

Total organic carbon transport by the Alaknanda River, Garhwal Himalayas, India

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Abstract Transport and fate of organic carbon by the fluvial system play a significant role in the global biogeochemical cycle of carbon. Previous studies show that the transportation of modern organic carbon from the Himalayan River system accounts for 10–20% of the total global flux to the oceans. Till date, no study has been published which dealt with the transport of organic carbon in the headwaters of the Ganga River. The Alaknanda River is a headwater stream of the Ganga, which flows in the Western Himalayas of India. Water and freshly deposited channel sediment samples were collected during the months of March 2014 and August 2014 and analysed for dissolved organic carbon (DOC), particulate organic carbon (POC) and channel organic carbon (COC). The observed variability of organic carbon concentration was correlated with factors such as discharge, physiography and suspended sediment concentration (SSC). The results show that seasonal erosivity in the basin influences its DOC concentration and physiography, thus acting as a key parameter which controls transportation, oxidation and residence time of the organic matter. The allochthonous input of sediments from the erosional activities is the major source of organic carbon. At Devprayag, Alaknanda contributes 66% of the total DOC flux carried by the Ganga River. The comparison with the previously published values indicate that due to differences in physiography and chemical weathering rate, the Ganga River transports organic carbon mainly as a dissolved load in its upstream and predominantly as POC down the Himalayan foothills.

Keywords Dissolved organic carbon (DOC) · Particulate organic carbon (POC) · DOC flux · Alaknanda River · Ganga River · Garhwal Himalayas

Introduction

Rivers are a crucial component of the global carbon cycle and act as an important link between the ocean and terrestrial ecosystem (Berner and Berner 1996; Leithold et al. 2006; Hilton et al. 2011; Bouchez et al. 2014). Annually, fluvial network transport, transform and store approximately 2 Pg of terrigenous organic carbon (Battin 2008). Assessing the fluvial organic carbon flux is a complex process primarily controlled by extrinsic and intrinsic fluvial processes such as rate of continental erosion, transporting capacity of the river, magnitude of leaching, mineralization and deposition of sediments. Over the past 15 Myr, the Ganga-Brahmaputra River system has deposited 0.6×10^{12} mol organic carbon (OC) in the Bay of Bengal accounting 10–20% of the global burial flux (Galy and France-Lanord 2001; Galy et al. 2007b). As the Ganga River transports more than 65% of sediments derived from the Higher Himalayan Crystallines (Galy and France-Lanord 2001; Singh et al. 2008), it is vital to estimate the organic carbon flux generated from the Upper Ganga basin and its fate during the fluvial transport. The Alaknanda River basin in the Garhwal Himalayas is an important sub-catchment area of the Upper Ganga basin exhibiting maximum natural land cover, heterogeneous lithology, diverse landscape and climatic conditions. Moreover, rapid uplift due to neotectonism, steep topography and heavy monsoon rainfall results in high physical weathering processes contributing high sediment yield to the Ganga River. Studying the organic carbon (OC) budget of the Alaknanda River basin is helpful in revealing the OC

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dynamics and the controlling factors in the Himalayan mountainous environment.

Previous studies of Ramesh et al. (1995), Aucour et al. (2006) and Galy et al. (2008) show that recent carbon (vegetation pool) is the biggest source of OC in the Ganga River. The middle and the lower Ganga River transports OC dominantly in the particulate form, whereas tributaries Kosi and Narayani flowing from the Nepal Himalayas carry low particulate organic carbon (POC) content (Ittekkot et al. 1985; Aucour et al. 2006 and Galy et al. 2008). The absence of data from the Upper Ganga Basin creates a lacuna in the assessment of the transportation mechanism and source of OC in the Ganga River. Using the spatial and temporal data varying over the pre-monsoon and monsoon season, in the present study, an attempt has been made to investigate the natural and anthropogenic factors influencing the OC concentration in the Alaknanda River and the amount of OC flux Alaknanda River contributes to the Ganga River.

Study area

The Alaknanda River originates from the snout of the Satopanth and the Bhagirath Kharak glaciers, which rises from Chaukhamba Mountain in the Garhwal Western Himalayas in India (Fig. 1). The total catchment area of the Alaknanda basin is 8716 km² of which forests cover 60% and glaciers cover 21% of the total land area (Table 1). After flowing ~200 km from its source, at Devprayag, the Alaknanda River confluences with the Bhagirathi River to form a mega stream known as the Ganga. The climate in the Alaknanda basin varies from sub-tropical to alpine and shows large spatial and temporal variation. During June to September, approximately 75% of annual rainfall occurs which increases the discharge of the river proportionally (CWC 2007). Figure 2 shows the temporal variability in the discharge of the Alaknanda River at different locations. Important tributaries of the Alaknanda River are Dhaulti Ganga, Nandakini, Pinder and Mandakini (Fig. 1). These tributaries are all perennial and contribute a large amount of water and sediment load to the Alaknanda River. Physiographically, the watershed comprises high to moderately dissected structural hills, steep slopes and deep cut gorges and valleys. The channel gradient is steep in the Higher Himalayas (approximately 20 m km⁻¹) and becomes gentler towards the south (AHEC 2011). Three geological successions of rocks are present in the Alaknanda basin—Tibetan Sedimentary Sequence, Higher Himalayan Crystallines and Inner Lesser Himalayas (Garhwal Group). The Tibetan Sedimentary Sequence lies in the north of the Higher Himalayan Crystallines and comprises shale, limestone, quartzite and phyllite. Occurring as a linear zone, the Higher Himalayan Crystallines form the oldest

crystalline rocks of the Himalayas and comprises gneiss, schists, amphibolites and migmatites. The Inner Lesser Himalayas comprises low-grade metasediments made up of quartzite with penecontemporaneous metabasics. Due to neotectonism, fragile landscape and heavy rainfall, instances of seismic activities, landslides and avalanches are frequent in the Alaknanda basin (CWC 2007; AHEC 2011; Shukla et al. 2014). The studies of Chakrapani and Saini (2009) and Panwar et al. (2016) show that physical weathering rate in the Alaknanda watershed is 3.25 mm year⁻¹ and weathering of silicate rocks yields more suspended sediment load whereas weathering of carbonate rocks results in more dissolved load carried by the river.

Methodology

Water and channel sediment samples were collected from the Alaknanda River and its tributaries during the months of March 2014 (pre-monsoon) and August 2014 (monsoon). For estimating the OC flux of the Alaknanda River and its contribution to the Ganga River, one representative sample from the Bhagirathi River at Devprayag and two samples from the Ganga River at Devprayag and Rishikesh were also collected. Figure 1 shows the sample collection sites. Water samples were collected in 125-ml amber glass bottles and 5–10 mg of HgCl₂ was added to prevent microbial growth (Tamooh et al. 2012). To estimate the suspended sediment concentration (SSC) and particulate organic carbon (POC) load, water samples were filtered through 25-mm Whatman GF/F glass fibre filters of 0.7 µm pore size. As the Alaknanda River carries approximately 80% of the annual sediment flux during the monsoon season (Chakrapani and Saini 2009), a good amount of suspended matter was obtained during August 2014 sampling which was used for estimating the particulate organic carbon (POC) content.

The freshly deposited channel sediment samples were collected in glass jars from the T0 active flood plain part to quantify channel organic carbon (COC) concentration. Freshly deposited channel sediments were sampled to exhibit fresh bank sediments as proxy samples for the suspended sediments. COC is not truly suspended, it sustains intermittent contact with the river banks. However, in situations where the flow rate is strong enough, some of the smaller channel particles can be pushed up into the water column and become suspended.

DOC, POC and COC content of the river were estimated using Analytik Jena TOC Analyser Multi N/C 3100 instrument. Potassium hydrogen phthalate (KHP) was used as a standard for the liquid module (DOC analysis). Calibration was done between 500 µg l⁻¹ and 5 mg l⁻¹. As inorganic

Fig. 1 The Alaknanda River basin with the sampling locations for the present study (A1-A10 samples were collected from Alaknanda River from Govindghat to Devprayag; G1 and G2, samples from the Ganga River at Devprayag and Rishikesh; and Dg, N, P, M and B represent samples collected from the tributaries, Dhaulti Ganga, Nandakini, Pinder, Mandakini and Bhagirathi)

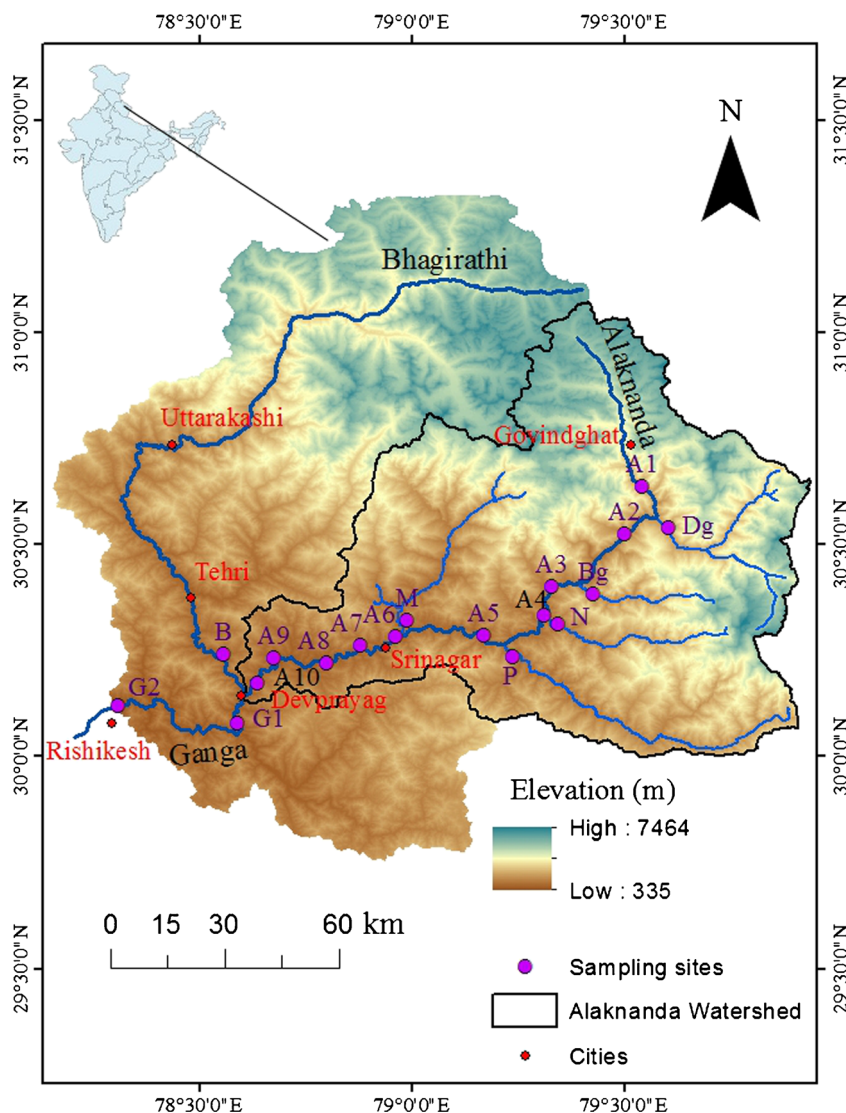
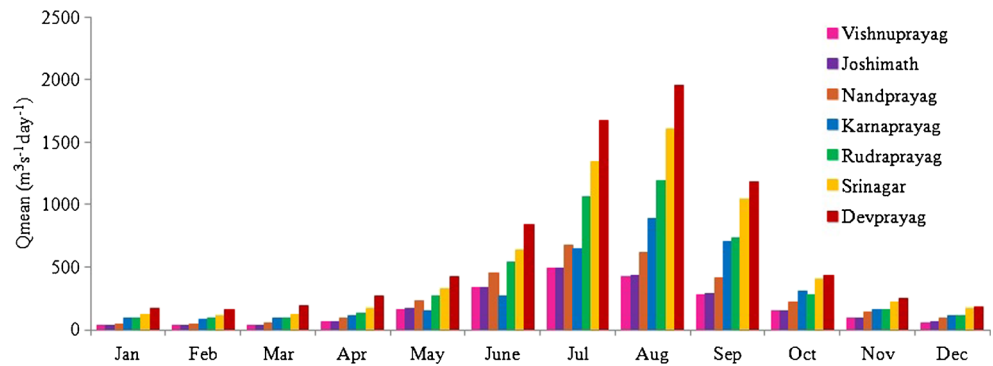


Table 1 Land use and land cover (LULC) of the Alaknanda basin of the year 2011

LULC class	Area (km ²)	Area (%)
Barren land	829.7	9.5
Built-up	16.5	0.2
Cropland	214.8	2.5
Evergreen forest	3849.6	44.2
Fallow land	373.4	4.3
Grassland	909.1	10.4
Mixed forest	565.9	6.5
Shrubs	44.3	0.5
Snow and ice	1856.2	21.3
Water bodies	56.6	0.6
Total	8716.1	100

carbon was present substantially in water samples, we adopted non-purgeable organic carbon (NPOC) method for DOC estimation. Prior to instrument analysis, all the water samples were acidified with a 2 N ultrapure HCl solution. The OC content in river sediments was determined by the direct method. Suspended and channel sediment samples were leached using 4 wt% HCl at 80 °C for 1 h to remove the traces of inorganic carbonates (Galy et al. 2007a). Calcium carbonate was used as a standard for solid module analysis. Six-point calibration was performed with 10, 25, 50, 100, 250 and 500 mg CaCO₃. For analysis, 0.5 g of a dried sediment sample was placed in a carbon-free porcelain boat and combusted at a temperature >950 °C. A continuous calibration check was performed after every eight samples. DOC flux was calculated using the mean discharge (Q_{mean}) data of the year 1989–2009 mentioned in AHEC (2011).

Fig. 2 Seasonal variation in mean discharge (Q_{mean}) of the Alaknanda River (based on mean monthly discharge data of the year 1989–2009, mentioned in AHEC 2011)



Results and discussion

Organic carbon in the Alaknanda basin

DOC and POC constitute important forms of organic carbon. The DOC concentration in the Alaknanda basin varied both spatially and seasonally. During the pre-monsoon and monsoon season of the year 2014, DOC varied from 0.60–1.10 to 0.97–1.61 mg l^{-1} , respectively (Table 2 and Fig. 3a). The DOC concentration in the Alaknanda basin is far less than the global average of 5.75 mg l^{-1} , Ganga (16.1 mg l^{-1}), Brahmaputra (3.2 mg l^{-1}) and Indus River (4.6 mg l^{-1}) DOC concentrations reported by Meybeck (1993) and Ramesh et al. (1995).

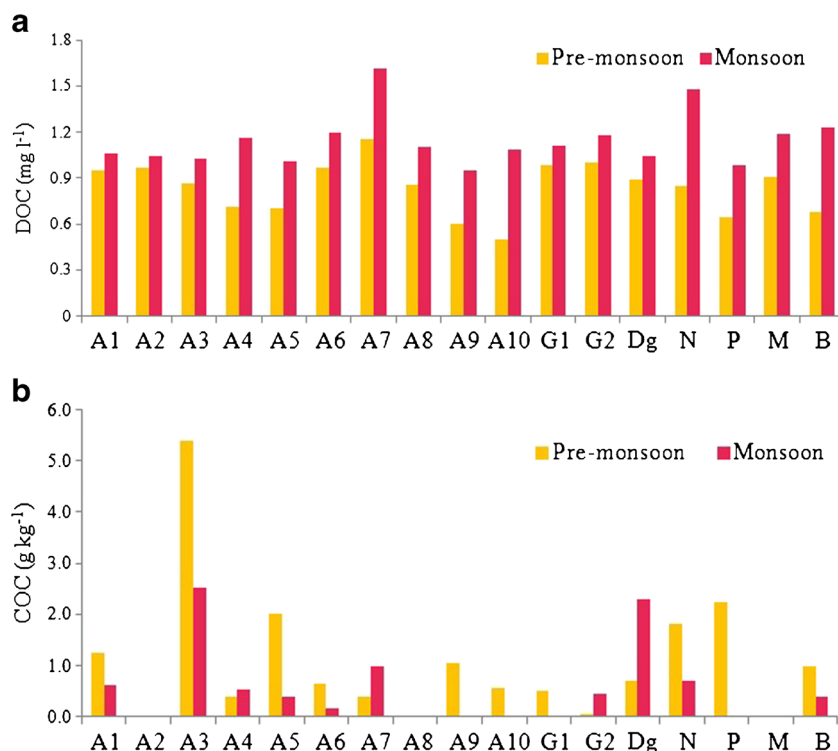
POC was significantly absent (or more precisely less than the detection limit of TOC Analyser, 4 $\mu\text{g l}^{-1}$) in all the

samples collected during the monsoon season. Therefore, to understand the role of river transportation and sedimentation, we used freshly deposited channel sediments as proxy samples for the suspended sediments. COC represents OC in the bulk fraction of channel sediments. Metabolism and decomposition of particulate matter take place at the sediment surface en route the sedimentation that results in the presence of OC in the freshly deposited sediments. Figure 3b shows the presence of low amount of COC during the pre-monsoon and monsoon season of the year 2014. Thurman (1985), Abril et al. (2002) and Wang et al. (2012) mentioned that POC has more residence time than DOC, but in the steep terrain of the Alaknanda basin, the residence time of POC is checked by the extrinsic factors such as physiography and seasonal erosivity of the basin. The longitudinal profile of the Alaknanda River,

Table 2 Seasonal and spatial variability of DOC and COC concentration and DOC flux

Sample	River	Pre-monsoon				Monsoon			
		Q_{mean} ($\text{m}^3 \text{s}^{-1}$)	DOC (mg l^{-1})	COC (g kg^{-1})	DOC flux (kg h^{-1})	Q_{mean} ($\text{m}^3 \text{s}^{-1}$)	DOC (mg l^{-1})	COC (g kg^{-1})	DOC flux (kg h^{-1})
A1	Alaknanda	8.4	0.95	1.25	0.48	306	1.06	0.62	19.46
A2	Alaknanda	37.7	0.97	0.00	2.19	425.3	1.04	0.00	26.54
A3	Alaknanda		0.86	5.39	–		1.03	2.51	–
A4	Alaknanda	51.7	0.71	0.39	2.21	612.1	1.16	0.52	42.60
A5	Alaknanda	92.1	0.70	2.00	3.87	887.8	1.01	0.38	53.80
A6	Alaknanda	94.1	0.97	0.64	5.48	1188.5	1.20	0.16	85.57
A7	Alaknanda		1.10	0.39	–		1.61	0.98	–
A8	Alaknanda	125.6	0.86	0.00	6.47	1607.1	1.10	0.00	106.07
A9	Alaknanda		0.60	1.03	–		0.97	0.00	–
A10	Alaknanda		0.60	0.56	–	1215.6	1.29	0.00	94.09
Dg	Dhaulti Ganga	14	0.89	0.71	0.75	165.7	1.04	2.28	10.34
N	Nandakini	52	0.85	1.81	2.65	57.2	1.48	0.70	5.08
P	Pinder	6	0.64	2.24	0.23	57.7	0.98	0.00	3.40
M	Mandakini	17.1	0.91	0.00	0.93	176.7	1.19	0.00	12.62
B	Bhagirathi	110.5	0.68	0.98	4.52	743.3	1.13	0.39	50.40
G1	Ganga	186.4	0.98	0.51	–	1958.9	1.21	0.00	142.22
G2	Ganga	350	1.00	0.04	–		1.19	0.45	–

Fig. 3 Variability of **a** DOC during pre-monsoon and monsoon season of the year 2014. **b** COC during pre-monsoon and monsoon season of the year 2014



with respect to the slope, also does not display a systematic variation in DOC and COC concentration (Fig. 4a, b). Lithology, geological structures and climatic conditions exert control on the distribution of channel slope which does not become gentler downstream. The complex interactions between discharge, slope and geology resulted in the absence of any downstream pattern in the DOC and COC concentration (Fig. 3a, b).

Generally, it is found that POC in the river sediments is inversely related to suspended sediment concentration (SSC) (Meybeck 1982; Bird et al. 1991; Moreira-Turcq et al. 2003; Galy et al. 2007b, 2008; Zhang et al. 2013; Lamoureux and Lafreniere 2014). Figures 5 and 6a show seasonal variation and high amount of SSC during August 2014 and a moderately positive relation between monthly mean discharge (Q_{mean}) and SSC. The slopes in the Alaknanda catchment are quite unstable, and a small disturbance during the monsoon season can lead to landslides resulting in an increase in the sediment load (Wasson 2003; Sati et al. 2011; Shukla et al. 2014; Roy et al. 2014). In Chamoli district, landslides and glaciers supply 2.75×10^5 ton year⁻¹ and 8.0×10^3 to 1.14×10^5 ton year⁻¹ of sediments, respectively (Wasson 2003). Permafrost is also an important source of sediment; near the proglacial source, the Alaknanda River was estimated to carry 2.16 g l^{-1} of SSC (Hasnain and Chauhan 1993). Figure 6b, c shows moderately positive correlation between Q_{mean} and DOC and SSC and DOC suggesting that as the concentration of SSC increases, dilution of sediments predominates resulting in high DOC concentration. The Upper Continental Crust normalized

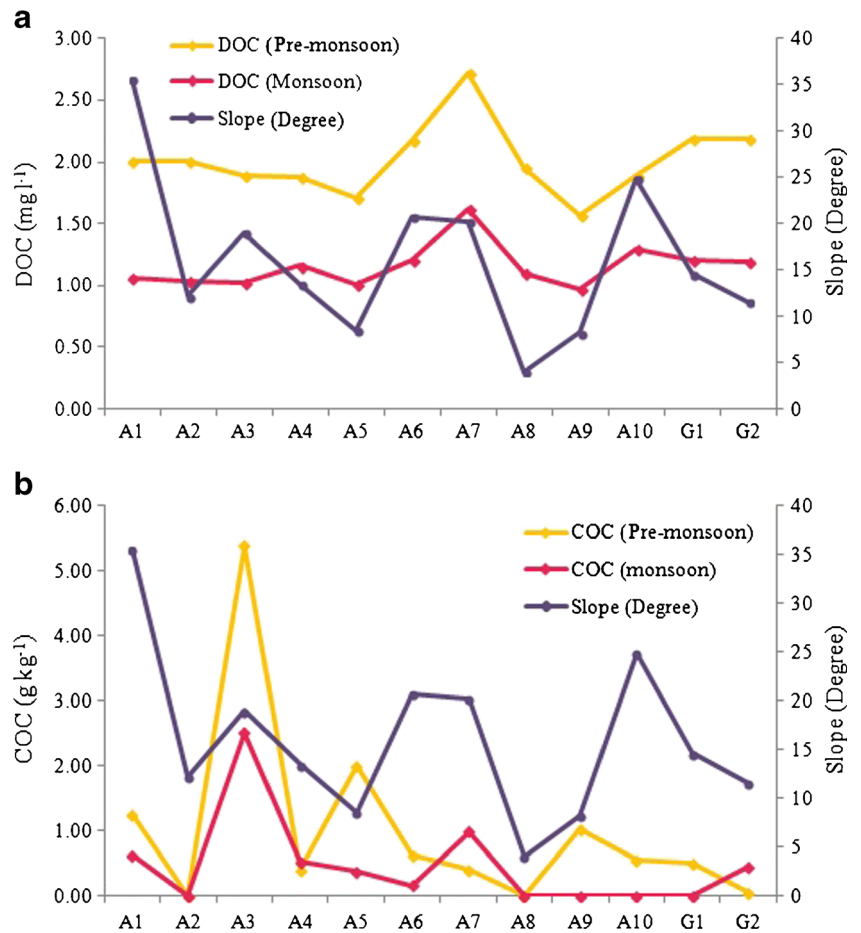
$\text{SiO}_2 > 1$ and a low amount of Al_2O_3 , P_2O_5 , CaO in the channel sediments also suggest that dilution of sediment predominates during the transportation process in the Alaknanda River (Panwar and Chakrapani 2016).

High SSC and turbulence during high flow reduce light penetration in the river and along with high current velocity affects the biogeochemical processes restraining the production of autochthonous organic matter and favouring the dilution of allochthonous OC (Ittekkot et al. 1985; Galy et al. 2007b; Bird et al. 1991; Moreira-Turcq et al. 2003). These findings indicate that during the monsoon season, OC is mobilized dominantly as a dissolved load and sediment input from the erosional activities (landslides and thawing of permafrost) acts as the biggest source of OC carried by the Alaknanda River.

Organic carbon flux

Using the mean monthly discharge (Q_{mean}) data of the time period 1989–2009 mentioned in AHEC (2011), DOC flux was estimated for the pre-monsoon and monsoon season (Table 2). The DOC flux at different stations varied from 3.40 to 142.22 kg h^{-1} . At Devprayag, the Ganga River carried the highest DOC flux of 142.22 kg h^{-1} out of which the Alaknanda River's share is 94.1 kg h^{-1} accounting for approximately 66% of the total. Although Bhagirathi basin has somewhat similar geology as the Alaknanda basin, the presence of dams along its middle path is influencing the geochemistry of the basin by trapping the sediment load. At Devprayag,

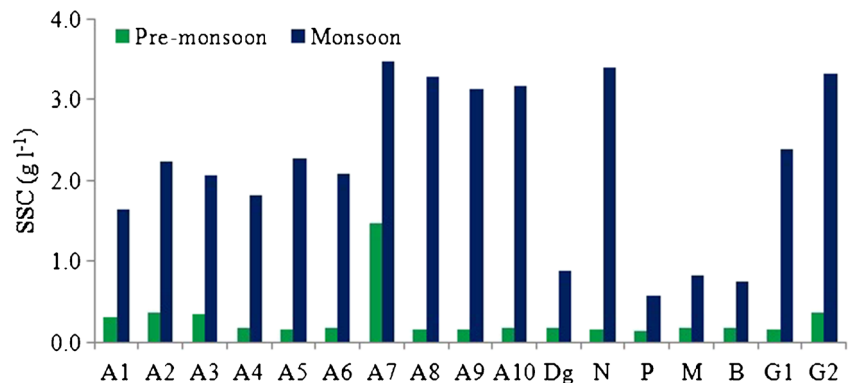
Fig. 4 **a** Spatial variation of DOC along the slope of the Upper Ganga basin. **b** Spatial variation of COC along the slope of the Upper Ganga basin



Bhagirathi River carried 0.7 g l⁻¹ of SSC in comparison to the Alaknanda River that carried 3.2 g l⁻¹ of SSC to the Ganga River. “Organic carbon in the Alaknanda basin” section elucidates an existence of a moderately good correlation between SSC and DOC. Factors such as relief, channel slope, basin size and land use land cover changes in terms of reservoir and dam constructions can influence the sediment load and DOC concentration of the river (Berner and Berner 1996; Galy et al. 2007b, 2008; Hilton et al. 2012; Raymond et al.

2013; Zhang et al. 2013; Li et al. 2015). However, a detailed sampling of the dammed Bhagirathi River is needed to understand its role in the total organic carbon transportation by the Ganga River. The highest DOC flux carried by the Alaknanda River was estimated at Srinagar (Table 2). At Srinagar, the Alaknanda River is affected by both natural and anthropogenic factors; the large sediment flux, high discharge and the presence of urban settlement can be the main reasons for high DOC flux.

Fig. 5 Spatial and temporal variability in suspended sediment concentration (SSC)



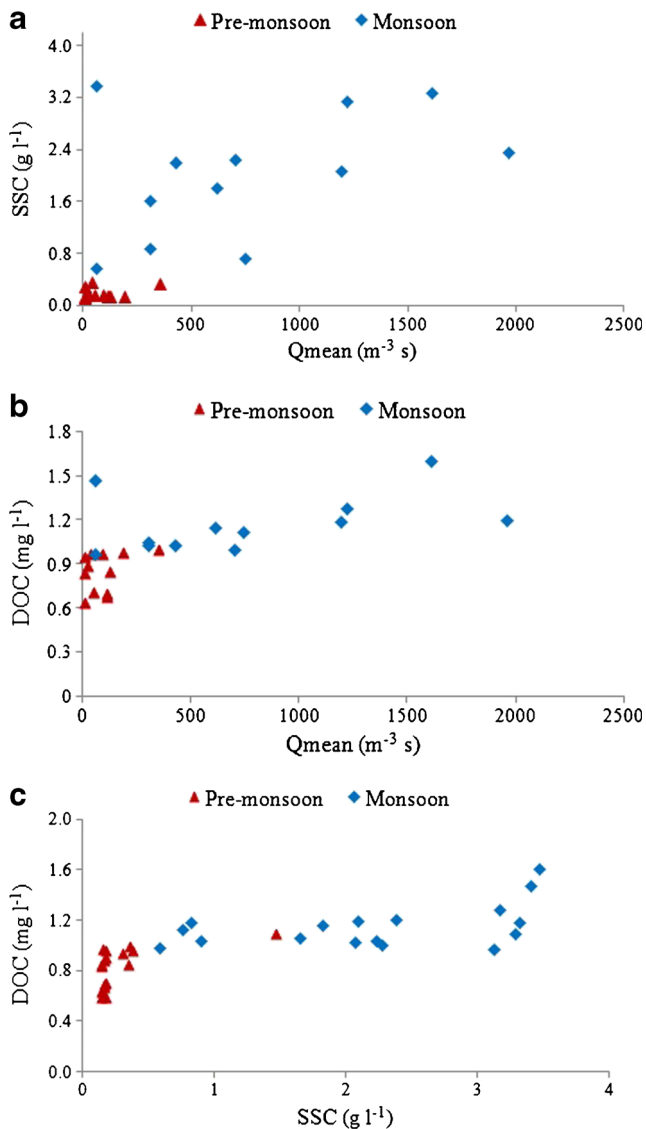


Fig. 6 Correlation between **a** monthly mean discharge (Q_{mean}) and SSC, **b** monthly mean discharge (Q_{mean}) and DOC and **c** SSC and DOC

Source of organic carbon

Raymond et al. (2007), Evans et al. (2007), Rosenheim and Galy (2012) and Butman et al. (2015) observed that DOC is mostly of recent origin assimilated by plants and old carbon (fossilized) comprises only 3–9% of the total DOC carried by the global rivers. Forest covers >60% of the total watershed area in the Alaknanda basin (Table 1). On steep slopes, during the monsoon season, well-drained soil is more readily swept away by excess water flowing down the streams. The $\delta^{13}\text{C}_{\text{org}}$ studies of the Bengal fan sediments by Aucour et al. (2006) and Galy et al. (2007b) established that Himalayan Rivers transport 70–85% of recent organic carbon. In the future, $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{14}\text{C}$ measurement can be used to understand the different sources of organic carbon in the Alaknanda watershed. Both C_3 and

C_4 vegetations are present in the Upper Ganga basin (Chakrapani and Veizer 2005).

However, the observation in this study that OC is significantly low in the channel sediments and absent in the suspended load helps in understanding the physiochemical conditions that influence OC transport in the headwater region and the Ganga plains. The average slope of the Alaknanda River basin at Rudraprayag is 24 m km^{-1} , whereas the average slope of the Ganga plains down the Himalayan foothills is 9.5 cm km^{-1} (Shrivastava 1999; AHEC 2011). The high chemical index (CIA) of alteration value indicates an increase in loss of labile minerals and elements (McLennan 1993). The Ganga plains have a CIA value of 65.9 as calculated by McLennan (1993), and the Alaknanda basin has a value of 56 (Panwar and Chakrapani 2016). The gentle slope favours the deposition of sediments, and due to the high rate of chemical weathering, degradation of organic matter takes place in the Ganga plains (Galy et al. 2007b, 2008).

The integration of the data generated in this study with high OC content reported by Galy et al. (2008) in the surface suspended sediments downstream of Varanasi (Ganga Plains) points that recent OC present in the Ganga River sediments is added from the Ganga flood plains or contributed from the downstream tributaries. Similar to the Alaknanda, Narayani-Gandak and Kosi Rivers (Trans-Himalayan tributaries of the Ganga River, joining down the plains) also carry low OC in the particulate form (Galy et al. 2008). The comparison clearly indicates that due to continuous flushing, the mountainous region of the Ganga basin acts as a supplier of sediment depleted in OC, and the high OC content in the Ganga River sediments is due to the addition of organic matter from the Ganga plains. The Ganga plains are over-populated with human settlements and agricultural activities.

Conclusion

In the Alaknanda River basin, a wide spatial and temporal variation in climate, physiography, geology, land use and land cover pattern controls the characteristics, transportation and transformation of organic carbon (OC). Monsoon has a good control on the hydrodynamics; SSC and discharge are the key factors that control the amount and mode of OC carried by the river. The results show that due to dilution of OC present in the sediments (channel and suspended), DOC concentration increases simultaneously. Fresh and labile POC is consumed quickly and locally without significant transport downstream and Upper Ganga basin exports OC dominantly in the form of dissolved load. At Devprayag, the Alaknanda River contributes 66% of the total DOC flux carried by the Ganga River accounting more than its companion river Bhagirathi. Findings indicate that during the monsoon season, the allochthonous input of sediments from erosional activities

(landslides and thawing of permafrost) is the major source of OC. The integration of the preliminary data generated in this study with Galy et al. (2008) points that high OC content in the Ganga River sediments is due to the addition of organic matter from the Ganga plains. The significance of this study lies in the fact that it is the first attempt relating to OC flux in the Upper Ganga Basin. However, given the lack of biogeochemical data from the Himalayan fluvial system, more work is needed to better understand the high variability of OC flux, source and age of the organic carbon carried by the major streams in the Ganga basin.

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References

- Abril G, Nogueira M, Etcheber H, Cabeçadas G, Lemaire E, Brogueira MJ (2002) Behaviour of organic carbon in nine contrasting European estuaries. *Estuar Coast Shelf Sci* 54(2):241–262
- AHEC (2011) Study on assessment of cumulative impact of hydropower projects in Alaknanda and Bhagirathi basins up to Devprayag. Ministry of Environment and Forest, New Delhi, India, Chapter 7: 1–134
- Aucour AM, France-Lanord C, Pedoja K, Pierson-Wickmann AC, Sheppard SMF (2006) Fluxes and sources of particulate organic carbon in the Ganga-Brahmaputra river system. *Glob Biogeochem Cycles* 20:2004–2034
- Battin TJ (2008) Biophysical controls on organic carbon fluxes in fluvial networks. *Nat Geosci* 1:95–100
- Berner RA, Berner EK (1996) Global environment: water, air, and geochemical Cycles. Prentice-Hall, Englewood Cliffs, NJ, p 376
- Bird MI, Chivas AR, Fyfe WS (1991) Carbon ratios in the Amazon. *Nature* 354:271–272
- Bouchez J, Galy V, Hilton RG, Gaillardet J, Moreira-Turcq P, Perez MA, France-Lanord C, Maurice L (2014) Source, transport and fluxes of Amazon River particulate organic carbon: insights from river sediment depth-profiles. *Geochimica Cosmochimica Acta* 133:280–298
- Butman DE, Wilson HF, Barnes RT, Xenopoulos MA, Raymond PA (2015) Increased mobilization of aged carbon to rivers by human disturbance. *Nat Geosci* 8:112–116
- Chakrapani GJ, Saini RK (2009) Temporal and spatial variations in water discharge and sediment load in the Alaknanda and Bhagirathi rivers in Himalaya, India. *J Asian Earth Sci* 35:545–553
- Chakrapani GJ, Veizer J (2005) Dissolved inorganic carbon isotopic compositions in the upstream Ganga river in the Himalayas. *Curr Sci* 89(3):553–556
- CWC (2007) Report of working group to advise WQAA on the minimum flows in the rivers central water Commission. Ministry of Water Resources, New Delhi
- Evans CD, Freeman C, Cork LG, Thomas DN, Reynold B, Billett MF, Garnett MH, Norris D (2007) Evidence against recent climate-induced destabilisation of soil carbon from ^{14}C analysis of riverine dissolved organic matter. *Geophys Res Lett* 34:L07407
- Galy A, France-Lanord C (2001) Higher erosion rates in the Himalaya: geochemical constraints on riverine fluxes. *Geology* 29:23–26
- Galy V, Bouchez J, France-Lanord C (2007a) Determination of total organic carbon content and d^{13}C in carbonate rich detrital sediments. *Geostand Geoanal Res* 31:199–207
- Galy V, France-Lanord C, Beyssac O, Faure P, Kudrass H, Palhol F (2007b) Efficient organic carbon burial in the Bengal fan sustained by the Himalayan erosional system. *Nature* 450:407–410
- Galy V, France-Lanord C, Lartiges B (2008) Loading and fate of particulate organic carbon from the Himalaya to the Ganga–Brahmaputra delta. *Geochim Cosmochim Acta* 72:1767–1787
- Hasnain SI, Chauhan DS (1993) Sediment transfer in the glaciofluvial environment—a Himalayan perspective. *Environ Geol* 22:205–211
- Hilton RG, Galy A, Hovius N, Horng MJ, Chen H (2011) Efficient transport of fossil organic carbon to the ocean by steep mountain rivers: an orogenic carbon sequestration mechanism. *Geology* 39(1):71–74
- Hilton RG, Galy A, Hovius N, Kao SJ, Horng MJ, Chen H (2012) Climatic and geomorphic controls on the erosion of terrestrial biomass from subtropical mountain forest. *Global Biogeochem Cycle* 26:GB3014
- Ittekkot V, Safiullah S, Mycke B, Seifert R (1985) Seasonal variability and geochemical significance of organic matter in the river Ganges, Bangladesh. *Nature* 317:800–802
- Lamoureaux SF, Lafreniere MJ (2014) Seasonal fluxes and age of particulate organic carbon exported from Arctic catchments impacted by localized permafrost slope disturbances. *Environ Res Lett* 9(4): 045002
- Leithold EL, Blair NE, Perkey DW (2006) Geomorphologic controls on the age of particulate organic carbon from small mountainous and upland rivers. *Glob Biogeochem Cycles* 20:GB3022
- Li G, Wang XT, Yang Z, Mao C, West AJ, Ji J (2015) Dam triggered organic carbon sequestration makes the Changjiang (Yangtze) river basin (China) a significant carbon sink. *J Geophys Res Biogeosci* 120(1):39–53
- McLennan SM (1993) Weathering and global denudation. *J Geol* 101: 295–303
- Meybeck M (1982) Carbon, nitrogen and phosphorus transport by world rivers. *Am J Sci* 282:401–450
- Meybeck M (1993) Riverine transport of atmospheric carbon: sources, global typology and budget. *Water Air Soil Pollut* 70:443–463
- Moreira-Turcq P, Seyler P, Guyot JL, Etcheber H (2003) Exportation of organic carbon from the Amazon River and its main tributaries. *Hydrol Process* 17:1329–1344
- Panwar S, Chakrapani GJ (2016) Seasonal variability of grain size, weathering intensity, and provenance of channel sediments in the Alaknanda River basin, an upstream of river Ganga, India. *Environ Earth Sci* 75(12):1–13
- Panwar S, Khan MYA, Chakrapani GJ (2016) Grain size characteristics and provenance determination of sediment and dissolved load of Alaknanda River, Garhwal Himalaya, India. *Environmental Earth Sciences* 75(2):91
- Ramesh R, Purvaja GR, Subramanian V (1995) Carbon and phosphorus transport by the major Indian rivers. *J Biogeogr* 22:409–415
- Raymond PA, McClelland JW, Holmes RM, Zhulidov AV, Mull K, Peterson BJ, Striegl RG, Aiken GR, Gurtovaya TY (2007) Flux and age of dissolved organic carbon exported to the Arctic Ocean: a carbon isotopic study of the five largest arctic rivers. *Glob Biogeochem Cycles* 21:GB4011
- Raymond PA, Hartmann J, Lauerwald R, Sobek S, McDonald C, Hoover M, Butman D, Striegl R, Mayorga E, Humborg C, Kortelainen P (2013) Global carbon dioxide emissions from inland waters. *Nature* 503(7476):355–359
- Rosenheim BE, Galy V (2012) Direct measurement of riverine particulate organic carbon age structure. *Geophys Res Lett* 39(19):L19703
- Roy P, Martha TR, Kumar KV (2014) Sediment influx in the Mandakini catchment due to landslides triggered by the June 2013 extreme rainfall event in Uttarakhand. ISRS Proceedings, ISRS Technical Commission VIII Mid-Term Symposium, Hyderabad, 2014

- Sati SP, Sundriyal YP, Rana N, Dangwal S (2011) Recent landslides in Uttarakhand: nature's fury or human folly. *Curr Sci* 100(11):617–1620
- Shrivastava VK (1999) Commercial activities and development in the Ganga Basin. Concept publishing company, New Delhi, p 58
- Shukla D, Dubey C, Ningreihon A, Singh R, Mishra B, Singh S (2014) GIS-based morphotectonic studies of Alaknanda river basin: a precursor for hazard zonation. *Nat Hazards* 71(3): 1433–1452
- Singh SK, Rai SK, Krishnaswami S (2008) Sr and Nd isotopes in river sediments from the Ganga Basin: sediment provenance and spatial variability in physical erosion. *J Geophys Res* 113:F03006
- Tamooch F, Meersche KV, Meysman F, Marwick TR, Borges AV, Merckx R, Dehairs F, Schmidt S, Nyunja J, Bouillon S (2012) Distribution and origin of suspended matter and organic carbon pools in the Tana River basin, Kenya. *Biogeosciences* 9:2905–2920
- Thurman EM (1985) Organic geochemistry of natural waters Nijhoff/Junk. Dordrecht
- Wang X, Ma H, Li R, Song Z, Wu J (2012) Seasonal fluxes and source variation of organic carbon transported by two major Chinese rivers: the Yellow River and Changjiang (Yangtze) river. *Glob Biogeochem Cycles* 26(2):GB2025
- Wasson RJ (2003) A sediment budget for the Ganga-Brahmaputra catchment. *Curr Sci* 84(8):1041–1047
- Zhang LJ, Wang L, Cai WJ, Liu DM, Yu ZG (2013) Impact of human activities on organic carbon transport in the Yellow River. *Biogeosciences* 10(4):2513–2524