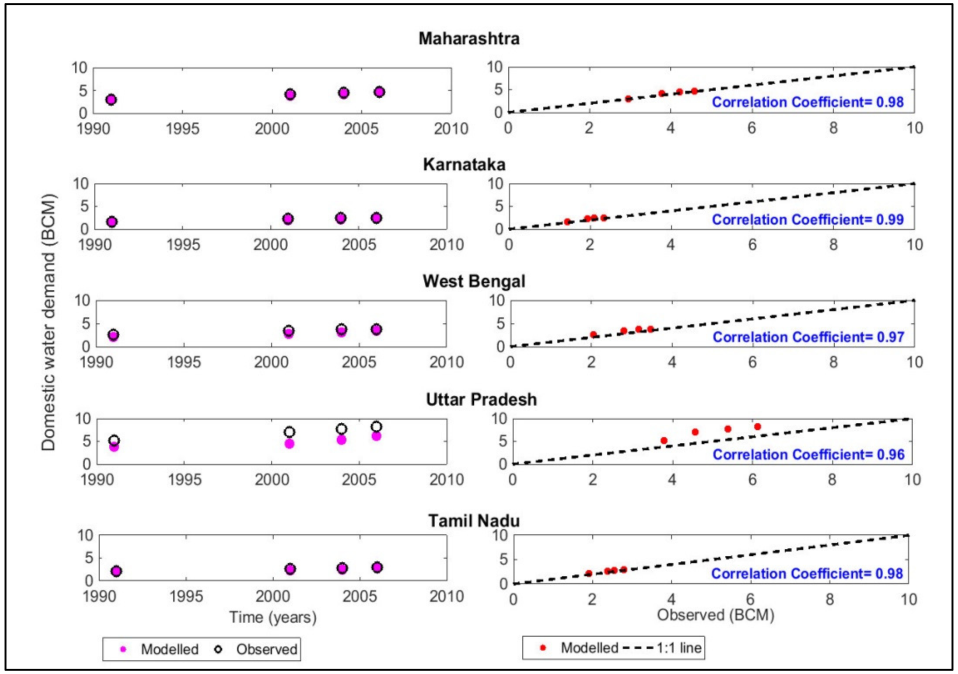


Figure 24. Domestic water demand modelled vs state-level statistic

Source: Indiastat

Environmental water demand

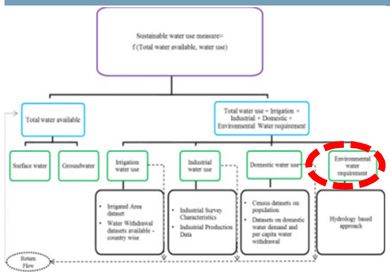


Table 2. Comparison of environmental flow calculation methods

Hydrological seasons	Low flow months	Low flow requirement	High flow months	High flow requirement
Tennant (1976)	MMF <= MAF	0.2*MAF	MMF>MAF	0.4* MAF
Tessmann (1980)	MMF <= 0.4*MAF	MMF	MMF>0.4*MAF & 0.4*MMF>0.4*MAF	0.4*MMF
Smakhtin et al. (2004)	MMF<=MAF	Q90	MMF > MAF	(0- 0.2)* MAF
Pastor et al. (2014)	MMF<=MAF	Q90	MMF > MAF	Q50

MMF - Mean Monthly Flow

MAF - Mean Annual Flow

Q50 - Flow exceeding 50% of period of record

Q90 - Flow exceeding 90% of period of record

Environmental water demand (contd.)

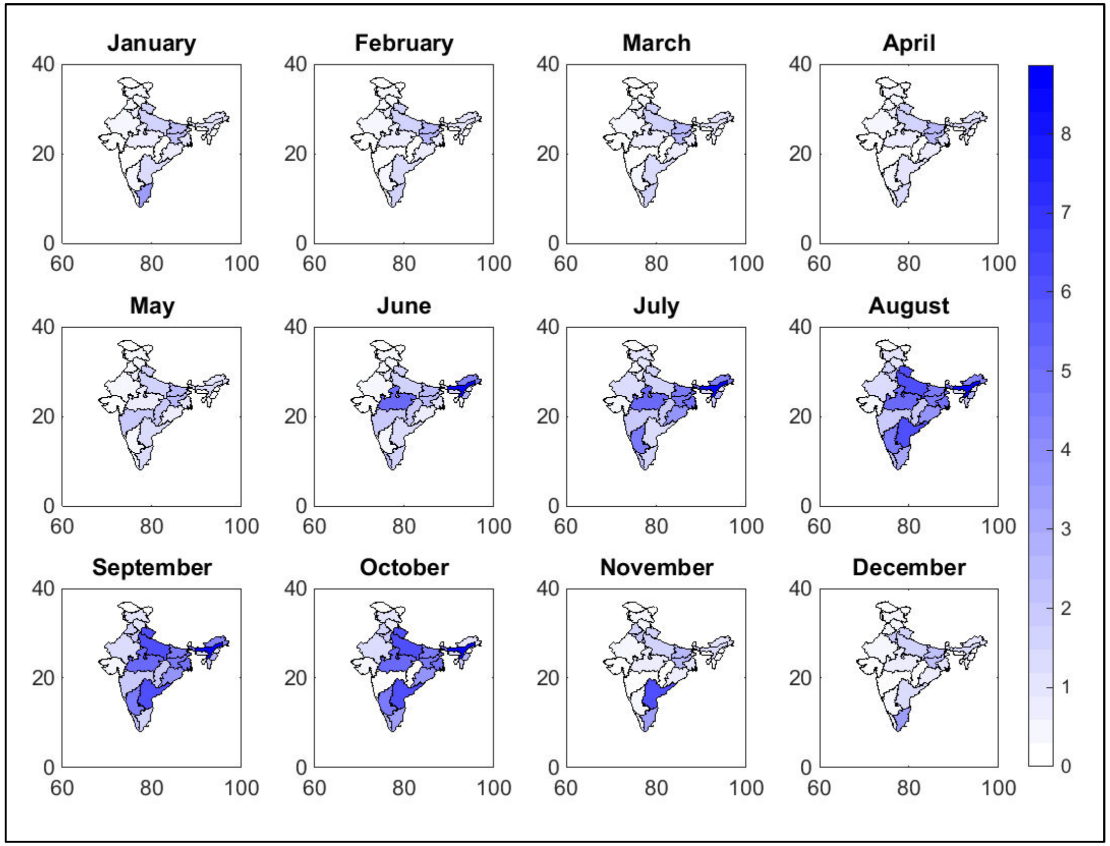


Figure 25. Average monthly environmental water demand (BCM) – 1991 to 1999

Classifying into low flow and high flow months

(Pastor et al., 2014)

Sustainability Measure - Components

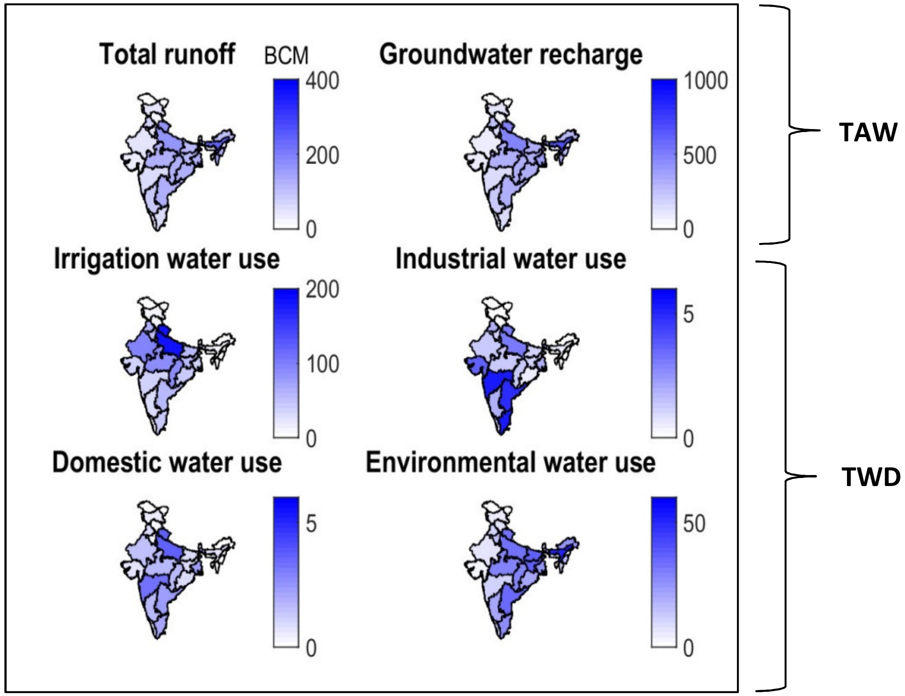


Figure 26. State-wise water use and available water components – annual average from 1991 to 1999

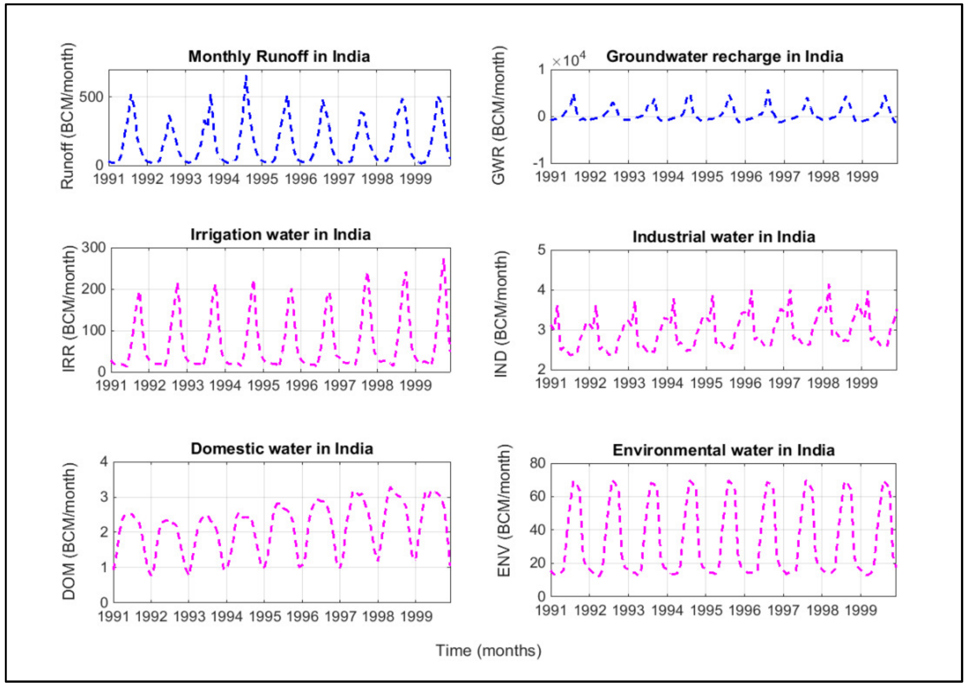


Figure 27. Water use and available water components – monthly from 1991 to 1999

TAW – Total available water; **TWD** – Total water demand

Water stress index

WSI (Water stress index): Ratio of water withdrawal to water available

- If WSI < 0.2 – Low water stress
- 0.2<=WSI<=0.4 – Moderate water stress
- WSI >0.4 – Severe water stress

(Wada et al., 2011)

- Excess water – carried over from month to month
- Validation of excess water – Reservoir live storage data

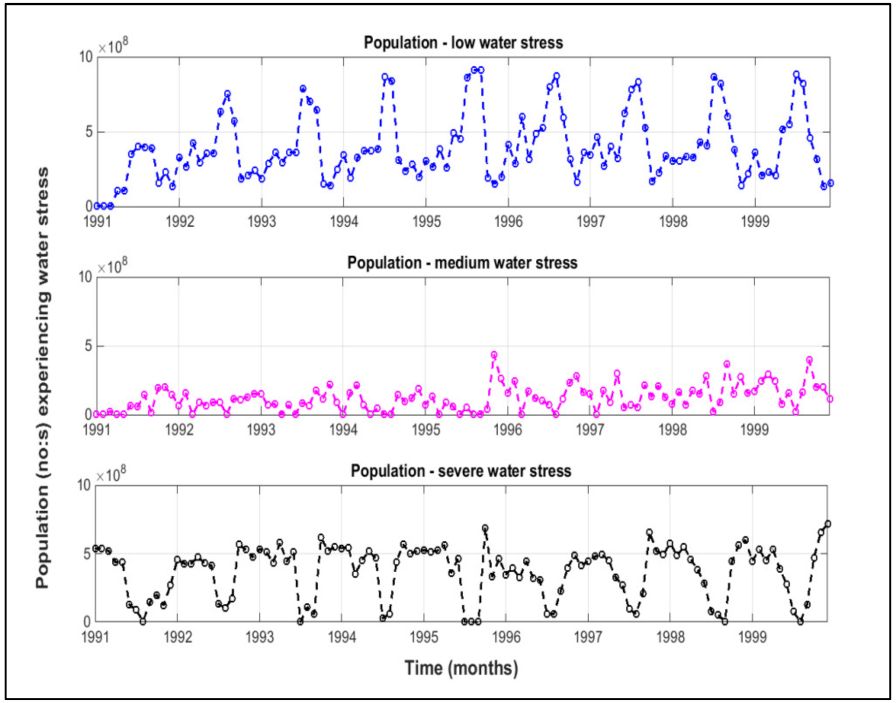


Figure 28. Population experiencing water scarcity in India – monthly from 1991 to 1999

Water stress index (contd.)

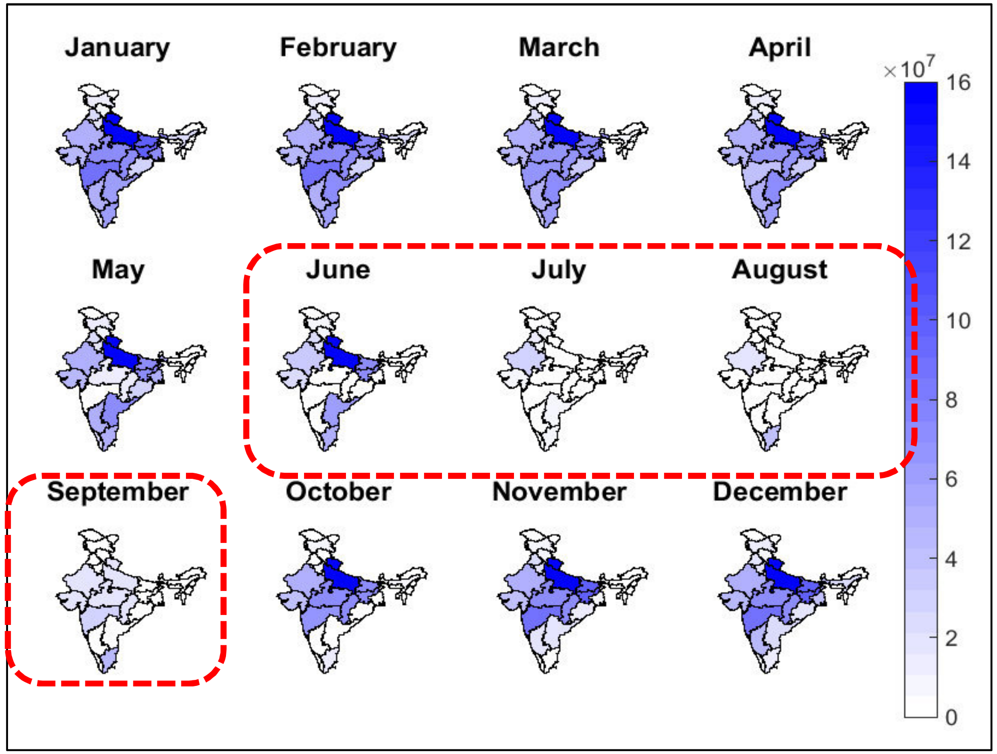


Figure 29. Population affecting severe water scarcity – Monthly average from 1991 to 1999 (*in number of people*)

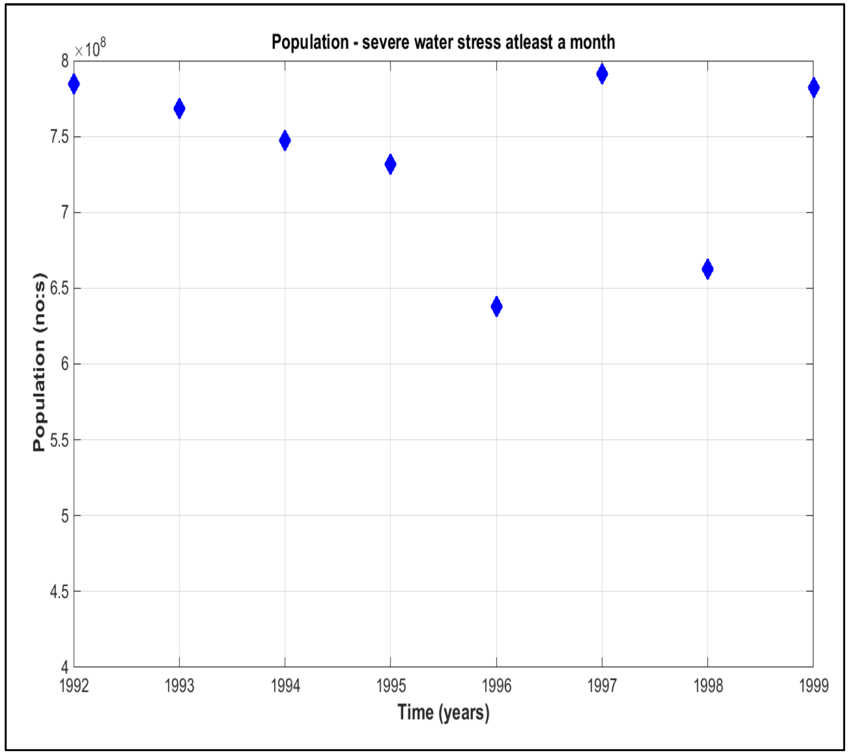


Figure 30. Population experiencing severe water scarcity: at least one month a year

Non-renewable groundwater abstraction

- Non-renewable groundwater abstraction = Groundwater recharge – Groundwater withdrawal
- Renewable groundwater availability – defined as the mean annual groundwater recharge

(Doll, 2009; Wada et al., 2010)

- Recharge – computed in CLM model as the vertical flux between the aquifer and the bottom soil
  - '+' recharge flows downward as gravity drainage and
  - '-' ve recharge flows upward by capillary fluxes

(Oleson et al., 2008, Lo et al.,2008)

- Simulated recharge flowing as gravity drainage – considered as maximum available groundwater
  - Negative modelled recharge – lack renewable supplies → no recharge available to replenish the system and level of stress is determined by magnitude of use alone

(Richey et al., 2015)

Non-renewable groundwater abstraction

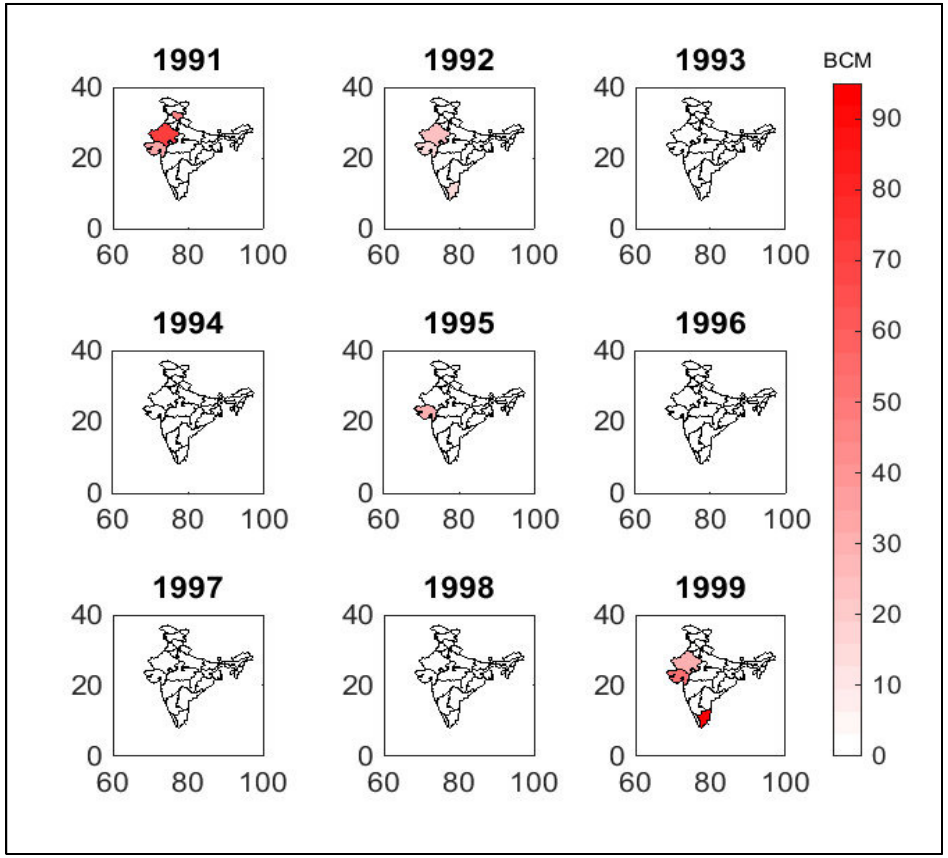


Figure 31. Non-renewable groundwater abstraction (BCM) from 1991 to 1999

Literature support

Severe depletion of groundwater in north-western India by GRACE satellites (for the years after 2000)

(Wada et al., 2014)

Conclusions

- Emerging modelling framework for estimation of sustainable water use measure
- Quantification of available water using land surface modelling approach
- Quantification of various water uses using census based database
  - Industrial water use estimation study – primary study in India
- Estimation of water stress in India at state-level and monthly time-scale
  - 40% of people face moderate to severe water scarcity every year
- Non-renewable groundwater abstraction estimate shows higher values of groundwater depletion in north-western India

Thank you

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