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A comparison of the sediment transport and yield characteristics of two adjacent glacier basins, Val d' Hérens, Switzerland

A. M. GURNELL, J. WARBURTON & M. J. CLARK

Department of Geography, University of Southampton, Southampton S09 5NH, UK

Abstract This paper provides preliminary calibrations of the amount of sediment trapped by meltwater intake structures on two proglacial streams. The calibrations permit the estimation of suspended sediment and bedload yield over prolonged periods and are used with more traditional monitoring techniques to characterise and explain differences in sediment yield from two adjacent glacier basins.

Une comparison du transport et de la production de sédiments de deux bassins glaciaires, l'un à côté de l'autre, Val d'Hérens, Suisse

Résumé Cette communication nous donne les premiers étalonnages des quantités des sédiments captés par les prises d'eaux sur deux ruisseaux proglaciaires. Les étalonnages nous permettent d'estimer les productions de sédiments en suspension et des sédiments charriés pendant de longues périodes et sont utilisés avec les téchniques d'observations plus traditionelles pour caractériser et expliquer les différences de production des sédiments entre deux bassins glaciaires, l'un à côté de l'autre.

INTRODUCTION

There are few alpine glaciated basins for which a long term suspended sediment record is available, but from the limited published information it appears that their suspended sediment yield is above the global average (when standardized for catchment area) in spite of the temporally restricted period of runoff production (Gurnell, 1987). Studies of the bed load yield from these basins are even more rare than studies of suspended load. Alpine proglacial rivers are characterized by steep gradients, extremely variable sized, often coarse, bed materials and roughness elements which are frequently of the same order of magnitude as the flow depth (Gomez, 1987). As a result of these characteristics, bed load transport has usually been monitored by observing the accumulation of bed material over long periods of time (even the complete ablation season) at locations where it becomes trapped, rather than by frequently monitoring transport rates. For example, Hammer & Smith (1983) estimated bed load transport by surveying the accumulation of bed material behind a wire mesh fence which traversed the proglacial stream of Hilda glacier, Alberta, Canada; bed load transport rates at Bondhusbreen, Norway, were estimated from the amount of bed material that accumulated in a gravel sedimentation chamber; whereas at Engabreen and Nigardsbreen, Norway, bed load yield was estimated from the rate of accumulation of deltas where the proglacial streams entered lakes (Kjeldsen & Østrem, 1980; Kjeldsen, 1981).

This paper addresses two research problems. First, it provides preliminary results from field calibrations of sediment purging structures operated by Grande Dixence SA as a part of their water intake works for a hydroelectric power scheme in southern Switzerland. Calibrations of such structures permit the estimation of both suspended sediment and bed load yield over prolonged periods. Second, the estimates of suspended load and bed load from the calibrations and from more traditional monitoring techniques are utilized to characterize and explain differences in sediment yield from two adjacent glacier basins in the Val d'Hérens, Switzerland.

THE STUDY AREA

Glacier de Tsidjiore Nouve and Bas Glacier d'Arolla occupy adjacent valleys in the Val d'Hérens. Both glacier basins are within the hydroelectricity scheme and the meltwater intakes form the lowest point of the two catchment areas for the purposes of this discussion. Each glacier tongue is located below an icefall which is fed from connected icefields. The two glaciated catchmernts have a similar catchment area (4.8 and 7.6 km^2 for Tsidjiore Nouve and Bas Arolla, respectively), underlying bedrock (gneiss and schists), glacierized proportion (71 and 70%), and glacier altitudinal range (2220–3795 m, 2135–3538 m). However, there are differences between the basins in that they are oriented slightly differently in the ablation area (northeast and north) although the accumulation area of both glaciers is oriented to the north, their proglacial zones have contrasting slopes (approximately 15 and 6 degrees) and there is a marked contrast in their management. The Tsidjiore Nouve basin is unmanaged and contains a single glacier tongue whereas the Bas Arolla catchment contains several high level glaciers, notably the Haut Glacier d'Arolla, which form part of a natural drainage basin of 25.1 km^2 total area. However, meltwater from the higher basins is now abstracted as part of the hydroelectricity scheme and does not contribute runoff to the residual "managed" catchment area of 7.6 km^2. The only input from these higher basins to the "managed" basin is the sediment which is periodically purged from the meltwater intakes. The current "managed" catchment of the Bas Glacier d'Arolla contains a single glacier tongue.

FIELD DATA COLLECTION

Figure 1 describes the meltwater intake structure employed on the proglacial

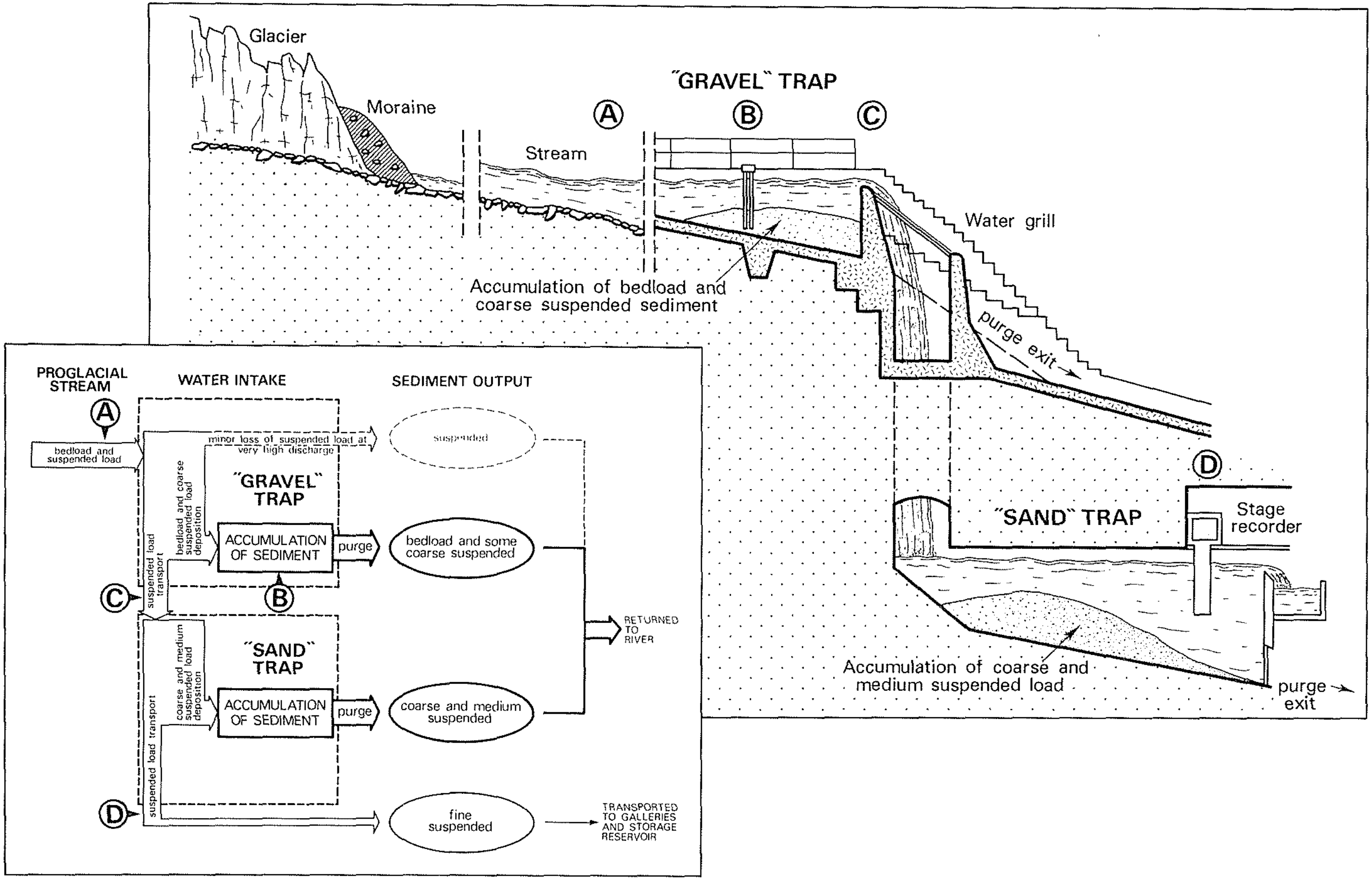

Fig. 1 *Sketch and flow diagram of the sediment trapping and purging mechanism of the meltwater intake structures.*

streams of the Tsidjiore Nouve Glacier and the Bas Glacier d'Arolla. The flow in the proglacial stream is diverted through a "gravel" trap, which traps the bed load and some of the coarse suspended load, and then through a "sand" trap which traps the medium to coarse fractions of the suspended sediment load. Discharge is continuously monitored using records from a stage recorder located behind a weir at the outlet from the sand trap at site D. The two sediment traps are periodically purged of sediment and although the traps are occasionally purged manually, the vast majority of these purges are a response to automatic sensing of the sediment accumulation. The water stage record from site D can be used to identify purge timing of the two traps because the water drops to two different levels according to which purge exit is opened, and so there is potential, with the provision of an acceptably accurate estimate of the amount of sediment automatically purged, to use the stage record to estimate sediment yield from the two basins.

Suspended sediment concentration was monitored using a continuously recording turbidity meter at site D where there is a mains electricity supply and where the turbidity record is unaffected by varying light and turbulence conditions. This record was transformed into estimates of suspended sediment concentration at sites A, C and D by filtration through pre-weighed Whatman 40 filter papers of water samples collected at the three sites using a USDH48 sampler. The suspended sediment concentration in the samples was related to the turbidity of the same water parcel as it passed site D (flow time was estimated using salt tracer) and calibration curves between suspended sediment concentration and turbidity were estimated for each of the three sites. The calibration curves permitted estimation of suspended sediment concentration variations at the three sites and also the amount of suspended sediment being deposited in the two sediment traps. It is accepted that there are potential problems of uneven intermediate sedimentation associated with variations in the particle size distribution of the sediment and trap filling. Nevertheless, the calibration data collected so far over two ablation seasons and under varying flow and sedimentation conditions, provide reassuringly stable calibration curves until more detailed short term studies can investigate the potential advantages of multivariate calibration curves.

Bed load transport was monitored by surveying the accumulation of sediment in the "gravel" trap (site B) and monitoring the packing density of the accumulating sediment in containers suspended in the trap. Such data can be used to estimate the volume and packing density of the sediment which is removed when the trap is automatically purged. Since the "gravel" traps also trap the coarser fraction of the suspended load, the suspended sediment calibration curves for sites A and C were used to estimate deposition of this load during periods for which sediment accumulation was monitored. It was then possible to subtract this quantity of suspended sediment from the total accumulated weight of sediment in the "gravel" trap and so derive a corrected estimate of the quantity of bed load.

The preliminary results presented below are for three month periods of the ablation seasons of 1986 and 1987 and illustrate the potential of trap calibration for extrapolating and estimating components of the sediment transport. Although calibration data were derived for both suspended sediment and bed load transport at both meltwater intakes, more emphasis was placed on suspended sediment load at the Tsidjiore Nouve intake, whereas the details of gravel trap sediment accumulation between purges was emphasized at the Bas Arolla intake. As a result there are some gaps in the suspended sediment record at the Bas Arolla intake, and estimates of a bed load range are used at Tsidjiore Nouve based on observations from a few purges with upper and lower "error margins" assessed from the potentially varied influence of the geometry of the "gravel trap" on sediment accumulation.

RESULTS AND DISCUSSION

Patterns of sediment transport over the ablation season

Figure 2 shows the accumulated weekly transport rates of suspended sediment and of total suspended load and bed load over the three month observation periods in 1986 and 1987. Gaps in the suspended sediment record at the Bas Arolla intake were filled using a relationship between purges of the "sand

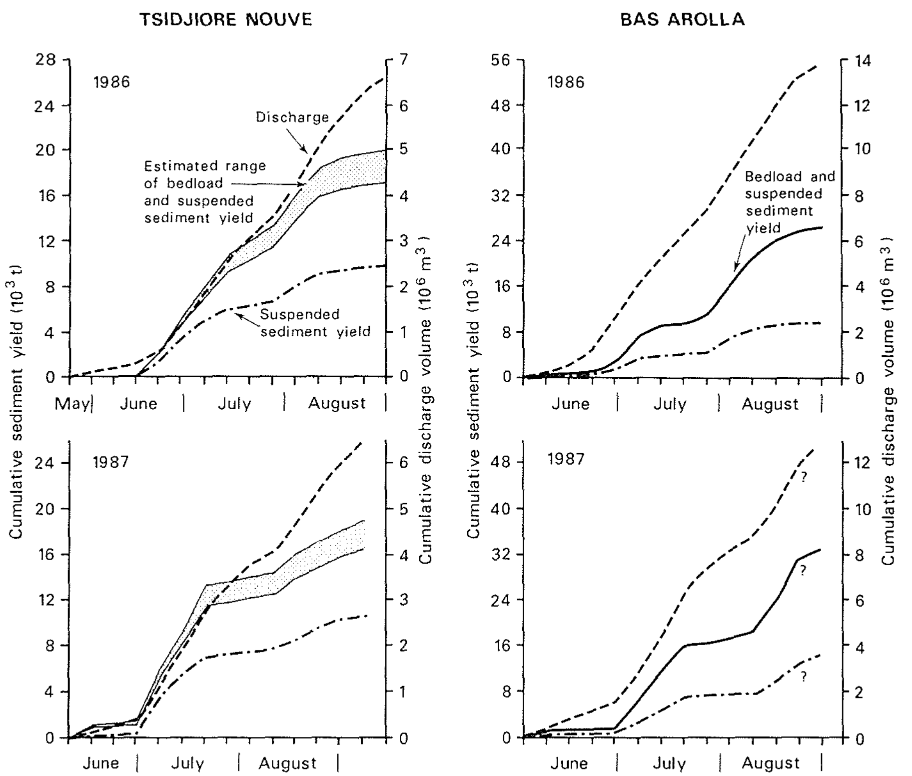

Fig. 2 Accumulated weekly discharge, suspended sediment and bed load yield from the Tsidjiore Nouve and Bas Arolla basins, 1986 and 1987.

trap" and suspended sediment transport in the river. Estimates of the bedload component of sediment yield were derived from the weekly total of purges of the "gravel" trap multiplied by the average observed volume and packing density of the purged sediment. The only period for which the data are unsatisfactory occurs at the end of the 1987 observation period at the Bas Arolla intake. Only minimum estimates of discharge, suspended sediment and bed load are presented here because a large managed flow event (possibly equivalent to the 50 year event and including inputs of water from higher catchments, which were transmitted through the Bas Arolla intake structure for flood control purposes) caused continuous purging of the Bas Arolla intake for almost 24 h.

There are strong contrasts between the two glacier basins. Both graphs for Tsidjiore Nouve in Fig. 2 show enhanced rates of sediment transport early in the ablation season followed by evidence of limitation on sediment supply later in the observation period, but this pattern is not as clear for Bas Arolla. The Tsidjiore Nouve basin yields much more sediment in relation to its water yield than the Bas Arolla; an average of approximately 2600 to 3000 mg l^{-1} of combined suspended and bed load from Tsidjiore Nouve in 1986 and 1987 in comparison with approximately 1900 and 2500 mg l^{-1} in 1986 and 1987, respectively, from Bas Arolla. In addition, the bed load forms a higher proportion of the total load from Bas Arolla (64% in 1986, 58% in 1987) than from Tsidjiore Nouve (43–51% in 1986, 36–44% in 1987).

There are differences in the rates of accumulation of the sediment yield between years. In both years there was an early and a late period of high flows, but in 1987 both of these high flow periods included a particularly large flood event caused by intense rainfall and associated with high sediment transport. The impact of the first flood event is seen in the graph for Tsidjiore Nouve, which has a steeply sloping total sediment yield curve during the first part of July, but the second event is not reflected in the weekly sediment transport rates, presumably as a result of limitation of sediment supply. Bas Arolla has a generally lower sediment transport rate in relation to discharge than Tsidjiore Nouve and less contrast in sediment transport for the two high flow periods in each year, although there is evidence of sediment supply limitation towards the end of each event.

Daily sediment transport rates

Figure 3 shows daily discharge and suspended sediment loads for the two proglacial streams. Both discharge and suspended sediment load are standardized for catchment area (managed area in the case of Bas Arolla) to allow direct comparison. In both years the yield of water per unit area is higher and the yield of suspended sediment is lower from the Bas Arolla than from the Tsidjiore Nouve catchment. This illustrates the negligible influence of discharge and sediment yields from the extra area of the natural catchment on the seasonal yield of suspended sediment and water from the managed Bas Arolla catchment. The two high flow events in 1987 on the Bas Arolla graph are augmented by transmission of water from other sites for flood control, but only the later event

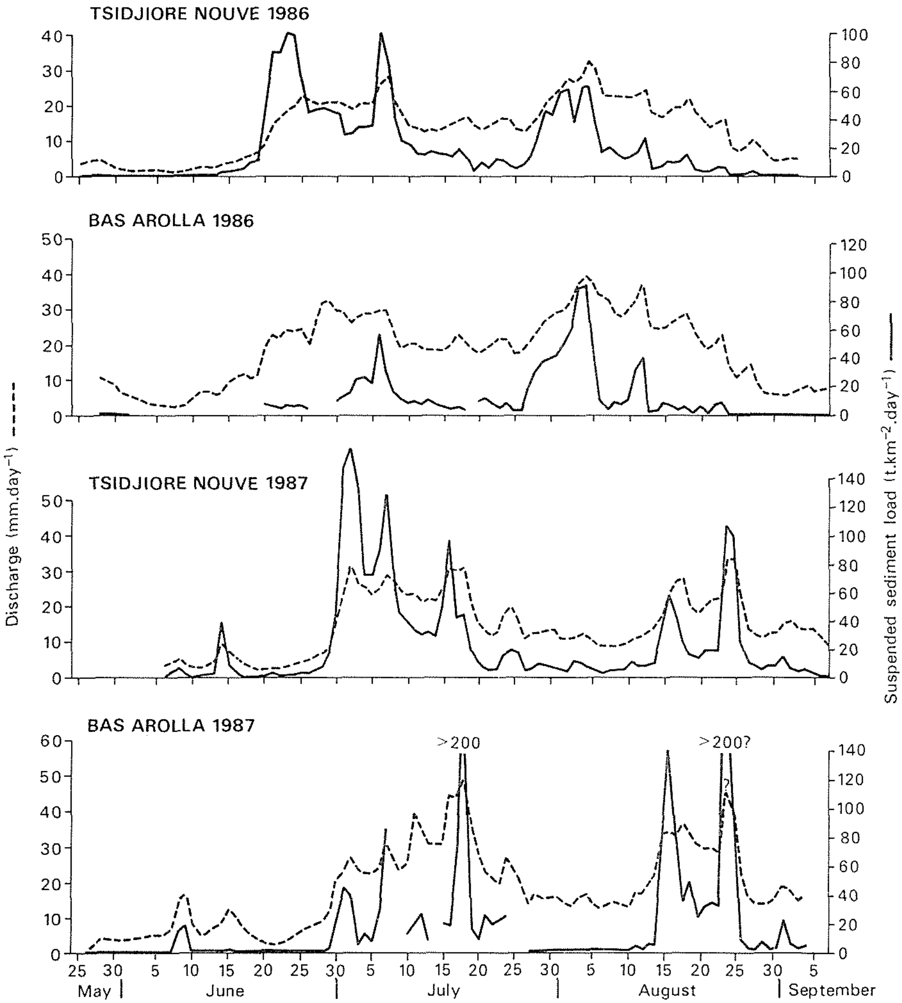

Fig. 3 *Variations in daily discharge and suspended sediment yield (standardized for catchment area) from the Tsidjiore Nouve and Bas Arolla basins, 1986 and 1987.*

caused significant gaps in the discharge record.

The pattern of suspended sediment load and discharge of the Tsidjiore Nouve proglacial stream in 1986 is typical of many alpine proglacial streams. High discharge events early in the ablation season transport large concentrations of sediment as the englacial and subglacial drainage system is developed, whereas later events transport less sediment because much of the available sediment has already been transported. A similar pattern is maintained in 1987, although the higher flood flows transport considerably higher loads of suspended sediment than were monitored in 1986.

In contrast there is little evidence of progressive limitation of sediment supply in the Bas Arolla stream. Indeed in 1986 there is a period in late July and early August when daily suspended sediment loads are higher than might be expected. In 1987 missing data make comparisons difficult but the background daily sediment loads in mid August appear to be higher than those in mid July. These late periods of relatively high suspended sediment transport appear to be related to inputs of sediment from the high level glaciers in the rest of the natural catchment area. As a result of their higher altitude, the commencement of the ablation season in these catchments is delayed and this delay is confirmed by the later commencement of purging of the high level meltwater intakes. Therefore, although the total load of suspended sediment from the Bas Arolla catchment does not appear to be significantly enhanced by sediment purges from the high basins, there does appear to be an effect on the temporal pattern of diurnal suspended sediment load.

Diurnal patterns of suspended sediment concentration and discharge

The majority of the discharge in a proglacial stream is derived from ice melt and so the discharge and suspended sediment record are frequently characterized by strong diurnal cycles. The average weekly pattern of hourly suspended sediment concentration and discharge was calculated for both glacier basins for 1986 and 1987 and parameters of these weekly average diurnal patterns were abstracted. Figure 4 shows seasonal trends in these parameters. In order to highlight trends rather than short term variability the graphs present three week running means of the parameters. Gaps in the suspended sediment record for Bas Arolla are evident in the 1986 graph and preclude the estimation of three week running means for 1987.

The upper graphs show the timing of peak and low discharge and suspended sediment concentration. The Tsidjiore Nouve data illustrate how timings become progressively earlier as the glacial drainage system becomes established, after which they stabilize. A similar pattern is exhibited by discharge timing at the Bas Arolla intake in 1986, but the timing of the sediment peaks and lows becomes later during late July and early August. This suggests late release of sediment during the day or a longer and more circuitous routing path for the majority of the sediment than for the water. Late release could be associated with late afternoon purging of the high meltwater intakes. This sometimes occurs but does not appear to be the entire explanation. The late timing may be partly caused by sediment release from higher in the managed catchment area during this phase of the ablation season, possibly from sources on the ice fall.

The lower graphs show how the ratio of peak to low discharge and peak to low suspended sediment concentration increased (and then for discharge stabilized or decreased) in both glacier basins during 1986. It also shows, through a plot of the ratio of suspended sediment concentration range to discharge range, how the amplitude of the suspended sediment cycle does not keep pace with that of discharge through the ablation season. In 1987 the two exceptionally high flow events disrupted the usual development of the diurnal discharge and suspended sediment concentration cycles in the Tsidjiore Nouve basin.

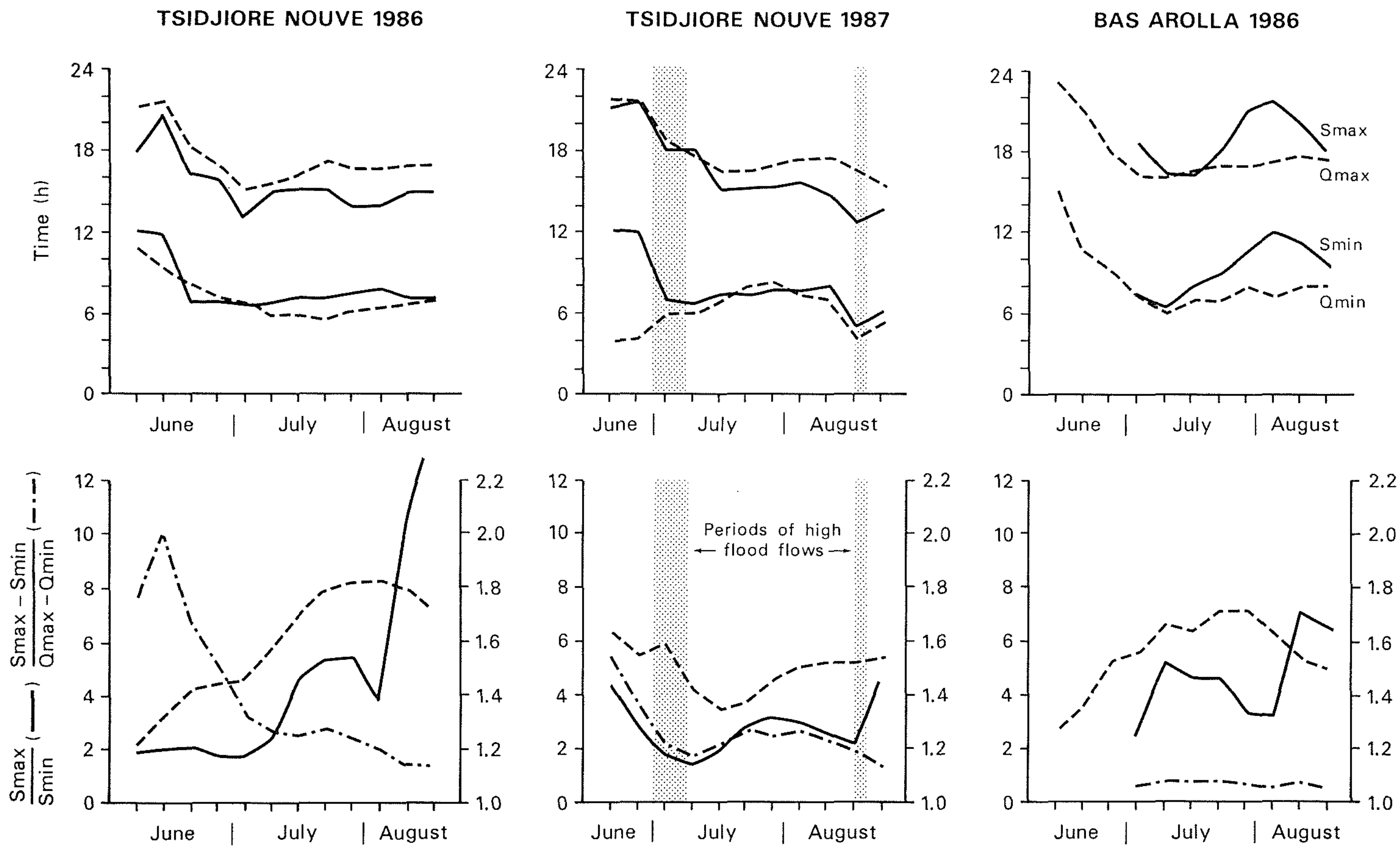

Fig. 4 Parameters of average weekly, diurnal cycles of discharge and suspended sediment concentration expressed as three week running means.

CONCLUSIONS

Although the sediment calibrations of the meltwater intake structures will be refined in 1988, this paper has shown that information from such calibrations can provide details of the sediment yield characteristics of these proglacial steams.

The basins of Glacier de Tsidjiore Nouve and Bas Glacier d'Arolla yield different quantities of suspended sediment and bed load and exhibit interesting contrasts in the temporal patterns of sediment yield at three different time scales. When standardized for catchment area, total sediment yield from the Tsidjiore Nouve basin is higher but the proportion of the bed load is lower than Bas Arolla. In spite of apparent limitation in suspended sediment supply through the ablation season, suspended sediment yield from the Tsidjiore Nouve basin remains responsive to discharge variations. In contrast, the lower sediment yield from the Bas Arolla basin suggests supply limitation within the ablation zone of the glacier for much of the ablation season. The late season rises in suspended sediment yield are presumably typical of glacier basins which receive sediment inputs from higher level glaciers, although the timing of suspended sediment concentration peaks during this period may well be an artifact of water management.

The contrasts in patterns of sediment yield may be caused by differences in the slope of the proglacial zone and the glacier bed below the ablation zone and associated differences in the stability of the glacial drainage system. The Tsidjiore Nouve proglacial zone is steeper than that of the Bas Arolla basin and whereas the slope of the latter has remained fairly stable during the last ten years of glacier advance, the Tsidjiore Nouve proglacial zone used to be much steeper [valley train slope 23 degrees, mean channel slope 18 degrees in 1978, Fenn (1983)] so that a very steep component of the old proglacial zone is now part of the bed below the glacier tongue. The Tsidjiore Nouve proglacial stream has been observed to issue from varied locations at the glacier snout (Gurnell, 1982; Röthlisberger & Lang, 1987) whereas such movement of the main Bas Arolla stream is rare. Short sediment flushes from Tsidjiore Nouve have also been attributed to possible adjustments in the subglacial drainage network (Gurnell, 1982). The Bas Arolla glacier tongue probably has a relatively stable main drainage system which only taps sediment from a restricted area of the glacier bed, whereas the Tsidjiore Nouve drainage system is more mobile and so generates a more marked response in suspended sediment concentration to variations in discharge. Whereas limitation of suspended sediment supply becomes progressively evident through the ablation season in the Tsidjiore Nouve basin, it appears to be almost always present in the Bas Arolla basin until higher level sediment sources become active later in the ablation season.

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