To cite this document: Balakrishna, K. and Probst, Jean-Luc (2005) *Organic carbon transport and C/N ratio variations in a large tropical river: Godavari as a case study, India*. Biogeochemistry, vol. 73 (n° 3). pp. 457-473. ISSN 0168-2563

DOI 10.1007/s10533-004-0879-2

Organic carbon transport and C/N ratio variations in a large tropical river: Godavari as a case study, India

K. BALAKRISHNA[1,2] and J.L. PROBST[1,3,*]

*[1]Laboratoire des Mécanismes de Transfert en Géologie, CNRS/Université Paul Sabatier, 14 avenue Edoua Belin, 31400 Toulouse, France; [2]Present address: Department of Chemical Engineering, National Institute of Technology Karnataka, P.O. Srinivasnagar, Mangalore 575 025, India; [3]Present address: Institut National Polytechnique, ENSAT-Agronomie Environnement Ecotoxicologie, Avenue de l' Agrobiopole, BP 107, 31326 Castanet Cedex, France; *Author for correspondence (e-mail: jean-luc.probst@ensat.fr; phone: +33-5-62-19-39-49; fax: +33-5-62-19-39-01)*

Key words: C/N ratios, Carbon fluxes, Godavari river, Particulate organic carbon, Phytoplankton, Soil

Abstract. This study gives an insight into the source of organic carbon and nitrogen in the Godavari river and its tributaries, the yield of organic carbon from the catchment, seasonal variability in their concentration and the ultimate flux of organic and inorganic carbon into the Bay of Bengal. Particulate organic carbon/particulate organic nitrogen (POC/PON or C/N) ratios revealed that the dominant source of organic matter in the high season is from the soil (C/N = 8–14), while in the rest of the seasons, the river-derived (*in situ*) phytoplankton is the major source (C/N = 1–8). Amount of organic materials carried from the lower catchment and flood plains to the oceans during the high season are 3 to 91 times higher than in the moderate and low seasons. Large-scale erosion and deforestation in the catchment has led to higher net yield of organic carbon in the Godavari catchment when compared to other major world rivers. The total flux of POC, and dissolved inorganic carbon (DIC) from the Godavari river to the Bay of Bengal is estimated as 756×10^9 and 2520×10^9 g yr^{-1}, respectively. About 22% of POC is lost in the main channel because of oxidation of labile organic matter, entrapment of organic material behind dams/sedimentation along flood plains and river channel; the DIC fluxes as a function of alkalinity are conservative throughout the river channel. Finally, the C/N ratios (~12) of the ultimate fluxes of particulate organic carbon suggest the dominance of refractory/stable soil organic matter that could eventually get buried in the coastal sediments on a geological time scale.

Introduction

Chemical composition of the river is controlled by various physico-chemical (pH, temperature, alkalinity, dissolved oxygen) and biological processes occurring in the river catchment and within the river. Understanding the biological processes especially the forms, sources and dynamics of organic material in rivers is important because they influence water quality, fishery production, and the global carbon budget (Likens et al. 1981; Meybeck 1982; Degens and Kempe 1982; Degens et al. 1983; Hedges et al. 1986) and provide a detailed, integrated recording of natural and anthropogenic activities within the drainage basin.

Organic geochemistry of tropical river systems are not as well studied as their temperate counterparts, although they supply $>60\%$ of the total water discharge and 34% of the total suspended load to the world oceans (Martin and Meybeck 1979; Meybeck 1988; Ludwig et al. 1996; Ludwig and Probst 1998). Most of the existing data on tropical river systems are concentrated within a few large river systems (Amazon, Zaire, Parana, Orinoco, etc). This study is an effort to fill the gap in an underrepresented tropical river type (tropical drylands). The objectives are to investigate the source of organic matter, the magnitude of mobilisation of particulate organic matter (POC and PON) from the catchment to the river channel, seasonal variability in the concentration of organics and the carbon budget within the mainstream and tributaries. C/N ratios have been used to decipher the forms, sources and fluxes of organic materials in the river (Meybeck 1982). Another important objective is to estimate the ultimate flux of total (organic and inorganic) carbon from the river to the land–ocean boundary. By knowing the C/N ratios of POC from the ultimate fluxes of the river, the amount of refractory/stable organic matter that is being buried in the coastal sediments can be estimated. These stable organic matter has the potential of locking up carbon on a geological time on burial with the coastal sediments. Furthermore, a dominant component of the stable organic matter may get buried in the coastal zone which is based on the studies made by Smith and Hollibaugh (1993), who concluded that approximately 20% of the total organic carbon, transported from the global rivers may get oxidized in the coastal zone.

Earlier, studies on organic carbon have been made elsewhere for major rivers like Amazon (Richey and Victoria 1993), Zaire (N'Kounkou and Probst 1987), and Parana (Depetris and Cascante 1985). Among Indian subcontinental rivers, scattered data exists for Ganga–Brahmaputra rivers (Safiullah et al. 1987), Indus (Arain 1987), and Godavari (Gupta et al. 1997). This is for the first time, an extensive seasonal sampling covering the entire Godavari river system, has been attempted for a better understanding of the biogeochemical processes in a large tropical river of India.

Study area

Godavari ranks 34th and 32nd in terms of catchment area and water discharge, respectively, amongst the 60 largest rivers of the world (Ludwig et al. 1996; Gaillardet et al. 1999). It is the third largest river in India, after Ganga and Brahmaputra. The Godavari river originates near Nashik (Figure 1), at an elevation of 1065 m in the Western Ghats, about 80 km east of the western coast. The river flows in an east southeasterly direction for a distance of 1465 km before it empties into the Bay of Bengal through three main distributaries namely, Goutami, Vainateyam and Vasishta. The Godavari catchment is spread out in an area of 3.1×10^5 km^2, with an annual discharge of 105 km^3 (Rao 1975). The catchment receives about 82% of the total annual rainfall during the southwest monsoon between June and October, and the

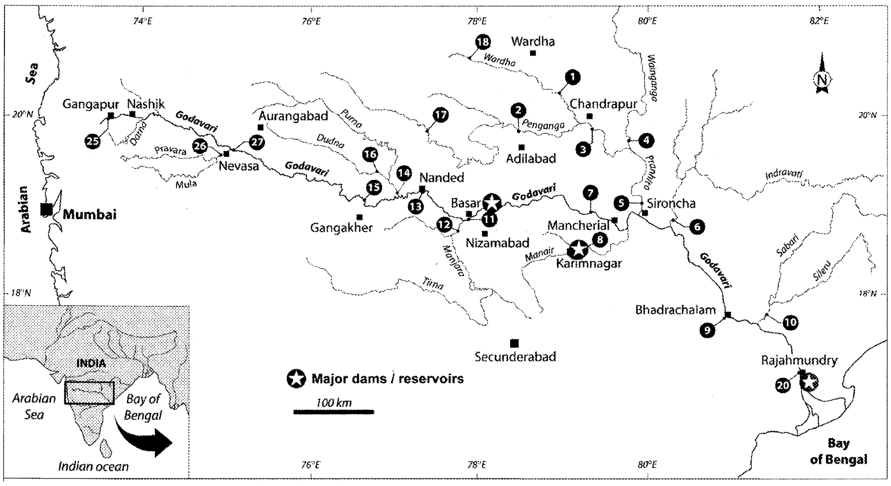

Figure 1. Location map of the sampling stations in the Godavari basin.

remaining between November and January (CPCB 1995). Plots of the average monthly rainfall and the average monthly discharge rate in the Godavari river is given in Gupta et al. (1997). The daily temperature over the basin varies from a minimum of 9 °C in the winter to as high as 48 °C in summer. About 61% of the catchment area is under agricultural cover. Vegetation and landuse data is given in Ludwig et al. (1996).

The geology of the area consists of Deccan Basalts in the upstream end, while granitic gneiss predominates in Indravati, Sabari and partly Pranhita catchments. Sedimentary rocks like sandstone, quartzite and shales are found in the lower part of the catchment area. The river basin, has a large number of coal deposits and mines, largely in the central part of the catchment.

Materials and methods

Godavari river has been sampled during moderate (November 1998), low (March 1999) and high (August 1999) flow seasons from its source at Nashik (Gangapur) to its mouth at Rajahmundry (Figure 1). Sampling was done once in each season. Samples were collected at different locations along the mainstream and the tributaries, before their confluence with the mainstream and after their confluence. Samples were collected mostly from the mid channel of the stream, using a road bridge as a platform or by a ferry. Depth integrated samples were not taken due to logistical difficulties. A clean plastic bucket tied with a nylon rope was used for sample collection. Samples for SPM, were collected in pre-cleaned 1-litre polypropylene bottles. They were filtered in 0.45 μm pore size, 47 mm diameter pre-weighed Nuclepore filters. The filters were dried and weighed at the laboratory for quantifying SPM. Samples for bicarbonate

(HCO_3^-) were collected in 100 ml pre-cleaned polypropylene bottles. Bicarbonate was measured in the laboratory, by acid titration on an auto titrator system using glass pH electrode; DIC is recalculated from the HCO_3^- data. Samples for POC and PON were collected in duplicates in distilled water soaked, pre-cleaned polypropylene wide mouthed 100 ml bottles. They were filtered within 5–6 h of the sample collection using pre-combusted (~350 °C), 25 mm diameter, pre-weighed GF/F glass fibre filters (Whatman make), mounted on a Millipore glass filtration apparatus. The filter bearing the sample was placed in an Al foil lined plastic box and transported to laboratory. In the laboratory, the filters were dried and weighed. The weighed filters are packed in an Al foil under the laminar flow bench for analysis. All organic C and N analysis are made using Fisons NA-1500 series 2 Elemental Analyser (NC Configuration). The instrument is calibrated with Deer River – Black shale as a standard with a known concentration of 2.53% C and 0.12% N. Duplicate samples were run for many samples and it had a precision within 5% for C and N.

Catchment area and discharge data for Godavari and its tributaries are obtained from Rao (1975). For those tributaries and river, where the data is not available, catchment area is calculated using a GIS based computer application Rivertools (make: Research Systems Inc., Boulder, CO, USA). The tool provided in this application is superposed over the drainage area that is to be calculated. The entire drainage network of Godavari river was culled from the USGS database available on the web (www.usgs.gov). Rivertools extracts the drainage network patterns and calculates the drainage area. The corresponding discharges were calculated assuming proportionality between the river discharge and catchment area. Seven samples with known area (A) and discharge (Q) are used to calculate the linear relationship. Using their slope and intercepts, discharge was calculated for the rest of the samples for which the area was extracted. The equation is given as:

$$Q = 0.0003A - 4.488$$

with $r = 0.993$, $n = 7$ and $p > 0.001$.

Discharge weighted concentration (C_w) is calculated considering that 82% of the annual discharge from Godavari is during high season, 15% during the moderate season and 3% in the low season (CPCB 1995). The calculation is represented, by the following equation:

$$C_w = 0.82C1 + 0.15C2 + 0.03C3,$$

where $C1$, $C2$ and $C3$ are respectively, the concentration measured during the high, moderate and low flow periods respectively.

Results and discussion

Details of sampling locations, suspended particulate matter (SPM), concentrations of POC and PON and C/N weight ratios in different seasons, in the

Godavari mainstream and its tributaries are given in Table 1. C/N ratios are frequently used to characterise the source from which the organic material is derived (Meybeck 1982). In our data (Table 1, Figure 2a), C/N ratios show large variations from 1.8 to 13.8. C/N ratios of 2/3 of the samples are in the range of 1–8, while the rest are between 8.1 and 14. The POC in the former category was collected from stagnant to slow moving clear waters composed of fine algal material mostly in the low season. The C/N ratio of the *in situ* algal material corresponds with the C/N ratios (4.6–7.5) of phytoplankton measured in different water bodies by earlier workers (Bordowskiy 1965; Muller 1977). The low C/N ratios observed in phytoplankton in comparison with fresh plant material ($C/N > 35$) is because of the presence of large amount of proteins rich in nitrogen. The abundance of algal material in the low season, is possibly due to the availability of nutrients in the river-discharged from sewages and industrial organic wastes. C/N ratios of <4 are observed in samples from Gangakher, Basar, Mancherial (GD1S, 11 and 7; Godavari mainstream; Figure 2a) and Manjara, Manair (tributaries; Table 1). These samples may derive the fine particles from montmorillonites produced by the weathering of Deccan basalts (Raman et al. 1995). Montmorillonites are known to sorb certain basic amino acids like arginine, histidine, ornithine and lysine with C/N ratios <3 (Muller 1977). The low C/N ratios might be also caused from ammonia and urea which are likely to be found in high concentrations downstream of the towns which are dumping sewage into the river. GD1S, 11 and 7 shows low C/N ratios in the high season contrary to other samples (Figure 2a). This could be due to dry conditions observed during the high season, due to a long break in monsoon at the time of sample collection. C/N ratios in the range of 8–14 are observed in samples obtained from, highly turbid, fast flowing rivers (Pranhita, Indravati, Sabari and Godavari at Bhadrachalam and Rajahmundry) mostly in the high and moderate seasons. These ratios correspond to C/N ratios measured in POC (8.1–12.9) for world's large rivers by Ittekkott and Zhang (1989). These ratios indicate a highly degraded soil organic matter source, transported from the forest catchment to the river. Sorptive fractionation of nitrogen rich labile organic materials into particulates were observed in river waters of the Amazon basin (Aufdenkampe et al. 2001) and sorptive preservation of labile organics in marine sediments (Keil et al. 1994), The conditions which has led to sorption in the above mentioned studies are unlikely in the Godavari basin, during the high season, as the river gets a lot of particulate input from the catchment, which obliterates any growth of labile organics in the river. Furthermore, even if there exists meagre amount of labile organics it could be disintegrated/destroyed by the high velocity currents by wear and tear with the sediments it interacts.

When C/N ratios were compared between, the mainstream and the tributaries, on an average, the ratios were lower by 1.5 times in the mainstream than that of the tributaries in all seasons (Table 1, Figure 2a). This is more enhanced in the Godavari upstream where the C/N ratios are mainly controlled

Table 1. Seasonal variations in supended matter (SPM), dissolved inorganic carbon (DIC), particulate organic carbon (POC), and C/N ratio in the Godavari river and its tributaries.

Code	River/Location	SPM (mg l^{-1})	DIC (mg l^{-1})			POC (μg l^{-1})			C/N		
		Moderate	Moderate	Low	High	Moderate	Low	High	Moderate	Low	High
Tributaries											
GD-26	Pravara	–	–	–	26	–	–	3000	–	–	6.3
GD-16	Dudhna	10	45	–	–	827	–	–	6.8	–	–
GD-14	Purna	29	42	52	48	1534	468	803	5.0	5.3	6.0
GD-17	Penganga	1	30	–	–	153	–	–	*	–	–
GD-2	Penganga	50	33	53	48	1444	436	1083	9.2	8.2	6.9
GD-18	Wardha	7	41	–	–	640	–	–	9.1	–	–
GD-1	Wardha	27	40	–	36	1401	–	3629	6.6	–	9.0
GD-3	Wardha	129	38	48	40	4274	459	14,182	11.2	7.3	13.8
GD-4	Wainganga	78	26	35	21	1948	241	3524	8.1	5.4	9.0
GD-5	Pranhita	113	32	40	20	2688	219	20,033	9.1	6.4	11.2
GD-6	Indravati	39	14	–	6	885	–	10,836	5.3	–	10.7
GD-10	Sabari	79	10	7	9	1068	299	4200	7.0	5.1	9.9
GD-12	Manjara	5	52	–	46	956	–	293	7.6	–	3.9
GD-8	Manair	1	30	–	–	360	–	–	2.5	–	–
Godavari mainstream[a]											
GD-25	Gangapur	–	–	–	20	–	–	377	–	–	4.4
GD-27	Nevasa	–	–	–	27	–	–	589	–	–	4.3
GD-15	Gangakher	10	41	48	52	1076	468	231	5.9	8.4	2.6
GD-13	Nanded	11	35	40	46	161	1924	917	*	5.9	6.3
GD-11	Basar	7	35	43	35	968	955	275	5.3	5.3	1.8
GD-7	Mancherial	3	31	53	52	507	359	299	2.7	5.9	3.3
GD-9	Bhadrachalam	13	31	41	21	579	452	9291	6.7	6.7	12.0
GD-20	Rajahmundry	–	–	26	23	–	258	8675	–	4.7	11.6

– Not sampled; * not detected; [a]sampling sites in the order of downstream flow.

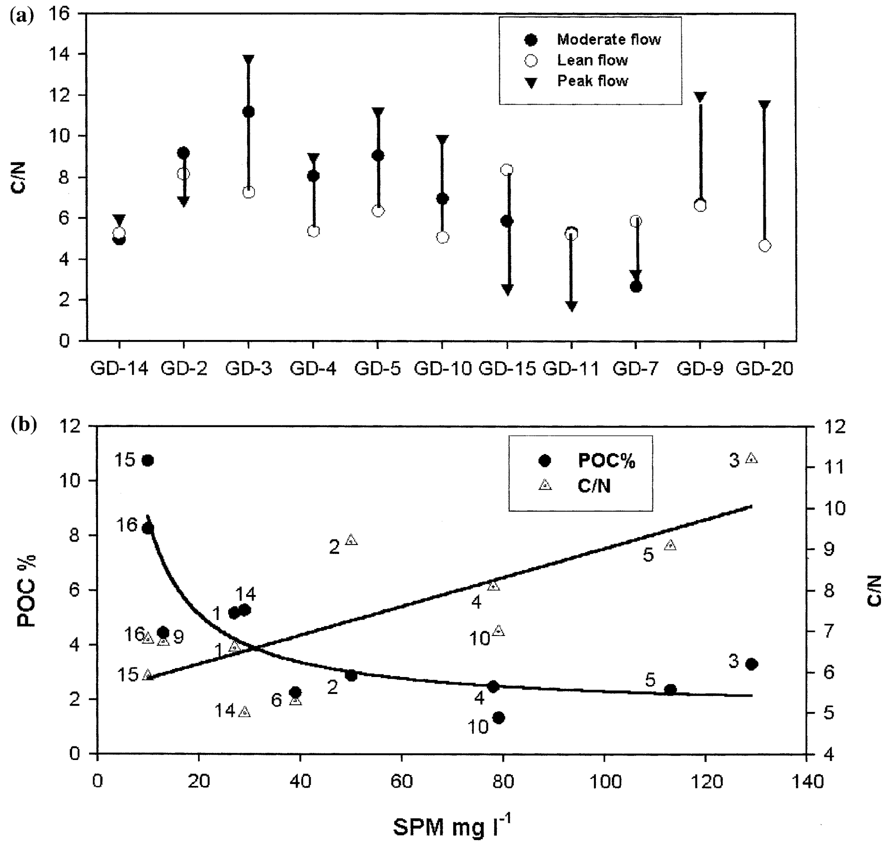

Figure 2. (a) Seasonal variations in C/N ratios observed in the Godavari river and its tributaries. (b) Relationships between POC%, C/N ratios and SPM weight in the Godavari river and its tributaries.

by phytoplankton; in addition, land input (soil derived) of organic matter with high C/N ratios, is relatively low because of the poor impact of monsoons.

To test our interpretation on the source of organic C, we plotted C/N ratios and POC% against SPM weight obtained from the moderate flow season data (Figure 2b). Only those samples with higher SPM weight were considered to minimise the errors that might be caused by using low weight SPM samples. In spite of some scatter, this plot delineates two end member sources and their mixing relationship. The samples with a low SPM weight, and a higher POC% corresponds to the phytoplankton, while a higher SPM weight, and a lower POC% corresponds to the soil organic matter. The curve tends to flatten out at 2% POC and SPM weight of 80 mg l^{-1}, indicating the limit of the soil organic matter end member. At this stage, primary production is largely diluted/ceases with an increase in turbidity. C/N ratios and SPM weight showed direct correlation, with lower C/N ratios and SPM weight corresponding to the phytoplankton and higher C/N ratios and SPM weight corresponding to the soil organic matter. The following equations are the best mathematical fit to describe the above relationships:

$$\text{POC\%} = (71.04/\text{SPM mg/l}) + 1.6068 \quad r = 0.9,\ n = 11,\ p \geq 0.001, \tag{1}$$

$$\text{C/N} = (0.0354 \times \text{SPM mg/l}) + 5.5041, \quad r = 0.8,\ n = 11,\ p \geq 0.001. \tag{2}$$

Similar relationship for POC% and SPM, has been observed for an earlier study on the Godavari river (Gupta et al. 1997) and for major world rivers (Ittekkott 1988; Martins and Probst 1991; Ludwig et al. 1996). The decreasing POC% with increasing SPM weight is due to two different processes. First, the decrease in POC% could be due to the decrease in the phytoplankton material (as observed by high C/N ratio in our data) with increasing suspended material. Higher SPM weight can also restrict the growth of phytoplankton because of the reduced availability of light. Second, a decrease in POC% with the increasing SPM could be due to the dilution of riverine POC with the mineral matter coming from the erosion of terrigenous soils. This is the first study which has shown the relationship of C/N ratios with SPM weight and POC% in a tropical river. This relationship is important as regards the riverine input of stable organic carbon to global oceans is concerned because it aides in estimating the percentage of their flux to the oceans.

Organic matter yield in a large watershed is controlled by anthropogenic as well as several edaphic, geologic, vegetation and climatic conditions (Brinson 1976). The annual yield of organic matter (Fs) in the Godavari and its tributaries catchments were calculated as:

$$F_s = C_w \times Q/A,$$

where C_w is the discharge weighted concentration, Q is the annual discharge of the river, and A is the catchment area.

The amount of organic matter yield from the catchment of each tributary (Figure 3a) is quantified. The yield obtained can be only a lower estimate, because of the lack of depth integrated sample data. Maximum yield of organic C was observed in the three major tributaries, Indravati, Pranhita and Wardha followed by Godavari mainstream at Rajahmundry. The yield of organic C is controlled by the large quantity of runoff observed in these catchments during the high season. The runoff carries large amount of fresh organic matter and loose soil organic matter from the thick forests to the mainstream. This loosening of soil organic matter is due to deforestation and intensive agricultural practices. Studies made by the Forestry Survey of India have shown that every year an average of 47,500 ha are lost due to deforestation and forest fire, with maximum forest denudation taking place in the state of Orissa (Silveira 1993), where Indravati river originates.

The net yield of organic C from the Godavari catchment is compared with similar yield from world's major rivers compiled by Ludwig et al. (1996)

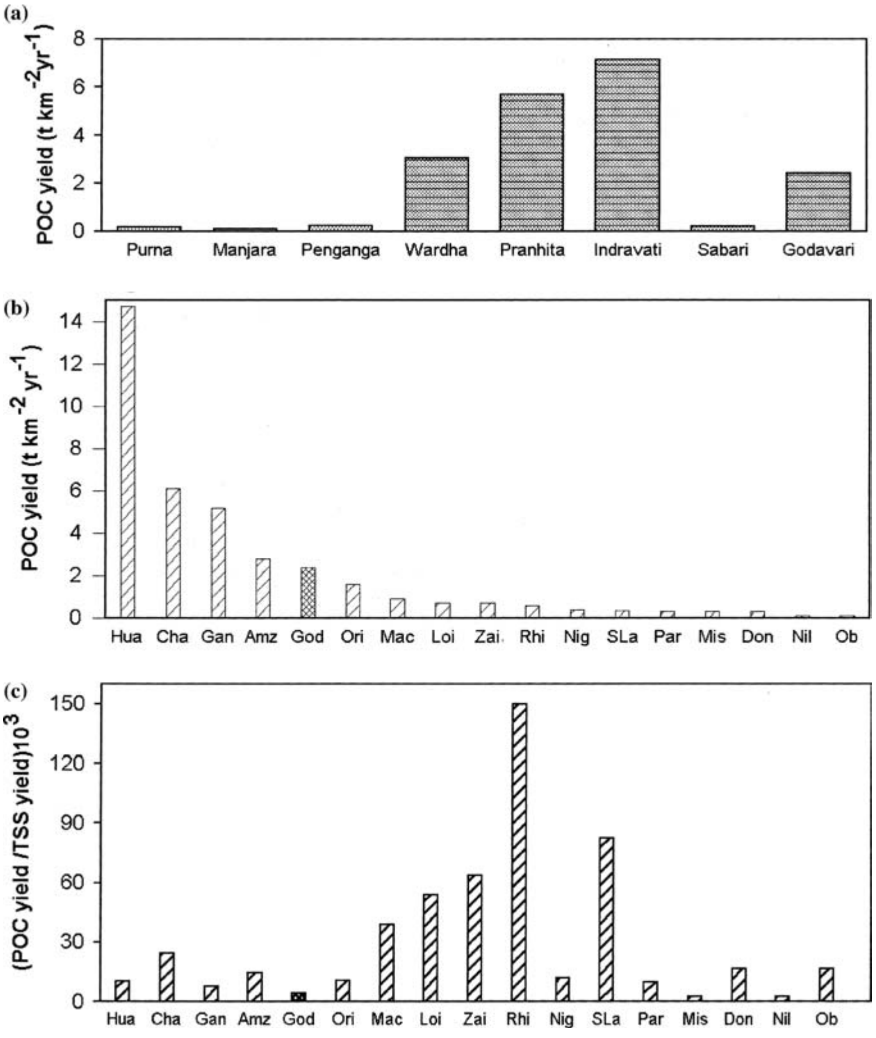

Figure 3. (a) Comparison of POC yield in the Godavari river and its tributaries. (b) POC yield represented in the order of decreasing yield for major world rivers (data from Ludwig et al. (1996); Godavari data from this study) (Abbreviation key: Hua – Huanghe; Cha – Changjiang; Gan – Ganga/Brahmaputra; Amz – Amazon; God – Godavari; Ori – Orinoco; Mac – Mackenzie; Loi – Loire; Zai – Zaire; Rhi – Rhine; Nig – Niger; SLa – St. Lawrence; Par – Parana; Mis – Mississippi; Don – Don; Nil – Nile; Ob – Ob). (c) Comparison of POC enrichment in the Godavari river with the major world rivers [data from Ludwig et al. (1996); POC data for Godavari from this study, TSS from Ludwig et al. (1998)].

(Figures 3b, c). The net yield of organic C per unit area in Godavari was much higher than most of the world rivers. Amazon has a slightly higher net yield than the Godavari because of erosion of soil organic matter derived from the thick Amazonian forests. Ganga–Brahmaputra and Chinese rivers

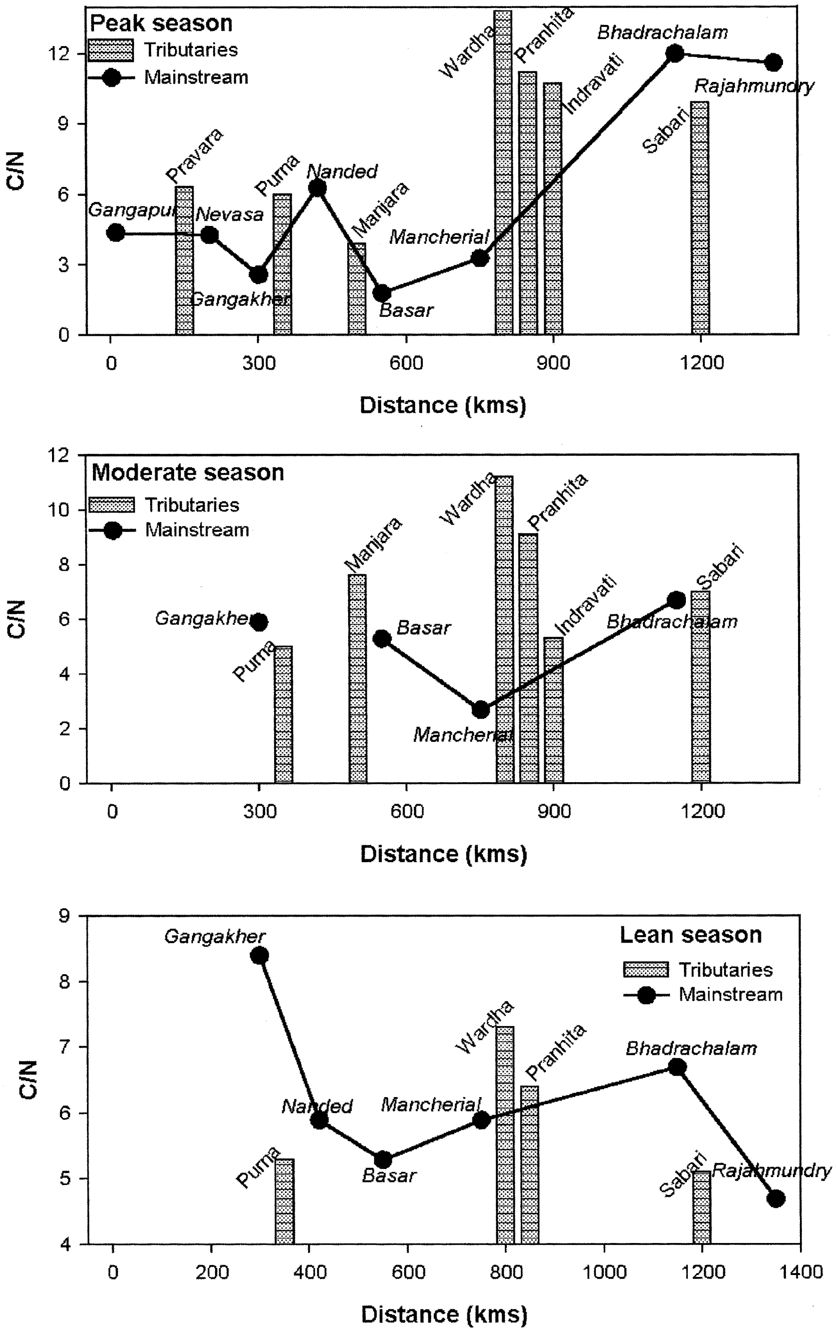

Figure 4. Comparison of downstream variations in C/N ratios in the Godavari river for different seasons.

like Changjiang and Huanghe have a net yield 2–4 times higher than the Godavari. This could be explained because of the intense erosion taking place in these catchments, especially so with the Chinese rivers, where large amount of loess deposits are eroded. Higher net yield of organic C in the Godavari could be due to a high degree of erosion of soils in the Godavari catchment, due to deforestation and intensive agricultural practices (Silveira 1993). The data for TSS (total suspended solids; Ludwig et al. 1998) yield for these rivers are proportional to the yield of organic C, indicating that erosion is the chief source of removal of organic C to the rivers. The organic C yield for the world's rivers are normalized with the TSS yield to know the enrichment of POC in these rivers (Figure 3c). There is no enrichment of POC in any of the above-discussed rivers. On the other hand, there is a high enrichment of POC in the Rhine, St. Lawrence, Zaire, Loire and Mackenzie rivers, which could be due to the abundant growth of phytoplankton in these rivers, promoted by the discharge of nutrients from pollutant sources. In the Godavari river, only one sample showed abnormally high concentration in the low season (GD-13, Table 1) which could be due to the supply of sewage effluents from Nanded town leading to the abundant growth of phytoplankton (C/N = 5.9).

Downstream variations in C/N ratios in the mainstream were studied (Figure 4) in all the seasons. It is apparent from the figure that tributaries are the main sources of organic C and N to the Godavari mainstream as they control the C/N ratio in the mainstream. It is also apparent that the mainstream receives organic C and N mainly from the phytoplankton source (C/N $\leq$ 6) up to Mancherial (except for one sample in the low season). This indicates a poor input of the land-derived soil organic matter into the mainstream. A higher C/N ratio of $\sim$12 at the Godavari mouth at Rajahmundry during the high season is largely contributed from the three major tributaries, Pranhita (and subtributary Wardha), Indravati and Sabari, joining the Godavari mainstream after Mancherial. These catchments receive heavy rainfall during this season, leading to a large input of soil organic matter into these rivers from the forest soil. This observation is substantiated by the rapid rise in POC flux by $\sim$100 times from Godavari sampled at Mancherial to the Godavari sampled at its mouth in Rajahmundry (Table 2; Figure 5).

The POC fluxes from the individual tributaries are calculated as the product of discharge (Rao 1975, www.usgs.gov) and discharge weighted concentration (Table 2) and pictorially represented in Figure 5. In the upstream section there is a rapid loss of POC from Nanded to Mancherial by about 45% (Table 2, Fig. 5), primarily because of their entrapment behind numerous small and large dams across the mainstream and tributaries. We also observe a larger loss of SPM between these two locations (Table 2), which possibly acts as a substrate for the settling POC.

Wardha, Wainganga and Penganga join to form Pranhita which combined carry a total POC flux of 620×10^9 g yr^{-1} into the mainstream (Figure 5), contributing $\sim$80% of the total POC flux exported from the

Table 2. Discharges, discharge weighted concentration and total carbon and sediment fluxes of the Godavari river and its tributaries.

River	Sample code	Catchment area (km^2)	Discharge (km^3 yr^{-1})	Discharge wt. conc. (mg l^{-1})			Flux (×10^9 g yr^{-1})		
				POC	DIC	SPM	POC	DIC	SPM
Pravara	GD-26	6634[a]	1.4	3.0	25.9	*	4.2	36	*
Purna	GD-14	15,579	2.83	0.91	47.1	29	2.58	133	82
Godavari at Nanded	GD-13	55,983[a]	14.96	0.81	43.9	11	12.21	657	165
Manjara	GD-12	30,844	7.64	0.41	47.0	5	3.14	359	38
Godavari at Basar	GD-11	91,097[a]	27.16	0.4	35.6	7	10.9	967	190
Godavari at Mancherial	GD-7	28,386[a]	23.00	0.3	48.7	3	7.6	1120	69
Manair	GD-12	12,313[a]	2.8	0.36	30.5	1	1.01	85	2.8
Wardha	GD-3	47,982	11.91	12.31	39.8	129	147	474	1536
Penganga	GD-2	23,895	5.11	1.12	45.7	50	5.72	234	256
Pranhita	GD-5	109,077	36.81	16.83	22.5	113	620	828	4160
Indravati	GD-6	41,665	32.85	9.04	7.4	39	297	244	1279
Sabari	GD-10	24,042	13.6	3.62	9.2	79	49.2	125	1074
Godavari at Bhadrachalam	GD-9	287,336[a]	95.34	7.72	23.3	13	736	2225	1239
Godavari at Rajahmundry	GD-20	310,000	105	7.2	24	13	756	2520	1365

*Data not available.

[a] Data calculated from the USGS data and River tools software; corresponding discharges are obtained assuming their linear relationship with catchment area. Rest of the catchment area and discharge data from Rao (1975).

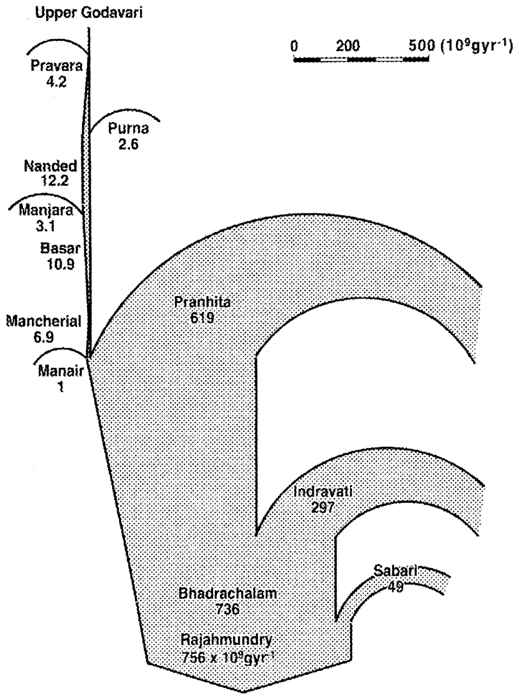

Figure 5. Pictorial diagram of the particulate organic carbon fluxes along the Godavari river (units in 10^9 g C yr^{-1}).

Godavari to the Bay of Bengal. Indravati contributes the second largest POC fluxes into the Godavari (297×10^9 g yr^{-1}), while Sabari adds $\sim 50 \times 10^9$ g yr^{-1} of POC.

When the fluxes from the tributaries joining the Godavari are added up, the total POC flux from the Godavari amounts to 972×10^9 g yr^{-1} . But the final flux of POC in the Godavari river at Rajahmundry is 756×10^9 g yr^{-1} which is 78% of the estimated flux. The loss (22%) of POC could be due to the oxidation of labile organic matter. It could also be from their entrapment behind dams, buried in riverbed sediments and flood plains (Figure 5). This observation is supported by similar behaviour of SPM fluxes that could adsorb POC and settle in the river bottom (Table 2). The final flux of POC from the Godavari was compared with the fluxes obtained for the same river by Gupta et al. (1997). They obtain the POC fluxes higher by 3.7 times than the flux obtained by us. The possible reason could be due to their sampling during episodic high sediment transport or sampling only during the high flow season. Furthermore, as mentioned earlier, our data can be a lower estimate as water samples were collected from the river surface. An exact estimate of POC fluxes could emerge only with a decadal scale POC data that is obtained after depth integrated sampling.

C/N ratios obtained from the samples at the Godavari river mouth (Rajahmundry and Bhadrachalam) during the high season ranged between 11 and 12 (Table 1). This indicates that POC export from the Godavari river into the coastal sediments is largely stable, corresponding to refractory soil organic matter which can be locked up in coastal sediments on a geological time scale. More data on the stable organic carbon fluxes from the major world rivers are needed to quantify the organic C burial in the coastal sediments, and their implications to the global C cycle as about 80% of the total organic carbon fluxes from world rivers are deposited in the coastal sediments (Ver et al. 1999).

Dissolved organic carbon data is not obtained for this study, but its concentration is assumed to be similar to that of POC. This is based on POC and DOC data for tropical rivers where POC/DOC $\sim$ 1 (Ludwig et al. 1996). Thus, the total organic C flux from the Godavari is estimated as 1512×10^9 g yr^{-1} which is 0.4% of the total organic C fluxes delivered to the oceans by rivers (Ludwig et al. 1996)

Flux calculations were made for dissolved inorganic carbon (DIC) from the same sampling locations (Table 2 and Figure 6) with the objective of estimating the total carbon flux from the Godavari to the Bay of Bengal. Contrary

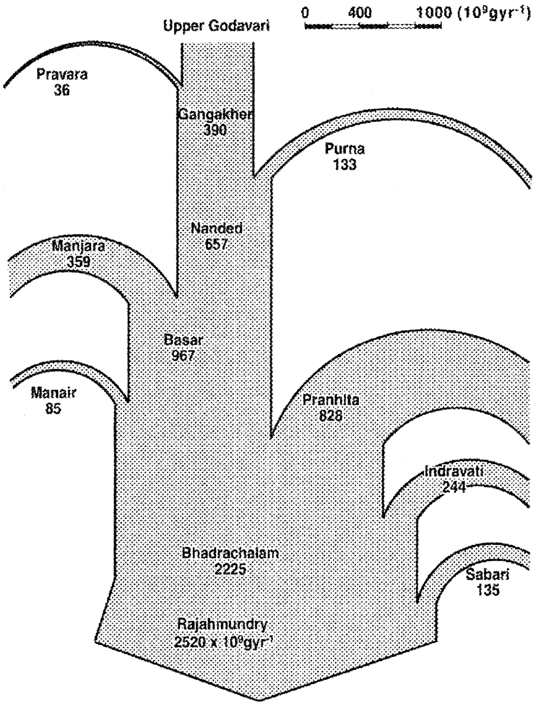

Figure 6. Pictorial diagram of the dissolved inorganic carbon fluxes along the Godavari river (units in 10^9 g C yr^{-1}).

to the behaviour of POC flux along the mainstream, we see a gradual increase in the DIC fluxes proportional to its input from the tributaries. The final flux of DIC at Rajahmundry is estimated at 2520×10^9 g yr^{-1}, which corresponds (within 10%) to the sum total of DIC fluxes from the tributary (Figure 6). This indicates that DIC as a function of alkalinity behaves conservatively in the river. This flux is ~3 times higher than the POC flux and 1.5 times higher than the total organic C flux. It constitutes 0.8% of the total inorganic C fluxes from the global rivers to the world ocean. Thus a total flux (DIC + POC + DOC) of 4032×10^9 g yr^{-1} from the Godavari constitutes 0.6% of the total C flux exported to the ocean by the global rivers. Out of the total C flux, the organic C contributes 38%. This flux corresponds to the flux estimates of world rivers made by Probst et al. (1994), Degens et al. (1991) and Meybeck (1993) who estimated ~40% of total C is transported as organic C and the remaining as DIC, to the world oceans. However, a clear picture of the C balance in the Godavari river system could emerge when the estimates are made for the net evasion of CO_2 from the DIC in the river surface, the quantity of CO_2 evolved due to respiration/oxidation of POC and DOC, and the concentrations and fluxes of DOC. pCO_2 calculations were not made due to the non-availability of data for pH and temperature.

Conclusions

This study has made a time series measurement of the POC, PON and DIC in the Godavari river system to know the source of organic C, the amount of organic C eroded from the catchment and the net fluxes of organic and inorganic C into the Bay of Bengal. The source of organic matter in the lower catchment of the Godavari river is from the soil (C/N ratios 8.1–14) during the high season, while in the rest of the seasons, the river derived (*in situ*) phytoplankton are the chief source (C/N ratios ~ 4). The intermediate C/N ratios (between 4 and 8) reflect a conservative mixing of phytoplankton and soil organic matter. Deforestation and agricultural practices coupled with heavy rainfall, result in heavy erosion leading to higher net yield of organic carbon in the Indravati, Pranhita and Wardha basins. Higher concentrations of organic matter in the river channel are observed during monsoons because of their contribution from catchment and flood plains. Downstream variations in concentrations of organic matter are largely controlled by the tributaries. The three major tributaries supplies the majority of total soil organic C into the mainstream during the monsoons. Godavari exports 756×10^9 g yr^{-1} of POC into the ocean. This represents about 78% of POC exported from the main channel; the rest of POC is lost due to oxidation of labile organic matter, entrapment of organic material behind dams/sedimentation along flood plains and river channel. Godavari exports stable, refractory organic matter (C/N ratio 12) into the coastal sediments, the dominant portion of which gets buried permanently in the coastal sediments for later diagenesis. Godavari river is ranked 8th in terms of the net export of POC into the world oceans. The total DIC export from the Godavari river constitutes approximately 1% of the total DIC fluxes from to suppress the world rivers to the oceans.

Acknowledgements

This work was supported by the institute post-doctoral fellowship at Physical Research Laboratory (PRL), Ahmedabad and French government fellowship at University Paul Sabatier (UPS) to KB. M.M. Sarin of PRL is thanked for the logistical help. Ravi Bhushan, J.P. Bhavsar and Amit of PRL are thanked for assistance in analysis and field trip; Hester Christiane, José Darrozes and Eric Maire at UPS, Toulouse, are thanked for help in drawing of map, figures and data analysis. Discussions with P. Amiotte-Suchet at the University of Burgundi (Dijon, France) and suggestions from one of the reviewers (A.K. Aufdenkampe) helped in the improvement of the manuscript.

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