# B. TECH. PROJECT REPORT On Phosphorus in high-altitude ecosystems of Gangotri and Chhota Shigri glaciers in Himalaya.

BY Devashish Shukla



# DISCIPLINE OF CIVIL ENGINEERING INDIAN INSTITUTE OF TECHNOLOGY INDORE Nov 2019

# Phosphorus in high-altitude ecosystems of Gangotri and Chhota Shigri glaciers in Himalaya.

# **A PROJECT REPORT**

Submitted in partial fulfillment of the requirements for the award of the degrees

of BACHELOR OF TECHNOLOGY in

## **CIVIL ENGINEERING**

Submitted by: Devashish Shukla

*Guided by:* **Dr. Mohd. Farooq Azam | Assistant Prof. DCE, IIT Indore** 



# INDIAN INSTITUTE OF TECHNOLOGY INDORE Nov 2019

## **CANDIDATE'S DECLARATION**

I hereby declare that the project entitled "Phosphorus in high-altitude ecosystems of Gangotri and Chhota Shigri glaciers in Himalaya" submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Civil Engineering' completed under the supervision of Dr. Mohd. Farooq Azam, Assistant Professor, Discipline of Civil Engineering, IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

## Signature and name of the student(s) with date

## **CERTIFICATE by BTP Guide(s)**

It is certified that the above statement made by the students is correct to the best of my/our knowledge.

## **Signature of BTP Guide(s) with dates and their designation**

# **Preface**

This report on "Phosphorus in high-altitude ecosystems of Gangotri and Chhota Shigri glaciers in Himalaya" is prepared under the guidance of *Dr. Mohd. Farooq Azam.* 

In this report, the phosphorus fractionation and its bioavailability in glacial environment have been analyzed. Phosphorus is a macronutrient, which is often found deficit on the glacial surfaces, which in turn limit the bio productivity and microbial growth. This study primarily focuses on two major glaciers of India: *"Gangotri"* and *"Chhota Shigri"*.

In the following study, I have tried to the best of my abilities and knowledge to explain the content in a lucid manner. We have also incorporated various bar graphs, tables and windrose diagrams to make it more illustrative.

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# **Acknowledgments**

I would like to express my special thanks of gratitude to my B.T.P guide *Dr*. *Mohd. Farooq Azam* for his kind support and valuable guidance. I am grateful to him for giving me this great opportunity to embark on this wonderful project and providing me all the facilities that were required.

I would like to thank my parents and my brother who kept motivating me for the entire duration.

It is their help and support, due to which I was able to complete the design and technical report. It also helped me in doing a lot of research and gain vast knowledge on "*Glaciology*" and "*Chemistry in glacier environment*".

Without his support, this report would not have been possible.

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## **Abstract**

In oligotrophic environments, like glaciers, the nutrients are restricted to a certain limit, yet the glaciers have the abundance of active microbial communities which includes photoautotrophic and heterotrophic bacteria. Phosphorus is found as limiting nutrients in high altitude terrestrial ecosystems, leading to detrimental effects on microbial communities. We quantified pools of phosphorus (P) in supra-glacial lakes and runoff streams in Gangotri Glacier (Central Himalaya) and supra-glacial and peri-glacial stream sediments in Chhota Shigri Glacier (Western Himalaya).

The mean total P content in Gangotri Glacier was 0.66 mg g<sup>4</sup> which was significantly lesser than the Chhota Shigri Glacier having dissolved P content of 1.64 mg g<sup>4</sup>. Chhota Shigri had P higher than global mean P content 0.7 mg g<sup>4</sup>. The organic fraction of P in Gangotri Glacier was in the range of 0.54 - 2.78% while in Chhota Shigri it varied between 22.44 - 33.19%with the Glacial surface site on the lower range of the values. Further in Gangotri glacier, supraglacial lakes had more P content 0.846 mg g<sup>4</sup> than runoffs stream 0.478 mg g<sup>4</sup>. Although in the Chhota Shigri Glacier, the difference between total P content in supra-glacial sediments and peri-glacial stream sediments was very less but dissolved organic P was found significantly higher in the latter one. Fe- and Al-bound P are the potential source of bioavailable P. Supraglacial lakes in Gangotri Glacier had a concentration of 11.42 µg g<sup>4</sup> of Fe-Al bound P while runoff streams had 45.85 µg g<sup>4</sup>. In spite of having high P content, the Fe-Al bounded P in Chhota Shigri Glacier, had an average value of 27.66 µg g<sup>4</sup>.

Further, major ion concentrations were analyzed in Gangotri Glacier to predict the weathering processes where Na/Cl ratios were in the range of 3 to 10, indicating carbonate weathering as a dominating process. C:N:P ratios with an average of 1093:90:1, were significantly higher from classic Redfield and Cleveland & Liptzin ratios for terrestrial ecosystems.

Total dissolved solids in Supraglacial lakes of Gangotri glacier were lower as compared to glacial runoff streams, consequently increasing the electrical conductivity in runoff streams. Carbonate rock weathering and debris input in the tributaries accounts for the increment. XRD analysis indicated the absence of major phosphatic minerals in a glacial environment in both Chhota Shigri and Gangotri glaciers. Some amount of aluminium silicates was found in the

Gangotri Glacier and local debris rocks on the Chhota Shigri Glacier surface had some amount of Graphite and phlogopite.

Wind patterns were analyzed using ERA5 data for 40 years as an estimate to the potential source of P in the glacier which includes the allochthonous input from nearby areas via aeolian dust and global winds. The input via winds varies seasonally, but still the contribution (P content) even in peak seasons is insignificant. The P cycle in both glacial environments is mainly controlled by geochemical and physical processes with a certain degree of dependency on other factors including biodegradation of natural habitants and allochthonous inputs.

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# **Chapter1: Introduction**

In India, glaciers are the prime source of numerous perennial rivers like Indus, Ganga, and Brahmaputra. which provides fresh water to the second largest populated country in the world. Ganga has become a source of life for 400 million people living in its basin, while Chenab is one of the major rivers in Punjab which flows in Indian as well as Pakistan. In the form of a confined stream, water gets drained out of glaciers into the rivers. As an oligotrophic environment, glacier surfaces harbor very limited number of nutrient, yet are dominated by abundant and active microbial communities which consist of photoautotrophic and heterotrophic bacteria (*Säwström et al., 2002; Kaštovská a et al., 2005; Hodson et al., 2008; Anesio et al., 2009).* They are found in cylindrical depressions, filled with water which forms on glacier surfaces when debris by allochthonous input melts down on the surface (*Wharton et al., 1985*).

Phosphorus (P) is a crucial element in the study of microbial growth as it consists of 2-4% of the dry weight of the microbial cells and is generally found to be deficient in the glacier environment. According to biological stoichiometric theory, there is a molar ratio 106:16:1 among carbon, nitrogen and phosphorus nutrients in equilibrium which signifies healthy ecosystem development (Sterner and Elser 2002). If one of the nutrients is found in excess or in deficit, it affects bio-productivity severely. In newly formed soils as compared to the longterm developed soils, Nitrogen (N) is found to be the major limiting element due to its shortage while P is the major limiting element in later one because it depletes continuously (Walker and Syers 1976; Vitousek et al. 2010). The P cycle is relatively a closed and slow process as compared to N. It occurs in the pedosphere and the biosphere (Smil 2000). A lot of studies have already been done in the aquatic and agronomic ecosystem. Thus it's bioavailability becomes essential in the mountains. Because they represent a typical terrestrial ecosystem, where the steep slope and thin soil layer cause easy loss and insufficient supply of P. According to some recent researches, P is found the major limiting element in some high latitude terrestrial ecosystems while N was present in adequate quantity (Bowman 1994; Seastedt and Vaccaro 2001; Wassen et al. 2005). Hence, P can limit the growth of microbes and their productivity. Furthermore, it can't be fixed from the atmosphere via rains or snow because it is primarily a rock derived nutrient (Walker and Syers 1976). Dissolved P in glacial meltwaters can be low,

(even lesser than  $0.7\mu$ M), but total P are of greater magnitudes. One of the possible reasons is that glacial meltwaters are dilute and Soluble Reactive P (SRP) gets adsorbed on the suspended sediment surfaces (*e.g. House et al., 1998*). In glacial runoffs, the majority of P present are bounded to sediments. Glacial environments are found to be more aligned towards physical denudation over chemical denudation (*e.g. Hodson et al., 2002a*), hence sediment-bound P as a proportion of Total P is of great importance. Sediment bound P loading in the supraglacial environment has both detrimental (reduce primary productivity because of turbidity) and beneficial effects (increase the fertility of soil). Hence, it becomes necessary to assess the status of ambient P in such environments.

Here we focus on the four major factors which includes (a) Analyzing the supraglacial environment characteristics which includes calculation of TDS, pH and Electrical conductivity in water as well as sediment samples, (b) the distribution of different phosphorus fractions in both glacial environment and organic P availability for microbial communities, (c) the interaction between P pools near both glaciers, and the factors like biological activity, aeolian dust which contributes to phosphorus content on the glacier. We also study the atmospheric import of phosphorus i.e. local and global winds, which play a significant role in the transfer of free nutrients from one place to another, and (d) Later on, we elucidate the potential export in the downstream ecosystems.

# **Chapter2: Study Site**

Study area includes two glaciers: Gangotri and Chhota Shigri in Central and Western Himalaya, respectively.

#### 2.1 Gangotri Glacier

It is estimated that the Himalayan glaciers provide around 8.6 x  $10^6$  m<sup>3</sup> of water annually (*Srivastava, D. et. al. 2012*). The three great rivers of India – the Indus, the Ganga, and the Brahmaputra collectively provide close to 50% (320 Km<sup>3</sup>) of the total country's utilizable surface water resources (690 km<sup>3</sup>). Gangotri glacier originating from Chaukhamba peaks (7138 m asl) is 30.2 km long with a glacier area of about 143.58 km2. The present-day snout is about 18 km from Gangotri Township.

Gangotri Glacier is one of the most important glaciers in Central Himalaya which is the source of the river Bhagirathi, the largest tributary of Ganges, emanating from the Gangotri group of glaciers in Uttarkashi district of Uttarakhand. The other major tributary Alaknanda emanating from the Satopanth and Bhagirathi-Kharak glaciers north of Badrinath in Chamoli district of Uttarakhand meet at Devprayag and give rise to Ganga river, which is the most important source of freshwater supporting the population of north Indian Himalaya and plains. Gangotri glacier and river Ganga has an important status in the Indian culture. Scriptures and faith of the population consider it a sacred river. Perhaps two billion of the world's people depend on these rivers for their water and food supply. Gangotri glacier extends between 30°43'50" to 30°56'59" N and 79°01'04" to 79°17'22"E. Gomukh, the terminus & the snout of the glacier has an elevation of 3976 m a.s.l. Bhagirathi & Alaknanda, the two major tributaries confluence in Devprayag and form Ganga. The Gangotri Glacier has an accretion of numerous supraglacial lakes. Mitkari et al. 2017) identified 136 supra-glacial lakes in Gangotri glacier using LISS IV (5.8 m) satellite data-set. Gangotri glacier is 31.2 km long & 2 to 4 km wide.

#### 2.2 Chhota Shigri Glacier

Innumerous studies have been carried out on the Chhota Shigri glacier which is one major representative glaciers in the Himalayas (*Azam et al., 2019*). The glacier lies in the east of Rohtang Pass, on the ridge of Pir Panjal Range of the Inner Western Himalayas. The glacier is

the primary source of the Chenab river which is one of the major tributaries of the Indus River System. Chhota-Shigri glacier is spread between 32°11'40''-32°17' N and 77°28'-77°33' E, in the Chandra river basin in the Lahaul- Spiti valley located in Himachal Pradesh, India. The catchment of the glacier is abundant in gneiss. It contains sulphites trace and stibnite deposits. The drainage area of the Chhota Shigri Glacier stream is 34.7 km<sup>2</sup>. The area between the ablation zone and the accumulation zone has a high slope. The glacier weather is dominated by Asian monsoon in summer and in winters by the mid-latitude westerlies, as it lies in the monsoon-arid transition zone. Chhota Shigri has a total length of 9 km and an area of 15.48 km<sup>2</sup>, extends from 5830 to 4050 m a.s.1 (*Azam et al., 2016*).



Figure\_1: Map of Gangotri Glacier & Chhota Shigri Glacier with schematically marked sampling sites

## **Chapter3: Methodology**

In this study, we analyzed supra-glacial lake sediments and tributary stream sediments on Gangotri Glacier and supra-glacial moraine sediment and downstream or periglacial stream sediment samples on Chhota Shigri Glacier. Electrical Conductivity, Total dissolved solids, and pH values were also analyzed to get the details of the supraglacial environment on Gangotri Glacier. Biogeochemical stoichiometric ratios (using CHNS data) were also analyzed to identify the limiting nutrients for microorganisms and discuss the atmospheric import. The major ion concentrations were also determined using an atomic absorption spectrophotometer which included the cations of Alkali and Alkaline earth metals and sulphate anion, Cl<sup>-</sup>, PO<sub>4</sub><sup>-</sup>. In lakes, oceans and other marine ecosystems, the C: N: P ratio of particulate matter including living and non-living organisms "sestons", is the basis of deriving relationships in fundamental ways to biogeochemical cycles. Redfield in 1962, concluded that the C: N: P ratios of particulates are found similar in the surface offshore ocean to the C: N: P ratios of the dissolved species of these same elements deep beneath the offshore ocean (Redfield et al. 1963). Since then, the Redfield ratio is widely used as a comparison of nutrients in different environments. It also implies the limiting factors for microbial growth in an environment based upon the variation from the classic Redfield ratio.

The levels of P content in glacial meltwaters of the Himalayan region are not documented till date. In the following study, we have used different extraction schemes to calculate phosphorus content at ten different sites on Gangotri Glacier (Garhwal Himalayas) which includes supraglacial lakes and various tributary river sites and 11 different sites of Chhota Shigri Glacier which includes supra-glacial moraine sediments and per-glacial stream sediments. In one of the widely used methods, phosphorus extractions are derived from the method of determination of P in natural waters (*J. Murphy and J.P. Riley 1962*). Glacier surfaces are taken into account because they receive all kinds of radiation and heat flux. They're the sites of deposition of debris flowed down by the surroundings and carried by aeolian dust. They are the locus of meltwater production. Later, we analyzed different fractions of P including organic and inorganic P. XRD analysis was also done in order to predict major phosphatic minerals present in sediment samples.

#### 3.1 Gangotri Glacier - Sampling Sites

Sediment and water samples were collected from six supraglacial lakes on Gangotri Glacier and four runoff streams: Gomukh, Raktavarna Nala, Nandavan Nala & Tapovan Nala. TThe supraglacial lakes were selected randomly on the glacier surface. Supraglacial lakes on the glacier surface get destroyed easily either by ablation or the flushing in a short period of time, hence all the lakes were observed in the period of sampling. The residence time of water in lakes varies from a few days to a few months.

| Sample No. | Sampling Site  | Sample    | Latitude                  | Longitude                 | Altitude |
|------------|----------------|-----------|---------------------------|---------------------------|----------|
| 1          | Gomukh         |           | 30 <sup>0</sup> 55.668' N | 79 <sup>0</sup> 04.739' E | 3953 m   |
| 2          | Raktvaran Nala |           | 30 <sup>0</sup> 55.558' N | 79 <sup>0</sup> 05.180' E | 4109 m   |
| 3          | Nandavan Nala  |           | 30 <sup>0</sup> 54.476' N | 79 <sup>0</sup> 06.026' E | 4276 m   |
| 4          | Tapovan Nala   |           | 30 <sup>0</sup> 55.352' N | 79 <sup>0</sup> 04.780' E | 4079 m   |
| 5          | Lake No. 1     | Water.    | 30 <sup>0</sup> 54.782' N | 79 <sup>0</sup> 05.636' E | 4228 m   |
| 6          | Lake No. 2     | Sediments | 30 <sup>0</sup> 54.142' N | 79 <sup>0</sup> 05.807' E | 4304 m   |
| 7          | Lake No. 3     | beaments  | 30°53'54.87"N             | 79° 05.61'E               | 4220 m   |
| 8          | Lake No. 4     |           | 30 <sup>0</sup> 54.332' N | 79 <sup>0</sup> 05.229' E | 4256 m   |
| 9          | Lake No. 5     |           | 30 <sup>0</sup> 53.453' N | 79 <sup>0</sup> 05.591' E | 4349 m   |
| 10         | Lake No. 6     | 1         | 30 <sup>0</sup> 52.334' N | 79 <sup>0</sup> 05.822' E | 4437 m   |
| 11         | Base Site      | Sediments | 30°56.179' N              | 79° 04.023' E             | 3916 m   |

Table 1. Sampling sites in Gangotri Glacier

\* - Indicates the samples from the runoff sites

The water samples collected, were filtered through 0.45  $\mu$ m nucleopore filters immediately and were stored into 60 ml High-Density Polyethylene bottles for later analysis. Precautions were taken while sampling:

- a. The glass bottles were filled up to the top, to avoid headspace and CO<sub>2</sub> exchange.
- b. Prior to sampling, the bottles were rinsed twice at least with the filtrate.
- c. Samples were stored away from the light at  $5^{\circ}$ C.

Sediment samples were collected from the rivers and supra-glacial lakes during the same sampling period. The samples were placed into 200 ml sterile polyethylene bottles and were kept under a temperature of -20°C. To avoid chemical or biological reactions, precautions were

taken in sediment samples too. In addition to this, in situ measurements of (1) Total dissolved solids, (2) electrical conductivity (EC) and (3) pH were carried out using a Hanna HI 9025 pH meter (Hanna Instruments, Woonsocket, RI) with a pH electrode (HI 1230). Electrical conductivity was measured with a WTW LF 315 conductivity meter with a KLF 315 probe. Major ion concentrations were measured using an Atomic Absorption Spectrophotometer.

#### 3.2 Chhota Shigri Glacier - Sampling Sites

Sampling was done on 11 different sites in Chhota Shigri Glacier catchment, of which three sites were located beneath the glacier snout and eight on the glacier surface. All the sampling sites were randomly selected and water-sediment samples were collected. All the necessary precautions were taken since the beginning, including sampling, transferring and preservation of all the sediment and water samples.

| Sample No. | Sampling Site | Sample Type         | Latitude     | Longitude    | Altitude |
|------------|---------------|---------------------|--------------|--------------|----------|
| 1          | Site 1        |                     | 32°13.614' N | 77°30.970' E | 4788 m   |
| 2          | Site 2        |                     | 32°14.005' N | 77°31.071' E | 4746 m   |
| 3          | Site 3        |                     | 32°14.424' N | 77°31.257' E | 4671 m   |
| 4          | Site 4        | <b>TT</b> 7 /       | 32°14.737' N | 77°31.439' E | 4591 m   |
| 5          | Site 5        | Water,<br>Sediments | 32°15.738' N | 77°32.591' E | 4539 m   |
| 6          | Site 6        |                     | 32°15.909' N | 77°31.726' E | 4262 m   |
| 7          | Site 7        |                     | 32°16.122' N | 77°31.742' E | 4201 m   |
| 8          | Site 8        |                     | 32°16.622' N | 77°31.951' E | 3932 m   |
| 9          | Site 9        |                     | 32º16.760' N | 77°31.959' E | 3899 m   |
| 10         | Site 10       | 1                   | 32°17.185' N | 77°31.837' E | 3860 m   |
| 11         | Site 11       |                     | 32º14.657' N | 77°31.384' E | 4611 m   |

Table 2. Sampling sites in Chhota Shigri Glacier

\* - Indicates the samples from beneath the glacier snout

### 3.3 XRD & Major Ion Chemistry Analysis

The mineralogy of the sediment samples was determined by X-ray diffraction (XRD). Philips PW1050 goniometer was used with a Philips PW1730 generator. It had a standard CuKa radiation X-ray tube ( $k = 1.5418 \text{ A}^{\circ}$ ).

The standard power settings were used with a voltage of 40 kV and a current of 30 mA. Patterns were obtained for 2 hr between 5° and 60°, at a scan rate of 1° min<sup>-1</sup>, with a step size of 0.08°. Necessary precautions were taken. Debris was kept in propanone, and placed onto the center of a low background holder. The sample was dried properly prior to analysis.

The X'PERT Highscore software and the MATCH software were used along with the ICDD (International Centre for Diffraction Data) by JCPDS (Joint committee on Powder Diffraction Standards) having a PDF2 database, for phase identification. All results were re-checked manually from "A practical approach to Sedimentology" (*Roy C. Lindholm et al. 1987*).

For the analysis of major ions in the samples, Atomic Absorption Spectrometer (AAnalyst400, Perkin Elmer) was used. It is used to analyze metals and ions at extremely low concentrations which range in the parts per million (ppm) or parts per billion (ppb) concentration. In the following study major alkali, alkaline metals (Ca, Mg, Na, K) and SO<sub>4</sub>, Cl, PO<sub>4</sub> were analyzed. Later ones were analyzed using Hanna spectrophotometer. Na/Cl ratios were also calculated to predict the cause of erosion in the rocks.

#### 3.4 Sediment Analysis

For the determination of total phosphorus in sediments a sequential extraction scheme (*M. Stilbal et al. 2008*) of samples was followed, which was an adaptation of a single solution method for the determination of phosphate in natural waters at five stages (*J. Murphy and J.P. Riley et al. 1962*). The amount of phosphorus related to different fractions was analyzed spectrophotometrically. The schematic plan of sequential extraction is shown in the figure given below.

#### Assessments and Measures

The sediment samples were kept in the oven for 16 hr at 105°C to remove all the moisture content. 0.2 g of dried sediments were taken in pre-cleaned autoclavable HDPE (High-Density Polyethylene) centrifuge bottles. The determination of total phosphorus was done in five different fractions.

*Extract -1*. For the extraction of loosely adsorbed phosphorus 12 ml of 1 M MgCl<sub>2</sub> was added to the sediments and agitated at 200 rpm on a reciprocating shaker for 16 h. After shaking the mixture tubes were centrifuged at 2600 for 12 min. The supernatant of the mixture was transferred to pre-cleaned HDPE bottles.

*Extract-1:* 12 ml of Milli Q was added to the retained sediment, again shaken for 2 h, centrifuged and the supernatant was added to the Extract-1. The latter step was repeated one more time.

*Extract-2:* The extraction of Al and Fe-bound P was done by adding 12 ml of 0.1 M NaOH to the retained sediment and treating the mixture the same as for Extract 1.

*Extract-3:* Ca and Mg-bound P were extracted by adding 12 ml of 1 M HCl to the retained sediment and treating the same as above.

*Extract-4:* The extraction of Organic-bound P was done by adding 12 ml of 30%  $H_2O_2$  to the retained sediment and heated it at 85° C on a hot water bath for 3 hr with intermittent agitation. The mixture was allowed to cool, centrifuged at 2600 rpm for 30 min. and the supernatant was collected in HDPE bottles.

Again 12 ml of 30%  $H_2O_2$  was added to the tubes, heated at 85° C in a hot water bath for 2 h with occasional agitation. The mixture was allowed to cool, centrifuged at 2600 for 30 min and the supernatant added to the bottles. Finally, 12 ml of Milli Q was added to the mixture and shaken for 2 h, centrifuged and the supernatant collected.

*Extract-5:* The sediments were transferred to HDPE autoclavable bottles for residual P extraction. 15 ml of sulphuric acid/potassium persulfate reagent (55 ml conc.  $H_2SO_4$  and 60 g of  $K_2S_2O_8$  in 1 litre of Milli Q; Jeffries et al. 1979) was added to the bottles, autoclaved for 1 h at 121°C and 25 psi and allow to cool slowly. All the extracts were filtered through a 0.45-micron filter immediately after extraction.

The sediment was kept at 5°C between extraction steps. A control tube without sediment was also processed with every extraction. The phosphorus content in different fractions was determined spectrophotometrically using the HAACH as SRP as described above (*Murphy and Riley, 1962*). Extract 1 and 2 were measured directly as described above. Extract 3 and 5 were

diluted 1:4 And 1:14 with Milli Q prior to analysis respectively. The fourth extract was boiled with 1 M NaOH (pH 10.5) for five hours on a hot water bath to remove the unreacted H<sub>2</sub>O<sub>2</sub>.



Flow chart for sequential extraction scheme:

Figure\_2: Sequential extraction scheme for different fractions of phosphorus in various samples. All steps were performed laboratory temperature and pressure. (J.P. Riley and J. Murphy 1962)

# **Chapter4: Results**

#### 4.1.1 Gangotri Glacier – Analysis in supra-glacial lakes

Supraglacial lakes are cold  $(0.1^{0} \text{ C})$  in comparison to glacier runoffs which ranges between  $3.5^{0}$  to  $5.5^{0}$ C. Glacier runoffs are often found to have more turbidity and more concentration having EC<sub>avg</sub> of 101.6 µS cm<sup>-1</sup>. While the water in supraglacial channels is stable relatively with EC<sub>avg</sub> of 20.732 µS cm<sup>-1</sup>. The Total Dissolved Solids (TDS) average for six supra-glacial lake samples (9.383 mg/L) were also found much less as compared to TDS<sub>avg</sub> for Glacier Runoffs (48.3 mg/L).



Figure\_3: Total Dissolved solids (TDS), Electrical Conductivity (EC) and pH in Gangotri Glacier samples (mean + S.D). Samples are numbered according to Table 1.

The exclusion of supra-glacial debris may account for the huge difference between the values of TDS in two different sampling sites. Also as tributaries possess more no. of ions as compared to stationary lakes. Debris may get flow in rivers which results in a higher no. of TDS. The total dissolved solids are basically acidic in nature (indicating carbonate rock weathering). As shown in figure 3, the  $pH_{avg}$  was higher in supraglacial channel water (5.57) as compared to the glacier runoff streams (5.1).

Water flows down into supra-glacial lakes from the ablation areas. This water originates from the melting of ice and snow. Supra-glacial lakes formed on the surface of glaciers are temporary. They can last up to months but also can get formed and flushed down within hours. The residence time of water in the supra-glacial lakes was very variable, ranging from minutes to hours according to different sites on the glacier. Supra-glacial debris in the period of sampling was settled down in the bed of the lakes, hence the surface sampling doesn't include the accounts of lower dense sediment.

The sediment samples in supra-glacial lakes on Gangotri Glacier mainly consisted of silicates, such as quartz, Sodium Aluminium Silicate, feldspars (albite), and other amorphous minerals, indicated by the high peaks obtained between 18° C and 32° C (Fig. 4). XRD analysis was done manually as well as by X'Pert Highscore using JCPDS mineral library. The overall debris composition in all the samples remained very similar but no rock phosphate minerals, such as apatite were found.



All peaks were identified but only distinctive ones have been labeled.

The mean total P content in the supra-glacial lakes samples was  $0.478 \pm 0.188 \text{ mg g}^{-1}$  debris. Most P (58.91%) was present in Extract 5 (Residual-P), followed by Extract 5 (Ca/Mg Bound P: 38.13%), Extract 2 (Fe/Al Bound-P: 2.39%), and Extract 4 (Organic P: 0.54%). P in Extract 1 was found to be very less in amount (Loosely adsorbed P: 0.09%). Hence, 0.475 mg g<sup>-1</sup> (approx. 99.46%) of the total P present in fractions can operationally be defined as inorganic P. The major amount of this phosphorus is found to be either bound within or adsorbed onto minerals (Fig. 5).



Figure\_5: Distribution of phosphorus in the different extractions in Supraglacial Lakes collected on Gangotri Glacier

The different fractions of phosphorus in samples (Fig. 6) showed great variability in each sampling site. The sampling doesn't take into account the phosphorus settlement on the bed of stagnant supraglacial lakes hence results are in high variance.

The C:P and N:P molar ratios within the supra-glacial lakes samples showed great variability. C:N ratio varied from 7.42 to 19.48 for six different samples with an average of 12.68. C:P and N:P ratio exceeded their typical Redfield ratio (116:16:1) in marine environment and 60:1 (for N:P) in terrestrial ecosystems (*Clevelend and Liptzin 2007*) The average ratio in supra-glacial lakes was found to be 1093:90:1, consequently owing to the fact that P is limiting nutrient in the environment for microbial growth.

| Sample No.           | C:P | N:P | C:N |
|----------------------|-----|-----|-----|
| SUPRA-GLACIAL LAKE 1 | 498 | 26  | 19  |
| SUPRA-GLACIAL LAKE 2 | 711 | 60  | 12  |
| SUPRA-GLACIAL LAKE 3 | 730 | 62  | 12  |

Table 3: C:N:P ratios in the Supraglacial Lake samples.

| SUPRA-GLACIAL LAKE 4 | 609    | 82  | 7     |
|----------------------|--------|-----|-------|
| SUPRA-GLACIAL LAKE 5 | 1517   | 144 | 11    |
| SUPRA-GLACIAL LAKE 6 | 2490   | 166 | 15    |
| Average              | 1092.5 | 90  | 12.66 |

#### 4.1.2 Gangotri Glacier – XRD analysis and phosphorus content in river samples

The sediment samples in the river sites of the Gangotri Glacier mainly consisted of silicates, such as quartz, fluorite, bornite, and feldspars (albite). No major rock phosphate minerals, such as apatite were found in the four river samples.



*Figure\_6: XRD trace collected from River samples of Gangotri Glacier. All peaks were identified but only distinctive ones have been labeled.* 



Figure\_7: Distribution of phosphorus in the different extractions in Rivers collected on Gangotri Glacier

The average value of phosphorus in river samples was relatively low. The mean total P content in the supra-glacial lake samples was  $0.846 \pm 0.122$  mg g<sup>-1</sup> debris. Phosphorus content, unlike supra-glacial lake samples, was maximum (66.46%) in Extract 2 (Ca/Mg Bound-P), followed by Extract 5 (Residual P: 25.18%), Extract 3 (Fe/Al Bound-P: 2.39%), and Extract 4 (Organic P: 2.78%). P in Extract 1 was lowest i.e. Loosely adsorbed P: 0.09%. Hence, 0.824 mg g-1 (approx. 97.61%) of the total P present was inorganic P. Loose phosphorus content is very less in all the samples. Metal bound phosphorus has more content than any other P-type.

#### 4.1.3 Gangotri Glacier - Major Ion Concentration in supra-glacial lakes

A systematic study for the assessment of the chemical weathering processes in high altitude Himalayas was carried out. The major ion concentration for all the four runoff streams Gomukh, Raktavaran Nala, Nandavan Nala & Tapovan Nala and six supraglacial were analyzed. Among all the major ions, Ca, Mg, K, and SO<sub>4</sub> are the most abundant in glacial runoffs while Mg concentration in Supraglacial lakes was considerably less, which implies the carbonate rocks weathering is dominant in the runoff streams. On average, Sulphates have a much higher concentration in both the samples with approximately 30 times of other ions.

The equivalent ratio of Na/CI lies in the range of 3 to 9 which indicates the excess of sodium ions and suggesting that most of the sodium in both Supraglacial lakes and runoff streams are produced from silicate weathering. The equivalent ratio of Na\* + K and TZ+ is about 15 on an average, which indicates prevailing silicate weathering (*Stallard and Edmond 1983; Sarin et al 1989*).

| Sample  | Na      | K      | Mg    | Ca     | Cl    | PO <sub>4</sub> | Silica | Sulphates |
|---------|---------|--------|-------|--------|-------|-----------------|--------|-----------|
| 1       | 0.6072  | 1.5325 | 1.801 | 7.0797 | 0.98  | 0.00            | 2.52   | 25.305    |
| 2       | 0.5641  | 2.9398 | 4.506 | 16.109 | 0.24  | 0.01            | 2.82   | 43.81     |
| 3       | 1.3465  | 3.6354 | 3.238 | 10.775 | 4.73  | 0.02            | 6.21   | 48.155    |
| 4       | 0.5962  | 1.1269 | 1.320 | 1.8588 | 0.92  | 0.01            | 3.54   | 26.525    |
| Avg.    | 0.78    | 2.31   | 2.72  | 8.96   | 1.718 | 0.01            | 3.773  | 35.949    |
| SGL - 1 | 0.1718  | 1.2863 | 0.296 | 3.0787 | 0.260 | 0.02            | 1.48   | 10.882    |
| SGL - 1 | 0.0945  | 0.3075 | 0.312 | 0.5323 | 0.640 | 0.00            | 0.46   | 1.426     |
| SGL - 1 | 0.0285  | 0.2587 | 0.214 | 0.134  | 0.020 | 0.01            | 0.3    | 1.621     |
| SGL - 1 | 0.4082  | 1.8251 | 0.708 | 1.5131 | 1.300 | 0.01            | 2.31   | 19.603    |
| SGL - 1 | 0.4422  | 1.9985 | 0.557 | 1.6084 | 1.000 | 0.00            | 2.07   | 16.886    |
| SGL - 1 | 0.2281  | 0.776  | 0.328 | 2.3734 | 1.440 | 0.02            | 0.97   | 3.757     |
| Avg.    | 0.22888 | 1.0753 | 0.402 | 1.5399 | 0.78  | 0.01            | 1.27   | 9.03      |

Table 4: Major Ion Concentration in the Gangotri Glacier.

#### 4.2.1 Chhota Shigri Glacier – XRD analysis of surface samples

Major minerals obtained in local rocks of Chhota Shigri Glaciers were Quartz, Albite, Silicates & Phlogopite. Chhota Shigri Glacier was also found deficit phosphatic mineral. All the samples were taken from the glacier surface.



Figure\_8: XRD trace collected from samples on the surface of Chhota Shigri Glacier. All peaks were identified but only distinctive ones have been labeled.

#### 4.2.2 Chhota Shigri Glacier – Phosphorus content from peri-glacial & surface sites

Chhota Shigri harbors a high phosphorus content relatively to Gangotri Glacier. Sampling was done in two phases a) eight samples were taken from the surface of the glacier while b) the other three samples were from below the glacier snout. The mean total P content in the surface samples was 1.63 mg g<sup>-1</sup> debris on the surface while 1.65 mg g<sup>-1</sup> for the samples below the snout, which is almost double of Gangotri Glacier. Organic phosphorus responsible for life in the marine environment was found the highest after Ca/Mg bound P, in both the type of samples, which primarily indicates a high possibility that P is not limiting nutrients in the glacier environment. Glacier surface samples contained 0.366 mg g<sup>-1</sup> (Organic P) while the samples beneath the snout have P concentration of 0.547 mg g<sup>-1</sup> debris.



Figure\_9: Distribution of phosphorus in the different site on Chhota Shigri Glacier

# **Chapter5: Discussion**

The probable P sources in the Gangotri Glacier and Chhota Shigri Glacier includes local rocks debris & wind-borne debris (aeolian dust). Aelion dust carries secondary biospheric P while the rocks debris have primary lithospheric P (*Marshall and Chalmers 1997*). Secondary biospheric P contains biomass and decayed organic matter particulates. The mean total P content in Gangotri Glacier (0.631 mg/ g debris) was found slightly less as compared to the global mean P content of Earth surface rocks (0.7 mg/ g) while Chhota Shigir has an abundance of P (1.64 mg/ g). As evident from XRD analysis, although Chhota Shigri Glacier has very high P content, no major phosphatic minerals were found in any of its sediment-water samples, neither in Gangotri Glacier. Inorganic P in both the glacier samples was found in the range of metamorphic rocks P. Hence, the debris flowing down in glacier runoff consists mainly of metamorphized rocks (*Majka and Budzyn* 2006).

#### 5.1 Allochthonous input via local and global winds

The wind direction of global winds (i.e. at 100m height) and local winds (i.e at 10m height) was analyzed using ERA 5 data for a period of 40 years i.e. 1979 January to 2019 June for both the glaciers. Local winds consist of Anabatic and Katabatic winds that flow from the low to high elevation area in the day time and downslope in nights respectively.

Local winds are generally weaker winds as compared to the global winds. In India, global winds are dominated mainly by Indian Monsoon Winds which are measured to be (1.5 m/s) three times higher than local winds. Global winds were found greater in magnitude in Chhota Shigri Glacier.

For the analysis, a year was divided into four seasons including Monsoon, Pre-Monsoon, Post-Monsoon, and Winter. Gangotri katabatic winds are mainly the Indian Monsoon Winds which enters the area in June-July and lasts up to October end. A suitable site was chosen for the representation of the whole glacier such that wind direction at that point nearly represents the direction of the wind in the whole glacier.

#### Wind trajectory in Gangotri Glacier

The base camp in Gangotri Glacier was located at 2.27 km from Gomukh. As the glacier is surrounded by high elevated mountains hence wind direction at the base site represents the direction of the wind in the whole glacier. Hence, the base camp will give the wind trajectory. There is a rock phosphate mine in the Garhwal Himalayas, 30-40 km in the north-west of the glacier, which consists of 10% phosphorus minerals resource of India (*Indian minerals yearbook, 2016*). It has 24178386 tonnes of phosphorus. The base campsite was taken as the representation of the whole glacier because the glacier is surrounded by the high elevation mountains.



Figure\_10: Wind pattern at 10m height (Gangotri Glacier)



*Figure\_11: Wind pattern at 100m height (Gangotri Glacier)* 

It is possible that Indian monsoon winds might have been carrying phosphatic minerals from the desert of Rajasthan like Apes-Sahara. Also, other western winds might have been carrying Aeolian dust carrying sand which contains phosphate, from Gobi Desert. But on analysis, winds were found to be directed from Glacier to Garhwal throughout the year which is nearly opposite to the required transportation route. Hence the organic or loose P if present in the mines, might not have been carried onto the glacier surface.

#### Wind trajectory in Chhota Shigri Glacier

In Chhota Shigri Glacier, wind patterns were analyzed for the same period of time using ERA5 data. Location near *Site 6* was chosen as the representation of the whole glacier. Mathematical extrapolation was done to predict the wind for the site in between the grids of  $0.25^{\circ} \times 0.25^{\circ}$ . The global winds were found to be randomly distributed throughout the year, while the local winds were majorly in the same direction throughout 40 years. Unlike Garhwal, Lahul & Spiti has no rock phosphate mine. Hence, there is no significant input from the nearby areas as loose or organic P.



Figure\_12: Wind pattern at 10m height (Chhota Shigri Glacier)



Figure\_13: Wind pattern at 100m height (Chhota Shigri Glacier)

#### 5.2 Phosphorus content in Gangotri and Chhota Shigri Glacier

Extract 1 and 2 are the inorganic fractions which can be extracted with ease, and contributes to the bioavailable P. Inorganic P consists mainly of metal bound P (Extract 3) and the residual P (Extract 5) in both the glaciers, but organic P (Extract 4) content was found more than residual phosphorus in Chhota Shigri Glacier. Ca- and Mg- bound phosphorus includes crystalline phases generally like carbonates while the residual phase is found to contain aluminosilicates and apatite (*Reddy et al. 1999*).

XRD results indicated the absence of major phosphatic minerals in both the glaciers, which is in compliance with the fact that the Inorganic P content of the debris is low. Loosely bound P (Extract 1) is the only P available at ease, and accounts for 0.03 - 0.16% in Gangotri Glacier i.e ~0.454 µg g<sup>-1</sup> and 0.14 - 0.17% in Chhota Shirgi Glacier i.e ~2.54 µg g<sup>-1</sup>. P gets locked in the structure of the sparingly soluble phases and hence only a small amount of bioavailable P is found to be contained on the surface of minerals, which is utilized by microbial communities via desorption and dissolution (*Welch et al. 2002*). The locked P can be utilized by the dissolution of carbonates under favorable pH conditions.

Fe- and Al bound P (base extractable, Extract 2) is the adsorbed P on the disordered oxyhydroxides phases of iron and aluminum (*Ruttenberg 1992*). They are the potential source of bioavailable P. In Gangotri Glacier, it accounts for 2.39 - 5.42% i.e 18.6 µg g<sup>-1</sup> and 1.33 - 1.92% i.e 26.6 µg g<sup>-1</sup> in Chhota Shigri, which is well in excess than the global average microbial P demand for the primary production on the glacier surfaces (*Stbial et. al 2008*).

The P input on the glacial surface varies seasonally. In the ablation season, the major portion of input occurs from the transfer of surface biomass via winds, when desiccation occurs in the soil. Other inputs like rock debris from adjacent elevated cliff slopes increase in the ablation seasons but the contribution (as readily available P) from the debris input is relatively less. The allochthonous input via aeolian dust also becomes insignificant in the ablation season as biomass gets bounded in the wet soils.

#### 5.3 Stoichiometric coefficients in the sediments on Gangotri Glacier

C:N:P ratios vary more in the terrestrial systems as compared to the oceans, but on average, they're well constrained at the global scales between 186:13:1 To 60:7:1 (Cleveland and *Liptzin et al 2007*) and are useful to determine the dependency of biogeochemical cycles on biotic and abiotic factors to a certain extent. The dissolved C:N and N:P molar ratios in Supraglacial lakes of Gangotri glacier varied from 3-19 and 26-166 respectively, which implies a lack of biological control on the biogeochemical processes which is consistent with the fact that the supraglacial environment was not microbial abundant and had low biological activity. The C:P ratios were also far more than the balanced values (varied in between 498 -2490). One of the major reasons is that microorganisms are primarily associated with the debris instead of being naturally present in the environment. The C:N:P values increases as we move towards the south-eastern side of the glacier owing to the relatively high N content compared to P. The C:N ratios were constrained in the range of 7-19, with an average value of 12.6. Although ablation in mountain area influences the nutrient ratios, as a large part of the glacial biomass comes from the aeolian dust carried by the global and local winds, hence the stoichiometric ratios of the biomass (allochthonous input) can only be determined by their original environment. Therefore, great precautions should be taken before elucidating the limiting nutrient in such environments. Organic P dissolved in the supraglacial lakes primarily originates from the decaying of dead Capra Ibex and the biomass contained in the debris. Dissolved C: Dissolved P doesn't follow typical Redfield values (106:1 Redfield et al. 1963; 60:1 in terrestrial ecosystems Cleveland and Liptzin 2007) and in fact are higher in magnitudes by 10 times implying the lack of DOP in Supraglacial lakes. As microbial communities are less in population, it rules out the possibility for loss of DOP via intakes for microbial growth. Another possible alternative is the adsorption of Dissolved Organic P on mineral surfaces. It occurs when a reactive phosphate group  $-OPO_3^{2-}$  gets attached to amorphous minerals (Fe and Al oxyhydroxides) positively charged site (Stewart and Tiessen 1987, Reddy et al. 1999).

## **Chapter6: Conclusions and Scope for Future Work**

In Chhota Shigri glacier, the mean total P content (1.64 mg g-1) was more than Gangotri Glacier (0.478 mg g<sup>-1</sup>), while the average P content in global rock debris varies from 0.65-0.9 mg g<sup>-1</sup>. The average organic P content in Chhota Shigri glacier (25.37 %) was way more than the Gangotri Glacier (1.44%). The remaining fraction was present in inorganic form. Metal bound phosphorus apart from residual phosphorus can be counted in readily available phosphorus in certain circumstances. Dissolved P in supraglacial samples of Gangotri glacier were considerably lower than runoff samples owing to the phenomenon of flushing and readsorption on the mineral surfaces. Further after wind pattern analysis in Gangotri Glacier, it was concluded that global and local winds had no major contribution in microbial input. In Chhota Shigri glacier, the organic phosphorus content was more on the sites beneath the glacier snout as compared to the surface sites. In Gangotri Glacier, it is not possible to assess the limiting nutrient in the glacial environments solely on the basis C:N:P ratios, but large variance from the classic Redfield and Cleveland & Liptzin ratios implies the deficiency of the dissolved organic P in the supraglacial lakes. It is possible to have some degree of control biologically, on the ratios (C:N & N:P), but phosphorus cycling is predominantly controlled by the ablation, geochemical and the physical processes. But as implied by the analysis of wind, it does not seem to contribute to the glacier environment.

Glaciers are receding hence the high concentration of P on glacier ablation area will be released downstream and improve the soil fertility downstream, however, more research linking farming and glacier receding is required which is an independent topic of research and is beyond the scope of this present work. Now as all analysis has been done. Biological research needs to be done in more detail. Glaciers are receding hence the high concentration of P on glacier ablation area will be released downstream and improve the soil fertility downstream, however, more research linking farming and glacier receding is required which is an independent topic of research and is an independent topic of research and is beyond the scope of this present work.

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