SHORT COMMUNICATION

GLACIER DRAINAGE EVOLUTION AND CONTROL ON SUSPENDED SEDIMENT CONCENTRATION IN MELTWATER, DOKRIANI GLACIER, GARHWAL HIMALAYA, INDIA

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Discharge, electrical conductivity and suspended sediment concentrations of Dokriani glacial meltwater were observed from 8 May to 31 October 1994. The comprehensive database on hydrological parameters of an Indian Himalayan glacier so obtained suggests a close relationship between suspended sediment transfer characteristics and glacier drainage evolution during the 1994 ablation period.

Introduction

Study of the internal drainage system of a glacier is an important area of glaciological research. Subglacial hydrological processes are considered as a major factor controlling the sediment production, transportation and glacier motion (Willis et al. 1998). Understanding of glacier drainage characteristics is essential to interpret the diurnal and temporal characteristics of glacier runoff and sediment transfer. Glacial drainage system characteristics also control solute enrichment processes of meltwater during its passage through the glacier drainage system. The use of meltwater quality characteristics to derive information on the glacier hydraulic system has been employed widely by glacial hydrologists (Collins, 1979; Oerter et al. 1980; Collins and Young, 1981; Gurnell and Fenn, 1984; Tranter and Raiswell, 1991; Lecce, 1993). The two component mixing model (Collins, 1979) is based on the assumption that the mass of solute transported by the two flow components, distributed and channel systems remains unchanged after the mixing. Sharp et al (1995) pointed out the potential problems in applying this technique.

Field evidence indicates post mixing ionic enrichment of the meltwater due to the weathering of suspended sediments. Recent studies of the subglacial zone of the glacier with the help of boreholes have revealed complex hydrologic networking and ionic enrichment processes (Tranter et. al. 1998; Stone and Clarke, 1998). However little is known about the drainage system of Himalayan glaciers. In the absence of direct investigations at the glacier bed, it is imperative to use the indirect methods to derive information on glacier drainage characteristics of Himalayan glacier. Sulphate is identified as a useful marker for flow component separation (Tranter and Raiswell, 1991; Sharp et al. 1995). However study of major ion chemistry of the Dokriani glacier meltwaters showed sulphate domination over the bicarbonate during peak diurnal flow, even during the peak ablation season. Hence separation of flow components by using sulphate is not tenable for Dokriani glacier (Hasnain and Thayyen, 1999a). This communication is aimed to discuss a new approach in interpretation of two component mixing model by calculating the efficiency indices for glacier drainage systems using electrical conductivity of meltwater. The model results were used to evaluate the role of glacier drainage evolution in controlling the suspended sediment transfer characteristics of the glacier. Study carried out on Dokriani glacier in Bhagirathi basin, Uttarkashi district of Uttaranchal (30°50' N to 30°52' N and 78°47' E to 78°50' E). Discharge, electrical conductivity and suspended sediment data collected in 1994 was used in this study.

Efficiency Indices of Glacier Drainage Components

The subglacial drainage network is generally classified into arborescent and non- arborescent networks (Hubbard and Nienow, 1997) or channelised and distributed system (Walder and Fowler, 1994;Fountian, 1994). The distributed system drains large areas of the glacier bed at low flow rates. Such a non-arborescent drainage system consists of more resistive flow pathways. Subglacial conduits with low minimum diurnal water pressures coexist and interact with surrounding regions of high diurnal water pressures (Fountain, 1994; Hubbard et al. 1995). The efficiency of glacial drainage systems is regulated by the availability of water for transportation. Hence glacial drainage system characteristics vary temporally and seasonally, which is related to the production of meltwater at the glacier surface. Water routed through the subglacial distributed system is enriched by the ions on account of contact with solute rich basal hydrochemical environment (Collins, 1979), whereas the quick flow throughthe channels will have lower ionic concentration, 'channel flow' and 'distributed flow' are the terms used for these two broad categories of glacier drainage system flow components.

Two component mixing model (Collins, 1979) state that:

$$Q_t = Qc^{+}Q_d>$$

where subscript t, c and d represent total, channel and distributed *system* respectively.

$$Q_l Ec_t = Q_c EC_c + Q_d EC_4$$

•i.e. $$Q_{\wedge}. = \frac{(EC_t - EC_c)\ Q_t}{EC._a - EC_c}$$

where EC_d and EC_c are electrical conductivity of distributed flow and channel flow respectively.

The use of electrical conductivity (EC) in two component mixing model for glacier hydrological research is viewed critically for two major reasons: (i) EC of mixing waters from channels and distributed system is not conservative; post-mixing solute enrichment takes place within the channels from weathering of the sediment carried by the meltwater (ii) diurnal, temporal and seasonal variability may occur in the solute concentrations of water derived from the different glacier environments. Sharp et al. (1995) discussed these aspects in detail. To minimise the adverse effect of these factors on the result of the two component mixing model, it is proposed to calculate the minimum probable flow through the distributed system (Q_d). This has been calculated by using higher EC values for both the flow components. Efficiency indices for glacier flow components has been calculated from the values of minimum probable flow derived from the model. It is the ratio between water flowing through the distributed *or* channel *system and the* calculated maximum flow through the particular drainage system during an ablation period. Which can be expressed as [Qxi/Qx_{ma}J xlOO, where xi is the calculated unit discharge through the channel or distributed system and Qx is the maximum calculated discharge through the flow component during the ablation period. By choosing specific EC values for the flow components for the whole season, by ignoring the temporal variability in EC of the flow components, the model results generate spurious temporal variations in the component discharge. But by calculating minimum probable flow through the distributed system by using the higher EC values, the model make sure that the actual flow variations through the distributed system during the peak ablation period will be higher than the values derived by the model. Hence the efficiency indices of the flow components are a measure of variations in the water flow through the flow components. The channel flow component includes the flow through the supraglacial channels also. In Dokriani glacier few of the major supraglacial channels contribute dilute water into the glacier about 100m upstream of the snout The efficiency of channel flow represents water flow through the whole channelized drainage system of the glacier through which the dilute water flow. Maximum EC recorded in the supraglacial environment was 10.6 jiiS/cm in a small supraglacial *pond.* This value has been chosen to represent the EC of channel flow component (Hasnain and Thayyen, 1996). Maximum EC values recorded during the recessional phase of discharge in 1992, 1993 and 1994 was 59 uS/cm and selected to represent the distributed flow component.

Results and Discussion

Results of this study are summarisd in the Fig 1 and Table 1. The efficiency index curves show that the distributed system was more active during the major part of the ablation season except for 48 days starting from 19 July to 6 September. Before the dominance of channel system over the distributed system, gradual increase in the efficiency of channelised system was observed. The distributed system was most efficient between 25 June to 30 July. The sediment flux during this period amounts to 52% of the total sediment flux of 1994 ablation period. This was preceded by 26% sediment flux in June. Both these months shows very good relationship between efficiency index of distributed system and suspended sediment concentration (SSC) (r = 0.82 and 0.76 respectively). More importantly no correlation existed between SSC and efficiency index of channel system in July. In fact 78% of the total sediment flux occurred during

Table 1. Monthly discharge, sediment flux and correlation coefficients of efficiency indices, EC and discharge with SSC during the! 994 ablation period Qdi and Qci are the efficiency indices for distributed and channel system respectively

Month	Toul Discharge ($1Cm^3$)	Sediment flux (lO^4 tonnes)	% Sediment flux	Correlation (r)			
				Q-EC	Q SSC	Qdi-SSC	Qci-SSC
May	195 5	0 043	03	(-)0 81	0 61	0 52	0 55
June	867 9	3 92	26 0	017	0 77	0 82	0 48
July	2187 6	7 89	52 3	0 27	0 49	0 76	(-)0 19
August	1784 7	2 68	17 8	(-J0 19	069	0 26	0 67
September	9100	0 528	35	(-)0 76	0 63	0 36	0 60
October	292 5	0 027	02	(-)0 75	0 92	0 81	0 88
Total	**6238.1**	**15.1**		(-)0.44	**0.76**	**0.82**	**0.54**

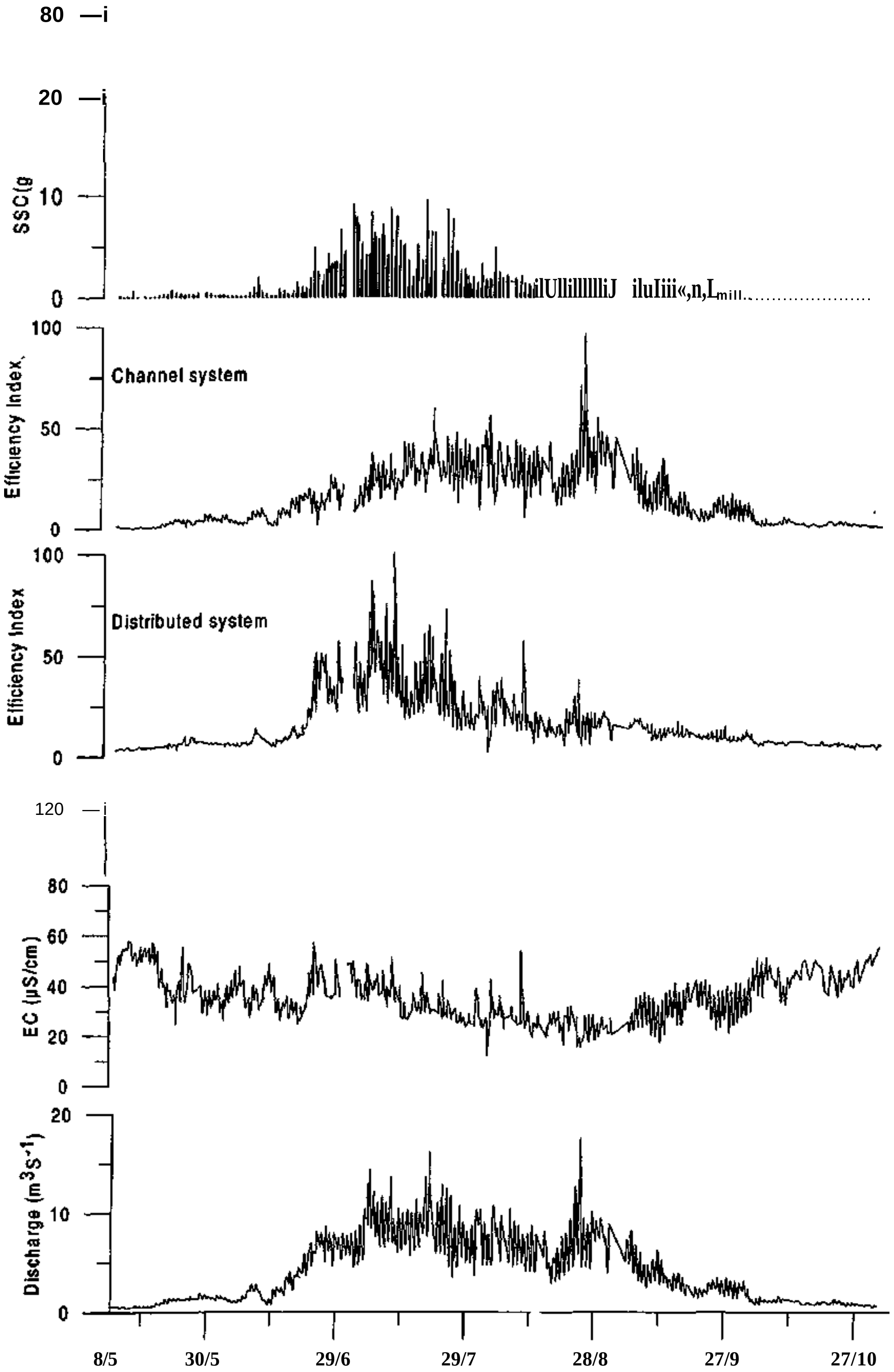

Fig.1. Discharge, electrical conductivity, efficiency variations of distributed and channel systems and suspended sediment concentrations during 1994 ablation period (May-October).

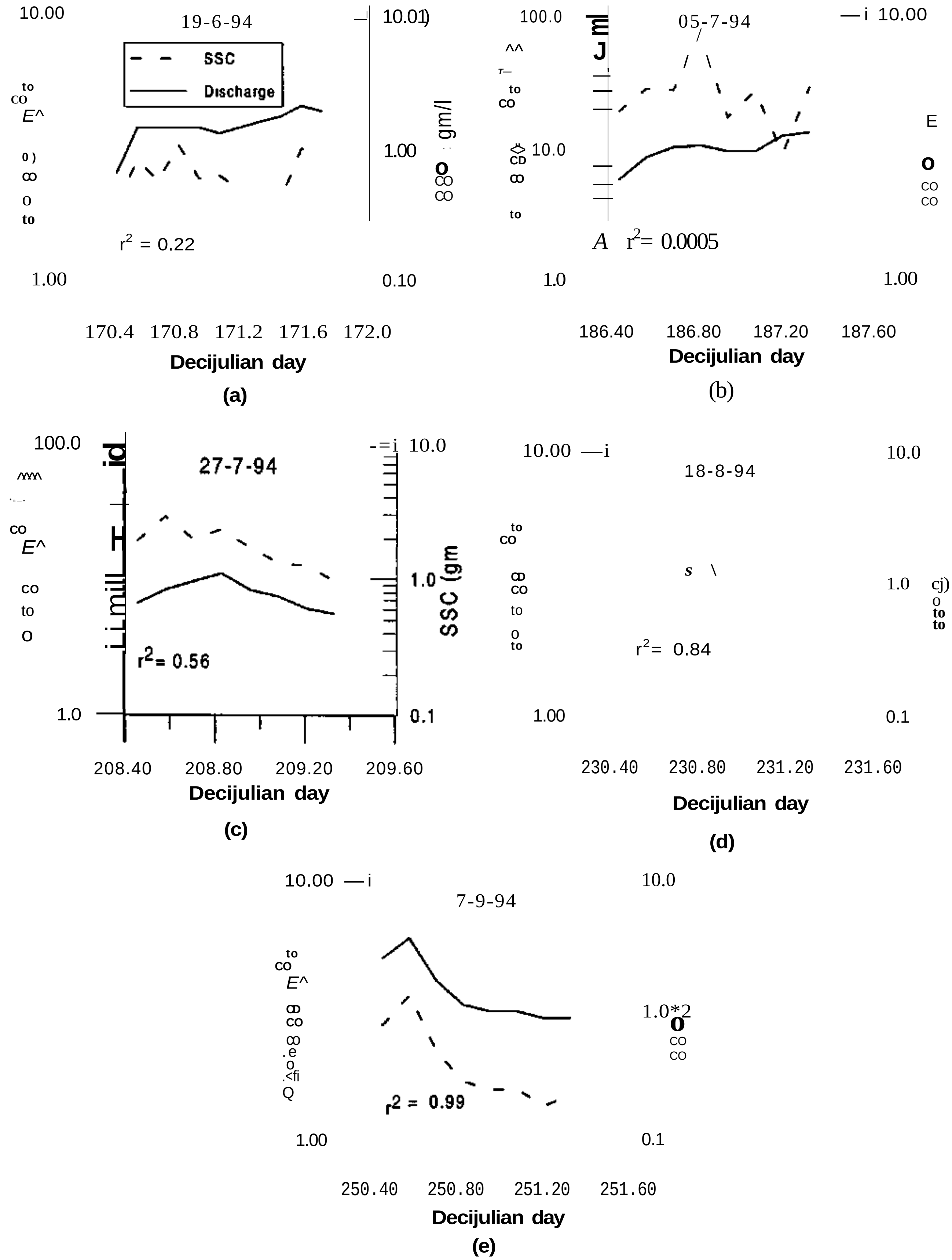

Fig.2. Diurnal variations in suspended sediment concentration and discharge at different stages of glacier drainage evolution processes.

this period and clearly indicates the dominant role played by the subglacial drainage evolution processes in controlling the sediment transfer during the 1994 ablation period. Thereafter the efficiency ofthe distributed system gradually reduced at the expense of increasing efficiency of channelised system and the efficiency index ofthe channel system shows improved relationship with SSC. Up glacier expansion and evolution of glacier drainage systems over the ablation period is controlled by weather condition during the season, the pattern of snowline retreat and distribution of moulins and crevasses over the glacier (Nienow et al. 1998). The efficiency index curve for distributed system has steep rising limb and extended recession limb where as the efficiency index curve of channel system has an extended rising limb and a steep recession limb. From these observations we infer that the distributed system opens fast and undergoes slow closure whereas the channel system develops slowly and closes faster. It implies that the subglacial distributed drainage system developed during the early part ofthe ablation period gradually convert into a more efficient channel system later (Nienow et al. 1998).

The role of glacier drainage evolution processes in controlling sediment transfer characteristics is more evident in the diurnal variations in the relationship between discharge (Q) and suspended sediments (SSC) at various stages of the ablation period. Diurnal Q-SSC variations show no correlation during the high efficiency period of distributed system (Fig 2a and b). As efficiency of the distributed system gradually declined the Q-SSC relationship improved dramatically (Fig 2c, d and e). It is clear from this observation that during the initial phase of the 1994 ablation season, evolution process of subglacial distributed flow system played a greater role in controlling the sediment transfer from the glacier than the discharge variation. Later, improvement in the diurnal Q-SSC relationship probably indicates increased hydraulic efficiency and stability of the channel system. Study of particle size distributions of suspended sediments suggests subglacial origin of suspended sediment during the high efficiency period of distributed system (Thayyen et al. 1999). These observations clearly indicate the major role of glacier drainage evolution processes in regulating the sediment transfer from a glacier catchment. However these characteristics need not be repeated during the consecutive ablation periods. Yearly variations in seasonal pattern of suspended sediment transport in meltwaters and differences in annual total yields result from variations in the spatial stability ofthe basal drainage network (Collins, 1990). Direct investigations of the hydrological characteristics of the subglacial zone are required for better understanding of subglacial hydrological processes.

The evidences emerge from this study and the study of particle size characteristics of suspended sediments (Thayyen et al. 1999) suggests that the direct influence of rainfall in glacier suspended sediment flux in 1994 was only marginal. More recent results from Dokriani glacier in 1998 and 1999 ablation period (May-October) support our point of view. Meteorological observatory at base camp (3763 m) recorded 1260 mm, 1383 mm and 1152 mm of rainfall in 1994,1998 and 1999 respectively and suspended sediment flux during these years (May-October) were 15.1 xlO^6, 3.2 xlO^6 and 4.4 xlO^6 tonnes (paper under preparation). This shows that the suspended sediment flux in 1998 and 1999 was only 21 % and 29% of that of 1994, while the catchment experienced even higher rainfall in 1998. These results substantiate our point of view that the subglacial hydrological processes warrants more intensive studies for a better understanding of sediment transfer and other related hydrological processes of the Himalayan glaciers.

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