Transport dynamics and morphology of a high mountain stream during the peak flow season: the Ürümqi River (Chinese Tian Shan)

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ABSTRACT: In order to get some insight into the poorly known dynamics of high mountain streams measurements of flow and sediment transport (both solute, suspended and bed load) were conducted at three different alluvial sites along the Ürümqi He (Chinese Tian Shan). The discharge of this high mountain stream (headwaters at 4000 m), is in part controlled by glacial melting. This first survey took place during the high flow season in July 2001. Although of short duration it brings some useful insight into the dynamics of flow and sediment transport by the river during the high flow season. (i) Bed load transport during peak flow can account for more than 80 % of the solid flux. (ii) Bed and solute loads together account for more than 90 % of the Total load of the river at the range front. (iii) In the glacial valley site, measurements made before and during a nearly bank-full flood event indicate that transport of gravel seems to be more or less a continuous process in riffle or step-pool sections, whereas larger pools, that temporarily store the material delivered by the riffles, are flushed during a flood event. (iv) A strong correlation exists between suspended and bed load. This suggests that movement along the bed is necessary to unhide the smallest particles and put them into suspension.

1 INTRODUCTION

Rivers are by far the main carriers of erosion products (Goudie, 1995). The rate at which and the mechanisms by which a river is able to incise relief and evacuate the eroded masses delivered from the slopes is essential to our understanding of both stream morphology and landscape evolution. It is even more crucial in active mountain ranges where sustained tectonic uplift, orographic precipitations and glacial melting, should maintain significant erosion rates and enhance river dynamics. Despite this datasets on sediment transport and morphodynamics of high mountain streams are sparse (Wohl, 2000).

We report hereafter results from a preliminary study on the morpho-dynamics of the Ürümqi He, a high mountain stream of the northern Tian Shan (China). The river headwaters are made by retreating glaciers. The Ürümqi River initiates at 3600 m ASL from the melt of a glacier known as Glacier N° 1.

The river flows through two steep sections separated by a flat basin where the town of Hou Xia and the glacial station of the Chinese Academy of science are located. The river length from its headwater to the piedmont where it enters a semi-desert environment is on order of 60 km.

2 MORPHOLOGY OF THE ÜRÜMQI RIVER AND ITS CATCHMENT

2.1 Sampling sites description

2.1.1 Site 1: Glacial valley

The first sampling site is located in the glacial valley at an elevation of 3300 m approximately 8 km downstream of glacier number 1 which is the source of the Ürümqi River (Fig. 1). The river flows on
glacial moraines though a series of cascades and flats (Fig. 1).

The long distance profile of the valley is steep and grain size of surface particles is gravel-like. $D_{50}$ of the surface samples is 21.5 mm and $D_{90}$ is equal to 158 mm. Figure 1 and 7 show the study site. It is located in a confluence zone between two riffles. Upstream the river is divided into two branches flowing around a central bar. Bed is step like with a mean slope of 4.9 %. A pool is located at the confluence. The long distance averaged bed slope is steep $S \sim 2.5$ %. Most of the measurements were carried at the downstream end of the pool where the river is the widest (average wetted perimeter $P_w$ varies from 9 to 12 m) and the shallowest (average hydraulic radius between $R$ between 0.2 and 0.4 m). Some measures were taken in the pool ($P_w \sim 7$ m, $R \sim 0.5$ m. Some where also carried in the riffle section upstream.

2.1.2 Site 2: Hou Xia

The second sampling site is located at the outlet of the upstream gorge before the town of Hou Xia (literally: after the gorge, Fig. 1). As in the case of the glacial valley, the measurement site is between two riffles or step-pool sections. At the end of the upstream riffle a pool stands as in the case of site 1 although no active confluence exist at present. Bed slope averages 1.5 % at the site. The wetted perimeter remained quite stable during measurement days $P_w$ between 22.5 and 23.5 m, more than twice the perimeter of the river upstream near the glaciers. Abandoned terraces can be seen in the valley, the glacial station being built on one of these.

2.1.3 Site 3: Range front

The third sampling site is located at the range front just outside the downstream gorge of the river. Our measurement, as for the above mentioned, is located before a riffle section where the river splits into three main branches. The wetted perimeter was between 21 and 22 m during measurements and the hydraulic radius between 0.5 and 0.6 m. The river is dynamic and measurements where difficult. At the range front the most prominent feature in the landscape is made by large terraces standing almost 100 m above the present day river bed. These terraces
which are fill-cut at the range front progressively turn into strath terraces a few kilometers downstream where tertiary red beds are seen to dip southward under a sub horizontal dark gray gravel bed layer marking the ancient river plain, a feature common to all the rivers of Northern Tian Shan.

2.2 Data Acquisition

Discharge was measured at each site using an OTT velocimeter. 295 velocity profiles were measured corresponding to 30 complete gaggings of the Ürümqi He (Fig. 2). Velocity profiles were measured regularly across the river (between 1 and 2 m distance depending on the site). Water was sampled 26 times with a USDH 48 depth integrating sampler for suspensions or solute load. The sampler was equipped with a 0.64 mm nozzle. Samples were filtrated to a threshold of 0.2 microns to separate suspensions and solute load and prevent chemical reactions in the bottles after sampling. Suspensions were dried and weighted in the laboratory. Bed load was measured using a 15 cm entrance Helley-Smith sampler. The Helley-Smith was equipped with 250 microns mesh bags. Each bed load section is composed of at least 6 to 10 point measurements regularly spaced along the section. At each point the sampler was left for 60 s (30s during the highest flows). 95 sections were measured during this survey. Topographic measurements were conducted at site 1 and 2 using a Wild T2000 Total station equipped with a laser distance meter that permits measurements with an accuracy of less than 1 cm. Surface granulometry was established using statistical counting (Wolman, 1954). Minimum size measured was 1 mm.

Solute transport in the Ürümqi river catchment has been discussed at length by Liu et al. (1995), and Williams et al. (1995), on the basis of sampling of the river at places near our sampling sites. We will therefore here concentrate on the solid load.

3 VELOCITY SCALE IN MOUNTAIN STREAMS

Velocity profiles were leveled regularly at each site of the Ürümqi He. Shear velocity estimates were performed by adjusting a logarithmic profile to the data according to:

\[
\frac{u}{u_*} = \frac{1}{\kappa} \ln \left( \frac{z}{k_s} \right)
\]

Where \( u \) is the velocity of the flow at depth \( z \), \( u_* \) is the shear velocity, \( k_s \) the bed roughness and \( \kappa = 0.4 \) the von Karman constant. In gravel bed rivers such as the Ürümqi He, the bed roughness usually scales with the \( D_{90} \) of bed material distribution (e.g. Wilcock 1996). Following Wilcock (1996) another estimate can then be derived using the average velocity but still assuming a logarithmic form of the velocity profile:

\[
\frac{U}{u_*} = \frac{1}{\kappa} \ln \left( \frac{h}{e k_s} \right)
\]

Here \( U \) is the depth averaged velocity, and \( h \) the flow depth. The estimates were then compared (Fig. 3). The results clearly show a poor agreement for the Hou Xia site. The two other sampling sites do not show a convincing correlation. If the velocity distribution was logarithmic throughout the flow depth as often supposed both estimates of the shear velocity should correlate with a 1:1 slope. As this is not the case velocity profiles can not be considered to follow a logarithmic distribution on the timescale of leveling (Wohl, 2000). The average velocity should then be preferred and considered the only relevant velocity scale at the scale of conventional sampling (60 s per measurement). Care should therefore be taken when devising transport equations with shear velocities.

![Figure 2: Sample velocity profile at site 2](image)

![Figure 3: Correlation between estimates of the shear velocity at site 2](image)
During July 19 and 20 fractional transport seems, to the first order to be independent of grain diameter. Parker et al. (1982) proposed that grains moved in proportion to their presence on the bed surface. This hypothesis was developed in order to explain transport of bed material in paved gravel Bed River and was checked against data from Oak Creek (Oregon). Parker et al. (1982) called this phenomenon equal mobility. It was then argued by others (Wilcock, 1997; Wilcock, & McArdell 1997) that equal mobility was but an end-member of partial transport. Partial transport of matter seemed to be more representative of bed load transport by rivers in which bed material does not move in large proportions.

4 SEDIMENT TRANSPORT

4.1 Importance of the Bed load component

Numerous studies have focused on bed load transport by mountain streams (Wohl, 2000). The reasons for this are that (1) bed load is probably an important component of the total mass transport, and (2) it bears a first order control on the morphology of many mountain streams. Measurements made in the Ürümqi River attest that bed load transport is significant during high flow. Daily averages of Bed load show that it represents approximately 64, 20 and 45 % of the total daily load at the glacial valley site, Hou Xia and at the range front respectively during the measurement period. These values are high especially in the glacial valley and, perhaps more surprisingly, at the range front 60 km downstream of the headwaters. Only at Hou Xia is suspension the dominant mode of transport of the solid load. One might find two explanations for this. The Hou Xia basin is the place where the river profile is the flattest. Flattening of the along stream profile of the river should therefore logically lead to lower values of bed load transport because of the concurrent reduction in stream power expenditure (Métivier & Meunier 2003 and references therein). The low value of bed load may also come from the fact that between the glacial valley and Hou Xia, the river cuts relatively deep into the range. There its bed is mostly rock floured. The river, when it enters the Hou Xia plain a few hundreds of meters before site 2, may not be a transport limited stream but a supply limited river. This then could explain why the bed load component of the solid load drops to 20 %. These results clearly show that any mass balance or sediment budget conducted in high mountain streams should incorporate bed load measurements.

4.2 Fractional I transport

Some samples were kept and dried in the laboratory. Sieving was performed and the bed load was decomposed into Φ-size fractions $\alpha_{l,D_i}$. The coarse fractions were then normalized to the corresponding fractions of the bed surface $\alpha_{b,D_i}$. Figure 4 shows the plot of these normalized fractions against grain diameter

$$\frac{\alpha_{l,D_i}}{\alpha_{b,D_i}} = f(D_i)$$

Figure 4 Comparison between the ratio of a given $i$th-size fraction in transport to the same fractions on the bed surface with the median diameter of the $i$th size fraction. Numbers indicate day of measurement.

Figure 5. Surface distribution of bed material in the Hou Xia Braid Plain.

In the Ürümqi He No true pavement can be defined over large surfaces of the bed. The unstable nature of braided channels is probably the reason for this. In fact the river presents a braiding morphology at several places in the glacial valley (site 1) and eve
where both in Hou Xia (site 2) and at the Range front. Surface granulometry performed at site 2 (Hou Xia plain) shows the local variability of grain size distributions and its relationship with bed structures (Fig. 5).

For example the grain size distribution in a confluence pool has a $D_{50}$ of 1 cm whereas the $D_{50}$ of a mid-bar nearby reaches approximately 4.5 cm. Bed material measurements in Hou Xia, on the braid plain, therefore show that grain size distribution of bed material varies according to flow structures and position on the bed. Equal mobility is clearly achieved downstream at the Range Front where transport rates are very high (Fig. 4 profiles 19 and 20). For other days and sites sands in the range 2-4 mm seem to be over represented in the bed load compared both to their respective abundance on the bed and to other grain sizes.

Fractional transport in braided streams should take the bed surface distribution of grains depicted above into account. Indeed in Hou Xia the measurement section was located after a very dynamic pool. As

Figure 6: open circles and dark shade of gray envelope: same as figure 4 for the Hou Xia sampling site. Dark circles and light shade of gray envelope: normalization is done with the surface granulometry of a pool.

Figure 7: Study site in glacial valley. Upper two photographs: sampling site and glacial valley views with head water glaciers at a distance. On left: pictures of sampling site during and before bank full discharge. Map of sampling site leveled with Wild T2000 theodolite and laser distance-meter.
selective surface granulometry was performed at this site, we tested the possible influence of spatial variations in the surface granulometry. Figure 6 shows the result. Although some variability remains due most probably to the small number of samples, the curves (dark circles) are strongly smoothed and approach equal mobility for the fractions with sizes less than 2 cm. The residual variability may possibly come from the subsurface (Parker et al., 1982) as it has been shown that the granulometry of the subsurface is often finer than the granulometry of the surface material.

4.3 The step/pool-pool transport unit

One very interesting feature of the Ürümqi He concerns the way bed load is transported. As the material is coarse its characteristic distance of travel is probably quite small. Does such river morphology exhibit some particular spatial scales or pattern that would be indicative of the distance of travel of the grains making up the bed? One striking pattern of the Ürümqi He in the glacial valley is the succession of steep riffles or step-pool sections that alternate with flatter pool sections (Fig. 7). During our survey of the river in the glacial valley we continuously measured bed load both in a step-pool section and after a large confluence pool (Fig. 7). Between July 11 and July 14 when we left for the second site downstream in Hou Xia, a nearly bank full flood wave passed through the measurement section. In two days the discharge rose by an order of magnitude. Peak discharge occurred on July the 13th and reached more than 6 m³/s. Figure 8 shows daily averages of bed load in both step-pool and pool sections together with the average daily discharge.

Our measurements indicate that bed load transport in the step-pool section is weakly dependent on discharge. The load remains high before during an after the flood. On the contrary transport in the pool is strongly discharge-dependent. Bed load rises by nearly two orders of magnitude between July 11 and July 13. This variable dependence can probably be explained by the difference in the local h/D₉₀ ratios. In the step-pool section this ratio varies little and is on order of 1 because large boulder of diameter similar to the flow depth strongly that regulate the flow like spill gates. In the pool where the water height is always large the bottom shear stress is probably much more dependant on flow conditions and therefore variable.

The mass balance between the flux transported into the pool along the step-pool section and the flux leaving the pool is approximately 2. Thus before and after the flood, bed load is transported to the pool efficiently by turbulence in the step-pool sections. Most of the mass is then stored in the pool. During the flood event the pool is flushed and sediments get delivered to the next step-pool section where they are transported at a seemingly constant rate.

Bed load granulometry clearly is affected by the passage of this wave (Fig. 9). Before the flood the size of the material transported from the step-pool to the pool is largely coarser than the granulometry of the material leaving the pool. Therefore sedimentation takes place and gravels are stored in the pool, in agreement with the mass balance (Fig. 8). During the flood the granulometry of the material leaving the pool rises and becomes of the same order of magnitude as the granulometry of particles fed to the pool from the step-pool section upstream. There again these results are in good agreement with the mass balance indicating that the pool is being flushed. The balance of fluxes into and out of the confluence pool equals approximately 2. This means that the flood wave washed out all the sediments stored during the preceding 3 days and that equilibrium is approximately achieved at the time scale of our survey. Future research will concentrate on trying to establish longer term balance of fluxes at the...
scale of morphologic structures as this balance is important to understand the characteristic lengths of transport of be material and the characteristic velocities at which such structures may evolve (e.g. Wohl 2000 and references therein).

4.4 Suspended load

Suspended load was measured with the use of a USDH48 depth integrated sampler attached to a wading rod. Between one and three samples were retrieved each day. Daily variations are insignificant with the exception of July 12 and 13 during the passage of a bank full flood wave. As suspension was sampled throughout the flow depth the concentration obtained should be representative of the true flux although depth integrated sampling may bear some uncertainties because of the very transient nature of suspended load near the bed. Sediments transported mainly consist in fine rock flour. Very few silts were sampled. Overlaps between suspended and bed load samples is therefore negligible.

There are clearly two striking features with the suspended load of the Ürümqi He. The first one is that suspended load clearly appears to be the minor mode of transport along the Ürümqi He. During our survey the water was clear except during July the 12th and the 13th when the flood wave passed through. Suspended load accounts for at most 22% of the total load carried by the Ürümqi in the glacial valley. It accounts for less than 10% both in Hou Xia and at the range front.

The second important observation that can be made is the strong correlation that seems to exist between suspended and bed load as shown in figure 10. Averages of bed and suspended load are well correlated through a power-law relationship.

This strong correlation clearly suggests that most of the suspended sediments come from the alluvial bed and are released by movement of coarse particles, sands, gravels and cobbles. This also implies that sediment feeding from the slopes is negligible. The Ürümqi Drainage lies in an arid environment. Very few precipitations occurred during our journey. When precipitations occur the principal mode of mass transport on the slopes seems to be gravity driven flows. Wash load is clearly not a dominant process and therefore explains why such a nice correlation occurs. This certainly deserves further research for at least two reasons. Understanding such a correlation may help us achieve correct estimates of the mass fluxes transported by mountain rivers without having to measure the bed load component explicitly. The difficulty of sampling bed load in gravel bed rivers has been known for long and estimating bed load movement through the measurement of suspended load clearly is an issue in studies of erosion and sediment transport by rivers. Further more such a relationship existing between bed load and fine particles release from the bed remains unclear and badly documented whereas it may shed light on the dynamics of fine particles movement and temporary storage in gravel bed streams. Rivers like the Ürümqi He may well be ideal places to study such entrainment.

5 SUMMARY

A survey was performed on three reaches of the Ürümqi He, a high mountain stream of northern Tian Shan (China). Our survey shows the close link between the morphology (step-pool to pool) and sediment transport in these step mountain rivers. Equal mobility of the grains seems to be achieved in one of the reaches. At all three sites suspended and bed load are strongly correlated. These results confirm the importance of further researches on bed load transport and the control it exerts on mountain stream morphology. Especially it is suggested that concurrent and systematic measurements of both velocity profiles bed load fluxes and granulometry are needed in order to understand the coupled evolution
of river morphology and transport dynamics. Furthermore local mass balance at the scale of morphologic structures such as step-pools and pools shows how grain sorting and temporary storage occurs in mountain streams. At lower flows sands are transported throughout the system whereas gravels only move in step-pool sections and are trapped in pools. Long term mass balance coupled with granulometry of bed material movement and hydraulic measurements should then lead to a better understanding of the timescales and lengthscales of grain movement and of the timescales of morphologic changes in mountain streams.

REFERENCES
