Journal of Hydrology: Regional Studies 30 (2020) 100706

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

# Seasonal and spatial variability in $\delta^{18}O$ and $\delta D$ values in waters of the Godavari River basin: Insights into hydrological processes

Frédérique M.S.A. Kirkels[a,*], Huub M. Zwart[a], Sayak Basu[b,1], Muhammed O. Usman[c,2], Francien Peterse[a]

[a] Department of Earth Sciences, Utrecht University, the Netherlands
[b] Department of Earth Sciences, Indian Institute of Science Education and Research, Kolkata, India
[c] Geological Institute, ETH Zürich, Switzerland

ARTICLE INFO

*Keywords:*
Water isotopes
Godavari River
Spatio-temporal patterns
Water provenance
River connectivity
Evaporation

ABSTRACT

*Study region:* The Godavari River is the largest non-Himalayan, monsoon-fed river in India, providing water resources for ~75 million people.

*Study focus:* Stable isotopes of Godavari River water in a pre-monsoon (dry) and monsoon (wet) season are used to evaluate seasonal and spatial dynamics and gain insights into hydrological processes, provenance and pathways of river water from source to sea.

*New hydrological insights:* Godavari River water isotopes shift from an evaporation- to precipitation-controlled signature between the pre-monsoon and monsoon season ($p \le 0.001$). Godavari waters plot below Global and Local Meteoric Water Lines ($p \le 0.01$), highlighting the importance of evaporation. In the monsoon season, low $\delta^{18}O$ and $\delta D$ values in the downstream catchment reflect an amount/convective effect caused by Southwest monsoonal rainfall. Continuously enriched signatures in the Upper Godavari suggest year-round evaporation due to a rainfall deficit and abundant dams creating stagnant waters. The Godavari ultimately discharges an integrated, monsoon signal into the Bay of Bengal. River depth profiles reveal that Godavari waters are well-mixed in both seasons. In the pre-monsoon season, Godavari water isotopes suggest basin-wide evaporation and seawater intrusion in the delta. A data compilation ($n = 399$) of $\delta^{18}O$ and $\delta D$ values in Indian Rivers reveals a strong seasonality for the Godavari River. The spatio-temporal patterns in Godavari River water isotopes confirm their suitability as sensitive recorders of monsoon precipitation variability and hydrological processes within monsoon-fed rivers.

## 1. Introduction

Rivers originating from monsoonal rainfall are a major source of freshwater in densely populated countries in South-Asia, like India. Currently, ⅔ of the Indian population relies on monsoonal precipitation and rivers for food production and their livelihood (Amrith, 2018; Biemans et al., 2013; Singh et al., 2014). Monsoon-fed rivers provide not only trade and transport but also water supplies for agriculture, industry and domestic use (Szabo et al., 2016; Varis et al., 2012). However, the future of river dynamics in Indian monsoon regions is highly uncertain, with more extreme precipitation and recurrent droughts resulting from climate change (e.g. Nair et al., 2018; Singh et al., 2014;

---

[*] Corresponding author.
*E-mail address:* f.m.s.a.kirkels@uu.nl (F.M.S.A. Kirkels).

[1] Current address: National Institute of Oceanography, Goa, India.

[2] Current address: Department of Physical & Environmental Sciences, University of Toronto Scarborough, Canada.

https://doi.org/10.1016/j.ejrh.2020.100706
Received 27 February 2020; Received in revised form 13 May 2020; Accepted 19 June 2020

Turner and Annamalai, 2012). For sustainable river basin management, it is crucial to understand the sources and pathways of river water, as well as tributary contributions to the final discharge, and thus gain insights into seasonal and spatial changes in monsoonal rivers.

The stable isotopic composition ($\delta^{18}$O and δD) of river water is a powerful integrator of hydrological processes in a river basin (e.g. Dutton et al., 2005; Gibson et al., 2002; Kendall and Coplen, 2001). In general, river water is assumed to reflect the isotopic variance of regional and large-scale continental precipitation, where the latter is predominantly a function of elevation, amount of rainfall, type, and distance of its source (e.g. Dansgaard, 1964; Gibson et al., 2002; Halder et al., 2015; Kendall and Coplen, 2001; Poage and Chamberlain, 2001). However, the isotopic composition of monsoon-fed rivers is unlikely to be static over space and time, as these rivers may receive input from multiple moisture sources such as contributions by the Southwest and Northeast monsoon systems in South-Asia, with the associated seasonal variability in hydrological conditions. Furthermore, secondary processes such as evaporation and recycling can also substantially modify river isotopic signatures (Dutton et al., 2005; Kendall and Coplen, 2001; Lambs et al., 2011; Ramesh and Sarin, 1992; Sharma et al., 2017). Evaporation increases $\delta^{18}$O and δD values and decreases deuterium-excess (d-excess) and thus can be used to gain insight into water loss downstream in semi-arid or arid environments or during dry periods in monsoon-influenced regions (Gibson et al., 2002). For instance, a downstream increase in $\delta^{18}$O and δD values in the middle stretch of the Ganges River (~800 to 1600 km from its source at Gomukh) was attributed to high evaporation of river water (Kumar et al., 2019; Ramesh and Sarin, 1992). In addition, artificial barriers, such as dams, are known to significantly alter river dynamics by regulation and fragmentation of the river flow in many basins worldwide (Nilsson et al., 2005). However, their effect on river water isotopic composition is often overlooked (Dutton et al., 2005). The presence of dams may lead to isotopic enrichment of stagnant river water due to increased evaporation and/or dams may buffer seasonal isotopic changes due to storage and mixing of (isotopically) different inputs into dammed reservoirs (Diamond and Jack, 2018; Li et al., 2016). Hence, river water isotopic patterns contain process-based information on the governing hydrology within a river basin. The contrasting flow regimes of monsoon-fed rivers provide a natural laboratory to investigate seasonal (wet and dry season) and spatial (longitudinal, lateral and vertical) variability in river water isotopic signatures.

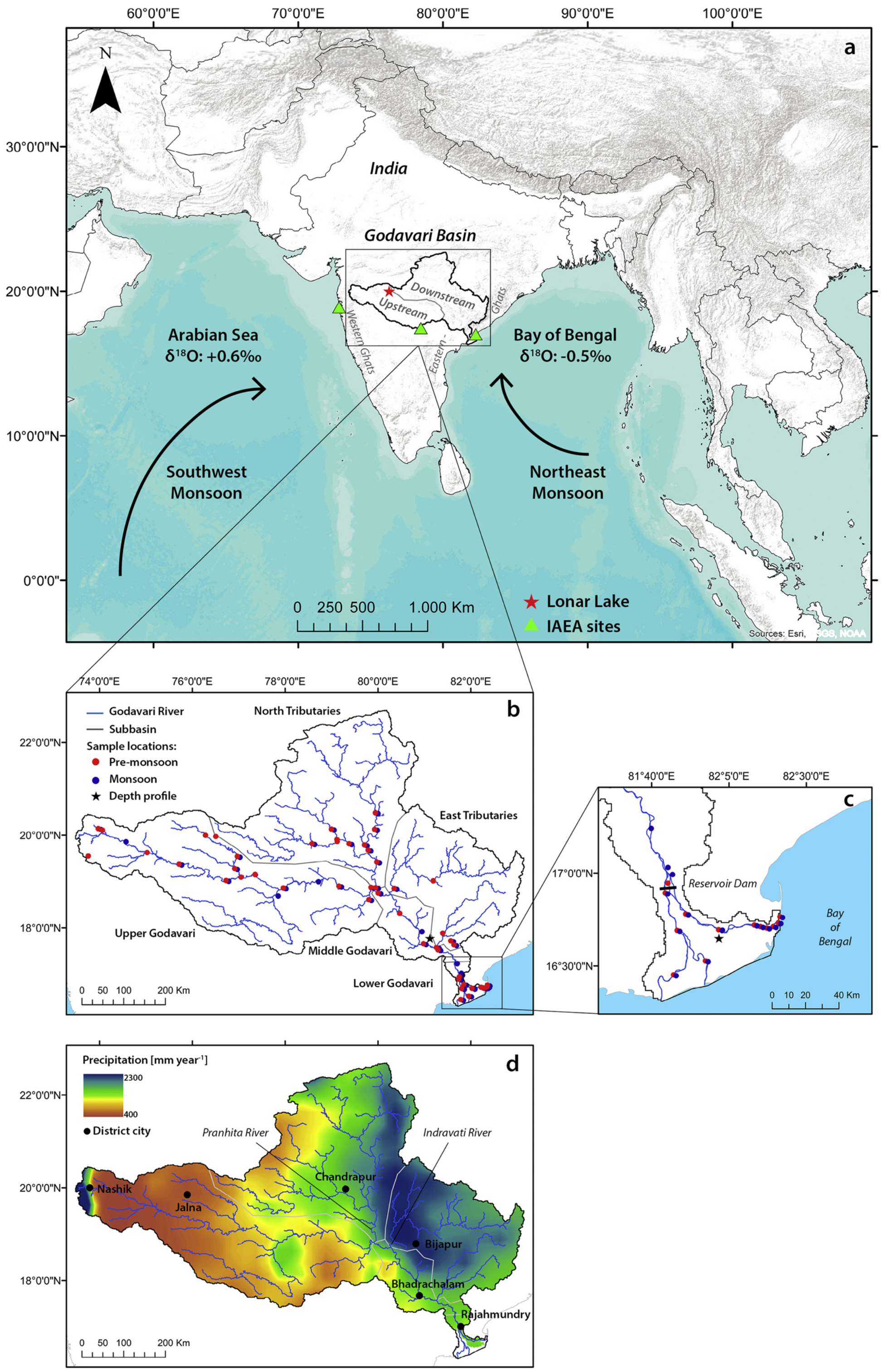
The Godavari River is the largest non-Himalayan river of India. Situated in the Core Monsoon Zone of India, it is fed by the Southwest and Northeast monsoon regimes. Global climate change has increased the variability in monsoonal rainfall with more extreme precipitation events on one hand (Deshpande et al., 2016; Goswami et al., 2006; Roxy et al., 2017; Turner and Annamalai, 2012) and prolonged periods with deficient rainfall on the other (Basu et al., 2020; Naidu et al., 2009; Nair et al., 2018; Rao et al., 2010; Singh et al., 2005). The Godavari River provides vital resources for the ~75 million (>100 million projected for 2050) people living in its basin (CWC, 2015a), challenging river management and food production in the basin and increasing the pressure on river water for irrigation, industrial and domestic use (Biemans et al., 2013; GDO, 2019). The Godavari River is furthermore strongly affected by damming, which directly influences ~28 to 37 % of its flow rate (Nilsson et al., 2005; Pradhan et al., 2014). So far, single point analysis of water isotopes at the Godavari mouth (Lambs et al., 2005) and in Lonar Lake, an isolated crater lake (Anoop et al., 2013), revealed a potential sensitivity in response to changing monsoon rainfall patterns. On geological time-scales, available records of past monsoon precipitation are based on shifts in the geochemical and isotopic composition of terrestrial materials stored in coastal marine sediments after mobilisation, transport and discharge by the Godavari River into the Bay of Bengal (e.g. Contreras-Rosales et al., 2014; Ponton et al., 2012; Usman et al., 2018). These records suggest a change in sediment provenance and aridification starting around 4500 years ago, likely caused by a shift in monsoon dynamics. However, in-depth knowledge on the variability of water isotopes in the Godavari River basin is limited. We hypothesise that water isotopes in the Godavari River vary (significantly) on a spatial and seasonal scale in response to variability in monsoon rainfall patterns and dominant hydrological processes. This information will lead to a better understanding of the hydrological dynamics in monsoon-fed river systems, and can contribute to future river management strategies (e.g. flood and drought mitigation) as well as sustainable use of the river as resource for irrigation and food production.

Here, we investigate river water isotopes ($\delta^{18}$O and δD) in the main stem, tributaries and depth profiles of the Godavari River in a pre-monsoon (dry) and monsoon (wet) season to reveal governing hydrological processes and trace pathways from source to sea. Fundamental steps are 1) to identify the river water provenance (i.e. monsoon rainfall source and tributary contributions) and 2) assess to what extent hydrological processes such as evaporation, water (re-)cycling and mixing alter the river water isotopic composition during transit through the basin. Our data will be placed in a regional perspective by comparison of Godavari River water isotopes with Global and Local Meteoric Water Lines as well as with water isotopes reported in the literature on Himalayan, Peninsular and Coastal Rivers in India. This high-resolution study on the Godavari River will provide insights into monsoon variability and basin hydrology in the Indian Core Monsoon Zone, and contribute to the global database on river water isotopes.

## 2. Materials and methods

### 2.1. Godavari River basin

The Godavari River is the second longest river in India, and flows ~1500 km from its source in the Western Ghats mountain range (700–2500 m above sea level, asl) eastward through the Core Monsoon Zone and drains into the Bay of Bengal (Fig. 1a–c). The Godavari River is monsoon-driven with large seasonal fluctuations in water levels between the monsoon season (June–Sept.) and dry period (Oct.–May), where the latter includes the post-monsoon (Oct.–Dec), winter and pre-monsoon season (Jan.–May) (IMD, 2015). The Godavari discharges 93–96 % of its total annual flow in the monsoon season (Biksham and Subramanian, 1988a, b; Gupta et al., 1997). Across the Godavari basin, precipitation increases from ~430 mm year$^{-1}$ in the semi-arid rain shadow of the Western Ghats to ~2300 mm year$^{-1}$ in the sub-humid lower basin (Gunnell, 1997) (Fig. 1d). The mean annual temperature is ~24 °C at the Godavari's source and increases eastward to a maximum of 29.4 °C at the mouth (Babar and Kaplay, 2018). Prominent crops range from aridity-adapted $C_4$ plants (e.g. sugar cane, sorghum, millet) in the upstream region to paddy-rice and rain-dependent crops downstream (Krishna et al., 2013; Pradhan et al., 2014), while the geology changes from weatherable Deccan Trap basalts (48 % of drainage area) to sedimentary



*(caption on next page)*

**Fig. 1.** Map showing (a) the location of the Godavari Basin in Peninsular India, divided into the upstream and downstream basin, with the Western Ghats and Eastern Ghats mountain ranges indicated. The solid black arrows represent the general direction of the Southwest (SW) and the Northeast (NE) monsoon, modern seawater $\delta^{18}O$ values of the Arabian Sea and Bay of Bengal are included (after Kumar et al., 2010) and sites for precipitation records (IAEA, 2019 – GNIP Database) at Kakinada, Hyderabad and Mumbai are indicated as well as the location of Lonar Lake, (b) Godavari River system and the subbasins, with locations of surface river water collection in the pre-monsoon (red) and monsoon (blue) season as well as the locations of river cross-sections and depth profiles (star), (c) Zoomed view on Godavari Delta, with the location of the Reservoir Dam at Rajahmundry marked, and (d) Precipitation map of the long-term annual rainfall distribution calculated with the APHRODITE data set (Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation of Water Resources, V1101 Monsoon Asia) using a 0.25° grid resolution and 30 years of daily data (Yatagai et al., 2012). The Pranhita River, a major tributary draining all North Tributaries and the Indravati River, a major tributary from the East Tributaries are indicated. For each subbasin, a major city is indicated, which is used as representative location for precipitation and back trajectory calculations, from source to sea: Upper Godavari: Nashik and Jalna, North Tributaries: Chandrapur, East Tributaries: Bijapur, Middle Godavari: Bhadrachalam, Lower Godavari: Rajahmundry.

rocks (11 %) and (erosion) resistant granites (39 %) (Biksham and Subramanian, 1988a, b).

The Godavari basin is here divided into 5 subbasins, including the Upper, Middle and Lower Godavari covering the main stem Godavari River, in addition to the North Tributaries (Weiganga, Wardha and Pranhita Rivers) and East Tributaries (Indravati, Sabari, Sileru, Pumuleru Rivers) (Fig. 1b). The latter drain the Eastern Ghats mountains (500–1700 m asl), that are covered by a dense tropical forest (Babar and Kaplay, 2018; Balakrishna and Probst, 2005). The North and East Tributaries cover 34.9 % and 24.8 % of the total drainage area, respectively (CWC, 2015b). The Lower Godavari comprises the Reservoir Lake with a dam at Rajahmundry and the tide-influenced delta with an ecologically renowned mangrove system (Bouillon et al., 2003; Dehairs et al., 2000). The Middle and Lower Godavari, North and East Tributaries are defined here as the downstream Godavari. The Upper subbasin represents the upstream Godavari (Fig. 1a).

The Godavari River is fed by two seasonally-separated monsoon sources, where the Southwest (SW) or Indian Summer monsoon (June–Sept.) brings the majority ( > 80 %) of rainfall (Balakrishna and Probst, 2005; Rao, 1998) by south-westerly winds sourced over the North Indian Ocean and Arabian Sea (Fig. 1a). The Northeast (NE) monsoon (Oct.–Dec.) picks up moisture by north-easterly winds over the Bay of Bengal and South China Sea supplemented by continental sources, and brings rainfall mostly in the form of erratic cyclones (Araguás-Araguás et al., 1998; Gadgil, 2003; Yihui and Chan, 2005). Each monsoon system has a source-specific isotopic signature owing to their different geographic origin. The seawater sourced from the Bay of Bengal is ~1‰ lower in $\delta^{18}O$ and ~8‰ in δD compared to that of the Arabian Sea due to the large inflow of isotopically depleted runoff from Himalayan (Indus and Ganges) Rivers (Delaygue et al., 2001; Kumar et al., 2010; Sarkar et al., 2015).

Anthropogenic changes through agriculture and dam building to enable irrigation, water storage and flow control have altered Godavari River dynamics (e.g. Biemans et al., 2013; Pradhan et al., 2014). Although already starting in the 19th century, dam building has intensified in the last decades and has reduced the Godavari's total discharge from 92.3 (1969–1979) to 29.7 $km^3$ $year^{-1}$ (1986–2010) (Acharyya et al., 2012; Biksham and Subramanian, 1988a, b). Currently, over 300 dams are in active operation and future plans for extensive inter-river water redistribution are estimated to further reduce the discharge by ~30 % (Best, 2019; Higgins et al., 2018; Pradhan et al., 2014).

### 2.2. River water sampling

River water was sampled from the Godavari main stem and its tributaries in the pre-monsoon (February/March, n = 52) and monsoon (July/August, n = 56) season in 2015 (Fig. 1b,c), traversing Central India from the mouth at the Bay of Bengal to the source. At each sampling location, surface water was collected by immersion of a 10 L bucket at mid-stream position from a bridge or boat or otherwise from the riverbank. In addition, river water was sampled at depth (2–3 depths per site) in the main stem's Lower (both seasons) and Middle Godavari (monsoon season), using a depth sampler (after Lupker et al., 2011). River water samples for $\delta^{18}O$ and δD measurements were filtered over 0.45 μm (cellulose acetate) and stored in tight-capped glass vials at ambient temperature until analysis. On-site measurement of physicochemical parameters, including temperature and electrical conductivity (EC) was done with a Hach multi-parameter instrument with conductivity probe.

### 2.3. Oxygen and hydrogen isotopic measurement of river water

$\delta^{18}O$ and δD values of river water were determined by laser spectroscopy using an 912 Off-Axis Integrated Cavity Output Spectrometry (OA-ICOS) liquid water analyser (Los Gatos Research, Mountain View, California, USA), at the Royal Dutch Institute for Sea Research (NIOZ), The Netherlands. Before analysis, samples were filtered through 0.45 μm polyethylene filters. Three certified standards (Los Gatos Research water isotope standard) were interspersed between every four samples. Out of 9 replicate sample injections, the first three were discarded and a mean of the last six runs was used. The measured $\delta^{18}O$ and δD values are reported against the Vienna Standard Mean Ocean Water (VSMOW)-Standard. Precision is ±0.1‰ for $\delta^{18}O$ and ±0.2‰ for δD, based on replicate analysis of Los Gatos Research certified standard no. 3 (LGR#3, n = 71). The deuterium excess (d-excess) is calculated according to Dansgaard (1964):

$$d - excess = \delta D - (8^{*}\delta^{18}O) \tag{1}$$

### 2.4. Back trajectory analysis

The origin of rainfall over the Godavari basin was evaluated with the air mass back trajectory model 'Hybrid Single Particle

Lagrangian Integrated Trajectory Model', developed by the National Oceanic and Atmospheric Administration (NOAA, 2019) (HYSPLIT, version 05092019) (Rolph et al., 2017; Stein et al., 2015). The model was run for six locations representing the Godavari subbasins (Fig. 1d) on their sampling dates. Calculations used air pressure, temperature, wind speed, vertical motion and solar radiation from the NOAA meteorological database (GDAS 0.5°). Back trajectories were modelled for five days (120 h) prior to sampling and originated at 500, 1000 and 2000 m above ground level (agl).

### *2.5. Statistical analysis and meteorological data*

Data processing (linear regression) and statistical analysis ((Welch's) ANOVA, t-test) were performed with software package R (RStudio, version 1.2.5033) and SPSS (IBM, version 25.0.0.1). The level of significance was evaluated at $p \leq 0.05$. Spatial distributions were analysed with ArcGIS 10.6.1 software (Geographic Information Systems, ESRI, USA). The Global Meteoric Water Line (GMWL) defined by Craig (1961) and later modified by Dansgaard (1964) is used as reference for precipitation, and Local Meteoric Waters Lines (LMWLs) are based on annual precipitation obtained from the GNIP (Global Network of Isotopes in Precipitation) database for Kakinada, Hyderabad and Mumbai (IAEA, 2019) (Fig. 1a). The average monthly precipitation $\delta^{18}O$ and δD values were calculated by the algorithm developed by Bowen and Revenaugh (2003) and Bowen et al. (2005) (OIPC, Online Isotopes in Precipitation Calculator, version 3.1; Bowen, 2017) for representative locations in each subbasin (Fig. 1d). An isotope mixing model for multiple sources (IsoError, version 1.04; Phillips and Gregg, 2001a, Phillips and Gregg, 2001bb) was employed to estimate tributary contributions to the downstream discharge. Salinity was estimated by multiplying EC by a factor $0.55*10^{-3}$ to get an approximate g $L^{-1}$ equivalent.

Rainfall statistics for 2015 were obtained from the Indian Meteorological Department (IMD, 2015). Rainfall over India was 9% deficient during 2015, and regional monthly data showed a bimodal distribution with peaks in June and August across the Godavari basin but a drop in July (Fig. 2). Compared to long-term precipitation data (1951–2000, mm $month^{-1}$), excess rainfall occurred in June 2015 (+84 to +206 %) in the downstream Godavari basin (i.e. Lower and Middle Godavari, North and East Tributaries), while reported rainfall was below-normal in the subsequent monsoon months. For the upstream Godavari, monsoonal rainfall was below the long-term average. Overall monsoonal rainfall in 2015: Upper Godavari (-27 % at Jalna) and (-20 % at Nashik), Middle Godavari (+3%), Lower Godavari (+17 %), North Tributaries (-9%) and the East Tributaries (+11 %) (IMD, 2015).

## 3. Results and discussion

### *3.1. Physicochemical parameters*

In the pre-monsoon season, EC is very high (>1000 μS $cm^{-1}$) in the delta reaching up to the Reservoir Dam at Rajahmundry in the Lower Godavari basin, typical of seawater intrusion (Fig. A1). In the monsoon season, such high values are only measured in the main outlet (Gautami branch) and progress less far inland (Fig. A2), suggesting a river-dominated outflow into the Bay of Bengal. Beyond the delta, EC is higher in the pre-monsoon (21.9–1013 μS $cm^{-1}$) than in the monsoon season (44.0–526.4 μS $cm^{-1}$), suggestive of increased evaporation in the former. Regional differences, with lowest EC in the East (<190.1 μS $cm^{-1}$) and part of the North Tributaries, can be explained by them draining the solute depleted Eastern Ghats. In the Upper Godavari River, mean EC is higher (pre-monsoon: 524.9 ± 283.5, monsoon: 389.8 ± 98.8 μS $cm^{-1}$, ±SD) than in other subbasins (besides the delta), which can be linked to the weatherable Deccan geology and suggests evaporative conditions in both seasons. In situ water temperatures range from 23.0 to 35.9 °C in the pre-monsoon and from 25.0 to 32.7 °C in the monsoon season.

### *3.2. Seasonal isotopic variability in the Godavari River basin*

Godavari surface water $\delta^{18}O$ and δD values range respectively from -3.9 to +3.8‰ and -25.9 to +15.4‰ in the pre-monsoon ($n = 49$) and from -7.7 to +4.3‰ and -57.0 to +20.7‰ in the monsoon season ($n = 47$), with significantly lower values in the monsoon season ($p \leq 0.001$) (Fig. 3a) (Supporting information: Kirkels et al., 2020). The $\delta^{18}O$ and δD values are closely correlated ($p \leq 0.001$) and linear regression translates into a correlation of $\delta D = \delta^{18}O * 4.74 (\pm 0.33) - 5.78 (\pm 0.59)$ ($R^2 = 0.82$) in the pre-monsoon and $\delta D = \delta^{18}O * 6.39 (\pm 0.22) - 2.10 (\pm 0.75)$ ($R^2 = 0.95$) in the monsoon season. The slopes of the Godavari River water lines plot significantly below the GMWL for global and LMWLs for local precipitation in both seasons ($p \leq 0.001$, except $p = 0.07$ for the monsoonal Godavari and the LMWL in Hyderabad) (Fig. 3b). The relative enrichment of Godavari River waters compared to precipitation, points towards evaporation across the Godavari basin. Notably, the regression slope in the monsoon season is significantly steeper than in the pre-monsoon season (6.39 vs. 4.74, $p \leq 0.001$) (Fig. 3b), suggesting that the magnitude of evaporation varies on a seasonal scale and is larger in the pre-monsoon season.

In the pre-monsoon season, the slope of the Godavari River water line (4.74 ± 0.33) is slightly higher than that of a fully evaporation-controlled (i.e. monsoon-fed and subsequently evaporated) open tank and pan in Hyderabad (4.19 ± 0.09; Négrel et al., 2011) (Figs. 1a, 3b), but resembles the slope of a typical evaporation line, which is theoretically close to 4 at very low relative humidity (<25 %) and between 4 and 5 at moderate relative humidity (<75 %) (Clark and Fritz, 1997). In addition, low average d-excess in the pre-monsoon Godavari waters (-4.9 ± 7.1‰) suggests direct river surface evaporation (Dutton et al., 2005). In Fig. 3c displaying $\delta^{18}O$ versus d-excess, monsoonal and pre-monsoonal Godavari waters plot between precipitation sampled across the basin (green) and an open tank sample (magenta) in Hyderabad (Négrel et al., 2011). The conceptual model based on these data (Fig. 3d) reveals an increasing influence of evaporation from the down- to the upstream Godavari basin in the monsoon season (Fig. 3c). Samples taken in the Upper Godavari plot towards the open tank (Négrel et al., 2011) in both seasons, pointing out that this subbasin experiences a dominant, year-round evaporative

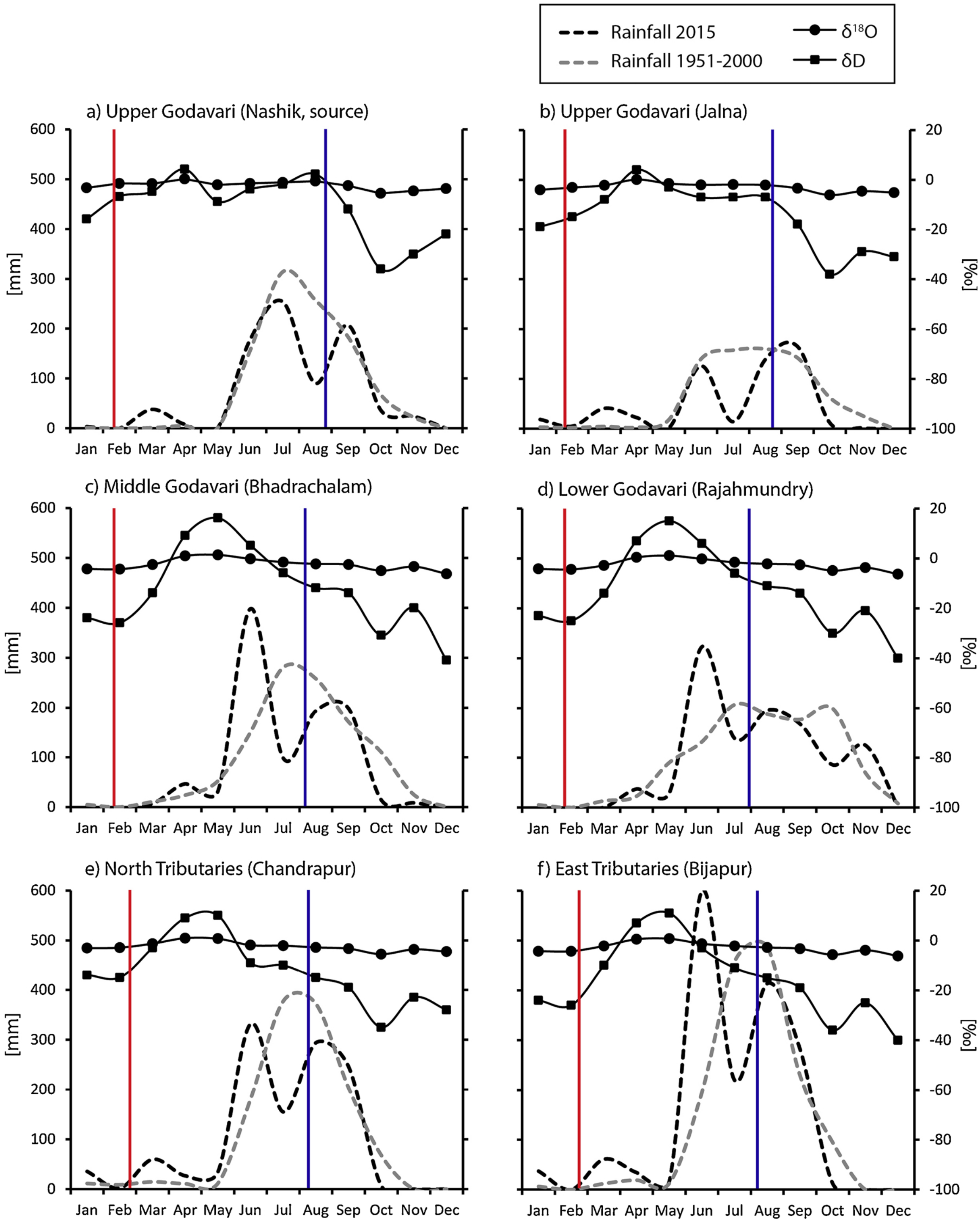


**Fig. 2.** Monthly rainfall amounts in 2015 and the long-term average for 1951-2000 (IMD, 2015) for the Godavari subbasins, labelled by their major city: (a) Upper Godavari (Nashik, source), (b) Upper Godavari (Jalna), (c) Middle Godavari (Bhadrachalam, Khamman district), (d) Lower Godavari (Rajahmundry, East Godavari district), (e) North Tributaries (Chandrapur) and (f) East Tributaries (Bijapur). The sampling date is indicated by a vertical line in the pre-monsoon (red) and monsoon (blue) season. Average monthly $\delta^{18}$O and δD values in precipitation are calculated by the algorithm developed by Bowen (2017) for the major cities listed.

effect on river water isotopes. Following this model (Fig. 3d), our data further suggest that the contribution of recycled water to the Godavari River is negligible in both seasons, as we do not observe the sharp increase in d-excess relative to $\delta^{18}$O that would occur upon condensation of once evaporated moisture into precipitation (Araguás-Araguás et al., 2000).

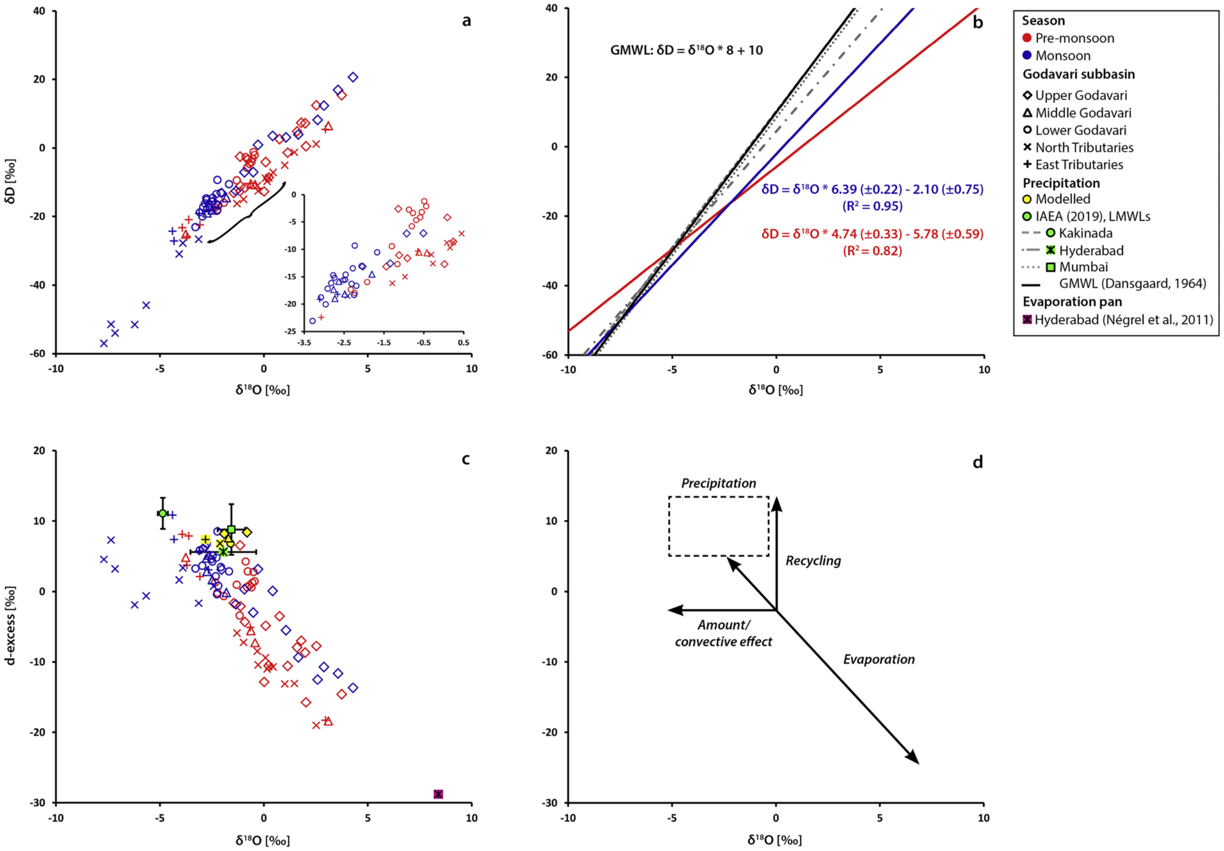


**Fig. 3.** a) Correlation between $\delta^{18}O$ and δD in Godavari river surface waters in the pre-monsoon and monsoon season, with the subbasins represented by different symbols. Inset: zoomed view. In (b) linear regression in the monsoon (blue line, n = 47) and in the pre-monsoon season (red line, n = 49). The Global Meteoric Water Line (GMWL) defined by Craig (1961) and modified by Dansgaard (1964) is given as reference for global precipitation (black line). Local Meteoric Water Lines (LMWLs) of precipitation are obtained at Kakinada, Hyderabad and Mumbai (IAEA, 2019 – GNIP Database), located at the mouth, south and west of the Godavari basin, respectively (see Fig. 1a). Linear correlations for Kakinada: $\delta D = \delta^{18}O * 7.86\ (\pm 0.29) + 10.29\ (\pm 1.61)$ ($R^2 = 0.97$, n = 23; dashed grey line), for Hyderabad: $\delta D = \delta^{18}O * 6.95\ (\pm 0.21) + 4.46\ (\pm 0.99)$ ($R^2 = 0.97$, n = 33; dashed/dotted grey line) and for Mumbai: $\delta D = \delta^{18}O * 7.94\ (\pm 0.29) + 8.4\ (\pm 0.75)$ ($R^2 = 0.94$, n = 48; dotted grey line). In (c) correlation between $\delta^{18}O$ and d-excess (see Eq.1) for Godavari River waters, in addition to precipitation data modelled in August for each subbasin (yellow) (Bowen, 2017) and at IAEA sites at Kakinada, Hyderabad and Mumbai (± SD, green), and data on an open tank near Hyderabad (magenta; Négrel et al., 2011). In (d) a conceptual model of hydrological processes based on $\delta^{18}O$–d-excess correlations. The intersection may be placed at any point along the precipitation-evaporation line, depending on the dominance of evaporation.

### *3.3. Moisture sources of river water in the Godavari basin*

In the downstream Godavari, we observe an average seasonal shift in isotopic composition of ~2.5‰ in $\delta^{18}O$ (min. 0.1 to max. 7.5), ~13.5‰ in δD (0.4–44.6) and ~7.0‰ in d-excess (0.3–27.3) from the pre-monsoon to the monsoon season (n = 35) (Fig. 4). Back trajectory analysis shows that this shift relates to a change in atmospheric circulation patterns, where moisture is dominantly sourced from the Indian Ocean/Arabian Sea in the monsoon season and from the continent and the Bay of Bengal in the pre-monsoon season (Fig. 5). These findings match with the dual monsoon regime of the Godavari basin, where the Southwest (SW) monsoon brings the majority (> 80 %) of basin-wide rainfall sourced from the Indian Ocean/Arabian Sea in the monsoon season (June–Sept., d-excess: ~8‰; Bhattacharya et al., 2003), and the Northeast (NE) monsoon brings heavy rains and erratic cyclones to the Peninsular Indian east coast by depressions formed in the Bay of Bengal (Oct. –Dec. i.e. prior to the pre-monsoon season, d-excess: ~13.5‰; Warrier et al., 2010).

In the pre-monsoon season, Godavari waters show a high spatial variability in $\delta^{18}O$ and δD values (range: 7.7 and 41.3‰, respectively) (Fig. 4a,b), coinciding with widely distributed origins in the back trajectories (Fig. 5a,c,e,g,i,k). The Upper Godavari and North Tributaries show mostly regional and subcontinental pathways (Fig. 5a,c,i), while for the other subbasins moisture originates from the Persian region or Arabian Peninsula with long traverses over continental areas (Fig. 5e,g,k). Pre-monsoon water isotopes in the Upper, Middle, and Lower Godavari and North Tributaries are enriched ($\delta^{18}O$:0.0 ± 1.5 and δD:-5.8 ± 8.5‰, n = 43) (Fig. 4a,b) compared to NE monsoon rainfall ($\delta^{18}O$: ~ -7 and δD: -45‰; Warrier et al., 2010). This likely results from deficient NE monsoon rainfall across the Godavari basin (average deficit: -46 %, range: -11 to -84 %; IMD, 2014) and evaporative enrichment of river waters in the year of sampling. These findings on the Godavari River contradict previous studies on South Peninsular Rivers and groundwater that report a significant contribution of the NE

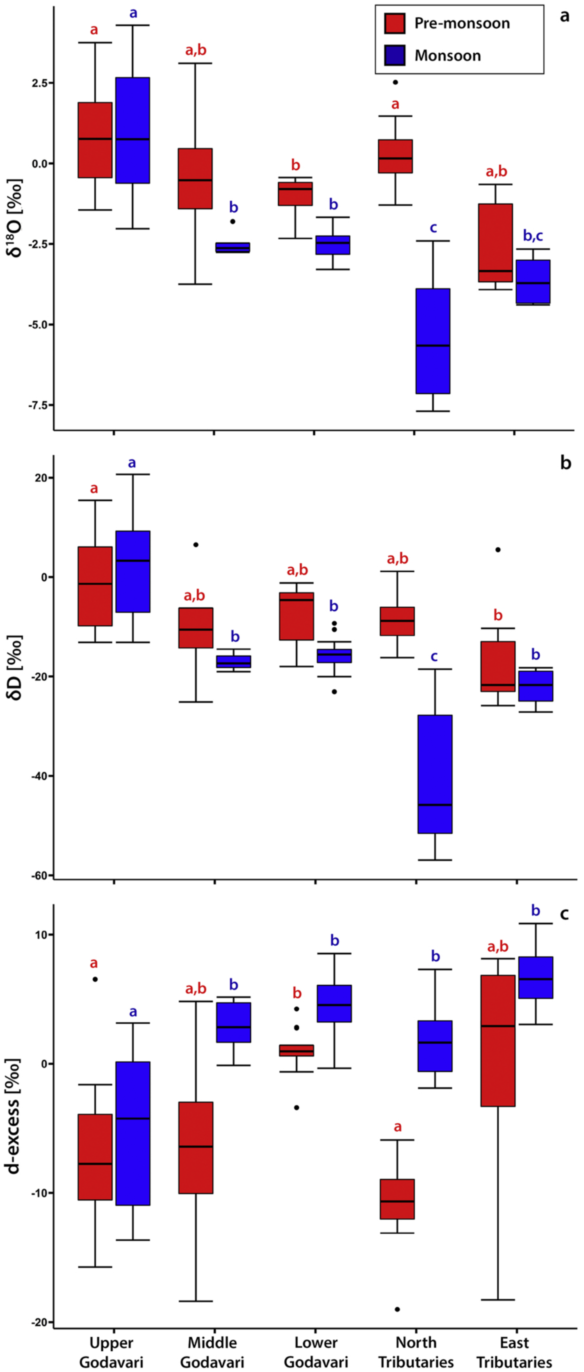


**Fig. 4.** Boxplots for $\delta^{18}O$ (a), δD (b) and d-excess (c) values in Godavari River surface water in the different subbasins in the pre-monsoon (red) and monsoon (blue) season. (Welch's) ANOVA was used to identify differences between subbasins, followed by a Tukey-B (equal variances) or Games-Howell (unequal variances) post-hoc test respectively for δD values in the pre-monsoon season and all other values in the pre-monsoon and monsoon season. Letters indicate statistically significant groups of data ($p \leq 0.05$) within a season. Black dots represent potential outliers.

monsoon in the early pre-monsoon season (Deshpande et al., 2003; Shivanna et al., 2004). Notably, a part of the East Tributaries waters (i.e. Sabari, Sileru and Pumuleru Rivers) shows exceptionally low $\delta^{18}O$ and δD values (~-3.5 and -23‰, respectively, n = 4) and high d-excess (max. ~8‰) in the pre-monsoon season (Figs. 4, A3, A5). Rahul et al. (2016) reported that tropical cyclones formed in the Bay of Bengal as part of the NE monsoon regime bring anomalously depleted precipitation (~-23‰ in $\delta^{18}O$) to the Indian east coast and can leave a temporary imprint ('spike effect') on surface waters (Lambs et al., 2018; Rahul et al., 2016). This suggests that the severe cyclone 'Hudhud' in October 2014 (prior to sampling) may have contributed to the observed anomalies in the East Tributary waters as this cyclone brought intense rainfall

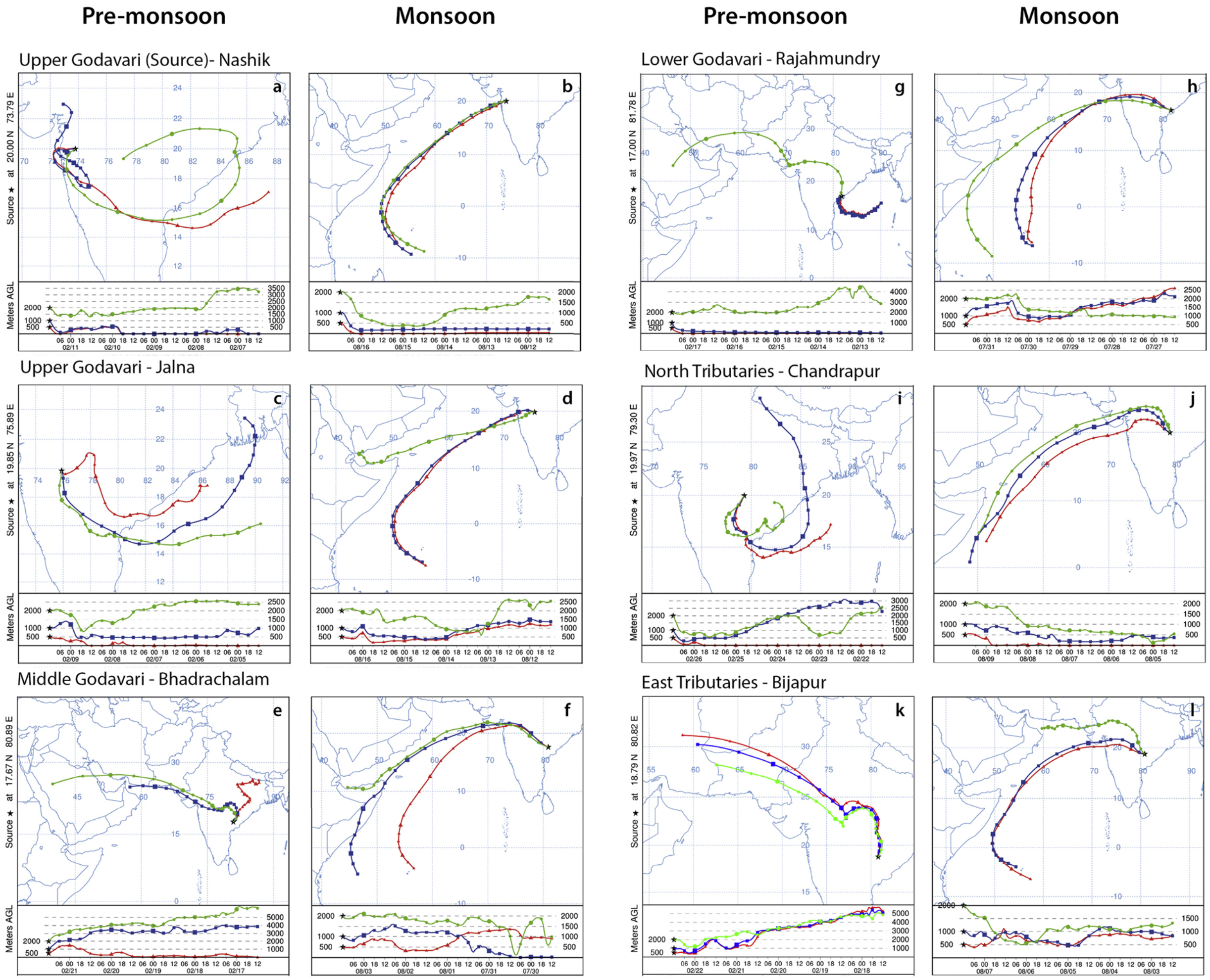


**Fig. 5.** Back trajectory simulations (HYSPLIT model, NOAA) for the Godavari's subbasins: the Upper Godavari at Nashik (source) (a, b) and Jalna (c, d), Middle Godavari at Bhadrachalam (e, f) and Lower Godavari at Rajahmundry (g, h), North Tributaries at Chandrapur (i, j), East Tributaries at Bijapur (k, l), in the pre-monsoon (left) and monsoon (right) season. Trajectories were calculated at 500, 1000 and 2000 m above ground level (agl) for 120 h (5 days) prior to river water sample collection.

to the Eastern Ghats. Subsequent evaporation that would have enriched surface waters was likely supressed by the dense forest cover in this region. Taken together, our findings confirm that the NE monsoon mostly affects the downstream Godavari, although it may occasionally reach the Godavari headwaters (Gupta et al., 1997, 2005; Kumar et al., 2010). The fact that the contribution by the NE monsoon was restricted to the East Tributaries during this sampling campaign, suggests a spatially and annually variable influence of this moisture source.

In the monsoon season, isotopic values ($\delta^{18}$O:-3.4 ± 1.6, δD:-23.0 ± 13.0‰, range: -7.7 to -1.7 and -57.0 to -9.3, respectively, n = 35) and relatively high d-excess (3.8 ± 2.9‰) in the downstream Godavari waters generally resemble SW monsoon precipitation signatures ($\delta^{18}$O: -2.2 to -2.8, δD: -15 to -11‰; Bowen, 2017) (Figs. 2, 4a-c). This fits with back trajectory analysis showing a consistent origin in the Indian Ocean, where the high trajectories (2 km agl) follow a path over the Gulf of Aden or Horn of Africa and the other trajectories follow a marine path and all continue over the Arabian Sea (Fig. 5b,d,f,h,j,l). Together, this suggests an effective pick-up of moisture en route over the Indian Ocean/Arabian Sea and a dominant SW monsoon input to the downstream Godavari River, consistent with the high rainfall amounts in this part of the basin in the monsoon season (Fig. 2c-f). Interestingly, trajectories for the downstream Godavari show a passage over the relatively lower, northern part of the Western Ghats, visualised by a moderate increase in trajectory heights, and follow a path north of the Godavari basin before turning south to the rainout location (Fig. 5f,h,j,l). The Upper Godavari shows more southerly trajectories over the high-altitude mountains with likely substantial rainout at the windward side. This is in line with observations of low rainfall amounts in the Upper Godavari subbasin, which is located in the Western Ghats' rain shadow (Figs. 1, 2a,b, 5b,d). Prior studies reported that Mediterranean moisture contributes significantly to Himalayan River discharges (Jeelani et al., 2013; Karim and Veizer, 2002; Meese et al., 2018; Sharma et al., 2017), and that its influence may reach southward along the Western Ghats to the Godavari basin (Lambs et al., 2011). Nevertheless, the low d-excess in monsoonal Godavari waters (≤10.9‰; Fig. 4c) and back trajectories starting in the Indian Ocean and Arabian Peninsula (Fig. 5) suggest that the input of Mediterranean-derived moisture, which is typically characterised by a high d-excess (~22‰), is negligible.

### *3.4. Water isotopes in Godavari surface waters in the monsoon season*

In the monsoon season, the isotopic composition significantly differs between the subbasins of the Godavari River ($p \leq 0.001$), linking to the spatial heterogeneity in monsoon precipitation at basin scale. The North ($\delta^{18}$O:-5.3 ± 2.0, δD:-40.4 ± 14.4‰, n = 9) and East Tributaries ($\delta^{18}$O:-3.6 ± 0.9, δD:-22.2 ± 4.2‰, n = 4), Middle ($\delta^{18}$O:-2.5 ± 0.4, δD:-17.0 ± 1.8‰, n = 5) and Lower Godavari ($\delta^{18}$O:-2.5 ± 0.4, δD:-15.8 ± 3.3‰, n = 17) all have relatively low isotopic values and high d-excess (mean ≥ 1.8‰), compared to the Upper Godavari ($\delta^{18}$O: +1.0 ± 2.1, δD: +2.5 ± 11.0‰, n = 12) (Fig. 4). Interestingly, the North Tributaries have the most depleted isotopic signatures, even below the long-term average for SW monsoon rainfall in this region ($\delta^{18}$O: -2.8, δD: -15‰; Fig. 2e). This strong depletion can be explained by a combination of factors, including the amount effect. This generally lowers isotopic values at high rainfall amounts, especially in tropical regions (Bowen and Revenaugh, 2003; Dansgaard, 1964; Feng et al., 2009; Gonfiantini et al., 2001), and fits with the anomalous rainfall peak observed in June 2015 (+84 to +206 %; Fig. 2). Also, organised cloud convective activity due to an extensive cloud cover across the downstream Godavari basin may have contributed to the extreme depletion in $^{18}$O, as this was previously observed for precipitation in southern India and along the Peninsular west coast (Lekshmy et al., 2014; Rahul et al., 2016; Rahul and Ghosh, 2019). In addition, the low trajectory height (mainly ≤ 1.5 km agl) and upward motion shown by the back trajectory analysis for the North Tributaries (Fig. 5j) are linked to increased pick-up of moisture from the warm Arabian Sea and/or sub-cloud layer. These trajectory features are reported to cause strong $^{18}$O depletion along India's west coast (Lekshmy et al., 2014). Furthermore, the North Tributary waters plot near the intersect of the GMWL/LMWLs and monsoonal Godavari waters in the $\delta^{18}$O-δD graph (Fig. 3a,b). In the $\delta^{18}$O-d-excess graph they show a depletion in $^{18}$O (i.e. shift towards left) compared to SW monsoon precipitation estimates (Fig. 3c). From a process-based perspective (Fig. 3d), this distinctive depletion in $^{18}$O compared to d-excess points towards a dominant amount/convective effect on the North Tributary waters.

The Upper Godavari River has exceptionally high $\delta^{18}$O and δD values, also compared to SW monsoon rainfall in this region ($\delta^{18}$O: -2.1 and -0.8, δD: -7.0 and +2.0‰, at Jalna and Nashik, respectively) (Figs. 2a,b, 4a,b). This enrichment points towards a (reversed) rainfall amount effect where low amounts cause an increase in $\delta^{18}$O and δD values (Gonfiantini et al., 2001). This matches with the rainfall deficit in the Upper Godavari in the 2015 monsoon season (-20 to -27 %; Fig. 2a,b). Moreover, d-excess is typically low in the Upper Godavari (-5.1 ± 6.2‰) (Figs. 3c, 4c), suggesting continuous river surface evaporation (Dutton et al., 2005). In addition, in the semi-arid environment of the Upper Godavari, light rainfall as experienced during sample collection in the monsoon season is known to cause evaporation of raindrops on their way to the ground (i.e. cloud-base evaporation) (Araguás-Araguás et al., 1998). This significantly lowers d-excess in precipitation, a phenomenon that is commonly noted at the leeward-side of mountain ranges across South Asia (Bershaw, 2018). Hence, spatial isotopic patterns in the Godavari basin closely reflect the observed SW monsoon rainfall distributions (Figs. 2,4, A4, A6).

In the downstream Godavari region, river water $\delta^{18}$O and δD values increase during transport from the North and East Tributaries, which receive high quantities of SW monsoon rainfall, to the Middle and the Lower Godavari by ~ +0.44 and +4.0‰ 100 km$^{-1}$, respectively (Figs. 2, 6 a,b). Similar trends were previously reported for other rivers (Gibson et al., 2002), such as for the middle stretch of the Ganges River where an increase in $\delta^{18}$O values of +0.15‰ 100 km$^{-1}$ (800 − 1600 km from source; Kumar et al., 2019) and of +1.1‰ 100 km$^{-1}$ in δD values (500 − 1700 km from source; Ramesh and Sarin, 1992) was observed. This enrichment was attributed to the inflow of enriched water from tributaries (Ramesh and Sarin, 1992), in combination with river water evaporation and the input of isotopically enriched precipitation in the Ganges River (Kumar et al., 2019). The increasing enrichment of Godavari River water downstream appears to be mainly caused by evaporation as tributaries and rainfall in the downstream region provide more depleted waters. The relatively invariant d-excess (3.8 ± 2.9‰) may further suggest that the extent of in-river evaporation is similar across the downstream Godavari basin, where river waters show consistently lower d-excess than SW monsoon precipitation (~8‰ at Mumbai; Bhattacharya et al., 2003) (Fig. 6c). Interestingly, Godavari water isotopes have a similar regression slope (6.39 ± 0.22) as groundwater in Central (~6.5) and Southern (~6) Peninsular India (Deshpande et al., 2003; Gupta et al., 2005) (Fig. 3b). This suggests that both the river and the groundwater are replenished by the same source, i.e. the SW monsoon. Although quantification of groundwater inputs is challenging with the limited data available, we note that the downriver enrichment observed here contrasts with earlier findings of a ~2‰ depletion in $^{18}$O from west-to east coast in groundwater in Central India (Gupta et al., 2005) and a ~3‰ depletion in (pre-monsoonal) river- and groundwater in South India (Deshpande et al., 2003). This discrepancy may imply limited groundwater input to the Godavari River, or other controlling mechanisms than gradual SW monsoon rainout and/or NE monsoon inputs which were suggested to explain the depletion reported by earlier studies (Deshpande et al., 2003; Gupta et al., 2005).

Finally, the spatial variations in isotopic composition can be used to identify the pathway and provenance of water that is finally discharged by the Godavari River to the Bay of Bengal. The low $\delta^{18}$O and δD values of the North Tributaries can be traced in downstream direction from the confluence with the Middle Godavari and then after joining with the East Tributaries, together providing the Lower Godavari signature (Figs. 1b, 6a,b, A4, A6). The low composite isotopic signature suggests an integrative effect in the downstream Godavari, with the North Tributaries as most important source area. The relatively depleted downstream Godavari signature suggests a renewal of river water by the SW monsoon. This would also imply that this precipitation drains rapidly into the river unaffected by soil percolation and/or groundwater evaporative processes causing enrichment (Jasechko, 2019). Contrastingly, the enriched signature of the Upper Godavari cannot be traced downriver, implying negligible input to the downstream Godavari. This is likely due to low rainfall in combination with abundant dams in this upstream region (Pradhan et al., 2014) (Fig. A7). Source apportionment by an end-member model using mean d-excess, which integrates both precipitation and evaporation processes, reveals that the majority (~80 %) of river water in the Middle Godavari comes from the North Tributaries while the East Tributaries contribute a smaller amount (~20 ± 27 %). The Lower Godavari shows equal inputs by the North and East Tributaries (50 ± 23 %) to the final discharge. At the Dam in Rajahmundry that regulates the flow to the Godavari delta, the Reservoir Lake and its outlet have similar isotopic signatures that do not change between the pre-monsoon and monsoon season ($\delta^{18}$O: -2.6 ± 0.6, δD: -19.0 ± 2.4‰). This suggests that Reservoir Lake waters are well-mixed and buffer spatial, seasonal and inter-annual variations. Indeed, the isotopic composition found in the delta is comparable

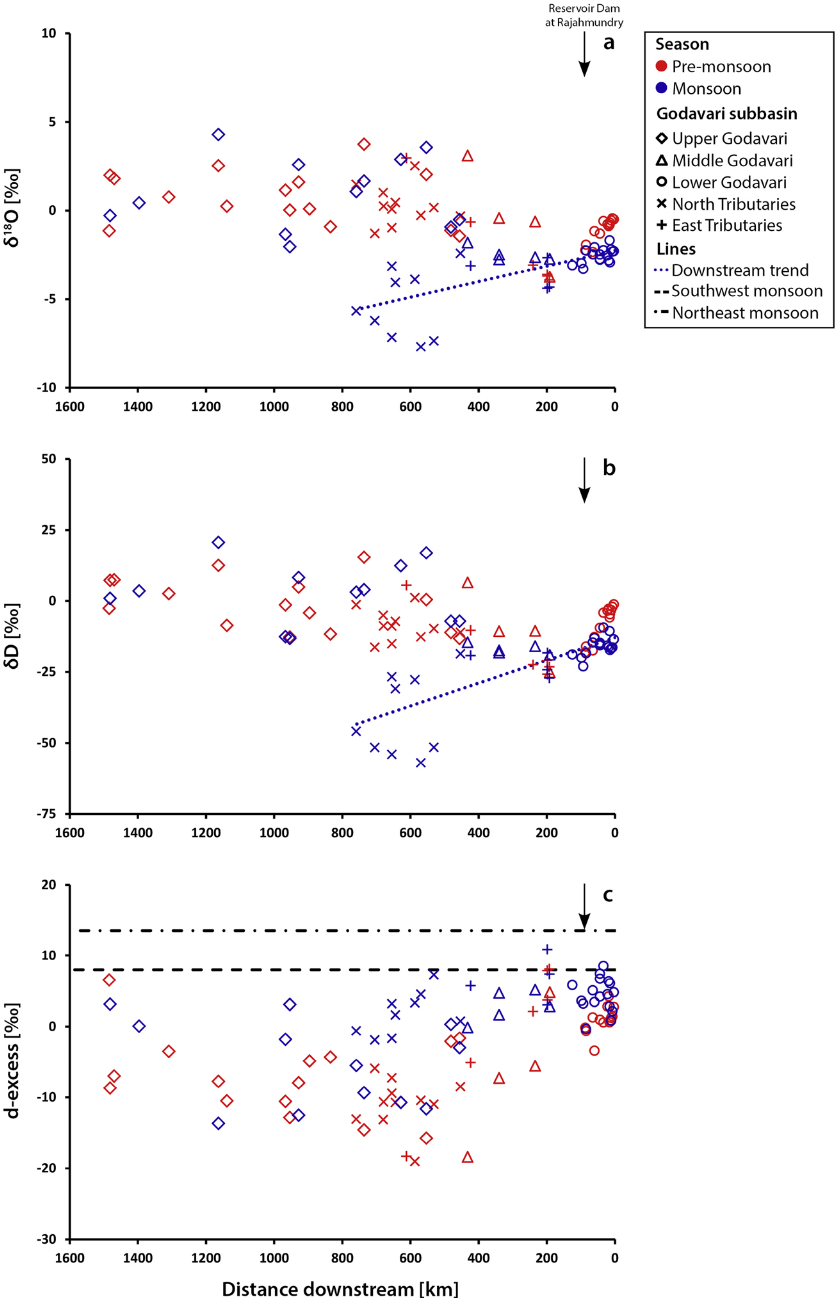


**Fig. 6.** Trends in $\delta^{18}O$ (a), δD (b) and d-excess (c) values in Godavari River surface water in downstream direction, in the pre-monsoon (red) and monsoon (blue) season for the Godavari subbasins. Distance downstream is in absolute km. Downriver $\delta^{18}O$ and δD correlations in the downstream Godavari in the monsoon season are marked by a dotted (blue) line (a and b). The arrow represents the location of the Reservoir Lake at Rajahmundry in the Lower Godavari. In (c) the dashed black line represents long-term average d-excess of Southwest monsoon precipitation (~8‰ at Mumbai) (Bhattacharya et al., 2003), the dotted/dashed black line of the Northeast monsoon (~13.5‰, at Kozhikode, at the southwest coast ~1000 km south of Mumbai) (Warrier et al., 2010).

to an estuary sample taken in the 2001 monsoon season ($\delta^{18}O$:-5.5, d-excess: +3.2‰; Lambs et al., 2005), which confirms a limited annual variability in the isotopic composition of water that is discharged to the Bay of Bengal. However, given the large year-to-year fluctuations in the Godavari's discharge (6.8–130 $km^3$ $year^{-1}$ (1969–2010); Acharyya et al., 2012; Biksham and Subramanian, 1988b), further monitoring at extended temporal scales is warranted. The small range in isotopic composition in the Godavari delta (Figs. A4, A6) and along a $\delta^{18}O$-salinity transect following the main branch (Gautami) to the Bay of Bengal ($\delta^{18}O$: -2.2 to -2.9‰, salinity: 0.06–3.6 g $L^{-1}$), suggest that the river plume extends beyond the Godavari mouth, and that minimal river-seawater mixing takes place within the estuary in the monsoon season.

### 3.5. Water isotopes in Godavari surface waters in the pre-monsoon season

In the pre-monsoon season, Godavari waters have high $\delta^{18}$O and δD values, suggesting that they are primarily influenced by surface evaporation (Fig. 4a,b). This is in line with the prevailing meteorological conditions, with low humidity, scarce rainfall and high temperatures across the Godavari basin (Fig. 2), enhancing large-scale evaporation. This evaporation may possibly exceed annual rainfall in the upstream region (Jhajharia et al., 2014). Significant isotopic differences between the subbasins ($p \leq 0.01$) suggest spatial variability in the magnitude of evaporation processes. The most depleted signatures in this season are found in the East Tributaries ($\delta^{18}$O:-2.0 ± 2.7, δD:-16.2 ± 11.9‰, n = 6) followed by the Lower ($\delta^{18}$O:-1.1 ± 0.7, δD:-7.7 ± 6.2‰, n = 13), Middle Godavari ($\delta^{18}$O:-0.4 ± 2.8, δD:-10.0 ± 13.0‰, n = 4) and North Tributaries ($\delta^{18}$O:0.3 ± 1.1, δD:-8.6 ± 5.3‰, n = 11). Most enriched signatures are found in the Upper Godavari waters ($\delta^{18}$O:0.8 ± 1.5, δD:-1.0 ± 9.2‰, n = 15). This suggests an increase in the magnitude of evaporation towards the upstream Godavari basin. In particular the Upper Godavari shows a high variability in isotopic content ($\delta^{18}$O: -1.4 to 3.8, δD: -13 d-excess: -15.7 to +6.6‰). The most extreme enrichment ($\delta^{18}$O: ≥2‰) and lowest d-excess (≤-5‰) is there found in the vicinity of dams, where standing water likely facilitates evaporation, as has been reported for rivers and reservoirs in monsoonal and (semi-)arid climates (e.g. Diamond and Jack, 2018; Li et al., 2016).

The relatively depleted signature of several East Tributaries (i.e. Sileru, Sabari and Pumuleru Rivers) is transferred downstream, where their influence can be traced based on the lower $\delta^{18}$O and δD values in the main stem Godavari after their confluence with the Middle Godavari, and remains recognisable up to the Reservoir Lake in the Lower Godavari (Figs. 1b–d, 6 a,b, A3, A5). However, there is no consistent longitudinal trend from source to sea in this season, which implies poor river connectivity within the Godavari basin. This is underlined by observations of pools with standing water interspersed with dry river beds. The river flow in the upstream Godavari is known to be disturbed by the proliferation of dams in this region (Pradhan et al., 2014). Dams influence ~28 to 37 % of the Godavari River flow, making it one of the most strongly affected rivers in Asia (Nilsson et al., 2005; Pradhan et al., 2014), and likely inhibit any recognisable contribution from the Upper Godavari to the isotopic signal in the downstream basin (Figs. A3, A5, A7). Together with recurrent droughts in the pre-monsoon season and lean monsoonal rainfall causing falling reservoir levels (CWC, 2019; GDO, 2019), dams further contribute to the extent of basin-wide evaporation.

Due to the limited input of direct precipitation, groundwater may be an important source for the Godavari River in the pre-monsoon season. Gupta et al. (2005) found that shallow groundwater may locally contribute to rivers, based on the resemblance between river- and groundwater isotopes in Central India. Groundwater in the Godavari region is enriched compared to SW and NE monsoon precipitation (Gupta et al., 2005). This may be due to cloud-base evaporation or – more likely at low rainfall in the pre-monsoon season – to evaporation of soil moisture before it recharges groundwater. The enriched isotopic signatures of Godavari River waters ($\delta^{18}$O: mainly ≥-1‰) compared to groundwater ($\delta^{18}$O: -1 to -3‰; Gupta et al., 2005), suggest that if groundwater substantially contributes, this signal is further altered by in-river evaporation. Similar findings for Peninsular Rivers in South India, with enriched signatures compared to groundwater and low d-excess (≤6‰; Deshpande et al., 2003), suggest that in-river evaporation is a wide-spread phenomenon in the pre-monsoon season. However, quantitative estimations of groundwater-to-river inputs and subsequent evaporation would require detailed monitoring of the groundwater isotopic composition. The water isotopes of Lonar Lake, an isolated crater lake in the upstream Godavari basin fed by groundwater springs (and direct SW monsoon rainfall) (Fig. 1a), revealed that groundwater supplies were lithologically controlled by the Deccan Trap basalts which consist of alternating high- and-low permeable layers that underlie the majority of the upstream Godavari basin (Biksham and Subramanian, 1988b; Komatsu et al., 2014; Usman et al., 2018). Our sampling of Lonar Lake in the pre-monsoon season ($\delta^{18}$O:+6.9, δD:+30.6‰) shows more enriched values than groundwater ($\delta^{18}$O:-2.5 ± 0.6, δD:-16.6 ± 4.3‰) and late pre-monsoon signatures ($\delta^{18}$O:+4.3 ± 0.1, δD:+15.7 ± 0.9‰) (Anoop et al., 2013). Extrapolating these values to the upstream Godavari suggests that if the river water is derived from groundwater, it has undergone significant surface evaporation.

Currently, evaporation estimates range from ~5 to 16 mm $\text{day}^{-1}$ from the Lower to the Upper Godavari (CWC, 2015b), where the yearly evaporative loss from the Reservoir Lake at Rajahmundry in a sub-humid climate is estimated at ~46 % (Bharati et al., 2009). This highlights a significant loss from a reservoir surface purposed for water storage. From the Reservoir Lake to the Godavari delta, river water signatures become more enriched towards the outlets (i.e. three delta branches; Figs. 1b,c, 6 a,b, A3, A5). The abundance of irrigated fields (e.g. paddy rice and irrigated legumes) in the delta region and their reported high evaporation rates (Bouwer et al., 2008), may contribute to this enrichment when partially evaporated irrigation water drains back in the river. In the Godavari estuary, $\delta^{18}$O and δD values progressively increase towards sea. The $\delta^{18}$O values linearly increase with salinity ($R^2 = 0.94$) in the main branch, similar to the conservative behaviour reported for other estuarine systems in monsoonal regions (e.g. Somayajulu et al., 2002; Zhang et al., 1990). This is suggestive of efficient mixing of river- and seawater within the Godavari estuary and is consistent with seawater intrusion from the Godavari mouth in the pre-monsoon season.

### 3.6. Water isotopes along river depth profiles and cross-sections

Previous studies in large river basins have shown that the confluence of tributaries results in complex mixing processes, with characteristic vertical depth profiles for sediment (following hydrodynamic sorting effects) and solute distributions due to changed flow conditions (e.g. Bouchez et al., 2010; Feng et al., 2016; Freymond et al., 2018; Laraque et al., 2009). Stable water isotopes are an overlooked tracer in this perspective, despite their proven applicability to examine lateral mixing at river cross sections to evaluate mixing processes in downstream direction (Fritz, 1981; Krouse and Mackay, 1971; Matsui et al., 1976). Fritz (1981) reported on major seasonal rivers with fluctuating water levels, including the Rhine-Main (Germany), Rio Solimões-Rio Negro (Brasil) and Liard-MacKenzie (Canada) all with tributaries with different isotopic signatures, that a distance of respectively ~50, 120 and 300 km was needed for thorough lateral mixing of the river waters after their confluence.

For the Godavari River, the cross-section in the main stem Middle Godavari River reveals that isotopic signatures in the monsoon season show little variation across the river and with depth ($\delta^{18}$O:-2.7 ± 0.2, δD: -18.0 ± 0.7, d-excess:3.9 ± 1.3‰) (Figs. 1b–d, 7a–c). This points towards efficient lateral mixing of tributary waters, as this cross-section is sampled only ~100 km downstream of the confluence of the Upper Godavari and North Tributaries (which all drain via the Pranhita River) into the Middle Godavari, and ~60 km after joining of the Indravati River, a major

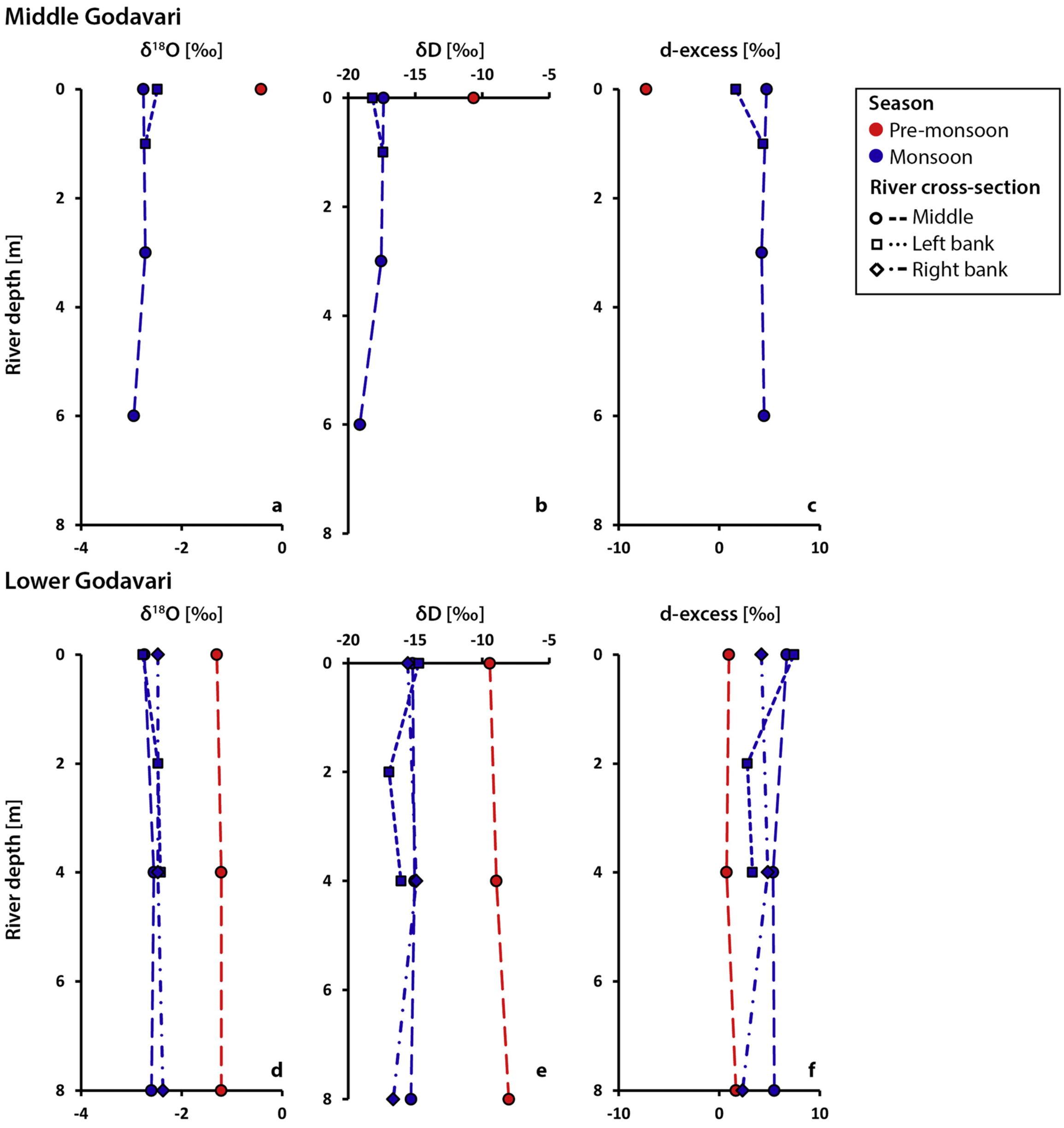


**Fig. 7.** River depth profiles of δ18O (a), δD (b) and d-excess (c) values in the Middle (upper) and Lower Godavari (below, d-f) in the pre-monsoon (red) and monsoon (blue) season (see Fig. 1b–d). In the monsoon season, several depth profiles were sampled across the river (i.e. cross-section) at the middle, and right and left from the middle to evaluate lateral mixing.

tributary of the East Tributaries (subbasin) and first to join the main stem Middle Godavari (Figs. 1b–d, A4, A6). In the Lower Godavari, the cross-section in the monsoon season shows some minor variation laterally and with depth in $\delta^{18}$O, δD and d-excess values (range: 0.4, 2.2 and 5.1‰, respectively) (Figs. 1c, 7d–f). This variation is likely associated with a lower flow velocity near the river banks, where shallowing of the river reduces vertical mixing. Nevertheless, in both the pre-monsoon and monsoon season, the δD, $\delta^{18}$O and d-excess values of samples collected from depth profiles in the middle of the river are constant (Fig. 7). This suggests that main stem Godavari River waters are generally well-mixed in the subsurface, without column stratification (Diamond and Jack, 2018) or surface enrichment due to in-river evaporation.

### *3.7. A regional perspective: the Godavari basin and other Indian rivers*

To provide a regional perspective on the water isotopic composition of Indian Rivers, we compare the $\delta^{18}$O and δD values in surface waters of the Godavari River (this study, $n = 96$) with values reported in the literature for other in Indian Rivers ($n = 399$; Supporting information: Kirkels, 2020). This includes Coastal Rivers draining the Western Ghats into the Arabian Sea, Peninsular Rivers flowing into the Bay of Bengal and major Himalayan Rivers such as the Indus and Ganges River, in the pre-monsoon and monsoon season (Fig. 8a,b). The Godavari, Coastal and Peninsular Rivers are primarily fed by monsoon precipitation, while the Himalayan Rivers receive additional inputs from meltwater. Within the Indian subcontinent, Godavari River surface waters (this study) are relatively enriched, particularly in the pre-monsoon season (Fig. 8a). The Himalayan Rivers have more depleted signatures than Godavari waters, attributable to a strong elevation effect on SW monsoon moisture and its transient storage in snow/glaciers feeding back into the Indus (pre-monsoon: $\delta^{18}$O:-15.3 to -2.6, δD:-108.0 to -17.0‰; monsoon: $\delta^{18}$O:-17.0 to -2.4, δD:-122.8 to -12.0‰; Karim and Veizer, 2002; Sharma et al., 2017) and Ganges River (pre-monsoon: $\delta^{18}$O:-14.4 to -2.4, δD:-103 to -19.0‰; monsoon: $\delta^{18}$O:-14.9 to -3.5, δD:-103 to -19.0‰; Kumar et al., 2019; Lambs et al., 2005; Ramesh and Sarin, 1992).

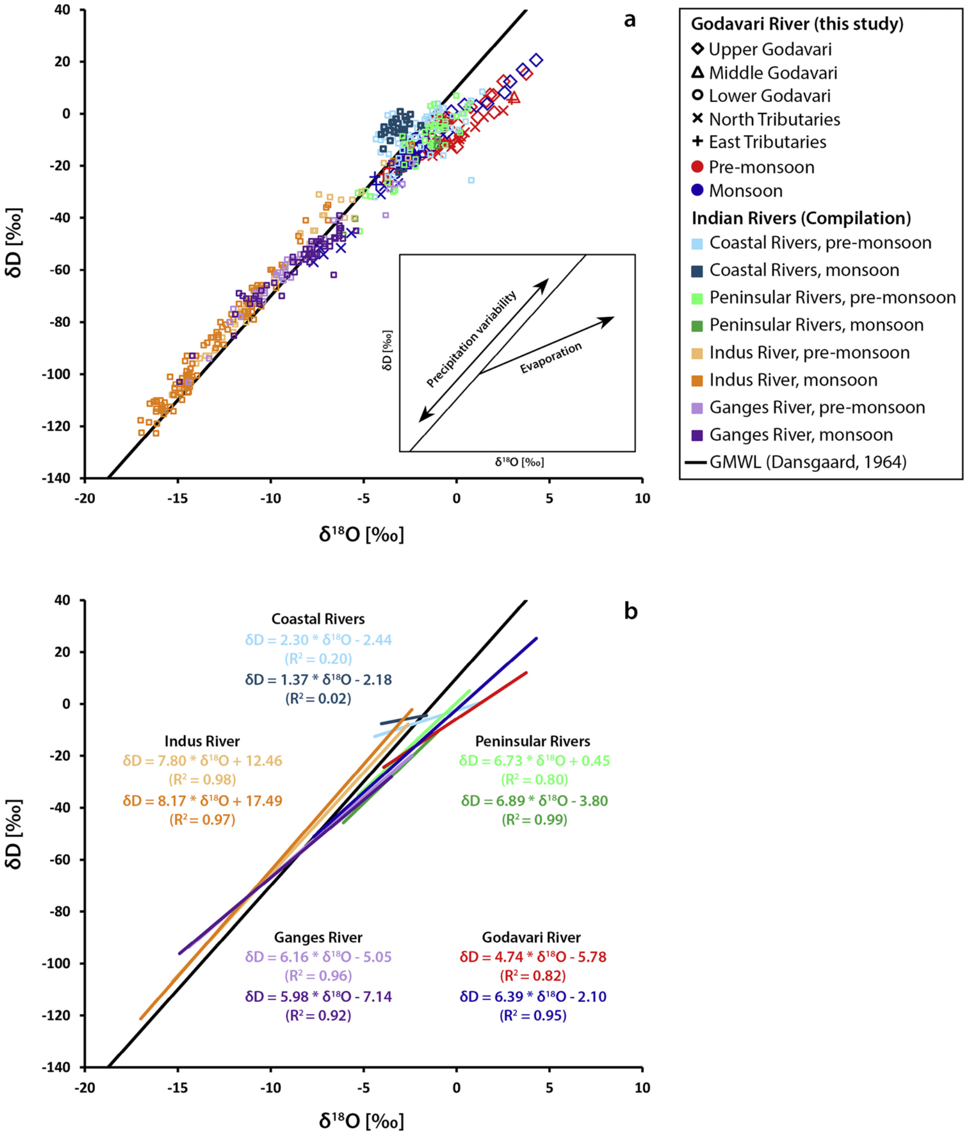


**Fig. 8.** a) Data compilation of $\delta^{18}$O and δD values in river surface waters of Indian Rivers reported in the literature (n = 399) (Supporting information: Kirkels, 2020) in the pre-monsoon and monsoon season, including data on the Godavari River (this study) in the pre-monsoon (red, n = 49) and monsoon (blue, n = 47). The other Indian Rivers are categorised as: Coastal Rivers draining the western coastal zone and Western Ghats (i.e. west-flowing into the Arabian Sea) in the pre-monsoon (light blue, n = 73) and monsoon season (petrol, n = 28) (Deshpande et al., 2003; Gupta et al., 2005; Lambs et al., 2005; Tripti et al., 2013, 2016, 2019), Peninsular Rivers draining Central and Southern India (i.e. east-flowing into the Bay of Bengal) in the pre-monsoon (light green, n = 42) and monsoon season (dark green, n = 4) (Deshpande et al., 2003; Gupta et al., 2005; Lambs et al., 2005), and the Himalayan Rivers separately for the Indus River draining into the Arabian Sea in the pre-monsoon (light orange, n = 43, Lower Indus only) and monsoon season (dark orange, n = 117) (Karim and Veizer, 2002; Sharma et al., 2017) and Ganges River draining into the Bay of Bengal in the pre-monsoon (light purple, n = 36) and monsoon season (dark purple, n = 56) (Kumar et al., 2019; Lambs et al., 2005; Ramesh and Sarin, 1992). For the Indus River, stable water isotope data for the Upper Indus (flowing through India) and the Lower Indus (flowing through Pakistan) are included to cover the entire river basin. This data compilation is based on basin-wide river water isotope studies, main stem and delta samples, not accounting for single point samples and (very) upstream tributaries. The inset schematically presents how hydrological processes may affect river water isotopic composition. In (b) linear $\delta^{18}$O–δD regression lines for the Coastal, Peninsular and Himalayan Rivers (Indus, Ganges) are given, with their equations. No significant ($p \leq 0.05$) differences in slope are found between the pre-monsoon and monsoon season for the Coastal, Peninsular and Himalayan Rivers. The solid black line represents the GMWL.

Isotopic signatures of Peninsular Rivers (pre-monsoon: $\delta^{18}$O:-5.3 to 0.7, δD:-45.2 to 7.0‰; monsoon: $\delta^{18}$O:-6.1 to -1.0, δD:-46.5 to -9.7‰; Deshpande et al., 2003; Gupta et al., 2005; Lambs et al., 2005) generally overlap with monsoonal Godavari River waters. The Coastal Rivers (pre-monsoon: $\delta^{18}$O:-4.4 to 1.4, δD:-32.0 to 8.5‰; monsoon: $\delta^{18}$O:-4.0 to -1.6, δD:-22.5 to 0.8‰; Deshpande et al., 2003; Gupta et al., 2005; Lambs et al., 2005; Tripti et al., 2013, 2016, 2019) show no linear δD-$\delta^{18}$O correlation implying a different control on isotopic signatures.

The Godavari River is characterised by a large seasonal difference in δD-$\delta^{18}$O regression slope ($p \leq 0.001$). However, the east-flowing Peninsular Rivers (e.g. Cauvery, Krishna) (regression slope: 6.7–6.9), as well as the Himalayan Indus (7.8–8.2) and Ganges River (6.2–6.0) all show insignificant changes in slope at a seasonal scale ($p \geq 0.11$) as revealed by the data compilation (Fig. 8b). Particularly in the pre-monsoon season, the Godavari River slope is low (4.74 ± 0.33) and plots significantly below the other Indian Rivers ($p \leq 0.001$). This highlights the large influence of evaporation in the Godavari basin compared to other Indian River basins (Fig. 8a, inset). Nevertheless, in the monsoon season, the Godavari River slope (6.39 ± 0.22) is comparable to other Indian rivers draining into the Bay of Bengal: the Ganges River and Peninsular Rivers (5.98 ± 0.24 and 6.89 ± 0.31; $p \geq 0.20$ and $p \geq 0.21$, respectively), signifying that they are fed by the same source i.e. the SW monsoon and subsequently experience similar hydrological processes.

## 4. Conclusions

The Godavari River, the largest non-Himalayan river of India, shows significant seasonal and spatial variability in $\delta^{18}$O and δD values in its surface waters. Seasonal differences in the Godavari basin are primarily driven by the dual Southwest and Northeast monsoon systems and subsequently altered by evaporation processes. Godavari waters in the pre-monsoon (dry) and monsoon (wet) season plot below the Global and Local Meteoric Water Lines, particularly in the pre-monsoon season, underlining the occurrence of basin-wide evaporation. A data compilation ($n = 399$) of $\delta^{18}$O and δD values in Indian Rivers reveals a stronger seasonality in the water isotopic composition for the Godavari River than for other monsoon-fed rivers in India.

In the monsoon season, isotopic signatures in the downstream Godavari basin reflect Southwest monsoon rainfall. Back trajectory analysis confirms that this moisture is sourced from the Indian Ocean and Arabian Sea. Spatial differences within the Godavari basin are linked to heterogeneity in rainfall patterns. The Upper Godavari, located in the rain shadow of the Western Ghats with a rainfall deficit in the 2015 monsoon season, has highly enriched signatures suggesting year-round evaporation. Moreover, abundant dam-building prevents any contribution to the downstream Godavari's discharge. The North and East Tributaries have depleted signatures due to high rainfall quantities causing an amount/convective effect. These depleted signatures are traced downstream through the Middle and Lower Godavari, and show a well-integrated signal, where both Tributaries contribute ~50 % to the final discharge. River depth profiles and cross-sections reveal well-mixed tributary waters as well as well-mixed surface and deeper waters. In the Godavari delta, isotopic patterns and salinity measurements show that the river plume extends beyond the Godavari mouth, indicating high discharge into the Bay of Bengal in the monsoon season.

In the pre-monsoon season, river water isotopes across the Godavari basin are enriched due to dominant in-river evaporation. Evaporation is more pronounced in the Godavari than for other Indian Rivers, as shown by an extensive data compilation. Northeast monsoon inputs are spatially limited to the East Tributaries, and this signal is not transferred downstream. Observations of dry river beds and stagnant water behind dams underline poor river connectivity. In the delta, conservative mixing of river- and seawater implies seawater intrusion and no discharge from the Godavari River in the pre-monsoon season.

This study on the Godavari River showed that river water isotopic composition is a sensitive recorder of seasonal and spatial variability in monsoon rainfall patterns. Improved understanding of the basin hydrology of the monsoon-fed Godavari River and further monitoring of the spatio-temporal evolution of river water isotopes in monsoonal rivers may help to develop integrated river management strategies for the future, dealing with water scarcity, flood and drought mitigation and sustainable river resources for food production.

## CRediT authorship contribution statement

**Frédérique M.S.A. Kirkels:** Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Huub M. Zwart:** Investigation, Visualization, Writing - review & editing. **Sayak Basu:** Investigation, Writing - review & editing. **Muhammed O. Usman:** Investigation, Writing - review & editing. **Francien Peterse:** Investigation, Supervision, Funding acquisition, Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This research was supported by the Dutch Research Council [NWO-Veni Grant No. 863.13.016 to F.P]. In India, we thank the drivers Munna and Abdul for logistical assistance and Prof. Prasanta Sanyal of the Indian Institute of Science Education and Research (IISER) Kolkata for general support to work in the Godavari Basin. ETH Zurich (Switzerland) is acknowledged for the use of the depth sampler, and Dr. Maarten Lupker for his guidance in the field and on the use of this instrument. For preparation of the fieldwork materials and river fieldwork assistance, we are grateful for the help provided by Chris Martes. We thank Piet van Gaever for technical support to measure $\delta^{18}$O and δD at the Royal Dutch Institute for Sea Research (NIOZ), Texel, The Netherlands. We acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT model (http://www.ready.noaa.gov) used in this publication. We would like to thank two anonymous reviewers for their valuable comments.

## Appendix A

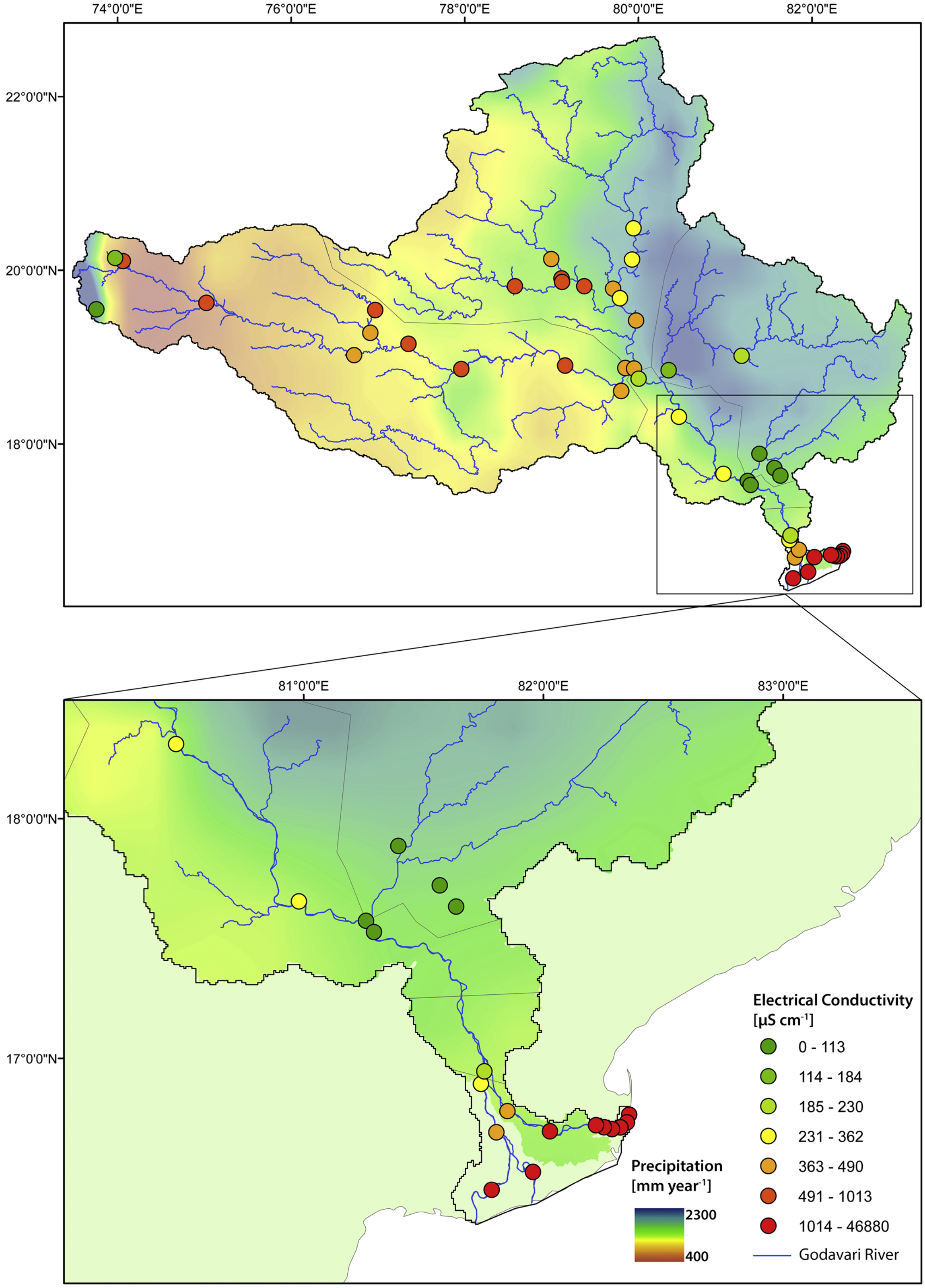


**Fig. A1.** Map showing Electrical Conductivity (EC) measurements of river water at sampling locations in the pre-monsoon season in the Godavari Basin (upper) and zoomed in on the delta (lower). Colours refer to μS $cm^{-1}$, background represents the long-term average rainfall distribution.

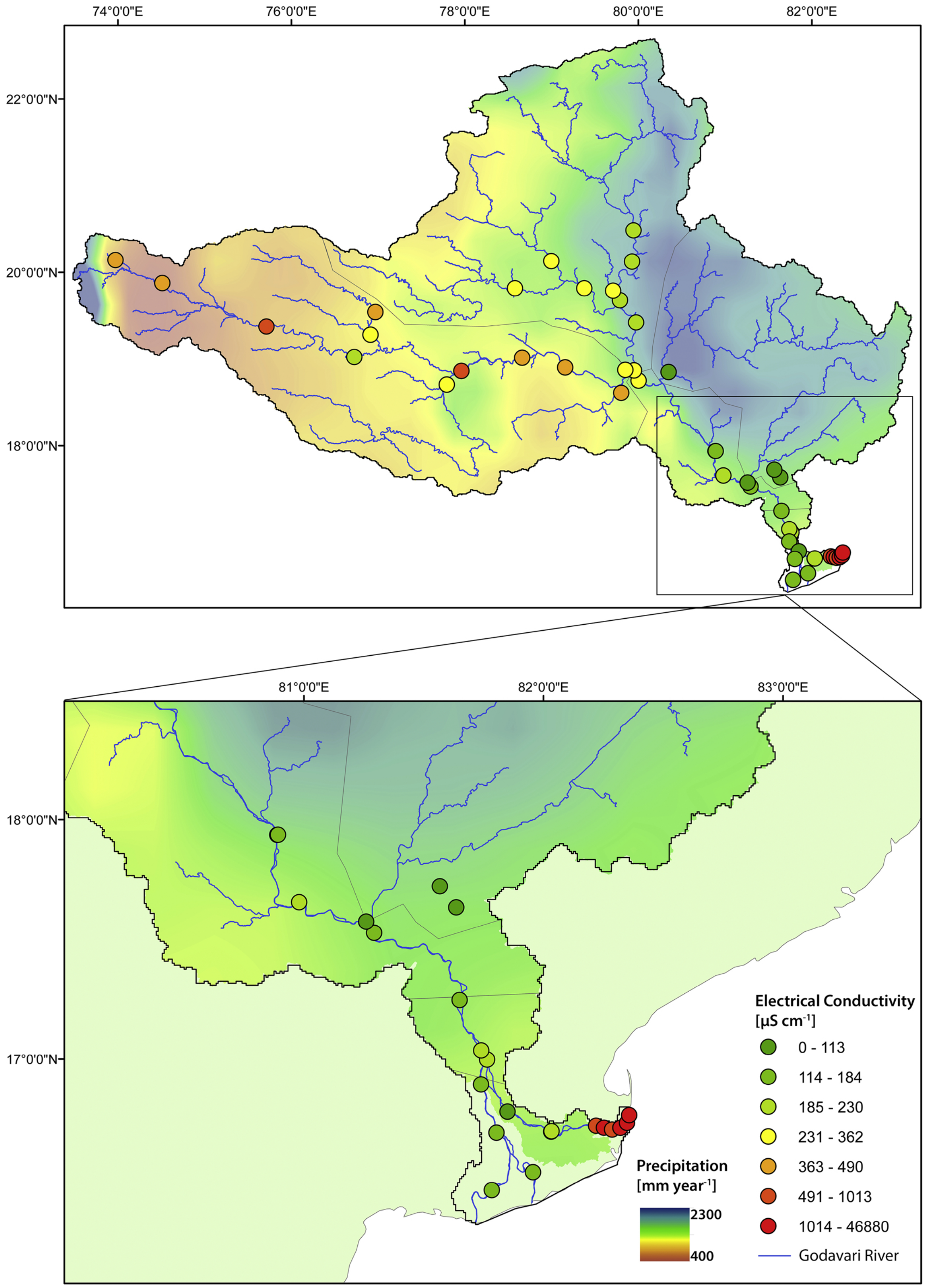


**Fig. A2.** Map showing Electrical Conductivity (EC) measurements of river water at sampling locations in the monsoon season in the Godavari Basin (upper) and zoomed in on the delta (lower). Colours refer to µS $cm^{-1}$, background represents the long-term average rainfall distribution.

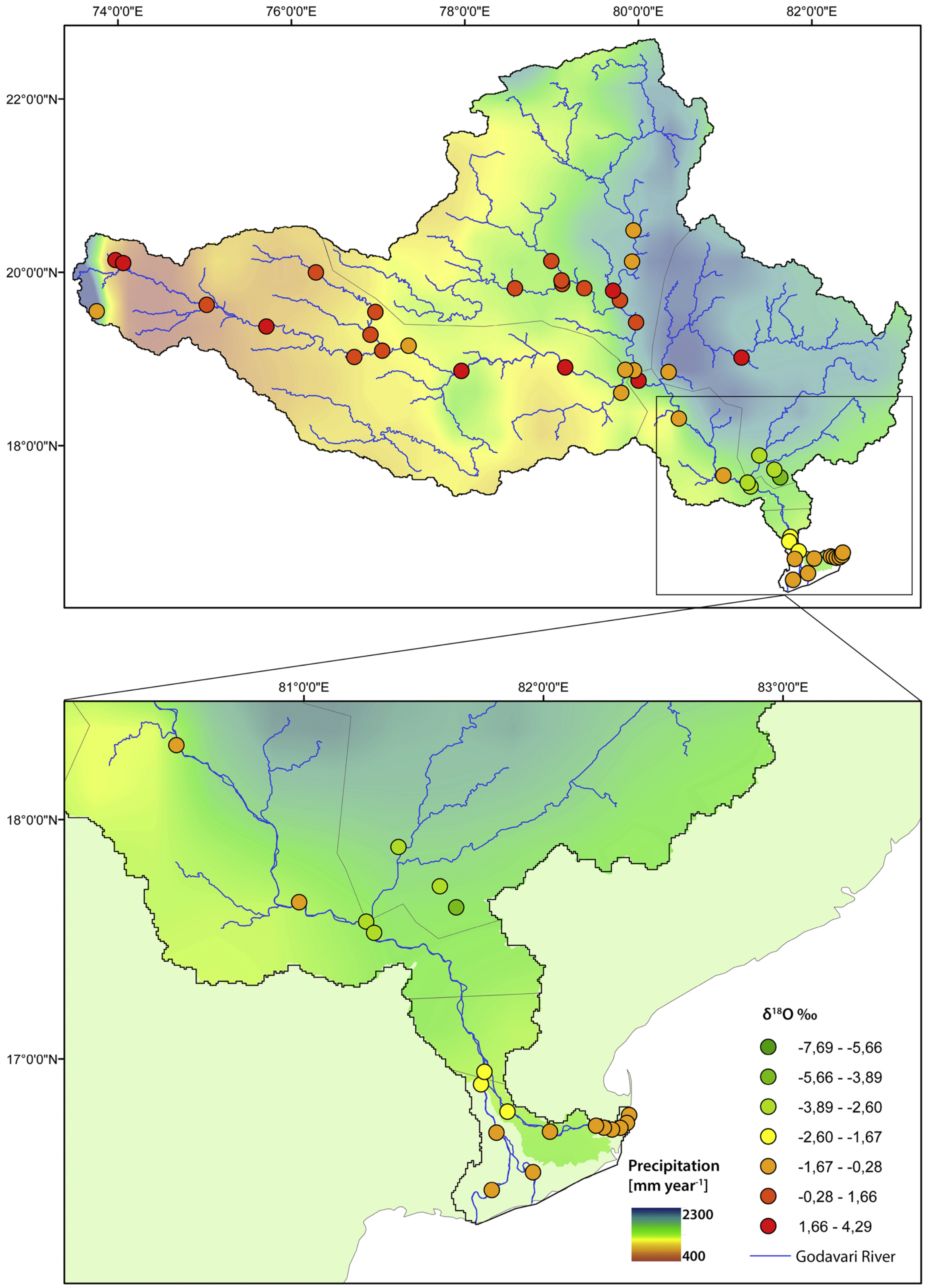


**Fig. A3.** Map showing $\delta^{18}$O measurements of river water at sampling locations in the pre-monsoon season in the Godavari Basin (upper) and zoomed in on the delta (lower). Colours refer to ‰, background represents the long-term average rainfall distribution.

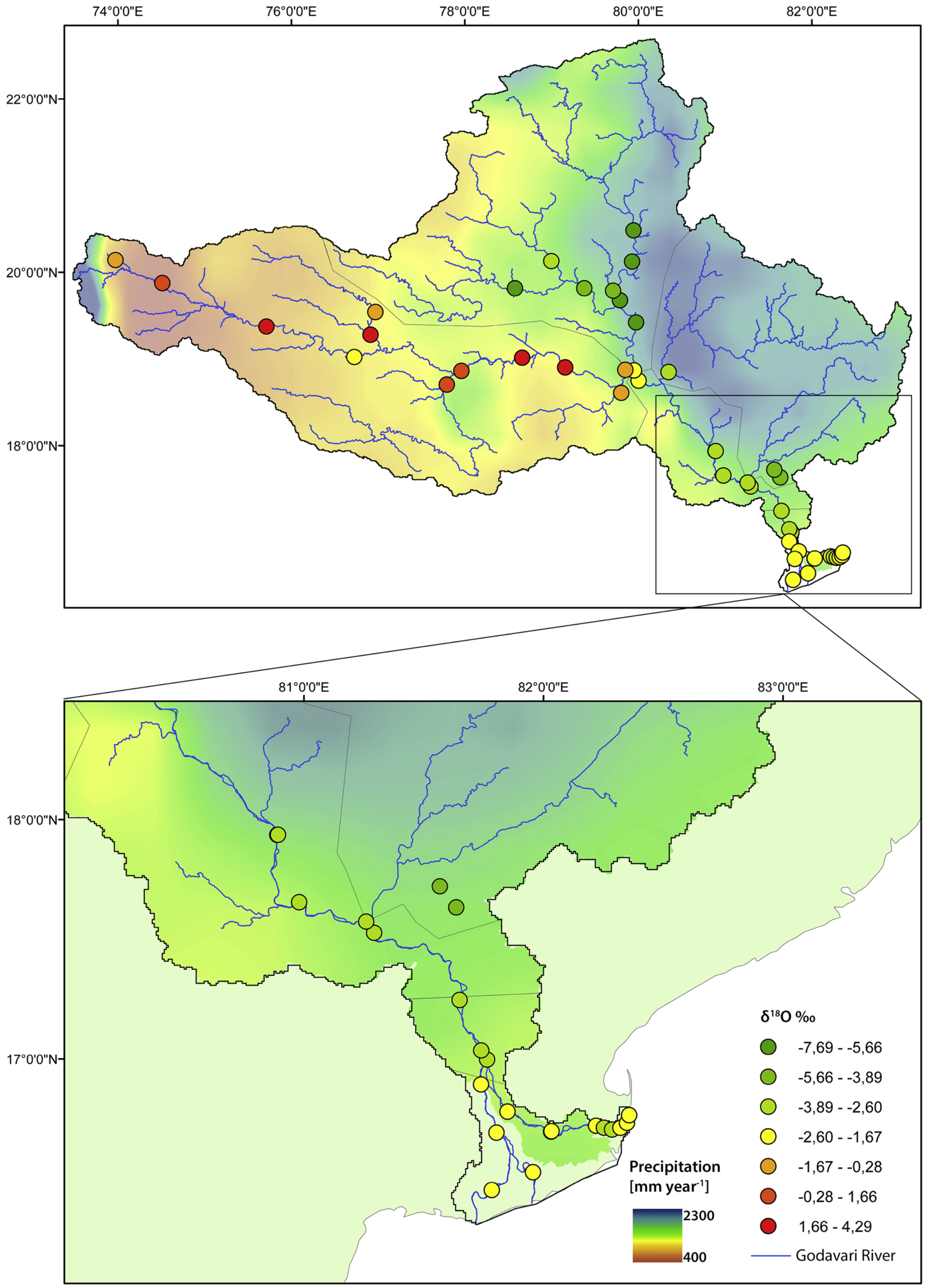


**Fig. A4.** Map showing $\delta^{18}$O measurements of river water at sampling locations in the monsoon season in the Godavari Basin (a) and the delta (b). Colours refer to ‰, background represents the long-term average rainfall distribution.

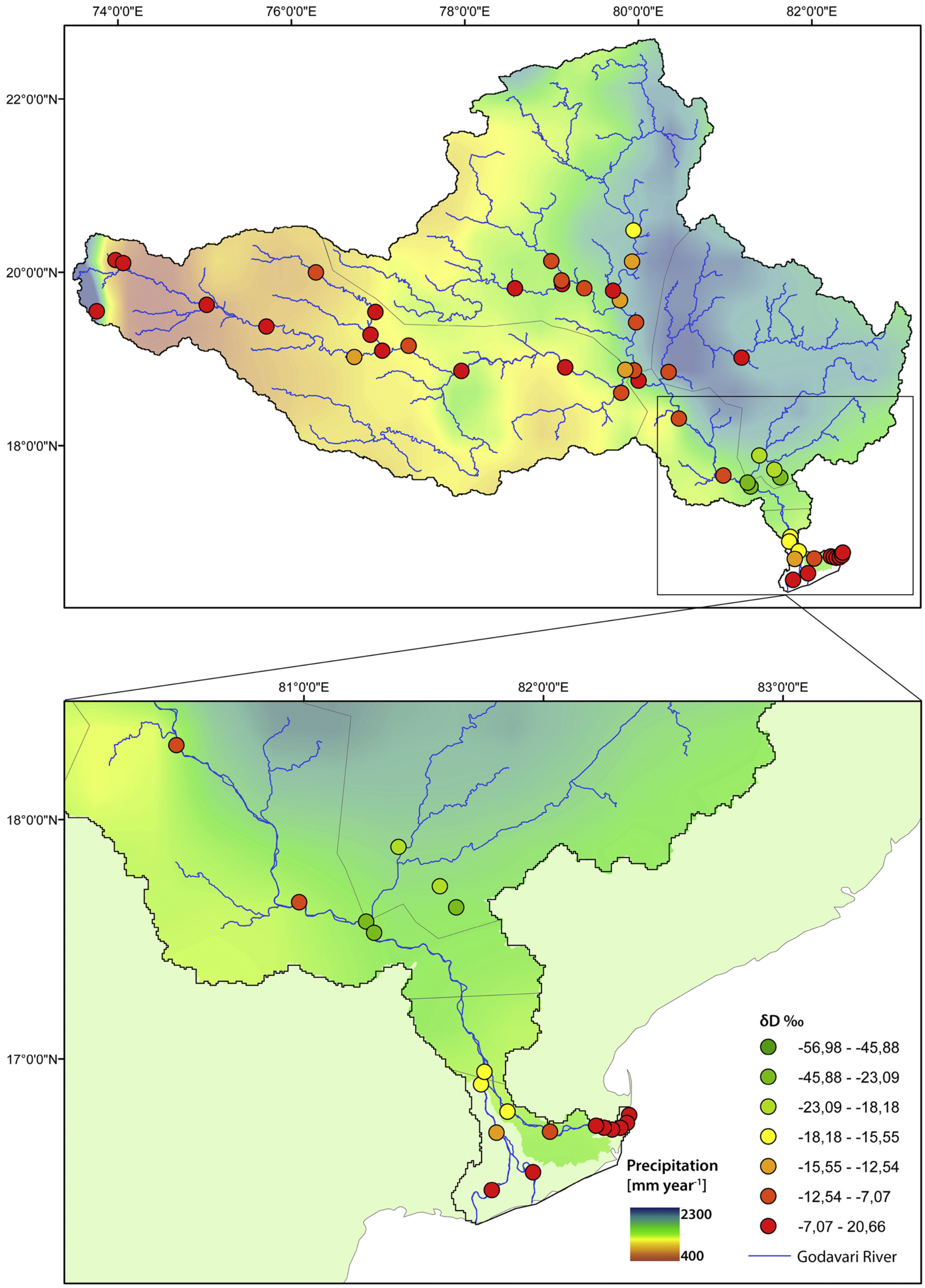


**Fig. A5.** Map showing δD measurements of river water at sampling locations in the pre-monsoon season in the Godavari Basin (upper) and zoomed in on the delta (lower). Colours refer to ‰, background represents the long-term average rainfall distribution.

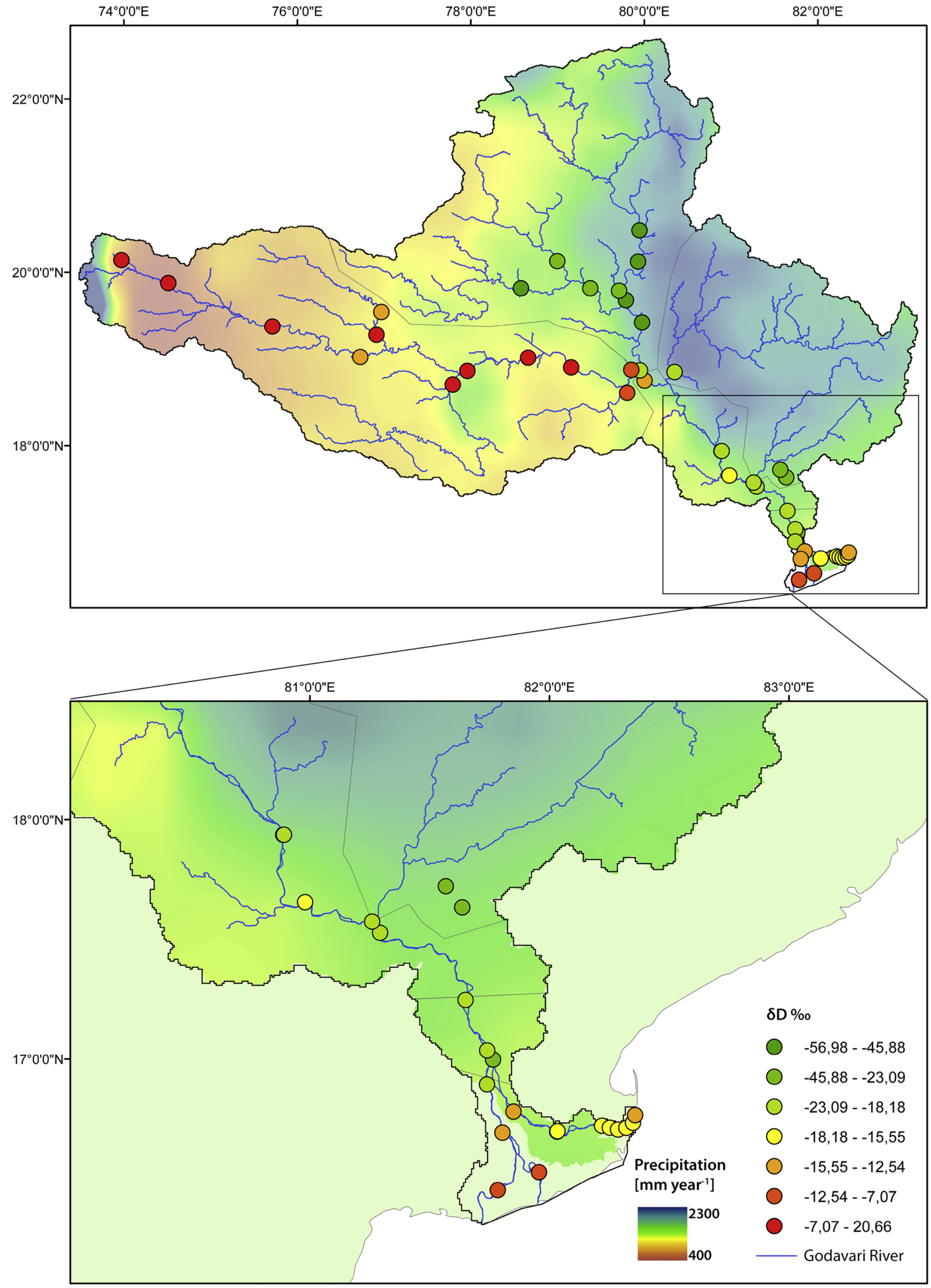


**Fig. A6.** Map showing δD measurements of river water at sampling locations in the monsoon season in the Godavari Basin (upper) and zoomed in on the delta (lower). Colours refer to ‰, background represents the long-term average rainfall distribution.

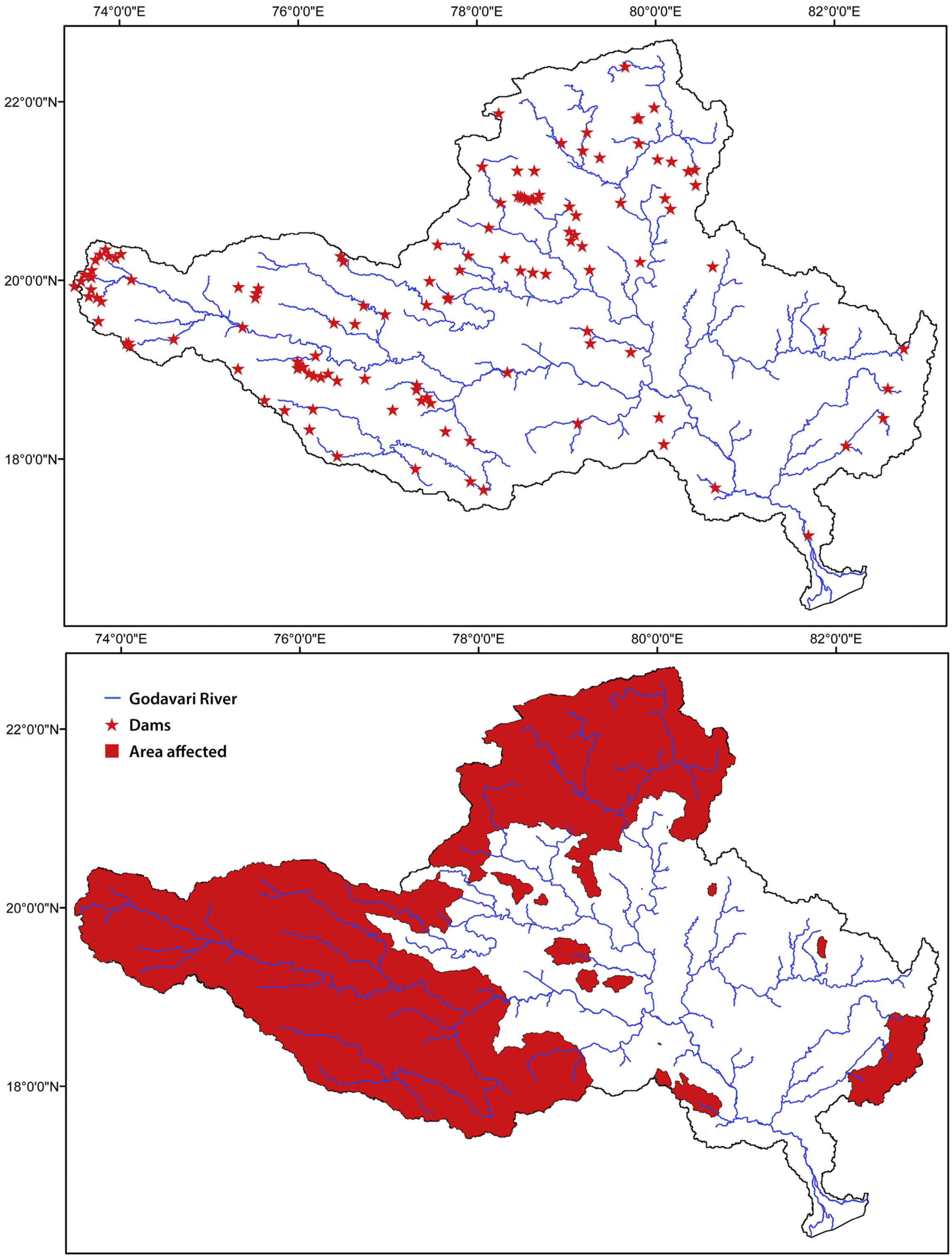


**Fig. A7.** Map showing the location of dams in the Godavari basin (upper) as well as the area where the Godavari River flow is affected by dam-building (lower).

## Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2020.100706.

## References

Acharyya, T., Sarma, V., Sridevi, B., Venkataramana, V., Bharathi, M.D., Naidu, S.A., et al., 2012. Reduced river discharge intensifies phytoplankton bloom in Godavari estuary, India. Mar. Chem. 132, 15–22. https://doi.org/10.1016/j.marchem.2012.01.005.

Amrith, S.S., 2018. Risk and the South Asian monsoon. Clim. Change 151, 17–28. https://doi.org/10.1007/s10584-016-1629-x.

Anoop, A., Prasad, S., Plessen, B., Basavaiah, N., Gaye, B., Naumann, R., et al., 2013. Palaeoenvironmental implications of evaporative gaylussite crystals from Lonar Lake, central India. J. Quat. Sci. 28, 349–359. https://doi.org/10.1002/jqs.2625.

Araguás-Araguás, L., Froehlich, K., Rozanski, K., 1998. Stable isotope composition of precipitation over southeast Asia. J. Geophys. Res. Atmos. 103, 28721–28742. https://doi.org/10.1029/98JD02582.

Araguás-Araguás, L., Froehlich, K., Rozanski, K., 2000. Deuterium and oxygen-18 isotope composition of precipitation and atmospheric moisture. Hydrol. Process. 14, 1341–1355. https://doi.org/10.1002/1099-1085(20000615)14:8<1341::AID-HYP983>3.0.CO;2-Z.

Babar, M., Kaplay, R.D., 2018. Godavari River: geomorphology and socio-economic characteristics. In: Singh, D.S. (Ed.), The Indian Rivers. Springer, Singapore, pp. 319–337.

Balakrishna, K., Probst, J., 2005. Organic carbon transport and C/N ratio variations in a large tropical river: Godavari as a case study, India. Biogeochemistry 73, 457–473. https://doi.org/10.1007/s10533-004-0879-2.

Basu, S., Mohanty, S., Sanyal, P., 2020. Possible role of warming on Indian summer monsoon precipitation over the north-central Indian subcontinent. Hydrol. Sci. J. 65 (4), 660–670. https://doi.org/10.1080/02626667.2020.1714050.

Bershaw, J., 2018. Controls on deuterium excess across Asia. Geosciences 8, 257–267. https://doi.org/10.3390/geosciences8070257.

Best, J., 2019. Anthropogenic stresses on the world's big rivers. Nat. Geosci. 7–21. https://doi.org/10.1038/s41561-018-0262-x.

Bharati, L., Smakhtin, V.U., Anand, B.K., 2009. Modeling water supply and demand scenarios: the Godavari–Krishna inter-basin transfer, India. Water Policy 11, 140–153. https://doi.org/10.2166/wp.2009.109.

Bhattacharya, S.K., Froehlich, K., Aggarwal, P.K., Kulkarni, K.M., 2003. Isotopic variation in Indian Monsoon precipitation: records from Bombay and New Delhi. Geophys. Res. Lett. 30, 2285–2288. https://doi.org/10.1029/2003GL018453.

Biemans, H., Speelman, L.H., Ludwig, F., Moors, E.J., Wiltshire, A.J., Kumar, P., et al., 2013. Future water resources for food production in five South Asian river basins and potential for adaptation—a modeling study. Sci. Total Environ. 468, S117–S131. https://doi.org/10.1016/j.scitotenv.2013.05.092.

Biksham, G., Subramanian, V., 1988a. Nature of solute transport in the Godavari basin, India. J. Hydrol. 103, 375–392. https://doi.org/10.1016/0022-1694(88)90145-X.

Biksham, G., Subramanian, V., 1988b. Sediment transport of the Godavari River basin and its controlling factors. J. Hydrol. 101, 275–290. https://doi.org/10.1016/0022-1694(88)90040-6.

Bouchez, J., Lajeunesse, E., Gaillardet, J., France-Lanord, C., Dutra-Maia, P., Maurice, L., 2010. Turbulent mixing in the Amazon River: the isotopic memory of confluences. Earth Planet Sci. Lett. 290, 37–43. https://doi.org/10.1016/j.epsl.2009.11.054.

Bouillon, S., Frankignoulle, M., Dehairs, F., Velimirov, B., Eiler, A., Abril, G., et al., 2003. Inorganic and organic carbon biogeochemistry in the Gautami Godavari estuary (Andhra Pradesh, India) during pre-monsoon: the local impact of extensive mangrove forests. Glob. Biogeochem. Cycles 17, 1114–1125. https://doi.org/10.1029/2002GB002026.

Bouwer, L.M., Biggs, T.W., Aerts, J.C., 2008. Estimates of spatial variation in evaporation using satellite-derived surface temperature and a water balance model. Hydrol. Process. 22, 670–682. https://doi.org/10.1002/hyp.6636.

Bowen, G.J., 2017. The Online Isotopes in Precipitation Calculator (OIPC). version 3.1. http://www.waterisotopes.org.

Bowen, G.J., Revenaugh, J., 2003. Interpolating the isotopic composition of modern meteoric precipitation. Water Resour. Res. 39, 1299–1312. https://doi.org/10.1029/2003WR002086.

Bowen, G.J., Wassenaar, L.I., Hobson, K.A., 2005. Global application of stable hydrogen and oxygen isotopes to wildlife forensics. Oecologia 143, 337–348. https://doi.org/10.1007/s00442-004-1813-y.

Clark, I., Fritz, P., 1997. Environmental Isotopes in Hydrogeology. Lewis Publishers, Boca Raton, New York.

Contreras-Rosales, L.A., Jennerjahn, T., Tharammal, T., Meyer, V., Lückge, A., Paul, A., et al., 2014. Evolution of the Indian Summer Monsoon and terrestrial vegetation in the Bengal region during the past 18 ka. Quat. Sci. Rev. 102, 133–148. https://doi.org/10.1016/j.quascirev.2014.08.010.

Craig, H., 1961. Isotopic variations in meteoric waters. Science 133, 1702–1703. https://doi.org/10.1126/science.133.3465.1702.

CWC, Central Water Commission, 2015a. Water and Water Related Statistics. Government of India, Ministry of Water Resources, pp. 1–168. http://cwc.gov.in/publications.

CWC, Central Water Commission, 2015b. Integrated Hydrological Databook. Government of India, Ministry of Water Resources, pp. 1–525. http://cwc.gov.in/publications.

CWC, Central Water Commission, 2019. Reservoir Level and Storage Bulletin. Government of India, Ministry of Water Resources. http://cwc.gov.in/reservoir-storage.

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16, 436–468. https://doi.org/10.3402/tellusa.v16i4.8993.

Dehairs, F., Rao, R.G., Mohan, P.C., Raman, A.V., Marguillier, S., Hellings, L., 2000. Tracing mangrove carbon in suspended matter and aquatic fauna of the Gautami–Godavari Delta, Bay of Bengal (India). Hydrobiologia 431, 225–241. https://doi.org/10.1023/A:1004072310525.

Delaygue, G., Bard, E., Rollion, C., Jouzel, J., Stiévenard, M., Duplessy, J., et al., 2001. Oxygen isotope/salinity relationship in the northern Indian Ocean. J. Geophys. Res. Oceans 106, 4565–4574. https://doi.org/10.1029/1999JC000061.

Deshpande, R.D., Bhattacharya, S.K., Jani, R.A., Gupta, S.K., 2003. Distribution of oxygen and hydrogen isotopes in shallow groundwaters from Southern India: influence of a dual monsoon system. J. Hydrol. 271, 226–239. https://doi.org/10.1016/S0022-1694(02)00354-2.

Deshpande, N.R., Kothawale, D.R., Kulkarni, A., 2016. Changes in climate extremes over major river basins of India. Int. J. Climatol. 36, 4548–4559. https://doi.org/10.1002/joc.4651.

Diamond, R.E., Jack, S., 2018. Evaporation and abstraction determined from stable isotopes during normal flow on the Gariep River, South Africa. J. Hydrol. 559, 569–584. https://doi.org/10.1016/j.jhydrol.2018.02.059.

Dutton, A., Wilkinson, B.H., Welker, J.M., Bowen, G.J., Lohmann, K.C., 2005. Spatial distribution and seasonal variation in $^{18}O/^{16}O$ of modern precipitation and river water across the conterminous USA. Hydrol. Process. 19, 4121–4146. https://doi.org/10.1002/hyp.5876.

Feng, X., Faiia, A.M., Posmentier, E.S., 2009. Seasonality of isotopes in precipitation: a global perspective. J. Geophys. Res. Atmos. 114, D08116–D08128. https://doi.org/10.1029/2008JD011279.

Feng, X., Feakins, S.J., Liu, Z., Ponton, C., Wang, R.Z., Karkabi, E., et al., 2016. Source to sink: evolution of lignin composition in the Madre de Dios River system with connection to the Amazon basin and offshore. J. Geophys. Res. Biogeosci. 121, 1316–1338. https://doi.org/10.1002/2016JG003323.

Freymond, C.V., Lupker, M., Peterse, F., Haghipour, N., Wacker, L., Filip, F., et al., 2018. Constraining instantaneous fluxes and integrated compositions of fluvially discharged organic matter. Geochem. Geophys. Geosyst. 19, 2453–2462. https://doi.org/10.1029/2018GC007539.

Fritz, P., 1981. River waters. In: Gat, J.R., Gonfiantini, R. (Eds.), Stable Isotope Hydrology: Deuterium and Oxygen-18 in the Water Cycle. Technical Report Series No. 210. International Atomic Energy Agency, Vienna, pp. 177–201.

Gadgil, S., 2003. The Indian monsoon and its variability. Annu. Rev. Earth Planet. Sci. 31, 429–467. https://doi.org/10.1146/annurev.earth.31.100901.141251.

GDO, Global Drought Observatory, 2019. Analytical Report - Drought in India. Joint Research Centre (JRC), Emergency Response Coordination Centre (ERCC) Analytical Team, European Commission (EC), pp. 1–17. http://edo.jrc.ec.europa.eu/gdo.

Gibson, J.J., Aggarwal, P., Hogan, J., Kendall, C., Martinelli, L.A., Stichler, W., et al., 2002. Isotope studies in large river basins: a new global research focus. Eos Trans. Am. Geophys. Union 83, 613–617. https://doi.org/10.1029/2002EO000415.

Gonfiantini, R., Roche, M., Olivry, J., Fontes, J., Zuppi, G.M., 2001. The altitude effect on the isotopic composition of tropical rains. Chem. Geol. 181, 147–167. https://doi.org/10.1016/S0009-2541(01)00279-0.

Goswami, B.N., Venugopal, V., Sengupta, D., Madhusoodanan, M.S., Xavier, P.K., 2006. Increasing trend of extreme rain events over India in a warming environment. Science 314, 1442–1445. https://doi.org/10.1126/science.1132027.

Gunnell, Y., 1997. Relief and climate in South Asia: the influence of the Western Ghats on the current climate pattern of peninsular India. Int. J. Climatol. 17, 1169–1182. https://doi.org/10.1002/(SICI)1097-0088(199709)17:11 < 1169::AID-JOC189 > 3.0.CO;2-W.

Gupta, L.P., Subramanian, V., Ittekkot, V., 1997. Biogeochemistry of particulate organic matter transported by the Godavari River, India. Biogeochemistry 38, 103–128. https://doi.org/10.1023/A:1005732519216.

Gupta, S.K., Deshpande, R.D., Bhattacharya, S.K., Jani, R.A., 2005. Groundwater $\delta^{18}$O and δD from central Indian Peninsula: influence of the Arabian Sea and the Bay of Bengal branches of the summer monsoon. J. Hydrol. 303, 38–55. https://doi.org/10.1016/j.jhydrol.2004.08.016.

Halder, J., Terzer, S., Wassenaar, L.I., Araguás-Araguás, L.J., Aggarwal, P.K., 2015. The Global Network of Isotopes in Rivers (GNIR): integration of water isotopes in watershed observation and riverine research. Hydrol. Earth Syst. Sci. 19, 3419–3431. https://doi.org/10.5194/hess-19-3419-2015.

Higgins, S., Overeem, I., Rogers, K., Kalina, E., 2018. River linking in India: downstream impacts on water discharge and suspended sediment transport to deltas. Elem Sci Anth 6, 1–24. https://doi.org/10.1525/elementa.269.

IAEA, International Atomic Energy Agency, 2019. Global Network for Isotopes in Precipitation. The GNIP Database. https://nucleus.iaea.org/wiser.

IMD, India Meteorological Department, 2014. Rainfall Statistics of India - 2014. Hydromet Division, Ministry of Earth Sciences, pp. 1–103. http://hydro.imd.gov.in/hydrometweb.

IMD, India Meteorological Department, 2015. Rainfall Statistics of India - 2015. Hydromet Division, Ministry of Earth Sciences, pp. 1–103. http://hydro.imd.gov.in/hydrometweb.

Jasechko, S., 2019. Global isotope hydrogeology—review. Rev. Geophys. 57, 835–965. https://doi.org/10.1029/2018RG000627.

Jeelani, G., Kumar, U.S., Kumar, B., 2013. Variation of $\delta^{18}$O and δD in precipitation and stream waters across the Kashmir Himalaya (India) to distinguish and estimate the seasonal sources of stream flow. J. Hydrol. 481, 157–165. https://doi.org/10.1016/j.jhydrol.2012.12.035.

Jhajharia, D., Dinpashoh, Y., Kahya, E., Choudhary, R.R., Singh, V.P., 2014. Trends in temperature over Godavari river basin in southern peninsular India. Int. J. Climatol. 34, 1369–1384. https://doi.org/10.1002/joc.3761.

Karim, A., Veizer, J., 2002. Water balance of the Indus River Basin and moisture source in the Karakoram and western Himalayas: Implications from hydrogen and oxygen isotopes in river water. J. Geophys. Res. Atmos. 107, 4362–4373. https://doi.org/10.1029/2000JD000253.

Kendall, C., Coplen, T.B., 2001. Distribution of oxygen-18 and deuterium in river waters across the United States. Hydrol. Process. 15, 1363–1393. https://doi.org/10.1002/hyp.217.

Kirkels, Frédérique M.S.A., 2020. Compilation of Stable Water Isotopes in Indian Rivers. PANGAEA Data Repository. https://doi.org/10.1594/PANGAEA.912582.

Kirkels, Frédérique M.S.A., Zwart, Huub M., Basu, Sayak, Usman, Muhammed O., Peterse, Francien, 2020. Physicochemical parameters and stable water isotopes in the Godavari River basin, India. PANGAEA Data Repository. https://doi.org/10.1594/PANGAEA.912579.

Komatsu, G., Kumar, P.S., Goto, K., Sekine, Y., Giri, C., Matsui, T., 2014. Drainage systems of Lonar Crater, India: contributions to Lonar Lake hydrology and crater degradation. Planet Space Sci. 95, 45–55. https://doi.org/10.1016/j.pss.2013.05.011.

Krishna, M.S., Naidu, S.A., Subbaiah, C.V., Sarma, V., Reddy, N., 2013. Distribution and sources of organic matter in surface sediments of the eastern continental margin of India. J. Geophys. Res. Biogeosci. 118, 1484–1494. https://doi.org/10.1002/2013JG002424.

Krouse, H.R., Mackay, J.R., 1971. Application of $H_2{}^{18}O/H_2{}^{16}O$ abundances to the problem of lateral mixing in the Liard–Mackenzie River system. Can. J. Earth Sci. 8, 1107–1109. https://doi.org/10.1139/e71-096.

Kumar, B., Rai, S.P., Kumar, U.S., Verma, S.K., Garg, P., Kumar, S.V., et al., 2010. Isotopic characteristics of Indian precipitation. Water Resour. Res. 46, W12548–W12562. https://doi.org/10.1029/2009WR008532.

Kumar, A., Sanyal, P., Agrawal, S., 2019. Spatial distribution of $\delta^{18}$O values of water in the Ganga river basin: insight into the hydrological processes. J. Hydrol. 571, 225–234. https://doi.org/10.1016/j.jhydrol.2019.01.044.

Lambs, L., Balakrishna, K., Brunet, F., Probst, J., 2005. Oxygen and hydrogen isotopic composition of major Indian rivers: a first global assessment. Hydrol. Process. 19, 3345–3355. https://doi.org/10.1002/hyp.5974.

Lambs, L., Gurumurthy, G.P., Balakrishna, K., 2011. Tracing the sources of water using stable isotopes: first results along the Mangalore–Udupi region, south-west coast of India. Rapid Commun. Mass Spectrom. 25, 2769–2776. https://doi.org/10.1002/rcm.5104.

Lambs, L., Bompy, F., Dulormne, M., 2018. Using an “isotopic spike” from a tropical storm to understand water exchange on a large scale: case study of Hurricane Rafael in the Lesser Antilles archipelago, October 2012. Rapid Commun. Mass Spectrom. 32, 457–468. https://doi.org/10.1002/rcm.8055.

Laraque, A., Guyot, J.L., Filizola, N., 2009. Mixing processes in the Amazon River at the confluences of the Negro and Solimões Rivers, Encontro das Águas, Manaus, Brazil. Hydrol. Processes Int. J. 23, 3131–3140. https://doi.org/10.1002/hyp.7388.

Lekshmy, P.R., Midhun, M., Ramesh, R., Jani, R.A., 2014. $^{18}$O depletion in monsoon rain relates to large scale organized convection rather than the amount of rainfall. Sci. Rep. 4, 5661–5665. https://doi.org/10.1038/srep05661.

Li, C., Yang, S., Lian, E., Yang, C., Deng, K., Liu, Z., 2016. Damming effect on the Changjiang (Yangtze River) river water cycle based on stable hydrogen and oxygen isotopic records. J. Geochem. Explor. 165, 125–133. https://doi.org/10.1016/j.gexplo.2016.03.006.

Lupker, M., France-Lanord, C., Lavé, J., Bouchez, J., Galy, V., Métivier, F., et al., 2011. A Rouse-based method to integrate the chemical composition of river sediments: application to the Ganga basin. J. Geophys. Res. Earth Surf. 116, 1–24. https://doi.org/10.1029/2010JF001947.

Matsui, E., Salati, F., Friedman, I., Brinkman, W., 1976. Isotopic hydrology in the Amazonia: 2. Relative discharges of the Negro and Solimões rivers through $^{18}$O concentrations. Water Resour. Res. 12, 781–785. https://doi.org/10.1029/WR012i004p00781.

Meese, B., Bookhagen, B., Olen, S.M., Barthold, F., Sachse, D., 2018. The effect of Indian Summer Monsoon rainfall on surface water δD values in the central Himalaya. Hydrol. Process. 32, 3662–3674. https://doi.org/10.1002/hyp.13281.

Naidu, C.V., Durgalakshmi, K., Muni Krishna, K., Ramalingeswara Rao, S., Satyanarayana, G.C., Lakshminarayana, P., et al., 2009. Is summer monsoon rainfall decreasing over India in the global warming era? J. Geophys. Res. Atmos. 114, D24108–D24123. https://doi.org/10.1029/2008JD011288.

Nair, P.J., Chakraborty, A., Varikoden, H., Francis, P.A., Kuttippurath, J., 2018. The local and global climate forcings induced inhomogeneity of Indian rainfall. Sci. Rep. 8, 6026–6037. https://doi.org/10.1038/s41598-018-24021-x.

Négrel, P., Pauwels, H., Dewandel, B., Gandolfi, J., Mascré, C., Ahmed, S., 2011. Understanding groundwater systems and their functioning through the study of stable water isotopes in a hard-rock aquifer (Maheshwaram watershed, India). J. Hydrol. 397, 55–70. https://doi.org/10.1016/j.jhydrol.2010.11.033.

Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world’s large river systems. Science 308, 405–408. https://doi.org/10.1126/science.1107887.

NOAA, National Oceanic and Atmospheric Administration, 2019. Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT). May 9, 2019. https://www.ready.noaa.gov/HYSPLIT_traj.php.

Phillips, D.L., Gregg, J.W., 2001a. IsoError. Version 1.04. https://www.epa.gov/eco-research/stable-isotope-mixing-models-estimating-source-proportions.

Phillips, D.L., Gregg, J.W., 2001b. Uncertainty in source partitioning using stable isotopes. Oecologia 127, 171–179. https://doi.org/10.1007/s004420000578.

Poage, M.A., Chamberlain, C.P., 2001. Empirical relationships between elevation and the stable isotope composition of precipitation and surface waters: considerations for studies of paleoelevation change. Am. J. Sci. 301, 1–15. https://doi.org/10.2475/ajs.301.1.1.

Ponton, C., Giosan, L., Eglinton, T.I., Fuller, D.Q., Johnson, J.E., Kumar, P., et al., 2012. Holocene aridification of India. Geophys. Res. Lett. 39, L03704–L03709. https://doi.org/10.1029/2011GL050722.

Pradhan, U.K., Wu, Y., Shirodkar, P.V., Zhang, J., Zhang, G., 2014. Multi-proxy evidence for compositional change of organic matter in the largest tropical (peninsular) river basin of India. J. Hydrol. 519, 999–1009. https://doi.org/10.1016/j.jhydrol.2014.08.018.

Rahul, P., Ghosh, P., 2019. Long term observations on stable isotope ratios in rainwater samples from twin stations over Southern India; identifying the role of amount effect, moisture source and rainout during the dual monsoons. Clim. Dyn. 52, 6893–6907. https://doi.org/10.1007/s00382-018-4552-1.

Rahul, P., Ghosh, P., Bhattacharya, S.K., Yoshimura, K., 2016. Controlling factors of rainwater and water vapor isotopes at Bangalore, India: constraints from observations in 2013 Indian monsoon. J. Geophys. Res. Atmos. 121, 13936–13952. https://doi.org/10.1002/2016JD025352.

Ramesh, R., Sarin, M.M., 1992. Stable isotope study of the Ganga (Ganges) river system. J. Hydrol. 139, 49–62. https://doi.org/10.1016/0022-1694(92)90194-Z.

Rao, G.N., 1998. Interannual variations of monsoon rainfall in Godavari river basin—connections with the Southern Oscillation. J. Clim. 11, 768–771. https://doi.org/10.1175/1520-0442(1998)011<0768:IVOMRI>2.0.CO;2.

Rao, S.A., Chaudhari, H.S., Pokhrel, S., Goswami, B.N., 2010. Unusual central Indian drought of summer monsoon 2008: role of southern tropical Indian Ocean warming. J. Clim. 23, 5163–5174. https://doi.org/10.1175/2010JCLI3257.1.

Rolph, G., Stein, A., Stunder, B., 2017. Real-time Environmental Applications and Display System: READY. Environ. Model. Softw. 95, 210–228. https://doi.org/10.1016/j.envsoft.2017.06.025.

Roxy, M.K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., et al., 2017. A threefold rise in widespread extreme rain events over central India. Nat. Commun. 8, 708–718. https://doi.org/10.1038/s41467-017-00744-9.

Sarkar, S., Prasad, S., Wilkes, H., Riedel, N., Stebich, M., Basavaiah, N., et al., 2015. Monsoon source shifts during the drying mid-holocene: biomarker isotope based evidence from the core 'monsoon zone'(CMZ) of India. Quat. Sci. Rev. 123, 144–157. https://doi.org/10.1016/j.quascirev.2015.06.020.

Sharma, A., Kumar, K., Laskar, A., Singh, S.K., Mehta, P., 2017. Oxygen, deuterium, and strontium isotope characteristics of the Indus River water system. Geomorphology 284, 5–16. https://doi.org/10.1016/j.geomorph.2016.12.014.

Shivanna, K., Kulkarni, U.P., Joseph, T.B., Navada, S.V., 2004. Contribution of storms to groundwater recharge in the semi-arid region of Karnataka, India. Hydrol. Process. 18, 473–485. https://doi.org/10.1002/hyp.1323.

Singh, N., Sontakke, N.A., Singh, H.N., Pandey, A.K., et al., 2005. Recent trend in spatiotemporal variation of rainfall over India—an investigation into basin-scale rainfall fluctuations. In: Franks, S., Wagener, T., Bogh, E., Gupta, H., Bastidas, L., Nobre, C. (Eds.), Regional Hydrological Impacts of Climate Change – Hydroclimate Variability. IAHS Press, Wallingford, United Kingdom, pp. 273–282.

Singh, D., Tsiang, M., Rajaratnam, B., Diffenbaugh, N.S., 2014. Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. Nat. Clim. Chang. 4, 456–461. https://doi.org/10.1038/nclimate2208.

Somayajulu, B., Rengarajan, R., Jani, R.A., 2002. Geochemical cycling in the Hooghly estuary, India. Mar. Chem. 79, 171–183. https://doi.org/10.1016/S0304-4203(02)00062-2.

Stein, A.F., Draxler, R.R., Rolph, G.D., Stunder, B.J., Cohen, M.D., Ngan, F., 2015. NOAA's HYSPLIT atmospheric transport and dispersion modeling system. Bull. Am. Meteorol. Soc. 96, 2059–2077. https://doi.org/10.1175/BAMS-D-14-00110.1.

Szabo, S., Brondizio, E., Renaud, F.G., Hetrick, S., Nicholls, R.J., Matthews, Z., et al., 2016. Population dynamics, delta vulnerability and environmental change: comparison of the Mekong, Ganges–Brahmaputra and Amazon delta regions. Sustain. Sci. 11, 539–554. https://doi.org/10.1007/s11625-016-0372-6.

Tripti, M., Lambs, L., Otto, T., Gurumurthy, G.P., Teisserenc, R., Moussa, I., et al., 2013. First assessment of water and carbon cycles in two tropical coastal rivers of south-west India: an isotopic approach. Rapid Commun. Mass Spectrom. 27, 1681–1689. https://doi.org/10.1002/rcm.6616.

Tripti, M., Lambs, L., Gurumurthy, G.P., Moussa, I., Balakrishna, K., Chadaga, M.D., 2016. Water circulation and governing factors in humid tropical river basins in the central Western Ghats, Karnataka, India. Rapid Commun. Mass Spectrom. 30, 175–190. https://doi.org/10.1002/rcm.7424.

Tripti, M., Lambs, L., Moussa, I., Corenblit, D., 2019. Evidence of elevation effect on stable isotopes of water along highlands of a humid tropical mountain belt (Western Ghats, India) experiencing monsoonal climate. J. Hydrol. 573, 469–485. https://doi.org/10.1016/j.jhydrol.2019.03.086.

Turner, A.G., Annamalai, H., 2012. Climate change and the South Asian summer monsoon. Nat. Clim. Change 2, 587–595. https://doi.org/10.1038/nclimate1495.

Usman, M.O., Kirkels, F.M.S.A., Zwart, H.M., Basu, S., Ponton, C., Blattmann, T.M., et al., 2018. Reconciling drainage and receiving basin signatures of the Godavari River system. Biogeosciences 15, 3357–3375. https://doi.org/10.5194/bg-15-3357-2018.

Varis, O., Kummu, M., Salmivaara, A., 2012. Ten major rivers in monsoon Asia-Pacific: an assessment of vulnerability. Appl. Geogr. 32, 441–454. https://doi.org/10.1016/j.apgeog.2011.05.003.

Warrier, C.U., Babu, M.P., Manjula, P., Velayudhan, K.T., Hameed, A.S., Vasu, K., 2010. Isotopic characterization of dual monsoon precipitation-evidence from Kerala, India. Curr. Sci. 98, 1487–1495.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., Kitoh, A., 2012. APHRODITE: constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. Bull. Am. Meteorol. Soc. 93, 1401–1415. https://doi.org/10.1175/BAMS-D-11-00122.1.

Yihui, D., Chan, J.C., 2005. The East Asian summer monsoon: an overview. Meteorol. Atmos. Phys. 89, 117–142. https://doi.org/10.1007/s00703-005-0125-z.

Zhang, J., Letolle, R., Martin, J.M., Jusserand, C., Mouchel, J.M., 1990. Stable oxygen isotope distribution in the Huanghe (Yellow River) and the Changjiang (Yangtze River) estuarine systems. Cont. Shelf Res. 10, 369–384. https://doi.org/10.1016/0278-4343(90)90057-S.