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# Status of the River Krishna: Water quality and riverine environment in relation to fisheries

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*The River Krishna, the second largest peninsular river of India, was investigated during pre-monsoon, monsoon, and post-monsoon seasons to improve the understanding of its ecology through analysis of physical and chemical parameters of water and sediment. Important tributaries of the river were also studied simultaneously to understand their influence on the main stream of the River Krishna. In addition to 25 sampling sites along the main stream of the River Krishna, sampling was also done in 13 important tributaries at sites upstream of the confluence point. Dams, barrages and anicuts have visible impacts on all of the observed physical and chemical properties of water and soil. Statistical analysis revealed that water parameters have a strong association with sediment parameters. However, the study was unable to find any relation between primary production and water quality parameters. Fish species distribution was strongly influenced by temperature and water depth, as well as specific conductivity, as observed through Canonical Correspondence Analysis.*

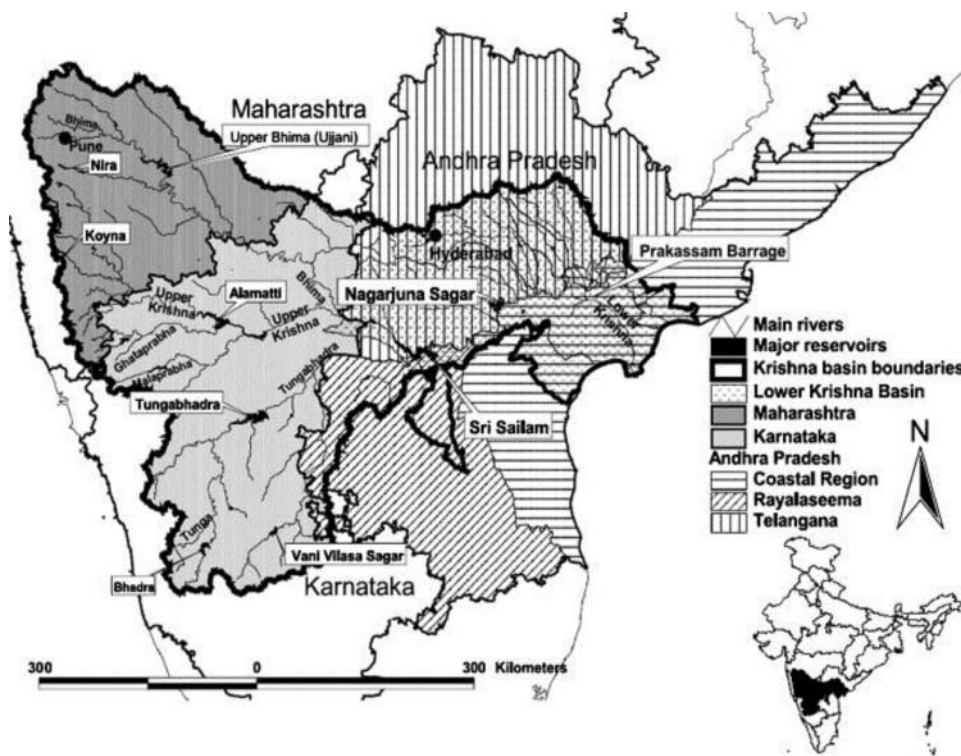
**Keywords:** Water-sediment-fish relationship, MANOVA, canonical correlation analysis

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## Introduction

The River Krishna is the second largest peninsular river of India after the River Godavari and has a drainage area of 268,786 km<sup>2</sup>, of which 25.8% falls in the state of Maharashtra, 42.4% in Karnataka and 31.8% in Andhra Pradesh (Figure 1). Originating from the Mahabaleswar Hills (1337 m asl) of the Western Ghats in Maharashtra, it traverses 1,400 km from west to east through the three states before emptying into the Bay of Bengal. Important tributaries of the River Krishna are Wenna, Urmodi, Tarli, Koyna, Ghataprabha, Malaprabha, Bhima, Tungabhadra and Musi. During recent decades, the flow of the River Krishna and most of its tributaries has been

entirely modified by regulated water releases from a number of dams, barrages, anicuts, constructed on the main channel as well as on tributaries, to meet the ever-increasing demand for water. Total storage capacity from various irrigation projects on the Krishna basins was 29,860 MCM (Central Pollution Control Board, 1989), with 90% of stored water from large irrigation projects being used entirely for agricultural purposes. Additionally, a number of irrigation projects commissioned after 1980 further reduced the river flow, converting streams into a combination of stagnant pools. The major dams on the main river are Dhom, Almatti, Naryanpur, Srisailem and Nagarjunasagar, along with a number of anicuts and barrages. The flow of the River Krishna is first obstructed by

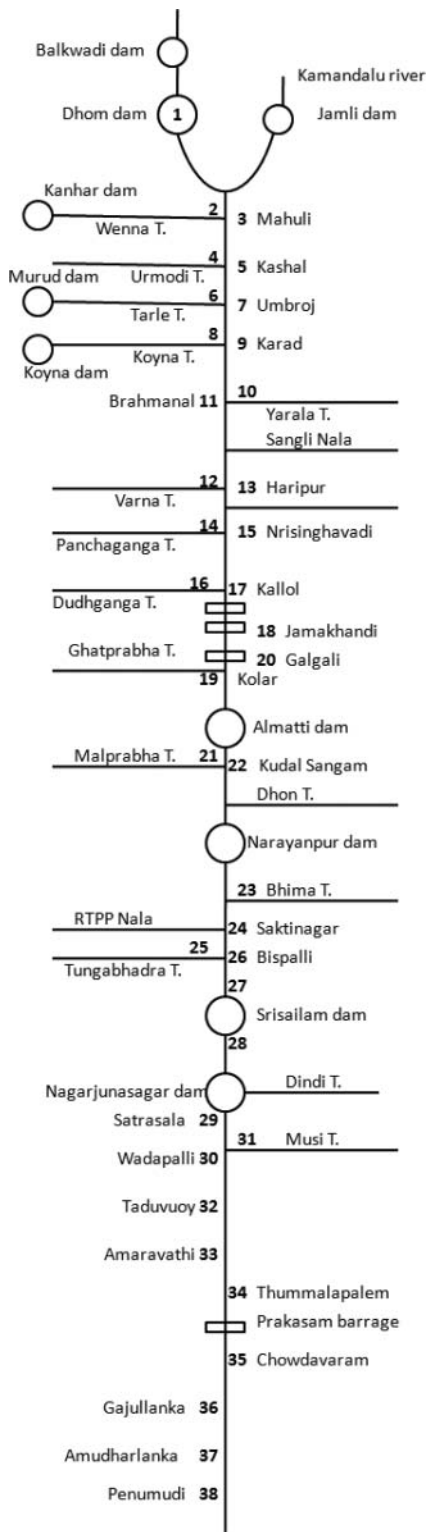


**Figure 1.** Map of the River Krishna basin (based on Molle et al., 2010).

the Balkwadi dam, followed by the Dhom dam, where the Kamandalu River joins with the Krishna (Figure 2). Upstream of the Kamandalu River, water flow is also checked by the Jamli dam. Downstream of the Dhom dam and up to Wai, there is very sparse water flow over a rocky and gravely riverbed during post- and pre-monsoon seasons, but the flow improves slightly during the monsoon season. Downstream of Wai, the riverbed is sandy, sandy-loam, or sandy-clay-loam. The Krishna River from Wai to Kurnool is joined by more than 15 tributaries. These tributaries play a significant role in bringing silty-clay particles into the main river, producing large changes in the nature and properties of riverbed sediments. The maximum annual run-off from the Krishna R. basin is high at 1,066,349 MCM, while the minimum is only 9.0 MCM, with a mean discharge of 67,305 MCM. Thus, with a total catchment of 268,786 km<sup>2</sup> and a mean rainfall of 1510 mm, the run-off per unit of catchment is about 0.250 MCM km<sup>-2</sup>. Over 80% of the annual flow occurs in the three monsoon months and, coupled with the uneven distribution of rainfall (6000 mm annually in the Western Ghats, 500 mm in the Western

Peneplains, 1500 mm in the Eastern Ghats, and 1000 mm in the Coastal Plains), water flows can be drastically reduced in places, e.g. 1 MCM in the main Krishna channel at Kunchi and, at Nagarjunasagar, which normally has the highest flow during the monsoon (31,784 MCM), dropping to a mere 285 MCM during summer (CPCB, 1989; Rao, 1979).

Most Indian rivers flow through tropical and sub-tropical regions with a high potential for fresh-water fish diversity (Oberdorff et al., 1995). However, a severe decline in capture fisheries of Indian rivers has been observed during the past few decades because of intense human intervention resulting in habitat loss and degradation. As a consequence, many indigenous as well as endemic fish species have become highly endangered. The main causes behind the decline of riverine fish diversity are: habitat destruction (Cuizhang et al., 2003), heavy siltation, water abstraction/diversion for industries, irrigation (Szollosi-Nagy, 2004), faulty river embankment strategies for flood control, anthropogenic loads, pollution (Lima-Junior et al., 2006), and construction of weirs and barrages obstructing migration of fish. These stresses



**Figure 2.** Schematic diagram of the River Krishna showing the sampling sites.

are coupled with overexploitation and unscrupulous fishing practices like dynamiting/poison baiting, and exotic species introduction (Copp et al., 2005), which will be further worsened by global climate change (Leveque et al., 2005; Mas-Marti et al., 2010). The situation is aggravated by the failure of rainfall in certain areas, especially in seasonal rivers when stream flows drop far below the environmental flows required for sustainable survival of aquatic organisms, including fish. Consequently, there is a need for information on the present status of river ecology and fisheries. This could help in the development of holistic management guidelines for any Indian river to aid in sustaining fisheries, fish, and other aquatic organisms. However, for most of the Indian rivers, information on the present status of ecology and fisheries is grossly lacking. This article examines the limno-chemical status of the entire stretch of the River Krishna and its environment in relation to fisheries. The purpose of this study is to help unravel the present capacity of the eco-physiography of this peninsular river in order to sustain the riverine ecology as well as its fisheries.

**Sampling program and methodology**

The entire stretch of the River Krishna was divided into two study regions—the upper stretch (Maharashtra & Karnataka) and the lower stretch (Andhra Pradesh). In the upper and lower stretches, 15 and 10 sampling sites were selected, respectively (Table 1 and Figure 2). In addition, sampling was done in 13 important tributaries at sites upstream of the confluence point (indicated with the suffix T in Table 1 and Figure 2). At each site, sampling was done for various limnological parameters and assessment of phytoplankton primary production. Data on fish and fisheries were also collected. Samples were collected in three time periods: post-monsoon (Oct–Nov, 2001); pre-monsoon, i.e. summer (S, May–June, 2002); and monsoon (M, September, 2002).

Samples of sediment and water were collected from across the river in three sub-sites: (i) one km upstream of the confluence, (ii) the second one at the confluence and (iii) the third one at one km below the confluence of any tributary with the main River Krishna. If there is no tributary at the sampling site, limnological samplings were done from

**Table 1.** Sampling sites in the River Krishna and its tributaries (shown with suffix T.).

Sl. No.	Sl. No. (Tributary)	Sampling stations	Abbreviation
1.		Dhom dam	DH
1.	1.	Wenna T.	WP
2.		Mahuli	MH
3.	2.	Urmodi T.	UM
4.		Kashal	KS
5.	3.	Tarle T.	TL
6.		Umbroji	UJ
7.	4.	Koyna T.	KT
8.		Karad	KD
9.	5.	Yerala T.	YL
10.		Brahmanal	BN
11.	6.	Varna T.	VN
12.		Haripur	HP
13.	7.	Pancha Ganga T.	PG
14.		N. Vadi	NV
15.	8.	Dud Ganga T.	DG
16.		Kallol	KL
17.		Jamakhadi	JK
18.	9.	Ghatprabha T.	GP
19.		Galgali	GL
20.	10.	Malaprabha T.	MP
21.		Kudalasangam	KS
22.	11.	Bhima T.	BT
23.		Shaktinagar	SN
24.	12.	Tungabhadra T.	TB
25.		Bisipalli	BP
26.		Srisailem up	SU
27.		Srisailem Down/ Lingalaghattu	SD
28.		Satrasala	SS
29.		Wadapalli	WP
30.	13.	Musi T.	MT
31.		Taduvouy	TV
32.		Amaravathy	AV
33.		Thummalapalayam	TP
34.		Choudavaram	CV
35.		Gajullanka	GL
36.		Amudharlanka	AL
37.		Penumudi	PM

only one location in the river. All samples were collected at 9:00 am. Sediment samples were randomly collected from between five and six locations across the river from each sub-sector. Except for nutrient parameters, other physico-chemical features of the water were determined in

situ immediately after collection. Water samples were fixed with preservatives and analyzed in the laboratory. Chemical analyses of water were performed following APHA (1992) Standard Methods. Soil analysis was undertaken using standard methods described by Tandon (1993). Primary production was estimated up to one meter depth using the dark and light bottle technique (Vollenweider, 1969) utilising an incubation period of 4 hrs (10:00 to 14:00). Data related to fish and fisheries were collected in situ, and from local markets, landing centers, and the respective State Fishery Offices, as well as respective Fishermen Cooperative Societies along the riverine course. Experimental fishing was also done, as required and when feasible, along the entire course of the River Krishna by project personnel and the local fisher folk. Sampling was carried out both by day (06:00 to 10:00) and at night (18:00 to 21:00) at three sub sites of 10–50 m length each, at almost all the sites during the study period. The types of gear used to collect fish included cast nets, gill nets, drag nets (all with varying mesh sizes), and other local improvised gear (Manna et al., 2011). Each type of gear was used at least 10–12 times in all the sites across the river. Fish Species Richness (FSR) was determined by counting the number of fish species encountered at least five times at each sampling site. Representative specimens ( $n = 10$ ) of all fish species were fixed in 10% formaldehyde and transferred to the laboratory for identification. Identification was performed following Jayaram (1981, 1999), and Talwar and Jhingran (1991). The relative abundance (percentage of catch) of fish species by weight and by numbers across different sites was determined.

Multivariate analysis was carried out to characterize the environment, species community structure, and their interaction. Multivariate Analysis of Variance (MANOVA) was used to test statistical significance of the seasonal variation of sediment and water quality. The relationship between water and sediment quality variables was examined using Canonical Correlation Analysis (CCA). Constrained Correspondence Analysis was performed to explore species–environment relationships.

## Physical features of the River Krishna and its tributaries

The catchment of Mahabaleswar is covered with evergreen forest comprising forest-origin red

soil. Below Wai, the river is slow, descending down to plains, and the width is extended wherever a tributary joins the Krishna. Maximum depths were noticed at barrages and anicuts like Brahmanal, Jamakhandi, Galgali, Kudal sangam, and Bispalli, as well as in some zones of the Krishna delta. The river is the widest downstream of Vijayawada, at between 500 and 3,000 m, as compared to upstream at 50 to 500 m, except at Kudalsangam, where it was more than 9,000 m wide, being swollen by the Narayanpur reservoir. Most of the tributaries were narrow, having minimum depth particularly at confluence points. However, many of the tributaries at and below their origin are quite deep as they pass through gorges such as Wenna, Urmodi, Tarle, Koyna, Pancha Ganga, Ghataprabha, Malaprabha and even Tungabhadra. The water flow in tributaries is obstructed/hindered by dams/anicuts/barrages. However, even with the low volume of water being diverted into the main river, the tributaries of Krishna exert visible impacts on the sediment and water chemistry of the main river (Manna and Das, 2004). These impacts were more pronounced during monsoon (Table 1). Spatiotemporal variation of physical features of the river like water depth, flow, temperature, and transparency are described below.

## Depth

Depth variation in the River Krishna showed the impact of water flow regulation by dams, barrages and anicuts. The very high water depth at DH and SU were due to water retention by the Dhom and Srisailem dams, respectively (Figure 3a). Satrasala (SS) is a gorgy deep pool located between two hillocks (Manna et al., 2003). The higher water depth at Thummalapalem (TP) is due to water regulation by the Prakasam barrage at Vijayawada.

## Flow

The impacts of human intervention were well pronounced in the flow regime of the entire stretch of the River Krishna. Release of water from upstream dams or local tributaries mostly controlled the flow pattern of the river (Figure 3b). The higher flow at Wadapalli (WP) in the lower stretch of the river was due to the curve and slope of the Krishna.

## Water temperature

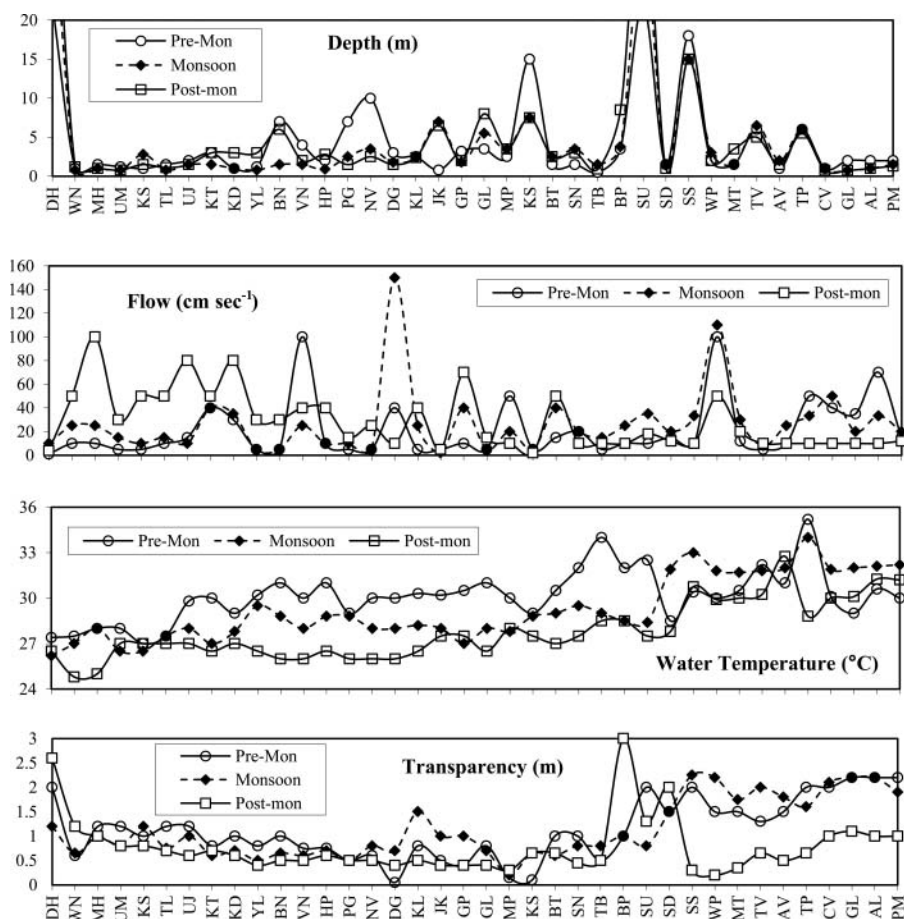
Surface water temperature increased sinusoidally, keeping parity with air temperature. Accordingly, higher water temperatures ( $^{\circ}\text{C}$ ) were observed in summer (27.0–35.2; av. 30.13), followed by monsoon (26.5–34.0; av. 29.24) and post-monsoon (24.8–32.8; av. 27.8) in the entire river course (Figure 3c). Higher temperatures occurred in the riverine sheet flow compared to deeper waters (lotic waters of downstream reservoirs, anicuts, barrages), even in the same season. Unlike other Indian rivers, the River Krishna basin, especially in Maharashtra and Andhra Pradesh, is predominantly covered with black soil having high heat retentive capacity, which is reflected in the higher water temperatures. In general, water temperature was slightly lower than air temperature, except at Thummalapalem (TP) where the water temperature was higher due to hot water discharge from a nearby thermal power station.

## Transparency

Water transparency was observed to be influenced by local factors. Significantly higher water transparency, especially in the lower stretch of the River Krishna, may be attributed to higher regulated water flow from Nagarjunasagar reservoir, as well as hindered water flow at Prakasam barrage at Vijayawada. This has helped in the growth of dense aquatic macrophytes, especially the rooted submerged varieties, along the shoreline of the river (Manna et al., 2010). Those shoreline macrophytes have a definite role in the higher transparency regime, as they prevent soil erosion as well as trap suspended silt through their leaves. Higher transparency below the Prakasam barrage (CV to PM) is due to controlled water release from the barrage as well as the sandy bottom of this stretch of the river (Figure 3d).

## Sediment characteristics of the River Krishna

Sediment analysis was not performed at only four of the total 38 sampling stations. At Srisailem Down (SD), the river bottom is rocky and full of boulders and pebbles, and hence no sampling for sediment was performed. Below the Prakasam



**Figure 3.** Spatiotemporal variation of water depth, flow, temperature and transparency in the River Krishna.

barrage at Vijayawada, the riverbed is full of sand and water is flowing through a very narrow channel in the wide river bed. Due to this, no sampling was performed for bottom sediment at Chowdavararam (CV), Gajullanka (GL), and Amudharlanka (AL). Results of selected sediment parameters of the remaining 34 sampling stations on the main channel of Krishna and its tributaries are given below.

### Sediment pH

Soils in the Krishna basin are red, black, laterite, alluvium, etc. Soil pH was moderately alkaline in the range of 7.30–8.52 (av. 7.68), 6.97–8.34 (av. 7.56), and 7.46–8.40 (av. 7.84) in pre-monsoon, monsoon, and post-monsoon seasons respectively, and increased gradually from upstream to downstream (Figure 4a). Higher soil

pH was recorded in the Musi tributary. Lower pH at a few stations can be linked to higher organic matter accumulation, either due to deep pools (Manna et al., 2003) or local anthropogenic input. Higher pH was observed to be associated with higher  $\text{CaCO}_3$  content of the sediment ( $r = 0.58$ ,  $p < 0.001$ ).

### Sediment specific conductance

Moderate values of specific conductance ( $\text{mScm}^{-1}$ ) were also noticed in the entire river course, with higher values pre-monsoon (0.15–1.96; av. 0.68) as compared to monsoon (0.142–3.77; av. 0.58) and post-monsoon (0.12–3.39; av. 0.58) (Figure 4b). Higher organic accumulation at the bottom was generally associated with higher specific conductance ( $r = 0.64$ ,  $p < 0.001$ ).

Soil organic carbon

Sediment carbon content (%) was moderate in the River Krishna, with 0.26–2.19% (av. 0.77) during pre-monsoon, 0.33–5.85% (av. 0.81) during monsoon, and 0.3–1.99% (av. 0.83) during post-monsoon, except at Satrasala (SS), where high accumulation of dead filamentous algae over the sediment surface resulted in very high organic carbon accumulation (up to 5.85%), especially during monsoon (Figure 4c). Shoreline submerged macrophytes might have a role in organic accumulation in the Taduvouy (TV) region.

Soil total N

Soil total N (%) of the River Krishna varied in the range of 0.024–0.290 (av. 0.09) during pre-monsoon, 0.019–0.476 (av. 0.104) during monsoon, and 0.021–0.498 (av. 0.12) during post-monsoon (Figure 4d). Levels paralleled those of soil organic carbon ( $r = 0.59$ ,  $p < 0.001$ ).

Soil C/N ratio

Sediment C/N ratios were 2.47–27.69 (av. 10.80) during pre-monsoon, 3.15–20.22 (av. 8.77)

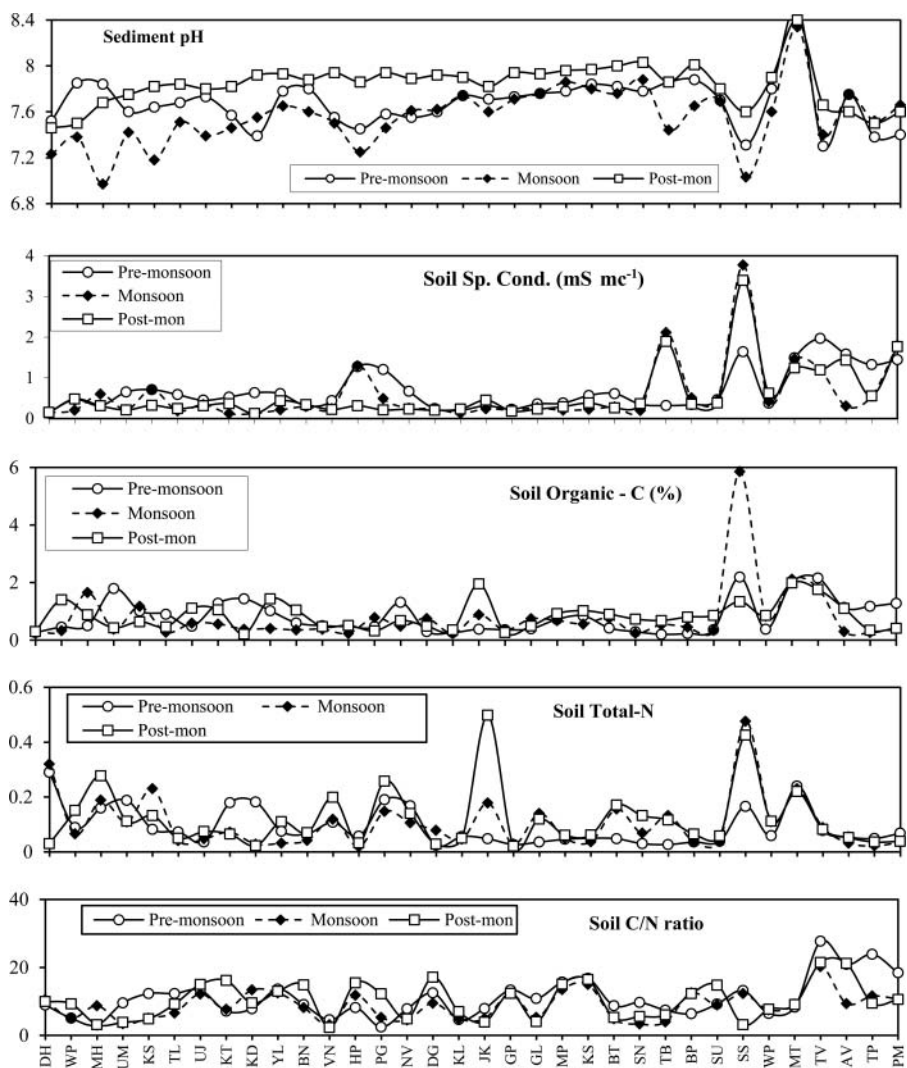


Figure 4. Spatiotemporal variation of Sediment pH, sp. conductance, organic carbon, total N and C/N ratio in the River Krishna.



during monsoon, and 2.36–21.46 (av. 10.19) during post-monsoon (Figure 4e).

## Soil available nitrogen

Soil available nitrogen (mg/100 g) was in the moderate range of 10.89–76.66 (av. 28.27), 10.60–80.50 (av. 28.05), and 4.25–80.62 (av. 29.92) in pre-monsoon, monsoon, and post-monsoon, respectively (Figure 5a). Soil available nitrogen was correlated with soil total N ( $r = 0.81$ ,  $p < 0.001$ ).

## Soil available P

Available P (mg 100 g<sup>-1</sup>) was fairly rich in the River Krishna sediments, unlike other Indian rivers, and ranged from 0.56–13.00 (av. 2.61), 0.56–20.56 (av. 4.11), and 0.44–12.55 (av. 3.10) in pre-monsoon, monsoon, and post-monsoon, respectively (Figure 5b). Local pollution has a visible impact on high available phosphorous at Amaravathy (AV), especially during monsoon season.

## Soil CaCO<sub>3</sub>

Soil CaCO<sub>3</sub> (%) was observed to be in the range of 1.0–3.6 (av. 2.62), 0.5–3.5 (av. 2.37), and 0.8–3.8 (av. 2.82) in pre-monsoon, monsoon, and post-monsoon, respectively (Figure 5c). In the middle

stretch of the river from Nrsinghavadi (NV) to Wadapalli (WP), sediment contains higher CaCO<sub>3</sub> content as compared to the uppermost or lowermost stretches of the river.

## Limno-chemical features of the water of the River Krishna

### Water pH

Water was moderately alkaline in the entire river stretch and varied in the range of 7.90–8.48 (av. 8.20), 7.78–8.30 (av. 8.00), and 7.76–8.47 (av. 8.13) during pre-monsoon, monsoon, and post-monsoon, respectively (Figure 6a). Slightly lower pH levels during monsoon may be attributed to lower photosynthetic activity in this season.

### Water specific conductance

Specific conductance ( $\mu\text{Scm}^{-1}$ ) trended higher from the origin to downstream and fluctuated widely in tributaries (Figure 6b). Penumudi, the extreme lowest estuarine station, showed higher values of sp. conductance (1,440, 16,820, and 1,350  $\mu\text{Scm}^{-1}$  in pre-monsoon, monsoon, post-monsoon, respectively) due to ingress of seawater during high tide. In general, tributaries showed much higher specific conductivity as compared to

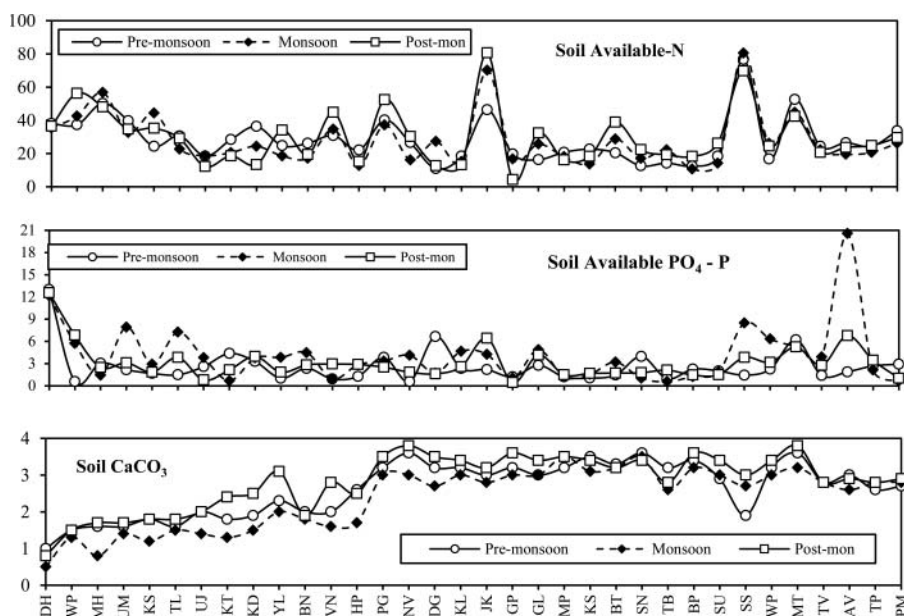


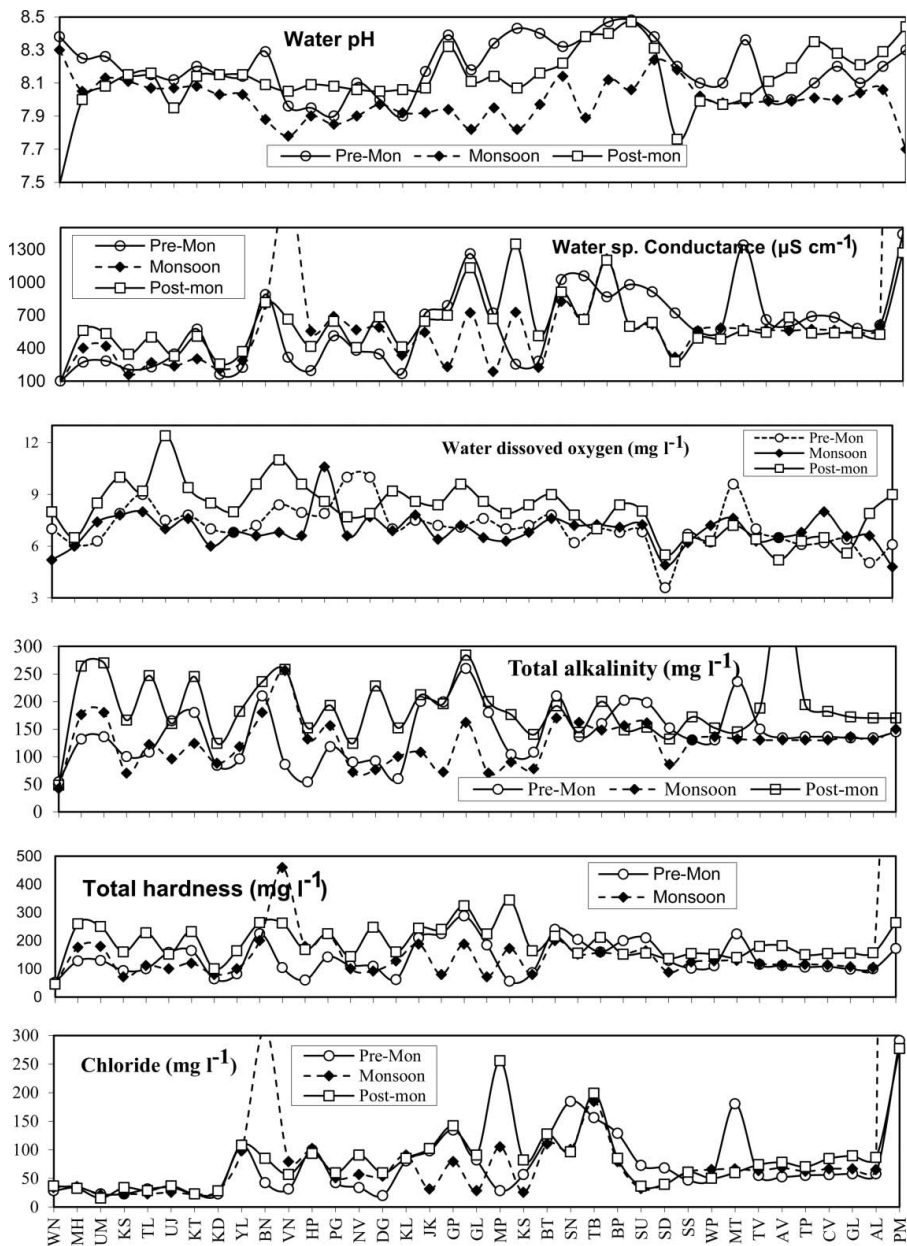
Figure 5. Spatiotemporal variation of soil-available N, P and CaCO<sub>3</sub> in the River Krishna.

the main stream of the river, indicating nutrient loading by tributaries.

Dissolved oxygen (DO)

Amongst dissolved gases, DO was fairly rich in Krishna water at most of the sampling sites. DO ( $\text{mg l}^{-1}$ ) varied in the range of 3.6–10.0 (av. 7.15),

4.8–10.6 (av. 6.91), and 5.2–12.4 (av. 8.11) in pre-monsoon, monsoon, and post-monsoon, respectively (Figure 6c). The lowest DO ( $3.6 \text{ mg l}^{-1}$ ) was recorded at Srisailam Down (SD) due to the release of bottom water from the dam. Higher DO during post-monsoon may be due to relatively lower water temperatures, as well as higher photosynthetic activity in relatively less disturbed waters.



**Figure 6.** Spatiotemporal variation of important water parameters (pH, conductivity, dissolved oxygen, total alkalinity, total hardness and chloride) of the River Krishna.

## Free CO<sub>2</sub>, carbonate, bicarbonate and total alkalinity

Free CO<sub>2</sub> (mg l<sup>-1</sup>) remained absent downstream from Taduvouy (TV) onwards in all the seasons, probably due to rapid consumption by dense shoreline aquatic vegetation; in the mid-stretch, it was 1.0–3.0 year round, and Haripur (HP) showed the highest value of free CO<sub>2</sub> (5 mg l<sup>-1</sup>) during pre-monsoon due to local pollution. Carbonates measured nil to 36 mg l<sup>-1</sup> in the entire river. Bicarbonate content (mg l<sup>-1</sup>) fluctuated in the range 54–232 (av. 129.3), 42–256 (av. 116.1), and 48–420 (av. 180.2) during pre-monsoon, monsoon, and post-monsoon, respectively. Accordingly, total alkalinity ranged between 54–260 (av. 140.5), 42–256 (av. 125.9), and 48–428 (av. 189.4) during pre-monsoon, monsoon, and post-monsoon, respectively (Figure 6d). Very high total alkalinity (428 mg l<sup>-1</sup>) at Amaravathy (AV) during post-monsoon was due to severe local pollution as a result of such as activities as washing of clothes in the river.

## Total hardness, calcium and magnesium

Total hardness (mg l<sup>-1</sup>) ranged between 52 and 288 (av. 137.7) in pre-monsoon, and 44–460 (av. 187.0) in monsoon, 45–344 (av. 192.6) in post-monsoon, except for a high value of 2000 mg l<sup>-1</sup> at Penumudi (PM) in monsoon due to ingress of seawater (Figure 6e). Calcium (mg l<sup>-1</sup>) was fairly rich in the Krishna, unlike other Indian peninsular rivers, and registered low values in pre-monsoon (9.62–46.22; av. 25.6) as compared to monsoon (9.61–91.38; av. 41.8) and post-monsoon (12.03–57.72; av. 39.7). Magnesium (mg l<sup>-1</sup>) also was moderately rich and ranged from 2.90 to 56.26 in the entire river stretch during the study period. Penumudi (PM) recorded significantly higher Ca and Mg contents (625.25 mg l<sup>-1</sup> and 106.62 mg l<sup>-1</sup>) in monsoon due to mixing of seawater.

## Chloride

Local pollution was well pronounced in the Krishna due to influx from its tributaries, as indicated by higher chloride content in tributaries like Yerala (YL), Ghataprabha (GP), Malaprabha (MP), Bhima (BT), Tungabhadra (TB) and Musi (MT), as compared to chloride content in nearby

stations on the main river (Manna and Das, 2004) (Figure 6f). At times, local anthropogenic pollution of the main stream also played a role in the higher chloride content. Penumudi (PM) registered the highest values of chloride in all three seasons, mainly due to the impact of estuarine tidal influence. Also, high local pollution at Brahmanal (BN) during monsoon was indicated by high chloride content (312.4 mg l<sup>-1</sup>).

## Nutrient status of the water of the River Krishna

### Nitrate-N

Amongst dissolved nutrients, nitrate (N) (μg l<sup>-1</sup>) fluctuated widely from 5 to 654, 9 to 345, and 3 to 1095 during pre-monsoon, monsoon, and post-monsoon months, respectively, in the entire river stretch. Jamakhandi (JK) registered the highest nitrate content (8058 μg l<sup>-1</sup>) in the post-monsoon period (Figure 7a).

### Phosphate-P

Soluble reactive phosphorus (μg l<sup>-1</sup>) was evenly distributed in the entire river course, with increases at some downstream sites, and ranges of 4–165, 20–320 and 28–252 in pre-monsoon, monsoon and post-monsoon periods, respectively (Figure 7b). Local pollution at Amaravathy (AV) had a perceptible influence, with significantly higher phosphate content.

### Silicate-silica

Silicate (SiO<sub>2</sub>) varied in the range of 5.03–18.29 (av. 8.95), 6.58–17.15 (av. 10.03) and 4.92–8.42 (6.21) in pre-monsoon, monsoon, and post-monsoon, respectively (Figure 7c). Overall, the Krishna system showed higher values of dissolved nutrients in water than other Indian rivers.

## Statistical analysis of sediment and water quality parameters of River Krishna

Multivariate Analysis of Variance (MANOVA) was employed to test the hypothesis regarding

seasonal variation of water and sediment quality parameters. For both water and sediment parameters, four test statistics—Wilks’ Lambda, Pillai’s Trace, Hotelling–Lawley Trace and Roy’s Greatest Root—were found to be statistically significant ( $p$ -value  $< 0.001$ ) for sediment quality parameters. Seasonal variation of individual parameters were analysed under one-way ANOVA. It indicated that excepting specific conductivity of water quality and available P of sediment quality, all other parameters were significantly different during different seasons. The boxplot showed that temperature and transparency significantly differ from summer months to those in the monsoon and post-monsoon seasons. Similarly, DO and TA are significantly higher in the post-monsoon season than during monsoon and summer. Apart from available P, all other parameters of sediment quality differ significantly between the post-monsoon season and the other two seasons.

Association between water quality and sediment quality parameters

Canonical Correlation Analysis was carried out for characterizing the association between water

and sediment quality parameters. The results (Table 2) showed that three canonical variates explain 92.0% of the correlation and they are statistically significant ( $p$ -value  $< 0.001$ ). Multiple regressions for predicting the sediment parameters from water quality parameters are given in Table 3. Except for sediment sp. conductivity and C/N ratio, all other parameters have associations with one or more water parameters.

Primary productivity of River Krishna

The overall range of gross primary production (GPP,  $\text{mg C m}^{-3} \text{ h}^{-1}$ ) in pre-monsoon, monsoon, and post-monsoon seasons was 15.00 to 281.25 (av. 87.08), 9.375 to 693.75 (av. 64.28) and 18.75 to 164.06 (av. 64.28), respectively (Figure 8a). The highest GPP recorded was 693.75 mg at Hari-pur (HP) during monsoon due to anthropogenic local pollution stimulating a *Microcystis* bloom. Higher production at Jamakhandi (JK), Bispalli (BP), and Thummalapalem (TP) was due to an-cuts and stagnant conditions. The downstream stretch of the river zone is always more productive due to accumulation of more nutrients and ions.

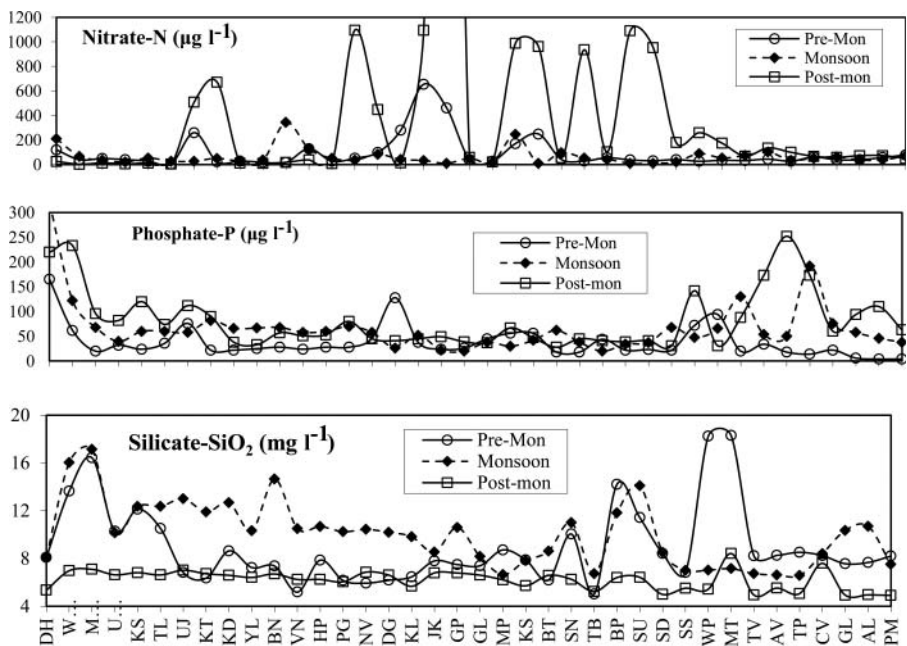


Figure 7. Spatiotemporal variation of available nutrients in water of the River Krishna.

**Table 2.** Results of canonical correlation analysis\* between water and sediment quality parameters.

Sl. No.	Canonical Correlation	Approximate Standard Error	Cumulative Proportion	p-value
1	0.871	0.027	0.450	<0.001
2	0.839	0.033	0.801	<0.001
3	0.671	0.061	0.920	<0.001
4	0.469	0.087	0.961	0.420

\*First 4 canonical correlations were shown.

Net production (NPP,  $\text{mg C m}^{-3} \text{ h}^{-1}$ ) also, in most sites, followed the same trend as observed for GPP and was approximately 50% of GPP at most stations irrespective of seasons (Figure 8b).

Community respiration (CR,  $\text{mg C m}^{-3} \text{ h}^{-1}$ ) varied widely amongst the centers and ranged from 1.88–67.76 (26.71), 3.75–93.75 (21.60) and 18.75–164.06 (64.28) in pre-monsoon, monsoon, and post-monsoon, respectively (Figure 8c). Bispalli (BP) and Haripur (HP) demonstrated higher community respiration.

P:R ratio (GPP:CR), an indicator of organic pollution, registered moderate amplitude of variation (1.8–3.3, 2.0–4.5 and 1.8–3.5) in upstream areas, and higher values (1.3–13.0, 2.0–5.4 and 2.0–13.5) in downstream regions during pre-monsoon, monsoon, and post-monsoon months, respectively. Upstream Haripur (HP) showed

somewhat higher values of the P:R ratio (4.8–7.5) due to local pollution. The phytoplankton biomass in this areas was the primary contributor to the respiration component.

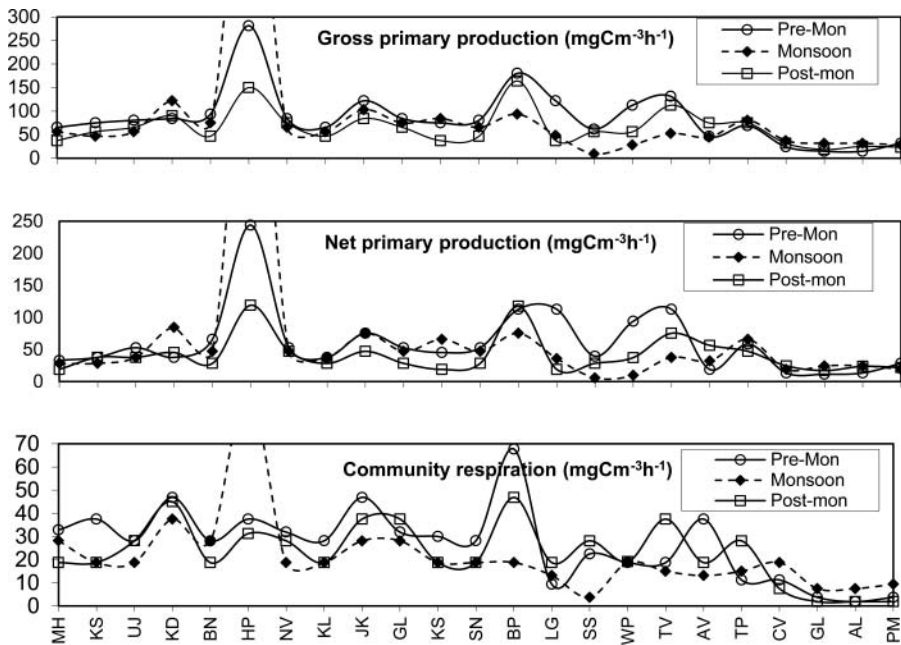
## Fisheries at a glance in River Krishna

The fish catch in the entire Krishna system has dwindled drastically, with a great reduction in catch structure as well as faunistic diversity. More catches are around areas of reservoirs, anicuts, and dead weirs due to stagnation. Some of the reservoirs in the main stream as well as in the upper Krishna complex are regularly stocked, mainly with Indian Major Carps (IMCs), thereby maintaining sustainable production with availability of fish in their lotic sectors as well. A total of 127 fish species were recorded during the survey. *Mystus* spp., along with *Labeo calbasu*, *L. gonius*, *L. fimbriatus*, *L. boggut*, *Puntius jerdoni* (*P. pulchellus*), *Cirrhinus reba*, *Mastacembelus armatus* and *Channa* spp., form the major fishery species in the upper stretches, with occasional catches of IMCs. Small indigenous fishes predominate the catch composition in the riverine stretches where water levels were very low. *Catla catla* is a major species of fishery in the Srisailem reservoir, whereas catch composition in the lotic area of Nagarjunasagar is reduced at present from what was available

**Table 3.** Results of test of significance of effect of water quality parameters on sediment quality parameters.

Water parameters	Soil parameters							
	S-pH	S-Sp. Cond	S-Org C	S-TN	S-C/N	S-Avail-P	S-Avail-N	S-CaCO <sub>3</sub>
Temperature	0.065	0.909	0.179	<0.05	0.362	0.313	0.054	0.756
Transparency	0.648	0.822	0.735	0.669	0.312	0.035	0.406	<0.05
Depth	0.501	0.438	0.596	0.207	0.071	0.621	0.214	<0.05
pH	0.025	0.401	0.607	<0.05	0.732	0.832	0.646	0.490
Sp. cond.	0.587	0.088	0.123	0.860	0.513	0.446	0.056	0.011
Flow	0.806	0.358	0.870	0.977	0.742	0.196	0.286	0.999
Total alkalinity	0.230	0.237	0.347	<0.05	0.257	<0.05	0.650	0.362
NO <sub>3</sub> -N	0.919	0.552	<0.05	<0.05	0.324	0.060	<0.05	0.396
PO <sub>4</sub> -P	<0.05	0.505	0.292	0.059	0.913	<0.05	0.425	<0.05
SiO <sub>2</sub> -Si	<0.05	0.304	0.675	0.841	0.155	0.748	0.192	<0.05
R <sup>2</sup>	0.503	0.136	0.244	0.501	0.107	0.630	0.372	0.614
P-value	<0.005	0.370	<0.005	<0.005	0.590	<0.005	<0.005	<0.005

Prob > |t| for the regression coefficients.



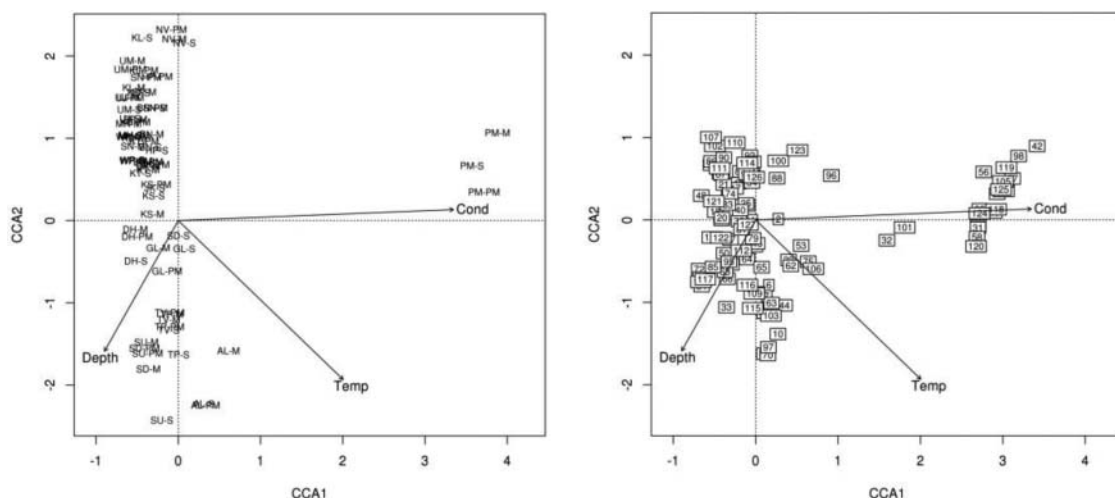
**Figure 8.** Spatiotemporal variation of GPP, NPP, and CR of the River Krishna.

in the seventies. In the downstream region, deep pools at Satrasala and Taduvouy contributed good catches with diversified species comprising *C. catla* (11%), *L. rohita* (9%), *P. kolus* (13.6%), *L. calbasu* (14%), freshwater eel (18.2%), *Rita pavementata* (15.9%) and *Sperata seenghala* (pre-monsoon sampling). Prawn (*Macrobrachium malcolmsonii*) added a good share to the catch from such deep pools. At the Prakasham barrage, the catch structure was comprised of *Etroplus suratensis*, *Xenentodon cancila*, freshwater eels, prawns, *Glossogobius giuris*, *Notopterus notopterus*, *Rita pavementata* and *Sperata* spp., with a pre-dominance of weed-associated fish in the catch.

A pattern of increasing species richness, diversity, and abundance from upstream to downstream has generally been followed amongst fish communities in riverine systems (Welcomme, 1985; Granado, 2000). But, the Krishna pattern of species richness, diversity, and abundance of fish contrasts sharply with the typical pattern. Species diversity and richness were lower in the downstream area in this study compared with the upper area, which might be due to relatively stagnant waters in dams and barrages (Habit et al., 2006). Sampling errors in this study were limited, as the same type of sampling gear was used in the entire Krishna system. The pattern encountered in this

river implies cumulative spatiotemporal effects of habitat loss, including environmental perturbation in the lower zone (Scrimgeour and Chambers, 2000; Wolter et al., 2000). While the upper and middle stretches of the river are fragmented due to lack of water, damming, and multiple water use, they supported more species as compared to the downstream locations. This might be due to the positive influence of reservoirs connected with the numerous tributaries in this region coupled with the existence of more open river, slow water, and pool habitats. Macrophyte abundance might also have influenced fish assemblage and aggregation (Gowns et al., 2003; Raghavan et al., 2008). Fish prefer open river habitat, as observed in tropical rivers (Lobb and Orth, 1991; Aadland, 1993; Arunachalam, 2000; Lakra et al., 2010). This was also evident in the Krishna. The reason for low species richness in the lower stretch might be due to discharges of domestic sewage and industrial effluents, the thermal power plant, degraded shoreline habitat, pollution, and illegal exploitation of fish (dynamiting). Anthropogenic interventions have damaged many riverine ecosystems with highly fragmented populations of many species (Bunn and Arthington, 2002).

Canonical Correspondence Analysis (CCA) has been carried out to explore the species–



**Figure 9.** Biplot of CCA analysis for species and water quality parameters. Left panel indicates site-specific environmental gradient and right panel indicates species-specific environmental gradient.

environment relationship. Nine water quality parameters, namely water temperature, transparency, water depth, pH, sp. conductivity, total alkalinity,  $\text{PO}_4\text{-P}$ ,  $\text{NO}_3\text{-N}$ , and  $\text{SiO}_3^{2-}\text{-SiO}_2$  were included to carry out CCA. There was no multicollinearity among the parameters, as the variance inflation factor for each of the parameters was below 3. The 56 axes of CCA explained 70.9% of species variation and 9 axes explained 29.1% of species variability due to environmental variables. It was found that water temperature, depth, and sp. conductivity are the statistically significant parameters for explaining species community structure in the study area. The biplots for site and environment, as well as species and environment, are shown in Figure 9. Conductivity and temperature are relatively higher at Penumudi (PM) than other sites. This might be due to tidal saline water influence from time to time.

## Conclusions

In general, most of the species were structured around the center of the biplot, indicating their distribution and abundance are indifferent from the available range of water quality (Figure 9). The negative quadrant of CCA1 has a relatively higher gradient of temperature and depth. It could be concluded that species assemblages are relatively more affected by temperature and depth than by other water quality parameters. There are species like *Butis butis*, *Chanos chanos*, *Caranx ignobilis*,

*Drepane punctata*, *Garra filamentosus*, *Tenualosa ilisha*, *Hilsa kelee*, *Leiognathus equals*, *Lutjanus argentimaculatus*, *Lutjanus quinquelineatus*, *Lutjanus johnii*, *Liza parsia*, *Mugil cephalus*, *Platycephalus indicus*, *Pampus argenteus*, *Rhabdosargus sarba*, *Rastelliger kanagurta*, *Sillago sihama*, *Sphyræna obtusata*, *Scomber microlepidotus*, *Trichiurus savala* and *Velamugil cunnesius*, whose assemblage are structured towards high conductivity and water temperature as compared to other species. Penumudi (PM) formed a separate group, with estuarine and marine fishes which migrated up to this sampling station.

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