Estimation of stream hydraulic parameters and suspended sediment load of River Neola in the foothills of the Panchachuli Glacier during the ablation period

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ABSTRACT

At a given cross-section, hydraulic parameters such as depth and velocity of a stream vary with discharge as a single power function. From the development and management perspective of the streams, the estimation of these parameters is very important for canal designing, irrigation works, and hydropower production, etc. Thus, in this context a field study from June to October 2018 was carried out at the outlet of the Panchachuli (Neola) catchment. In view of a limited number of studies, the present study has been conducted in the Himalayan glacier-fed Himalayan streams. The research related to the inclusion of these hydraulic characteristics of streams in the planning process is very rare. The discharge and other hydraulic parameters of the stream such as wetted width, average area, perimeter, hydraulic radius, hydraulic mean depth, and bed slope were estimated to understand the hydraulic geometry of the stream. The stream showed a subcritical state of flow with the Froude no, mean velocity, discharge, and sediment load 0.47, 1 m/s, 8.33 cu.m/s and 1312 t/day, respectively. The average Manning's coefficient varied from 0.31 to 0.65. The study concluded that the bed of section 1 contains larger boulders and gravel which restricted the flow as compared to the other sections. Although the results show the available discharge and velocity is sufficient for mini and micro hydel power plants but suspended sediment may adversely impact the hydraulic structures. These outcomes are expected to be helpful in understanding the flow dynamics of the stream and the erosion dynamics of the catchment.

Keywords: *Discharge, Hydraulic parameters, Manning's coefficient, Sediment load, Subcritical state, Wetted perimeter, Himalaya.*

INTRODUCTION

At present, glaciers occupy around 10% of the world's total land area, with most located in Polar Regions like Antarctica, Greenland, and the Canadian Arctic (DeBeer *et al.,* 2020). Glacial ice is the largest reservoir of fresh water on the Earth (Anesio and Laybourn, 2011). Glaciers are categorized as alpine, sub-alpine-temperate, and seasonal polar climates which store water as ice during the winter seasons and release it in the form of water later during the warmer seasons, creating a freshwater source. That is especially important for living as well as non-living organisms when other sources are negligible (Milner *et al.,* 2017). A study shows that about 68.5 % of the world's fresh water is stored by the glaciers and ice sheets (Stephens *et al.,* 2020). In high-altitude regions of the Himalaya, glacier runoff is one of the dominant sources of freshwater in the downstream regions during the dry seasons (Hocks *et al.,* 2006). Due to climate change and ongoing global warming, snow cover and glaciers are expected to reduce their water storage capacities, which introduce a major water supply crisis for the downstream regions (Kaser *et al.,* 2010).

In the present scenario, the water resources management projects and hydraulic engineering works are developing more rapidly, so knowledge of the hydraulic parameters must be essential to develop the hydraulic design of a structure (Lau and Afshar, 2013). In open flow, all hydraulic computations are required to gather the information about the roughness properties of the stream beds and banks. This is also responsible for the erosion of the bank and bed materials of the streams. It is required for predicting water flow in open stream networks and flood routing models (Barnes, 1967; Choi *et al.,* 2015). Hydraulic computations of a stream are much important because the downstream region will be affected by these in the case of high flows. Hydraulic parameters such as depth, velocity, roughness, cross-sections etc. are changing with time and space or the length of the stream (Singh *et al.,* 2003). All these parameters greatly affect the discharge and sediment load on the downstream region.

Manning's formula is widely used in open streams (artificial or natural) to determine the value of bed roughness (also called Manning's n-value) which is responsible for the flow resistance (George *et al.,* 1989). This is the indirect method of computation of stream flow which has further applications in the flood management studies, design of various hydraulic structures such as dams, bridges, canals, barrages, etc. (Lau and Afshar, 2013). Higher is the Manning's n-value, the higher will be the flow resistance and erosion of bed material (Muhtar and Albayati, 2016).

This study is carried out near the snout of a glacier-fed stream to estimate the stream flow, sediment yield, and the manning's coefficient during the monsoon and post-monsoon seasons. The field observations along with Remote Sensing (RS) and Geographic Information System (GIS) tools are used to estimate the stream bed slope which is used to estimate the bed roughness by using the empirical equation (Kebede *et al.,* 2020). Also, all stream hydraulic parameters are further used for the development of various hydraulic structures. These were used to fulfill the needs of nearby villages such as electricity and water supply which are generally not available in high altitude villages of Uttarakhand.

STUDY AREA

The catchment area of the Panchachuli (Neola) stream lies in the Pithoragarh district of Uttarakhand. The study area falls between the latitudes 30°12'6.735" N to 30°14'54.985" N and 80°25'55.086" E to 80°33'1.154" E longitude (Fig.1) with an area of 55.34 km^2. The stream originates from the Panchachuli glacier which is one of the largest glaciers situated in the Darma valley. The Panchachuli stream meets with the Dhauliganga river in the downslope of the village Dugtu. The total length of the stream is approximately 5 km from snout to the stream gauging station and travels a total distance of 6.20 kilometres. The manual stream gauging station was situated on the Panchachuli glacier stream at an elevation of about 3300 m MSL. The coordinates and elevation of the snout of the Panchachuli glacier are 30°14'5.75" N and 80°29'52.286" E having an elevation of 3450 m msl. The Panchachuli peaks are a group of five snowcapped peaks that lie in the eastern Kumaon region. The altitude of the peaks ranged from 6434 - 6904 m MSL. The ridge of the Panchachuli forms the two different watersheds as Gory Ganga and Dhauliganga.

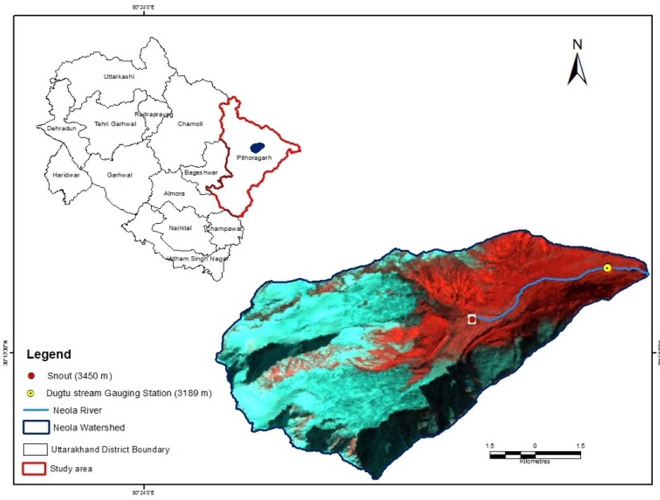

Fig.1. The catchment area of the Panchachuli glacier

MATERIAL AND METHODS

An appropriate manual stream gauging station is installed near the pedestrian bridge in Dugtu village to observe the daily fluctuations in the river stage. The co-ordinates of the stream gauging station are 30°15'1.6" N and 80°32'20.3" E with an elevation of 3206 m MSL (Fig.2). The field study is carried out for 4 months (July to October-2018). The cross-sectional profile of the stream is drawn by taking intervals of 40 cm. Data (i.e. stage, velocity, and SSC) were collected thrice a day, i.e., 8 AM, 12 PM and 5 PM (IST) throughout the gauging period. Sixteen samples were used for the computation of hydraulic parameters in increasing order of the stream stage.

Stream cross-section stream width was divided into 3 sub-sections for computation of the hydraulic parameters. Stream section 2 was considered as the mainstream and the rest of the two were considered as a flooded stream. The mainstream carries the flow for the entire year.

Wetted Area, Wetted Perimeter and Hydraulic Radius are the important parameters for the computation of stream discharge and the other parameters. For the natural streams, increment in the stage leads to increment in the wetted area

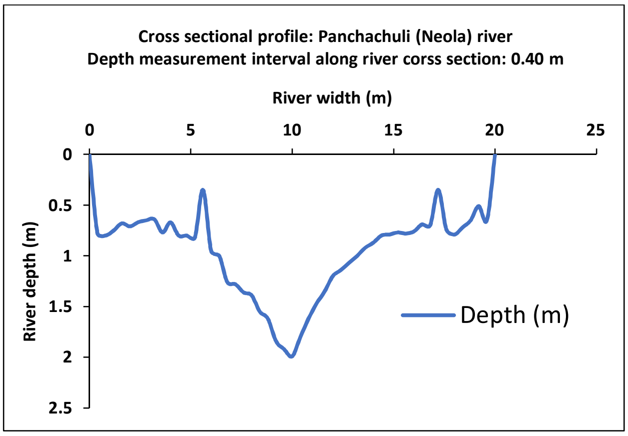

Fig.2. Cross-Section of the stream at the gauging station

perimeter or *vice versa*. For the computation of stream discharge, mean velocity is needed to apply a continuity equation (Ojha *et al.,* 2008) (Eq.3). The surface velocity of the stream is computed by a float method, using a 20m longitudinal section on the stream's water surface. The longitudinal section was further divided into 3 sub-sections. A wooden log was floated in each longitudinal sub-sections and time was noted down by the stopwatch (Chow, 1985) (Eq.1). Since the flow velocity decreases exponentially towards the bed and banks of the stream a coefficient (k=0.8) is used to convert the surface velocity into the mean velocity (Bisht *et al.,* 2020) (Eq.2). The Suspended Sediment Load (SSL) on the stream is estimated using the stream flow discharge multiplied by the Suspended Sediment Concentration (SSC) (Eq.5). Stream slope computed through freely available Digital Elevation Model (DEM) - Cartosat-I (30 metre) resolution by taking snout as the first point, and the gauging station the second point by making the 1m buffer along the stream in ArcGIS 10.2.

Dimensionless parameters such as Froude No. (Fr) and Manning's roughness coefficient (n) were also estimated to understand the nature of the stream. Froude no. gives the condition of flow whether the flow is sub-critical, critical, or super-critical (Eq.6). If the Froude No. is less than 1, then it is called the subcritical flow. If Froude No. is equal to 1, then the flow is called critical flow, and if the Froude No. is greater than 1, then it is termed as the supercritical flow (Petit and Bravard, 2009; Chow, 1985). While Manning's equation is an empirical equation that describes the relationship between the velocity of flow and geometry, slope, and friction coefficient of a stream expressed as Manning's n (Zhu *et al*., 2020) (Eq.8). In its essence, the Manning equation describes the energy balance between gravity and friction in a stream. Manning's coefficient gives the bed roughness of a stream (French, 1985; Jarrett, 1985). It is widely used and versatile in water resources to estimate the bed roughness or estimate the discharge of a channel in the open channel flow. Sections of the natural streams are made up of a different type of bed materials which has different manning's coefficient (Barnes, 1967). So that a concept developed is known as the composite section wherein equivalent manning's coefficient is estimated by different relations. Many expressions are currently available to be used to estimate the average roughness of a given stream, which is commonly known as the equivalent Manning coefficient (n_e). According to Horton, (1933) and Einstein and Blanks, (1950) "at any given section of a stream, the average velocity always equals the corresponding total average velocity" (Eq.10). The equivalent Manning's coefficient is estimating using the various relations between the wetted sectional area, perimeter, and hydraulic radius of the stream. According to Pavlovskii, (1931); Muhlhofer, (1933); Einstein and Banks, (1950) "the total resistive force equal the sum of all resistive forces in each sections" (Eq.11). According to Lotter (1933), "the equality of total discharge is the sum of all discharge of each sections" (Eq.12). According to Cox, (1973); Snoog and Hoffmann (2002), these four equations are known as Share force II equations (Eq.13, 14, 15 & 16).

$$Vsurface = \frac{Length\ of\ Longitudinal\ section}{Time} \quad (1)$$

$$V = 0.8 * Vsurface \quad (2)$$

$$Q = A * V \quad (3)$$

$$Q = \sum_{\mathrm{i}=1}^{3} \mathrm{Ai} * \mathrm{Vi} \quad (4)$$

$$SSL = Q * SSC \quad (5)$$

$$Fr = \frac{Q}{A * \sqrt{(g * D)}} = V/\sqrt{(g * D)} \quad (6)$$

$$D = \frac{A}{T} \quad (7)$$

$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$ (8)

The equation no. (7) is rearranged as:

$n = \frac{1}{V} R^{\frac{2}{3}} S^{\frac{1}{2}}$ (9)

$n_e=\{(P_1 n_1^{1.5}+P_2 n_2^{1.5}+P_3 n_3^{1.5})/P\}^{2/3}$ (10)

$n_e= \{(P_1 n_1^{2}+P_2 n_2^{2}+P_3 n_3^{2})/P)\}^{1/2}$ (11)

$n_e=(PR^{5/3})/\{(P_1 R_1^{5/3}/n_1) +(P_2 R_2^{5/3}/n_2)+ (P_3 R_3^{5/3}/n_3)\}$ (12)

$n_e= (A_1 n_1+A_2 n_2+A_3 n_3)/A$ (13)

$n_e=\{(P_1 R_1^{1/3}/n_1) +(P_2 R_2^{1/3}/n_2)+ (P_3 R_3^{1/3}/n_3)\}/(PR^{1/3})$ (14)

$n_e=\{(P_1 R_1^{1/6}/n_1) +(P_2 R_2^{1/6}/n_2)+ (P_3 R_3^{1/6}/n_3)\}/(PR^{1/6})$ (15)

$n_e= (P_1+P_2+P_3)/(P/_1 n_1+P_2/n_2+P_3/n_3)$ (16)

Where; '$V_{surface}$' represents surface velocity of stream (m/s), 'V_{mean}' represents average or mean velocity of stream (m/s), 'Q' represents discharge (cu.m/s), 'g' represents acceleration due to gravity (9.81 m/s), 'D' represents hydraulic mean depth (m), 'T' represents top width of a stream, SSC represents 'Suspended Sediment concentration', 'SSL' represents Suspended Sediment Load, 'Fr' represents Froude No. 'n' represents Manning's roughness coefficient, 'R' represents hydraulic radius, in metres, 'S' represents slope of the stream bed, 'n_e' represents equivalent manning's coefficient for the entire section, 'A' represents the total area of the section, 'P' represents the total perimeter of the section, 'R' represents the hydraulic radius of the section and suffix 1, 2 & 3 denotes the corresponding values of sections 1, 2 & 3, respectively.

RESULTS AND DISCUSSION

The hydraulic parameters of the natural streams are largely dependent on the stage of the river. A slight change in the stage of wide natural streams gives significant changes in the hydraulic parameters (Leopold and Maddock, 1953). During the ablation period of a glacier, the top width of the stream ranged between 7.4 m to 18.4 m. The average top width during the ablation period of the stream was 12.78 m (Table 1). The top width is further used in the estimation of various hydraulic parameters such as Hydraulic mean depth, Froude No., etc. (Essawy *et al.,* 2019). The larger wetted area of the stream corresponds to higher discharge. The average wetted area of the stream stood 5.84 sqm, while the average wetted area of the mainstream (section 2) was 3.83 sqm and the average wetted area of the flood streams was 2.01 sqm (Section 1 & 3) (see Table 1) during the ablation period. The average wetted perimeter of the stream was 14.39 m, while the average wetted perimeter of the mainstream (section 2) was 4.64 m and the flood stream (section 1 & 3) was 10.75 m during the ablation period (see Table 1). The average Hydraulic Radius of the stream was 0.41 m of sections 1, 3 which was 0.17 m, and 0.23m, while the average hydraulic radius of section 2 was 0.83 m during the ablation period (see Table 1). The average Hydraulic Mean Depth (HMD) of the stream was 0.47 m, while the average HMD of sections 1 & 3 was 0.18 m and 0.53 m and section 2 was about 0.96 meters during the ablation period (see Table 1). All these estimated parameters were used to measure the efficiency of a natural stream (Leopold and Maddock, 1953). The results show that section 2 was more efficient in carrying water as compared to sections 1 and 3 respectively because section 2 had a larger wetted area, perimeter, and mean velocity with a higher hydraulic radius. The mean velocity of the stream flow is computed for the compound stream was 1m/s by applying a correction factor; while the mean velocity of the stream flow in the sub-sections 1, 2, 3 were 0.57, 1.77, 0.65 m/s during the ablation period respectively (see Table 1). This higher flow velocity in section 2 was due to the larger depth of flowing water as compared to sections 1 and 3. The discharge of the first order glacier-fed is largely dependent on the melt received by the snow cover and glaciers (Latif *et al.,* 2020). The stream discharge is estimated by applying the continuity equation at the cross-section obtained by field survey. During the ablation period, the discharge ranged from 2-16 cu.m/s while the average daily discharge of the stream was 8.33 cu.m/s and the average daily discharge of the sub-sections is 1, 2 and 3 were 0.45, 7.00, and 0.88 cu.m/s (Table 1). The results show that section 2 carried a larger amount of water as compared to sections 1 and 3. This is due to section 2 that had a larger stage so that the section had the larger wetted area corresponding to high mean velocity. Similarly, section 2 carried a higher amount of sediment load. The suspended sediment load on the stream ranged from 61.85 to 7749.72 tonnes per day. Variations in the SSL are due to the variation in the stream flow discharge (Fig.3). Catchment receives larger SSL in the monsoon period due to the combined effect of melt and precipitation and thereafter, it decreases continuously throughout the winter season. In the glacier-fed streams, glaciers are the vital sources of sediments (Bisht *et al.,* 2020). Glacier-fed rivers show higher suspended sediment concentration during the ablation period. The higher sediment concentration in these streams may be due to ablation of debris cover glaciers, or intense precipitation events, or sub-glacial activities such as outbursts of the moraine-filled glacial lake (Bisht *et al.,* 2020: Kumar *et al.,* 2014). The larger entry of sediments to the stream will affect the ecology and geomorphology of the streams and also affect the downstream hydropower plants (Gabbud and Lane, 2016). The higher stream flow discharge and velocity are capable to run a small hydroelectric power plant to fulfill the daily demands of nearby villages.

Dimensionless parameters of the stream such as Froude No. is computed for the compound section of the stream and found 0.47 indicating the stream was in the sub-critical state (Chow, 1985). This type of flow occurs when the stream has less velocity or a larger depth or both. While the average Froude No. of sections 1 and 3 were 0.43 and 0.28, respectively and flow was sub-critical in sections 1 and 3. This is due to the sections having less velocity but with a lesser stage in both the sections. While Froude No. of section 2 was 0.57 and the flow in the mainstream was sub-critical; this is mainly due to the stream having a larger stage but high velocity. So that water measurement such as measurement of stage and sampling site was established easily due to accurate head readings because stream at this section is not able to produce upstream waves (Chow, 1985). Also, the development of hydraulic structure was safe due to sub-critical flow because it prevents the structure from the waves. The slope of the stream as computed for all the sub-sections was 0.06. The stream classified in the category of 'Type-A'. 'Type A' streams are steep (4–10% slope) with cascading and step/pool bed features (Church and Zimmermann, 2007). The average Manning's coefficient of the stream was 0.042 while the maximum and the minimum values of sections 1, 2 and 3 stood to be 0.04, 0.04 and 0.05 respectively (Table 2). The results show that the bed of the inner bank stream contains gravels, cobbles, and few boulders and the outer bank of the stream contains cobbles with large boulders (Table 3). The value of Manning's coefficients shows the type of bed materials. By using different relations between the wetted area, wetted perimeter, hydraulic radius, and Manning's ‘n’ value for different sections, the equivalent Manning's coefficient estimated (Table 4). The average equivalent Manning's roughness coefficient during July to October was 0.043 by Horton's and Einstein's, Pavlovskii, Snoog, and Hoffmann (1) and (2), 0.041 by Lotter and 0.042 by using Hoffmann (3) (see Table 4). In general, the mountainous stream equivalent to Manning's roughness coefficient is nearly equal to 0.045 (Chow, 1985). This Manning coefficient is sufficient to generate frictional force at the stream bed in the opposite direction of a flow. In natural streams, mostly the water flows through higher velocity, and higher Manning’s coefficient will erode the bed and banks of the streams. Considering hydraulic parameters, we can say that the high mountainous region is likely to change its sectional profile after every ablation period. Due to scouring of the streams, Manning’s roughness coefficient of the streams gets changed with the changing sectional profile.

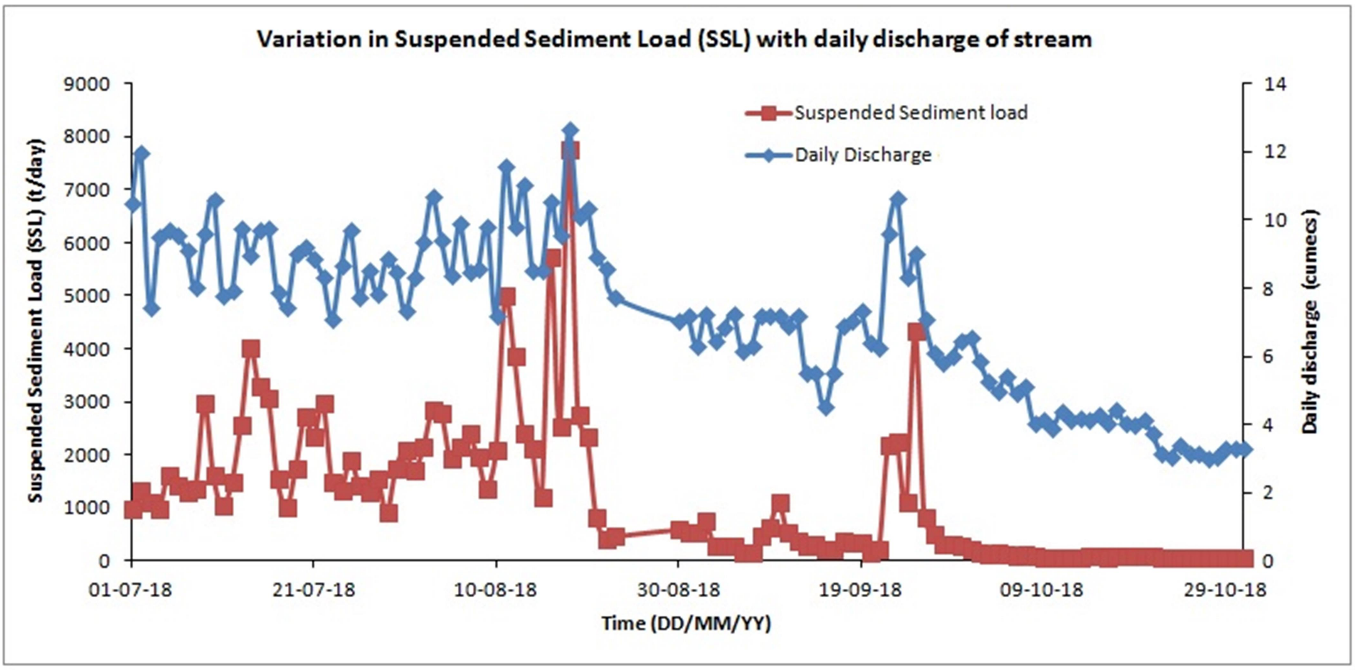

Fig.3. Variation in SSL with stream discharge

Table 1. Values of hydraulic parameters of River Neola

Hydraulic parameters	Section 1	Section 2	Section 3	Equivalent section
Top Width (m)	3.95	4.00	4.73	12.780
Wetted Area (m^2)	0.73	3.83	1.28	5.840
Wetted perimeter (m)	4.37	4.64	5.38	14.390
Hydraulic Radius (m)	0.17	0.83	0.23	0.414
Hydraulic Mean Depth (m)	0.18	0.96	0.53	0.470
Mean Velocity (m/s)	0.57	1.77	0.65	1.000
Discharge (m^3/s)	0.45	7.00	0.88	8.330
Froude No.	0.43	0.57	0.28	0.470
Manning's Coefficient	0.04	0.04	0.05	0.042
River Bed Slope	0.06	0.06	0.06	0.060

Table 2. Section wise Manning's coefficient of River Neola

Section	Manning's coefficient		
	Minimum	Normal	Maximum
1	0.031	0.041	0.053
2	0.031	0.040	0.068
3	0.037	0.046	0.065

Table 3. Manning's coefficient value for different channels (Chow, 1985)

Type of channel and description	Minimum	Normal	Maximum
Mountain streams, no vegetation in the channel, banks usually steep, trees and brush along banks submerged at high stages			
a. Bottom: gravels, cobbles, and few boulders	0.03	0.04	0.05
b. Bottom: cobbles with large boulders	0.04	0.05	0.07
c. Pasture, no brush			
1.Short grass	0.025	0.03	0.035
2. High grass	0.03	0.035	0.05
d. Cultivated areas			
1. No crop	0.02	0.03	0.04
2. Matured row crops	0.025	0.035	0.045
3. Matured field crops	0.03	0.04	0.05

Table 4. Equivalent Manning's coefficient using different relations

Equivalent Manning's coefficient						
Horton's & Einstein's	Pavlovskii	Lotter	Cox	Snoog and Hoffmann		
0.043	0.043	0.041	0.042	0.043	0.043	0.042

CONCLUSIONS

In essence, the study shows the values of the Manning's coefficient, equivalent Manning's coefficient, and suspended sediment load estimation for a glacier-fed stream near the snout during the ablation period. The site is selected near the snout wherein minimized influence of other tributaries were experienced. The estimated stream flow discharge and flow velocity are sufficient to develop small hydraulic structures at the outlet of the catchment. Higher Manning's roughness coefficient in section 3 restricts the flow as compared to others. Also, the erosion and scouring of bed material are higher in section 3. Higher sediment concentration during the ablation period indicates that the glaciers are the primary sources of suspended sediments in the streams. Due to climate change, the melting of glaciers takes place at a faster rate; this results in high quantity of sediments in the streams during the ablation period. This larger amount of sediment reduces the capacity of hydro electric power projects (HEP's) so the development of HEP's with silt extruding gates is required. These hydraulic parameters are then used for making an estimate for the future flow and development of hydraulic structures for mini/micro hydropower projects.

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