Characterisation of Sediments and their role in Solute Acquisition in Meltwater of River Bhagirathi, India

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Abstract: The main sources of production of sediment from the glacier fed channels are bedrock system, glacier system and channel system. Surface characteristics of sediments play an important role in solute acquisition during freshly grinded sediment-meltwater interaction. Solute acquisition is also affected with change in the climatic variables. In the present investigation, the surface characteristics of suspended and bed sediments of River Bhagirathi at Gomukh, Bhojwasa and Gangotri were studied under changing temperature regime. High suspended sediment concentration in melt season was observed in the meltwater of River Bhagirathi from Gomukh to Bhojwasa, mainly driven by the subglacial processes. The sediments derived from Gangotri glacier are mineral grains and not rock fragments. Further, suspended sediment of the site Gomukh of River Bhagirathi has higher potential of chemical dissolution as compared to other sites i.e. Bhojwasa and Gangotri. For understanding of low temperature solute acquisition, dissolution experiments of glacial meltwater-sediment interaction were conducted on bed and suspended sediments of River Bhagirathi considering different operating variables. Equilibrium time was observed to be 600 sec (10 minute). Further progressive increase in EC was observed from Gomukh to Gangotri suggesting change in sediment surface characteristics/or source. Maximum dissolution was observed from the bed sediments collected in the June. Therefore it can be inferred that solute acquisition during freshly grinded sediment-meltwater interaction is also governed by characteristics of sediment, which is also affected by change in environmental condition viz. temperature.

Keywords*:* River Bhagirathi; Solute acquisition; Sediment; Dissolution Experiment

1. Introduction

Mountain regions play a critical role in the water cycle, storing water in the form of snow and ice mainly during the cold/wet season, and releasing it as melt water during the dry/ warm season when it is greatly needed (Gino et al., 2009). Glaciers, especially mountain glaciers, are sensitive to climatic change (Li et al., 2007; Zhou et al., 2010). As these mountain waters with significant amount of snow, glacier meltwaters and rainfall is characterised by low ionic concentrations and play a major role in diluting the high solute load emanating from the Ganga plain catchments. Hence any change in the quality and quantity of the Himalayan tributaries of River Ganga under the climate change regime will impact the quality parameters of River Ganga. Hence a clear understanding of the characteristics and process driving the chemical enrichment of the glacial meltwater and its instream modification in the high altitude region is essential for evaluating the role of Himalayan component of the Ganga river system in maintaining the quality of the Ganges water.

The main sources of production of sediment from the glacier fed channels are bedrock system, glacier system and channel system. Suspended sediments in the stream play an important role in in-stream solute acquisition by its interaction with dilute glacial and snow melt waters (Brown et al., 2001; Tranter et al., 2002). This makes the ionic enrichment of meltwater very unique and is affected by surface characteristics of sediments. The Ganga-Brahmaputra river system holds first position for sediment transport and fourth position for water discharge in the world. Active tectonics coupled with monsoon rainfall facilitates the high sediment load in the Himalayan rivers. Significant diurnal and seasonal fluctuations

exists in the dissolved ions, suspended sediment concentration and suspended sediment load in the Gangotri proglacial stream (Singh et al., 2014).

Laboratory experiments have been widely used to study the kinetics and mechanism of mineral dissolution (e.g. Wollast, 1967; Busenberg and Clemency, 1975; Plummer et al., 1978; Holdren and Berner, 1979; Chou et al., 1989; Nagy and Lasaga, 1992). However, the knowledge of the rates of reactions controlling meltwater composition is available only qualitatively, and there have been few studies of the sources of solutes transported by meltwaters or the way in which these are determined by the nature of the hydrological environment at the glacier portal. Controlled laboratory studies of water-rock interaction, constrained by field data from the glacier in question, have allowed the effects of different geochemical parameters (e.g. water: rock ratio, sediment particle size, crushing, repeated wetting and proton availability) on solute acquisition in subglacial channels to be isolated and quantified.

However, little is known about the in-stream dissolution processes involving the glacial sediments and dilute meltwater interaction in the Ganga headwater. Therefore, understanding of low temperature solute acquisition processes is therefore very important for assessing the solute acquisition during meltwater-glacial sediment interaction. In the present paper, characterisation of sediments and their role in solute acquisition in meltwater of River Bhagirathi in low temperature environment, Uttarakhand, India has been attempted and further, for better understanding of low temperature solute acquisition, dissolution experiments of glacial meltwater- sediment interaction were conducted on bed sediments of River Bhagirathi considering different operating variables.

2. Materials and Methodology/Study Area and Methods

Gangotri glacier is the biggest glacier in the Ganga basin as well as the origin of the sacred River Ganga. This glacier, occupying the shape of valley, is situated in the Uttarkashi district of Uttarakhand state in central Himalaya. Geographically this glacier lies between 30º43’22”-30º55’49” (latitude) and 79º4’41”–79º16’34” (longitude) (Fig. 1). The snout of Gangotri glacier, known as Gomukh (meaning mouth of the cow) is situated at about 4000 m above mean sea level elevation (Arora, 2008). This is a religious place for Hindu pilgrims from where the River Bhagirathi originates. The total catchment area of the Gangotri glacier basin up to the snout at Gomukh is 513 km^2, up to the discharge gauging site established downstream of the snout by NIH at Bhojwasa is about 556 km^2, out of which about 286 km^2 (51.4%) is glacierized area (Haritashya et al., 2006; Singh et al., 2006; Arora, 2008) and up to Gangotri is 691 km^2. The Bhagirathi River and its tributaries drain mostly through the Lesser and Central Crystallines rocks (Agarwal and Kumar, 1973; Pandey et al., 1999; Jain et al., 2002; Singh et al., 2014). Geologically, the Gangotri glacier system falls in the higher and Tethys Himalayan zone (Kumar et al., 2009). Gangotri granite is one of the largest bodies of the Higher Himalayan Leucogranite belt located in the Garhwal Himalaya (Heim and Gansser, 1939; Gansser, 1964; Le Fort, 1975). The Gangotri glacier system geology comprises granite (tourmaline rich), sericite schist, mica schist, quartzite, phyllite, sulphide minerals like pyrite, chalcopyrite and arsenopyrites at the contact of quartz veinlets and massive, banded fine grained limestone (Bhatt, 1963).

Meltwater and sediment samples were collected using grab sampling method from River Bhagirathi at Gomukh, Bhojwasa and Gangotri during the period of May to October, 2016 and immediately filtered the samples for suspended sediment concentration through 0.45 µm membrane Whatman filter paper by using hand operated vacuum pump (Tarson make) and filtration apparatus. The bed sediments were also collected from the bed of River Bhagirathi at Gomukh, Bhojwasa and Gangotri monthly in polyethylene begs. The bed sediments were

dried at 50ºC before weighing. Size fractions 0-75, 75-150, 150-210, 210-250, 250-300, 300-425, 425-600 micron were derived by dry-sieving the bed sediment through sieves using a sieve shaker for 10 minutes and kept in polyethylene bags for later dissolution experiments.

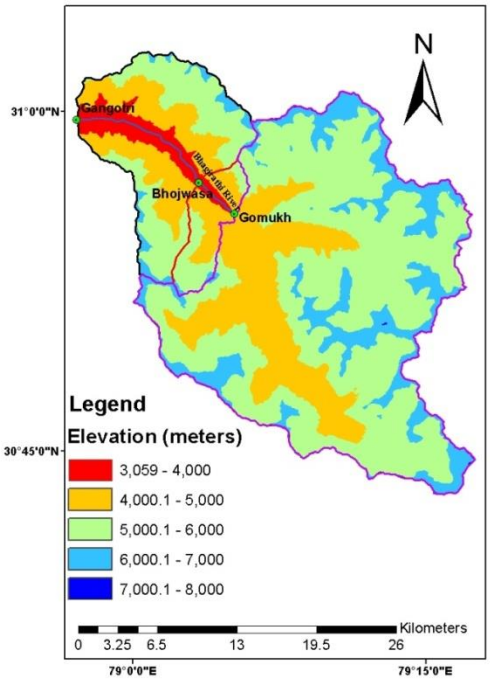


Fig. 1 Digital elevation map of the study area

Dried suspended and bed sediment collected from the River Bhagirathi at Gomukh, Bhojwasa and Gangotri during the year 2016 were analysed for surface characteristics using Scanning Electron Microscope (SEM) technique. For SEM analysis, suspended and bed sediments (0-75 µm) were sprinkled on the carbon tape, which was further gold coated to make the sample conducting. The sample was then inserted into the vacuum chamber of SEM (Model LEO 435 VP) and micrographs were recorded at different magnifications upto 10K at Institute Instrumentation Centre (IIC), Indian Institute of Technology (IIT), Roorkee.

Dissolution experiments of glacial meltwater-suspended and bed sediment interaction considering different operating variables viz; contact time and seasonality (different months), were carried out maintaining glacier environment condition in the Water Quality Laboratory, NIH, Roorkee. Dissolution experiments were carried out on 0-75 micron size fraction of bed sediments. The solution-sediment mixture was in free contact with the laboratory atmosphere for the duration of the experiments. The duration of the experiments is kept as 1 hour, considering representative of bulk meltwater residence times in arterial channels during the latter part of the ablation season. The temperature (0-3ºC) is realistic of field condition maintained by keeping solution-sediment mixture in a HDPE plastic beaker in the ice bath. Water to sediment ratios (8.0 g/L) were derived from the maximum suspended sediment concentration sampled during diurnal cycles in the field. Ultra pure water was used as a surrogate for icemelt with very low ionic concentration. Experiments were conducted in a HDPE grade plastic beaker containing 250 ml (±2 ml) of ultrapure water on a shaker with magnetic stirrer maintaining with a speed of 500±20 rpm. pH, electrical conductivity and temperature were measured using pH meter (Model: HQ11d, Make: Hach, USA) and EC meter (Model: HQ14d, Make: Hach, USA) continuously during the experiment. The samples (20 ml) were collected at set intervals during the course of the experiment, immediately syringe-filtered through Whatman 0.45 µm cellulose nitrate membranes and refrigerated at

4ºC for later analysis of major cations and anions on Ion Chromatograph (Metrohm, Switzerland). Details of the analysis are given in Sharma et al. (2019) and analytical precision was <5% for all the analytes (anions and cations) and accuracy <5%.

3. Results & Discussion

Surface Characterization of Sediments

Surface characteristics of sediments play an important role in solute acquisition during freshly grinded sediment-meltwater interaction. In the present investigation, the surface characteristics of suspended and bed sediments of River Bhagirathi at Gomukh, Bhojwasa and Gangotri were studied using SEM analysis. The proglacial meltwater stream always carries a huge amount of suspended sediments. Our sampling site around Gangotri glacier is no exception. The sediments derived are mineral grains and not rock fragments and it is also evident from the scale of the SEM images. It can be inferred from SEM images that the sediments are argillaceous (clay size) sediment. The grains are in-equigranular and sub-rounded. A few platy minerals can also be seen. SEM images of bed sediments collected from River Bhagirathi at Gomukh, Bhojwasa and Gangotri are given in Fig. 2. In the first image (Gomukh, June 2016), the grains shows one set of cleavage, possibly a micaceous mineral. The pits and grooves are the indicators of chemical weathering due to the solution. The second image (Bhojwasa, June 2016) shows two-sets of cleavage. The third image (Gangotri, June 2016) shows roundness in the mineral grains indicator of transportation by stream water.

Chemical characterization of sediments

Chemical characterization of suspended and bed sediments (0-75 μm) of River Bhagirathi collected from Gomukh, Bhojwasa and Gangotri during June 2016 were are given in Table 1. It can be inferred that suspended sediment of the site Gomukh of River Bhagirathi has higher potential of chemical dissolution as compared to other sites i.e. Bhojwasa and Gangotri.

Table 1. Chemical characteristics of suspended and bed sediment

Major ion	**Suspended sediment**			**Bed sediment**		
(μg/g)	**Gomukh**	**Bhojwasa**	**Gangotri**	**Gomukh**	**Bhojwasa**	**Gangotri**
Na	91	84	76	24	16	20
K	77	65	53	15	27	18
Ca	323	328	205	476	381	505
Mg	62	85	61	46	89	78
SO_4	1127	1008	1027	1568	3453	3245

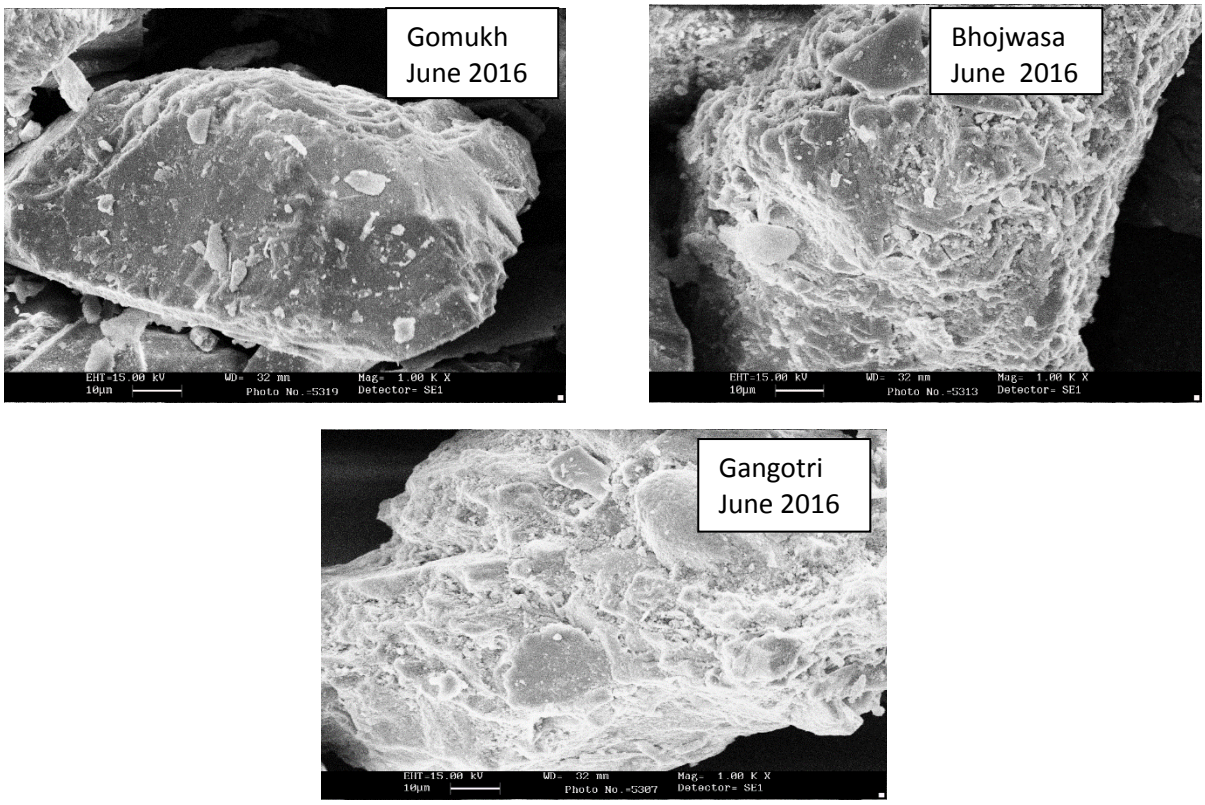


Fig. 2: SEM Images of bed sediments of River Bhagirathi at Gomukh, Bhojwasa and Gangotri collected during the month of June 2016

Role of sediment in controlling hydrochemistry

The discharge characteristics in a glacial system have direct bearing on the sediment transfer characteristics. It is also linked with the development and progression of subglacial channel network (Thayyen et al., 1999) as subglacial zone is the major source area of glacial sediments. The sediments, which get deposited throughout the winter period gets evacuated during the early stages of subglacial channel development. Further, suspended sediment load in the glacier fed streams play a significant role in solute acquisition by its interaction with dilute glacial and snow melt waters. High suspended sediment concentration in melt season was observed in the meltwater of River Bhagirathi at Bhojwasa followed by Gangotri and Gomukh (Fig. 3) which may be attributed to intensive melting (high discharge), increased stream area cross section and higher availability of glacier debris. The reduced suspended sediment concentration in the meltwater of River Bhagirathi at Gangotri during peak ablation/monsoon period suggests less sediment inflow vis a vis with discharge. It is to be noted that maximum suspended sediment concentration peak occurred in the meltwater of the River Bhagirathi on 30th June 2016 (Fig. 3) and EC, cations Ca^{+2} and Mg^{+2} and anion SO_4^{-2} concentration in the meltwater were also observed higher in the month of June as compared to other months of investigation (Fig. 3) suggesting that the introduction of freshly grinded sediment to bulk meltwater draining Gangotri glacier stream may have a greater impact on post mixing solute acquisition than the re-mobilization of previously weathered sediments deposited in the channelized system during low flow period. These observations indicate instream reactions favoring dissolution of ionic species from sediment are the main sources of solute acquisition in the meltwater at all three sites.

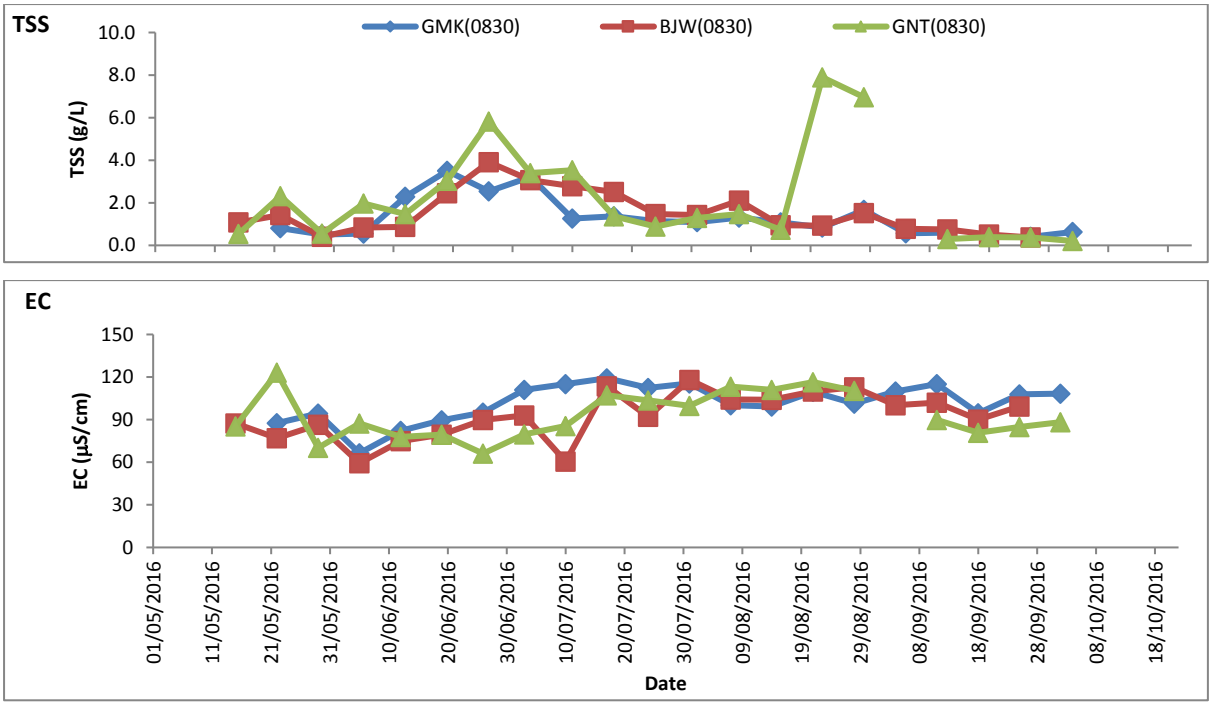


Fig. 3 Temporal variation of Total Suspended Sediment (TSS) and Electrical Conductivity (EC), in the meltwater of River Bhagirathi at Gomukh (GMK), Bhojwasa (BJW) and Gangotri (GNT) during the year 2016

Meltwater-Glacial Sediment Interaction

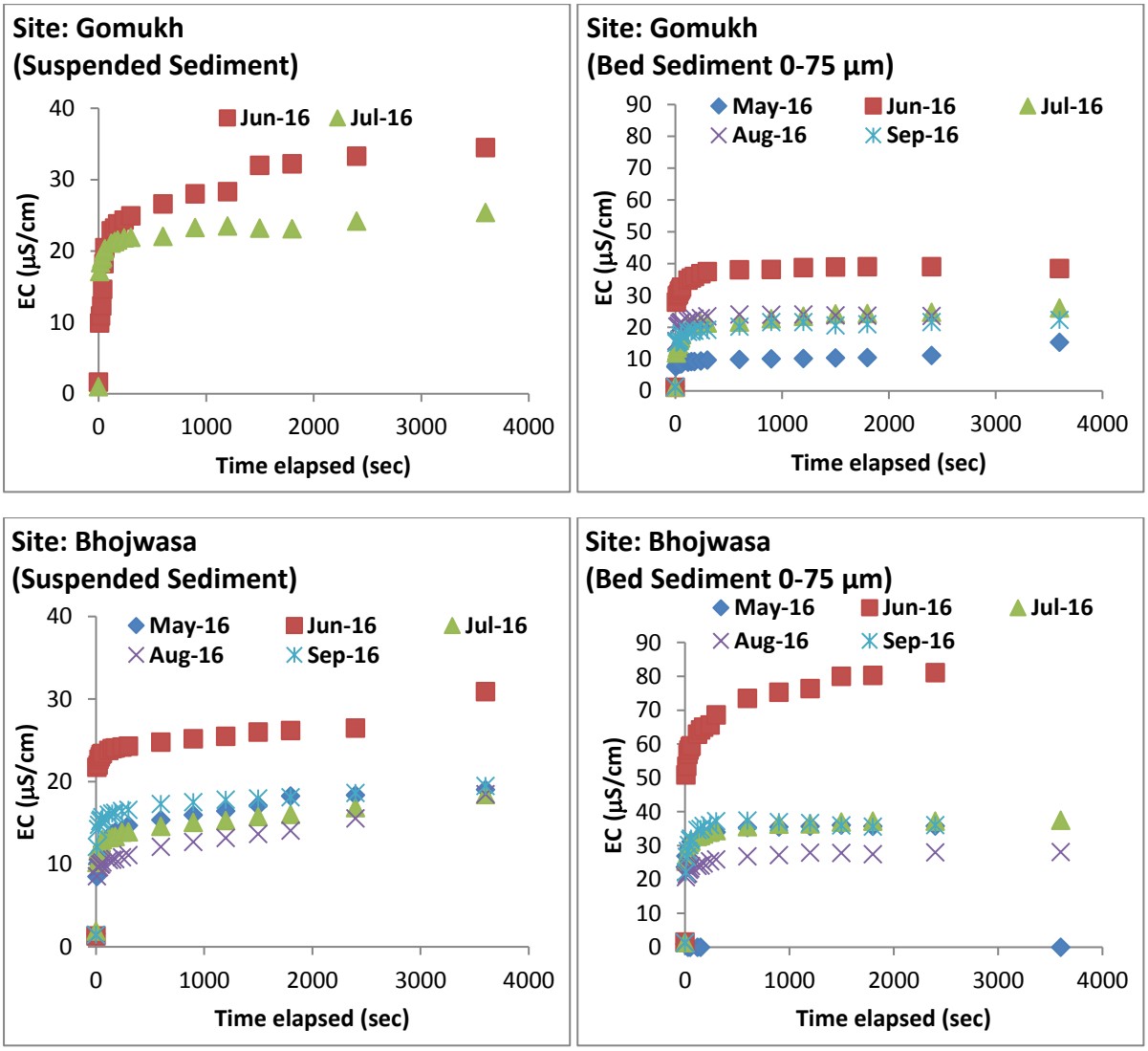
For understanding of low temperature solute acquisition, dissolution experiments of glacial meltwater – suspended and bed sediment interaction were carried out considering different operating variables viz; contact time and seasonality. Suspended and bed sediments of River Bhagirathi collected from Gomukh, Bhojwasa and Gangotri during the month of May, June, July, August and September 2016 were used for the experiment. Maximum dissolution was observed from the suspended and bed sediments collected in the month of June.

Table 2. EC (µS/cm) observed with bed sediment of June 2016 (0-75 µm, dose = 8.0 g/L)

Time elapsed (sec)	Gomukh	Bhojwasa	Gangotri
0	1.17	1.53	1.23
5	22.2	45.1	36.4
10	27.9	50.9	41.9
20	29.9	53.4	45.7
30	30.4	56.9	47.7
40	31.3	58.2	49.8
50	31.9	59.1	51
60	32.6	59.5	52.3
120	34.8	62.9	57.8

Dissolution experiments on suspended and bed sediments (0-75 µm size fraction) were carried out upto 3600 seconds (1 hour) for different contact time with sediment dose of 8.0 g/L and equilibrium time was observed to be 600 sec (10 min) for both suspended and bed sediments of all the sites i.e. Gomukh, Bhojwasa and Gangotri (Fig. 4). It can be seen that the most of the dissolution occur at first few seconds and very critical for this experiment (Table

2). This also demonstrates the importance of freshly grinded sediment in the glacial system and its eventual release of ions when in contact with the dilute waters from glacial system. Further progressive increase in EC was observed from Gomukh to Gangotri suggesting the change in sediment surface characteristics/or source (Fig. 2). Maximum dissolution was observed from the suspended and bed sediments collected in the month of June indicated by maximum EC value observed in the month of June at all three sites. The same trends were observed for cations Ca^{+2} and Mg^{+2} and anion SO_4^{-2}. These experiments indicate that glacial flour is extremely geochemically reactive and more dissolution takes place from bed sediments in comparison of suspended sediments of all three sites.



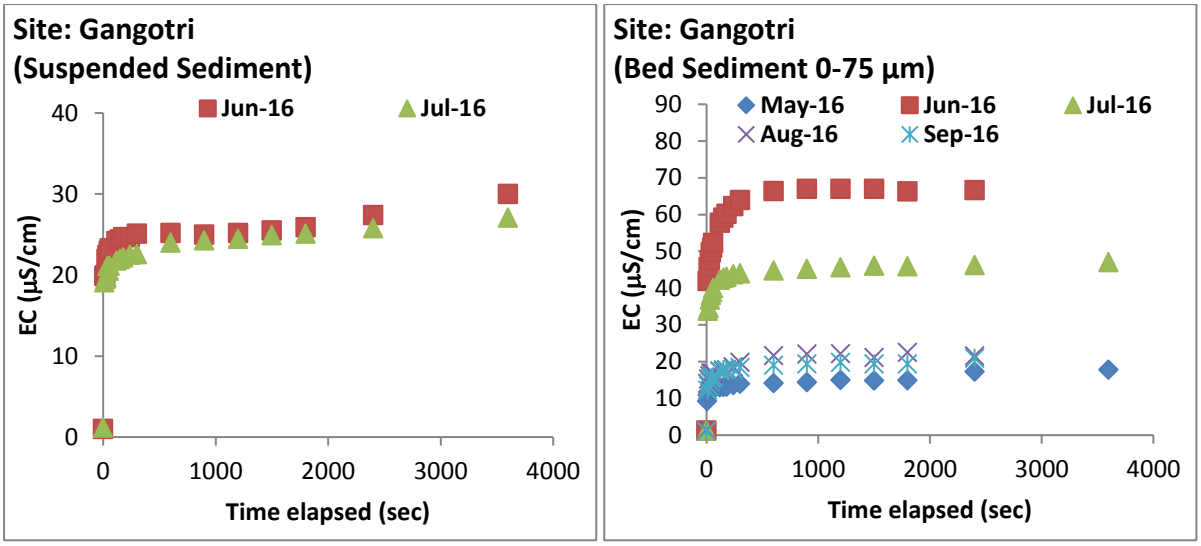


Fig. 4 Effect of contact time on EC for suspended and bed sediment
Volume of UPW taken = 250 ml; Background EC of UPW = 1.43 µS/cm; AT = 17.5°C, WT = 1.3°C, pH = 5.67; Sediment Dose = 8.0 g/L, RPM = 500

4. Conclusion

Hydrological interpretation of the solute content of glacial meltwater is dependent on a knowledge of the processes and rates at which meltwater acquires solute in the subglacial environment. Laboratory dissolution experiments help directly to improve hydrological interpretations of solute acquisition process under changing climatic regime. Solute acquisition during freshly grinded sediment-meltwater interaction is also governed by characteristics of sediment, which is also affected by change in environmental condition viz. temperature. Further, more solute acquisition takes place from bed sediments in comparison of suspended sediments of all three sites as indicated by dissolution experiments.

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