Evaluation of Meltwater Quality Using Dissolved Ions Chemistry and Multivariate Statistical Methods: A Case Study of the Manimahesh Glacier, Ravi Basin, Himachal Pradesh, India

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RESEARCH ARTICLE

Evaluation of Meltwater Quality Using Dissolved Ions Chemistry and Multivariate Statistical Methods: A Case Study of the Manimahesh Glacier, Ravi Basin, Himachal Pradesh, India

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Abstract The hydrogeochemical study on glacial meltwater gives important information about the quality of meltwater and weathering processes controlling dissolved ions chemistry in the glacierized area. Anionic abundance in the Manimahesh Glacier meltwater shows a trend of $HCO_3^- > SO_4^{2-} > Cl^- = NO_3^-$, whereas cationic abundance in the meltwater shows a trend of $Ca^{2+} > Mg^{2+} > K^+ > Na^+$. On the basis of high equivalent ratios of (Ca + Mg) versus (Na + K) and (Ca + Mg) versus TZ^+ (total cations) and low equivalent ratio of (Na + K) versus TZ^+, carbonate-type weathering has been identified as a major hydrogeochemical process regulating solute chemistry of the Manimahesh Glacier meltwater followed by silicate weathering. About 80% of bicarbonate in the meltwater of investigation area was mainly generated from carbonate weathering, whereas 20% of bicarbonate was produced from silicate weathering. The result of statistical methods (correlation, principal component and cluster analysis) shows that meltwater quality of the Manimahesh Glacier is mainly governed by carbonate and silicate-type weathering, oxidation of pyrite, dissolution of sulphate minerals and atmospheric input. The average value of suspended sediment concentration (SSC) in the glacier meltwater was calculated to be 46 mg/l and 63 mg/l during the month of June and July 2014, respectively, showing higher concentration of SSC during the month of July (peak-flow period) followed by June (low-flow period).

Keywords Dissolved ions chemistry · Meltwater quality · Hydrogeochemical processes · Suspended sediment concentration · Manimahesh Glacier · North-western Himalaya

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1 Introduction

The Hindu Kush Himalayan Mountains contain approximately 54,000 glaciers, extending over an area of about 60,000 km^2 with ice volume reserves of about 6000 km^3 [1]. The Himalayan glaciers are formed in a compound and single cirque basins having an area variation of ~ 0.5–143 km^2 [2]. These glaciers feed various important rivers of Asia such as Ganga, Brahmaputra, Indus, Salween, Yangtze, Mekong, Irrawaddy and Tarim. The meltwater draining from Himalayan glaciers along

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with seasonal and monsoonal precipitation supplies to the total stream discharge of Himalayan rivers [3]. Snowfall in the region of Himalaya is influenced by two atmospheric systems, i.e. South Asian monsoon and mid-latitude westerlies [4]. The western Himalaya receives snowfall or precipitation due to mid-latitude westerlies during the winter, whereas the eastern Himalaya receives snowfall or precipitation due to Indian Summer Monsoon (ISM) during the summer monsoonal period [5, 6].

Glacierized basins have a unique environment for chemical weathering characterized by low temperature that has negative effect on chemical weathering and high amount of rock comminution [7]. The chemical characteristics of meltwater are different from other aquatic system due to the presence of low temperature in the glacierized area [8]. Various ions in the meltwater are mainly derived when meltwater passes through subglacial environment at the interface of rock–ice and rock–meltwater [9]. Major ion chemistry of glacial meltwater plays an important role in understanding complex weathering and hydrogeochemical processes occurring in the glacier environment [10–17]. Suspended sediment concentration (SSC) in the meltwater of Himalayan glaciers is extremely variable, mostly due to the presence of different rock types, weathering state and influence of climate [18]. Various scientific studies are available on hydrogeochemistry and SSC in the meltwater of different glaciers situated in the Chandra–Bhaga basin of Himachal Pradesh [11, 14–16, 19–27]. But focused research on the Manimahesh Glacier situated in the Ravi basin of Himachal Pradesh is missing [28]. The present study has attempted to develop a baseline data for hydrogeochemistry and SSC in the meltwater of this area. The key objectives of this study are to characterize the meltwater quality, weathering and hydrogeochemical processes controlling solute chemistry and SSC in the meltwater of Manimahesh Glacier.

2 Area of Study

The Manimahesh Glacier (32°22′30″N and 76°40′4.8″E) is located in the Chamba District (Bharmour subdivision), Himachal Pradesh, India (Fig. 1). It is a debris-free glacier having total area and length of about 4.3 ± 0.1 km^2 and $\sim 3.2 \pm 0.03$ km, respectively [29]. The snout of this glacier is located at an altitude of about $\sim$ 4470 m a.s.l. and classified as mountain-type glacier. The Ghoi meltwater stream originates from Manimahesh Glacier and drains in SW (south-west) direction. It meets Budhil River at nearly 11.5 km in the downward direction from the glacier snout. The famous track of Manimahesh along Ghoi stream goes to Gauri Kund from where the glacier can be approached. Chand and Sharma [29] reported that Manimahesh Glacier retreated by 157 ± 34 m with total area vacated of 0.21 ± 0.01 km^2 between 1971 and 2013.

The regional geology of Ravi basin has been studied by Geological Survey of India [30]. Katari Gali Formation is well exposed in the Bharmour subdivision and its surrounding areas in Chamba District. It comprises limestone, calcareous siltstone and sandstone [28, 30–32]. Salooni Formation is also present in the Chamba area. It includes calcareous slate, black shale, slate and lenticels of limestone [33]. The climatic condition of Manimahesh Glacier is transitional between the highland climate of western Himalaya and dry winter climate of Indo-Gangetic plain [34]. The Manimahesh glaciated valley is situated between the transitional zone of minimum precipitation (Lahaul) and maximum precipitation (Dharamshala) regions of Himachal Pradesh [35, 36].

3 Materials and Methods

Meltwater samples were collected from the sampling site of Manimahesh Glacier during the month of June and July 2014. EC (electrical conductivity) and pH of meltwater were analysed onsite by EC and pH electrodes. The collected samples were filtered with the help of 0.45-µm Millipore membrane filter papers. The SSC content was calculated by drying and weighing of suspended sediment collected above the membrane filter paper. Dissolved silica, bicarbonate, sulphate and nitrate were measured by molybdosilicate, acid titration, turbidimetric and brucine-sulphanilic acid methods, respectively [37]. Chloride in meltwater was analysed by mercury (II) thiocyanate method [38]. Calcium, magnesium, sodium and potassium were analysed by using an AAS (atomic absorption spectrophotometer) instrument. Factor analysis, correlation matrix and cluster analysis were carried out by SPSS 21 software, whereas Aquachem (version 5.1) software was used for plotting of Piper trilinear plot.

4 Results and Discussion

4.1 Dissolved Ions Chemistry

The chemical composition of Manimahesh Glacier meltwater is given in Table 1. Cationic and anionic charge balance was calculated to be $< 10\%$, ensuring good data quality. The average value of EC in Manimahesh Glacier meltwater was analysed to be 21 ± 1 µs/cm (18–23 µs/cm), indicating the lower value of EC as compared to other glaciers situated in the western Himalayan region [14–16, 26, 27]. The average value of pH was measured to be 6.4 ± 0.2 (5.9–6.6), showing slightly acidic nature of glacial

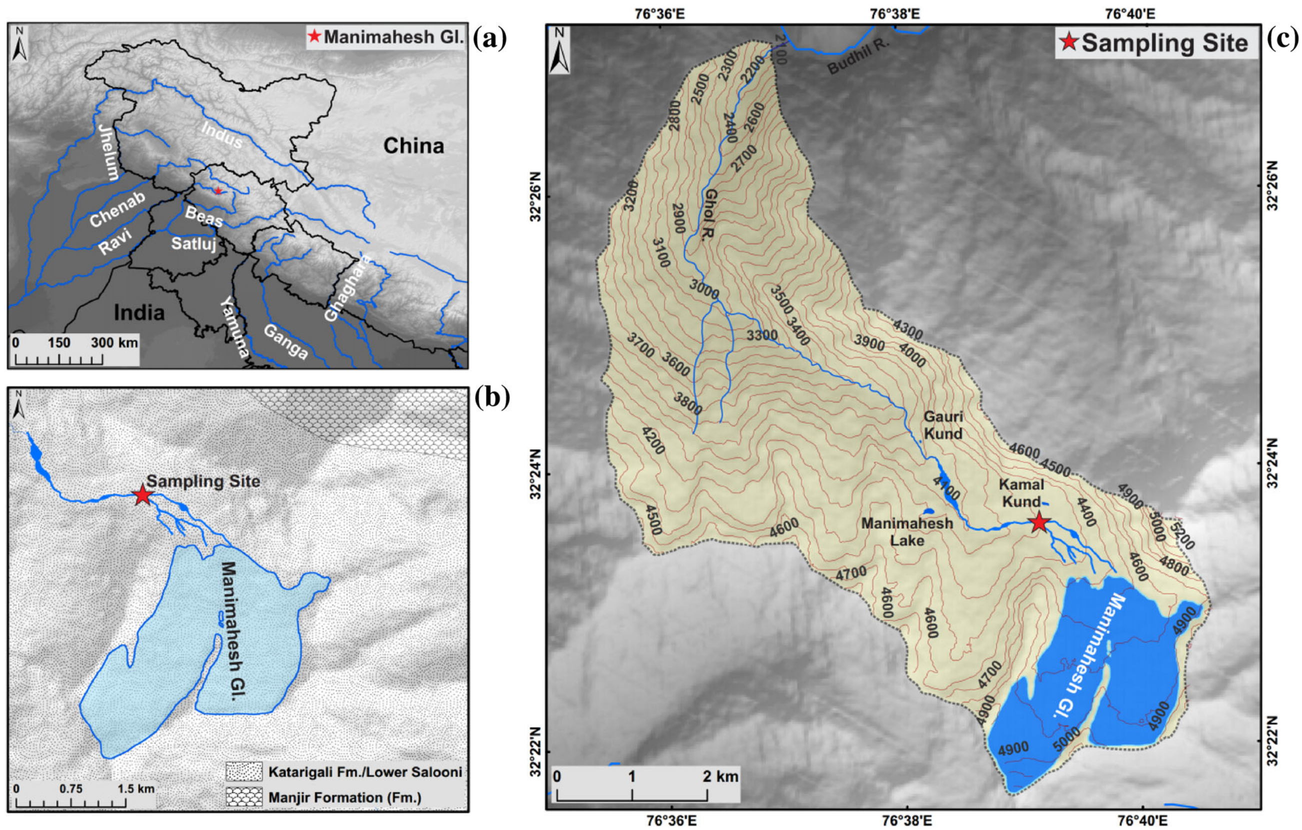

Fig. 1 Map of Manimahesh Glacier with sampling site

meltwater. Bicarbonate and calcium were major anion and cation, constituting to 66% of TZ^- (total anion) and 81% of TZ^+ (total cation) in equivalent units, respectively. The scatter plot between (Ca + Mg) and TZ^+ (Fig. 2) indicates strong relationship between these parameters with an average ratio of 0.90 ± 0.03, whereas (Ca + Mg) versus (Na + K) average ratio was calculated to be 9.5 ± 2.9. The (Na + K) versus TZ^+ scatter plot (Fig. 3) shows low input of (Na + K) to the TZ^+ with an average ratio of 0.10 ± 0.03. High equivalent ratios of (Ca + Mg) versus (Na + K) and (Ca + Mg) versus TZ^+ and the low equivalent ratio of (Na + K) versus TZ^+ demonstrate that solute chemistry of the Manimahesh Glacier was predominantly controlled by carbonate weathering with little input from silicate-type weathering in the investigation area. All sampling points of meltwater lie above 1:1 equiline in the scatter plot of (Ca + Mg) versus (HCO_3 + SO_4) (Fig. 4), showing dominancy of (HCO_3 + SO_4) over (Ca + Mg). Such a result indicates that excess of SO_4 and HCO_3 is balanced by Na and K generated from silicate-type weathering in the Manimahesh Glacier [14, 39, 40].

Bivariate mixing plots of Na-normalized Ca versus Na-normalized Mg and Na-normalized HCO_3 on log–log scale (Fig. 5a, b; Gaillardet et al. [41]) were used to monitor the relative contribution from weathering of major lithologies (carbonate, silicate and evaporites) to the meltwater chemistry. These diagrams show that meltwater samples fall closer to the carbonate end member. The average molar ratios of HCO_3/Na, Ca/Na and Mg/Na in the glacial meltwater were 22 ± 13, 22 ± 12 and 2.4 ± 1.2, respectively. These average ratios are much higher than the water emerging from Himalayan silicate dominant lithology (Mg/Na = 0.3 and Ca/Na = range from 0.2 to 1.0) [42] and lower than the water emerging from only carbonate-containing rock (HCO_3/Na ≈ 120, Ca/Na ≈ 50 and Mg/Na ≈ 10) [43–45]. Such results show that solute chemistry of Manimahesh Glacier was primarily regulated by carbonate weathering followed by silicate weathering. The model given by Raymahashay [46] was used for the assessment of bicarbonate generated from silicate and carbonate weathering.

$$\left[HCO_3^-\right]_{total} = \left[HCO_3^-\right]_{silicate} + \left[HCO_3^-\right]_{carbonate}$$
$$\left[HCO_3^-\right]_{carbonate} = 0.74\left[Ca^{2+}\right]_{total} + 0.4\left[Mg^{2+}\right]_{total}$$
$$\left[HCO_3^-\right]_{silicate} = \left[HCO_3^-\right]_{total} - \left[HCO_3^-\right]_{carbonate}.$$

Approximately 80% of bicarbonate in the meltwater was mainly produced from carbonate weathering, whereas 20% of bicarbonate was generated from silicate weathering. The two important proton delivery mechanisms (oxidation of sulphide and carbonation) required for weathering can be

Table 1 Summary of chemical composition of Manimahesh Glacier meltwater samples (n = 21)

Parameters	Min	Max	Avg.	SD
EC	18	23	21	1
pH	5.9	6.6	6.4	0.2
HCO_3^-	138	202	161	18
SO_4^{2-}	58	82	66	6
Cl^-	4	15	9	4
NO_3^-	5	11	9	2
Ca^{2+}	135	205	165	17
Mg^{2+}	13	25	18	3
K^+	5	18	12	3
Na^+	2	16	9	3
H_4SiO_4	1	3	2	1
TZ^+	165	249	203	23
TZ^-	212	308	244	23
TDS	16	23	18	2
Ca + Mg/TZ^+	0.84	0.94	0.90	0.03
Na + K/TZ^+	0.06	0.16	0.10	0.03
Ca + Mg/Na + K	5.3	17	9.5	2.9
Ca/Na	9.9	67	22	12
Mg/Na	1.1	6.8	2.4	1.2
HCO_3/Na	9.5	70	22	13
C-ratio	0.68	0.75	0.71	0.02

EC in µs/cm; dissolved ions, TZ^+, TZ^- in µeq/l; H_4SiO_4 in µmole/l; and TDS in mg/l

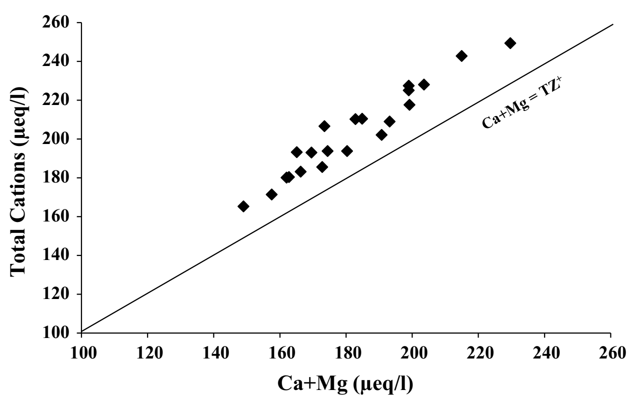

Fig. 2 Scatter diagram between (Ca + Mg) and total cations (TZ^+)

estimated by C-ratio [HCO_3/(HCO_3 + SO_4)] [47]. The mean value of C-ratio for Manimahesh Glacier meltwater was computed to be 0.71 ± 0.02, indicating dissolution and dissociation of CO_2 from atmosphere being the dominant producer of hydrogen ions followed by sulphide oxidation utilized for chemical weathering of rock in the investigation area [47–49].

Sulphide oxidation is one of the important hydrogeochemical processes through which glaciations may be self-limiting, shifting the global carbon cycle balance by

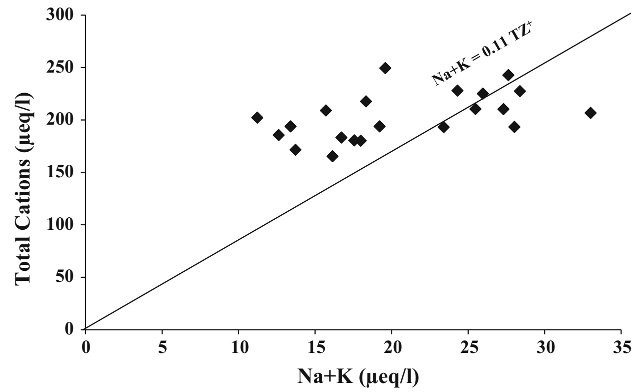

Fig. 3 Scatter diagram between (Na + K) and total cations (TZ^+)

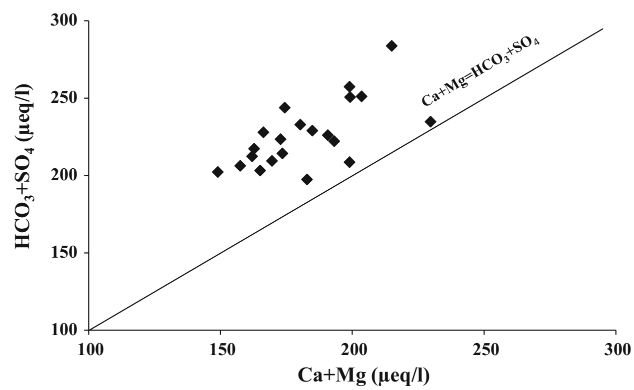

Fig. 4 Scatter diagram between (Ca + Mg) and (HCO_3 + SO_4)

enhancing the supply of CO_2 to the ocean–atmosphere system [50]. Sulphide minerals (FeS_2) weathered in the presence of H_2O and O_2 to form metal oxides and H_2SO_4 (sulphuric acid).

$$4FeS_2 + 15O_2 + 8H_2O \rightarrow 2Fe_2O_3 + 8H_2SO_4. \quad (1)$$

The resulting H_2SO_4 may react with various other minerals as shown by Eq. 2 (silicate dissolution) and Eq. 3 (carbonate dissolution) [55].

$$8CaSiO_3 + 8H_2SO_4 + 8H_2O \rightarrow 8Ca^{2+} + 8SO_4^{2-} + 8H_4SiO_4 \quad (2)$$

$$16CaCO_3 + 8H_2SO_4 \rightarrow 16Ca^{2+} + 16HCO_3^- + 8SO_4^{2-}. \quad (3)$$

No atmospheric CO_2 is consumed by H_2SO_4-mediated chemical weathering unlike carbonic acid-mediated weathering [51].

4.2 Hydrogeochemical Classification and Water Type

The term hydrogeochemical facies is a function of geology, water–rock interaction and solution kinetics which are used

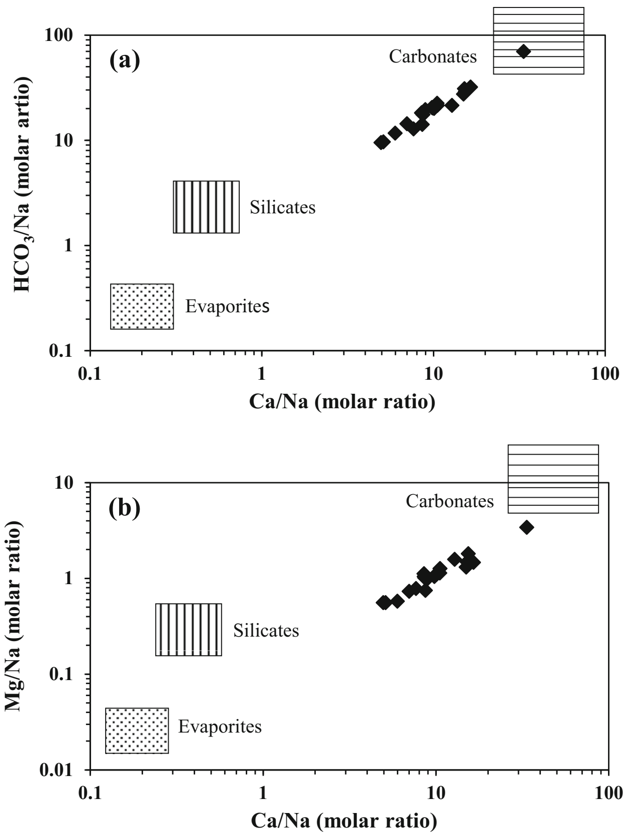

Fig. 5 Bivariate mixing plot of **a** Na-normalized HO_3 versus Na-normalized Ca and **b** Na-normalized Mg versus Na-normalized Ca to show weathering trends

to determine the water quantities that differ in their composition of chemical species [52]. Piper trilinear [53] plot has been used for the hydrogeochemical classification of meltwater. This plot shows similarities and differences among the water samples, i.e. similar types of water fall together as a group in this diagram [54]. The Piper plot indicates that (Ca + Mg) (alkaline earth metals) and HCO_3 (weak acid) dominate the meltwater chemistry and Ca–HCO_3 is the major hydrogeochemical facies in the study area (Fig. 6). This plot shows that meltwater chemistry of Manimahesh Glacier is mainly governed by carbonate weathering mediated by carbonic and sulphuric acid [14, 16, 27, 51].

4.3 Multivariate Statistical Methods

In the present study, various statistical methods such as correlation, principal component and cluster analysis are used for the characterization of meltwater quality of Manimahesh Glacier. Generally, multivariate statistical tools provide better result as compared to graphical analysis regarding the identification of solute sources because it takes into account limited number of variables [55]. These statistical tools also play an important role in the interpretation, modelling and classification of large data sets by reducing the dimensionality of the big data sets [56, 57].

4.3.1 Correlation Matrix

The correlation analysis is very useful to understand the relationship among different variables which play a crucial role in the identification of the sources of various ions [58]. The result of correlation analysis of analysed hydrogeochemical parameters in the meltwater samples of Manimahesh Glacier is given in Table 2. High correlation coefficient (r^2) was observed between HCO_3^- and Ca^{2+} ($r^2 = 0.68$, $p < 0.01$), HCO_3^- and Mg^{2+} ($r^2 = 0.70$, $p < 0.01$) and Ca^{2+} and Mg^{2+} ($r^2 = 0.88$, $p < 0.01$). These strong correlations show that dissolved ions chemistry of the investigation area is mainly controlled by carbonate-type weathering. H_4SiO_4 is highly correlated with K^+ ($r^2 = 0.74$, $p < 0.01$) and moderately correlated with Na^+ ($r^2 = 0.54$, $p < 0.05$), whereas Na^+ is strongly correlated with K^+ ($r^2 = 0.66$, $p < 0.01$), showing similar origin of these chemical species which may be generated from silicate-type weathering.

4.3.2 Principal Component Analysis

Principal component analysis is an important statistical tool useful in the establishment of relationship between analysed data sets by executing factors, which is helpful in the classification of original data sets [59]. The criterion of Kaiser's was applied for the extraction of principal components or factors [60]. This criterion indicates that principal components having eigenvalue greater than or equal to one is considered as a significant factor and recognized as the probable sources of variance in the data sets. The result of factor analysis including eigenvalues, communalities of every variable, the percentage of variance for each factor and percentage of cumulative variance for all three extracted factors (eigenvalue > 1) is given in Table 3. All three extracted factors together explain about 72% of the total variability in the analytical result, out of which the first factor explains about 40%, second factor explains about 21% and third factor explains about 11% of the variance. The strong loading of EC, HCO_3^-, SO_4^{2-}, Ca^{2+} and Mg^{2+} in factor 1 may be attributed to carbonate weathering, oxidation of pyrite and dissolution of sulphate-containing minerals. The second factor has a strong positive loading for Cl^-, Na^+ and K^+, showing contribution from atmospheric precipitation in the investigation area. The high positive loading of H_4SiO_4 and moderate loading of K^+ in factor 3 may be attributed to the silicate weathering in Manimahesh Glacier.

Fig. 6 Piper trilinear plot for analysed chemical parameters in the meltwater showing contributions from hydrogeochemical weathering of main rock types by carbonic and sulphuric acid (Spence and Telmer [51])

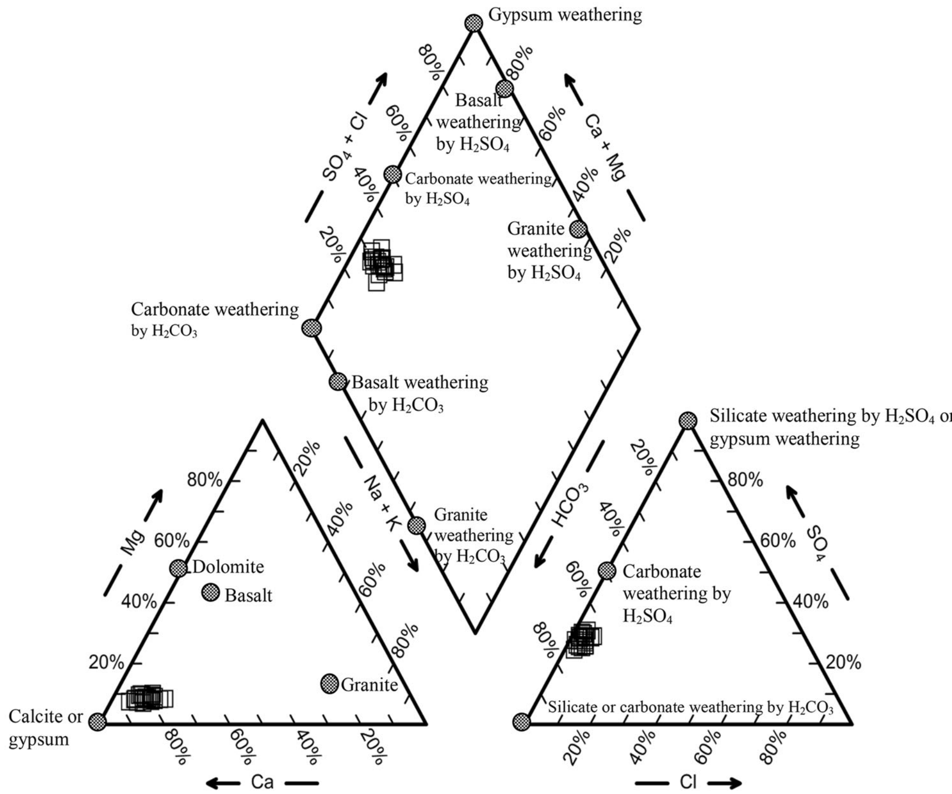

Table 2 Correlation analysis of the analysed physico-chemical parameters in the meltwater samples of Manimahesh Glacier

	EC	pH	HCO_3	SO_4	Cl	NO_3	Ca	Mg	Na	K	H_4SiO_4
EC	1.00										
pH	0.30	1.00									
HCO_3	0.71**	0.29	1.00								
SO_4	0.51*	0.14	0.64**	1.00							
Cl	0.16	0.47*	0.26	0.24	1.00						
NO_3	− 0.08	− 0.17	0.01	0.16	0.08	1.00					
Ca	0.64**	0.51*	0.68**	0.30	0.39	0.14	1.00				
Mg	0.50*	0.41	0.70**	0.44*	0.48*	0.05	0.88**	1.00			
Na	− 0.15	0.18	− 0.05	0.05	0.49*	− 0.19	0.05	0.20	1.00		
K	0.13	0.34	0.16	0.12	0.49*	− 0.22	0.35	0.52*	0.66**	1.00	
H_4SiO_4	0.29	0.12	0.14	0.11	0.16	− 0.44*	0.33	0.40	0.54*	0.74**	1.00

*Correlation is significant at the 0.05 level

**Correlation is significant at the 0.01 level

4.3.3 Cluster Analysis

Cluster analysis is a multivariate statistical tool which mainly aims to assemble various objects on the basis of specific features they possess [61]. In this technique, sorting of various objects into the groups or clusters takes place in such a way that the degree of relationship between two objects or variables is the highest when they are present in similar groups and lowest when they belong to different groups [62]. Euclidean distance method was applied in cluster analysis for determination of distance. The result of cluster analysis, i.e. dendrogram for analysed chemical parameters in the Manimahesh Glacier meltwater, is shown in Fig. 7. Two distinct clusters were identified in the dendrogram. Cluster-I was characterized by the combination of Mg^{2+}, H_4SiO_4, Na^+, Cl^-, NO_3^-, K^+, SO_4^{2-}, Ca^{2+}

Table 3 Varimax rotated factor matrix for Manimahesh Glacier meltwater samples

Variables	Factor 1	Factor 2	Factor 3	Communalities
EC	0.86	–	0.16	0.77
pH	0.36	0.51	–	0.39
HCO_3	0.91	–	–	0.83
SO_4	0.68	–	–	0.47
Cl	0.27	0.83	− 0.18	0.77
NO_3	–	–	− 0.81	0.68
Ca	0.80	0.36	–	0.78
Mg	0.76	0.48	–	0.81
Na	− 0.20	0.77	0.36	0.76
K	0.14	0.74	0.57	0.83
H_4SiO_4	0.20	0.36	0.82	0.84
Eigen value	4.4	2.3	1.3	
% of variance	40	21	11	
% of cumulative variance	40	61	72	

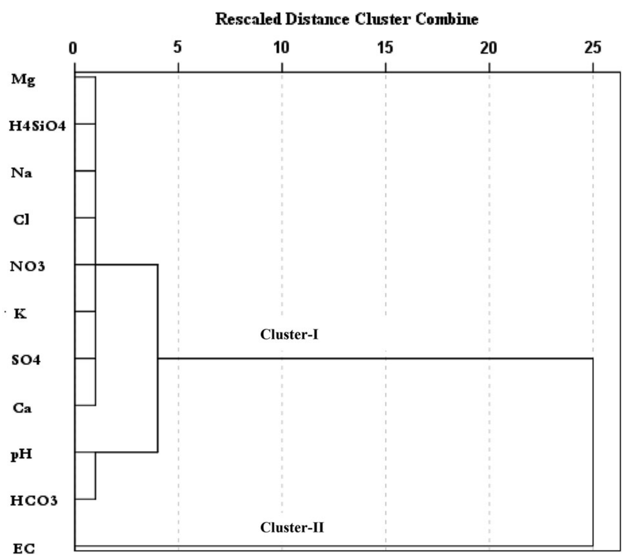

Fig. 7 Cluster analysis of meltwater samples

followed by pH and HCO_3^-, which mainly resulted from carbonate weathering, dissolution of sulphate minerals, silicate weathering and atmospheric input. On the other hand, cluster-II was characterized by EC.

4.4 Suspended Sediment Concentration

Huge quantity of rock debris is generated from the Himalayan glaciers [63]. Various types of rock materials such as boulders and moraines are present in the Manimahesh Glacier basin, which play a crucial role in the production of sediment in the investigation area. The average value of SSC in the Manimahesh Glacier meltwater was computed to be 46 mg/l during the month of June 2014, whereas during the month of July 2014 the average value of SSC in the meltwater was calculated to be 63 mg/l. These observations indicate that SSC was high during the month of July as compared to June; such results may be due to the availability of high discharge and enlarged cross-sectional area of the meltwater channel during the month of July in the investigation area [64, 65]. SSC in the Manimahesh Glacier meltwater and its comparison with different glaciers located in the region of Himachal Himalaya is given in Table 4. It shows that SSC in the Bara Shigri, Chhota Shigri and Batal glaciers meltwater was much higher than the Manimahesh Glacier. Such a result may be due to bigger size, more availability of rock debris and high discharge of these glaciers as compared to the Manimahesh Glacier.

Table 4 Suspended sediment concentration in the meltwater of Manimahesh Glacier and its comparison with other glaciers situated in the Himachal Himalayan region

Glacier	Basin	Suspended sediment concentration (mg/l)	References
Bara Shigri (2012/2013)	Chandra	1014/759	Singh et al. [15]
Chhota Shigri	Chandra	370	Singh et al. [25]
Patsio (2011/2012)	Bhaga	28/49	Singh et al. [24]
Batal	Chandra	402	Singh et al. [26]
Manimahesh	Ravi	56	Present study

4.5 Meltwater Quality of Manimahesh Glacier and its Comparison with Different Glaciers Located in the Region of Himachal Himalaya

Chemical composition of Manimahesh Glacier meltwater and its comparison with different glaciers situated in the region of Himachal Himalaya are given in Table 5. Meltwater of Bara Shigri, Chhota Shigri, Batal and Manimahesh glaciers is slightly acidic in nature, whereas meltwater of Patsio Glacier is nearly neutral in nature. Bicarbonate is the dominant anion in most of the studied Himachal Himalayan glaciers meltwater except Batal Glacier, where sulphate is the most abundant anion. Calcium is the dominant cation in most of the studied Himachal Himalayan glaciers. Anionic abundance in the meltwater of Bara Shigri, Patsio and Chhota Shigri glaciers varied as $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$, whereas concentration of anion in the meltwater of Batal Glacier follows the trend $SO_4^{2-} > HCO_3^- > Cl^- > NO_3^-$, hinting at possible dominance of sulphuric acid-mediated weathering in the

Table 5 Meltwater quality of Manimahesh Glacier and its comparison with other glaciers situated in the Himachal Himalayan region

Glaciers	EC	pH	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	Ca^{2+}	Mg^{2+}	K^+	Na^+	H_4SiO_4	References
Bara Shigri (2012/2013)	32/52	6.7/6.5	179/209	143/190	11/10	7/6	169/344	74/90	38/42	21/27	10/9	Singh et al. [15]
Chhota Shigri (2008/2009)	56/43	6.7/6.5	261/219	160/104	11/3	1/2	128/104	118/99	52/29	58/39	72/33	Singh et al. [14]
Patsio (2010/2011/2012)	155/143/156	7.0/6.8/7.1	671/707/800	586/483/541	11/14/13	9/5/5	890/982/1035	275/320/305	38/53/46	35/42/43	16/20/21	Singh et al. [16]
Batal	128	6.4	155	1028	10	3	838	224	30	34	11	Singh et al. [26]
Sutri Dhaka	60	8.2	221	72	0.3	3	242	44	15	5	–	Singh et al. [66]
Manimahesh	21	6.4	161	66	9	9	165	18	12	9	2	Present study

EC in µs/cm; dissolved ions in µeq/l; and H_4SiO_4 in µmol/l

Batal Glacier. On the other hand, concentration of anion in the meltwater of Sutri Dhaka Glacier varied as $HCO_3^{-} > SO_4^{2-} > NO_3^- > Cl^-$. Cationic abundance in the meltwater of Manimahesh, Bara Shigri, Patsio and Sutri Dhaka glaciers varied as $Ca^{2+} > Mg^{2+} > K^+ > Na^+$, whereas concentration of cation in the Chhota Shigri and Batal glaciers meltwater follows the trend $Ca^{2+} > Mg^{2+} > Na^+ > K^+$. The average equivalent ratio of (Ca + Mg) versus TZ^+ for Bara Shigri, Chhota Shigri, Patsio, Batal, Sutri Dhaka and Manimahesh glaciers meltwater was calculated to be 0.85, 0.76, 0.94, 0.94, 0.94 and 0.90, respectively. On the other hand, (Ca + Mg) versus (Na + K) average equivalent ratio for these Himachal Himalayan glaciers meltwater was computed to be 5.9, 3.3, 16, 17, 15 and 10, respectively. High equivalent ratios of (Ca + Mg) versus (Na + K) and (Ca + Mg) versus TZ^+ for the studied Himachal Himalayan glaciers meltwater demonstrate that solute chemistry of these glaciers was primarily governed by carbonate weathering [16, 23, 26, 27, 66].

5 Conclusions

Meltwater chemistry of the Manimahesh Glacier shows slightly acidic nature of meltwater. Calcium and bicarbonate were the major cation and anion constituting to 81% of the TZ^+ and 66% of TZ^-, respectively. High equivalent ratios were calculated between (Ca + Mg) and (Na + K), i.e. 9.5 ± 2.9, and (Ca + Mg) and TZ^+, i.e. 0.90 ± 0.03, showing dominancy of carbonate-type weathering in the glacierized basin. Approximately 80% of bicarbonate was derived from carbonate weathering, whereas 20% of bicarbonate was derived from silicate weathering in the meltwater of study area. The average value of C-ratio for Manimahesh Glacier meltwater indicates dominancy of CO_2 dissolution and dissociation in the basin [47–49]. Various statistical tools such as correlation matrix, principal component and cluster analysis were used for characterization of meltwater quality in the Manimahesh Glacier. Higher SSC in the meltwater was observed during the peak-flow period, pointing to strong linkage between climate and physical erosion.

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Compliance with Ethical Standards

Conflict of interest All the authors declare that they have no conflict of interest.

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