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Solid Earth
Discussions

Interactive comment on "Erosion rates deduced from Seasonal mass balance along an active braided river in Tianshan" *by* Y. Liu et al.

H. Wulf (Referee)

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General comments:

I assume that the authors put a lot of work and effort in this study and I appreciate that they try to place their results in the framework of existing literature. Unfortunately, the manuscript is not well written, neither concise nor in a correct grammar. This makes it in parts really challenging to understand the author's intention and to evaluate their procedures. As I am myself not a native speaker, I understand the difficulties involved in this process. But it is in my view the essence of science to be concise and understandable, otherwise it is hard to find an audience. I assume that one of the co-authors might be able to involve a native speaker to correct the grammar and give the manuscript more structure. Several paragraphs are placed in the wrong sections and

others are irrelevant for the message the authors try to convey.

Besides the high potential to improve the scientific writing style, I doubt that it is valid to infer the long-term sediment budget based on river discharge data. Extreme sediment flux events, which might be associated with glacial sediment discharge or rainfall induced landslides are not necessarily indicated by peak discharges. In my view the authors collected a highly valuable dataset. Therefore, it is more instructive, if they present their data in a plain way and avoid unknown assumptions about flood sediment transport or "long-term" budgets.

In addition, I suspect that the denudation rates the authors derive are rather low for a glaciated high-relief catchment in a tectonically active environment. I did not quite understand, how they bridge the gap to other studies presenting orders of magnitude higher denudation rates.

Specific comments:

Title: Erosion rates deduced from Seasonal mass balance along an active braided river in Tianshan - What does the word "active" refer to? Is that important for the erosion rates? - Suggestion: Erosion rates deduced from fluvial sediment flux data of the Urumqi River, Tianshan

542, 2-3: "an active mountain range in" - The Tianshan is known as a mountain range not necessary to mention that. - Further information of the sampled catchment area might be interesting.

542, 6: "secular" - you mean "long-term"? -

542, 6: "this high mountain catchment of Central Asia." - redundant -

542, 9: "can not be neglected" - double negative, say clearly what you mean and keep it short - i.e. "Bed load in form of sand and gravel is significant, as it accounts for one third of the solid load of the river."

542, 10-11: “Overall, the mean denudation rates are low, averaging 46 t°âĂŤkm−2 °âĂŤyr−1(17–18mMyr−1).” - Why is that so? “averaging 46 t°âĂŤkm−2 °âĂŤyr−1(17–18mMyr−1), because . . .”

542, 13-16: “The rates we obtain are in agreement with rates obtained from the mass balance reconstruction of the Plio- 15 Quaternary gravely deposits of the foreland but significantly lower than the rates recently obtained from cosmogenic dating of river sand.“ - you mean the Tianshan foreland? - Where is the location of the cosmogenic dates?

542, 20: “remains an essential topic of research” - is an important research field

Additional specific comments are given in the attached pdf file. My apologies for this unorthodox editing style, but given the scale of comments I found this the most convenient way.

Please also note the supplement to this comment:
http://www.solid-earth-discuss.net/3/C301/2011/sed-3-C301-2011-supplement.pdf

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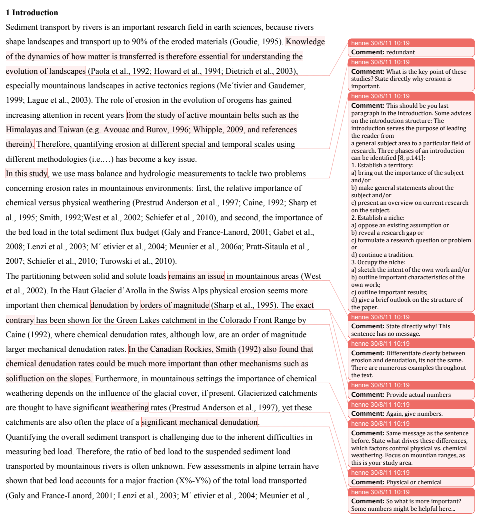
Interactive comment on Solid Earth Discuss., 3, 541, 2011.



1 Introduction

Sediment transport by rivers is an important research field in earth sciences, because rivers shape landscapes and transport up to 90% of the eroded materials (Goudie, 1995). Knowledge of the dynamics of how matter is transferred is therefore essential for understanding the evolution of landscapes (Paola et al., 1992; Howard et al., 1994; Dietrich et al., 2003), especially mountainous landscapes in active tectonics regions (Me´tivier and Gaudemer, 1999; Lague et al., 2003). The role of erosion in the evolution of orogens has gained increasing attention in recent years from the study of active mountain belts such as the Himalayas and Taiwan (e.g. Avouac and Burov, 1996; Whipple, 2009, and references therein). Therefore, quantifying erosion at different special and temporal scales using different methodologies (i.e.…) has become a key issue.

In this study, we use mass balance and hydrologic measurements to tackle two problems concerning erosion rates in mountainous environments: first, the relative importance of chemical versus physical weathering (Prestrud Anderson et al., 1997; Caine, 1992; Sharp et al., 1995; Smith, 1992;West et al., 2002; Schiefer et al., 2010), and second, the importance of the bed load in the total sediment flux budget (Galy and France-Lanord, 2001; Gabet et al., 2008; Lenzi et al., 2003; M´ etivier et al., 2004; Meunier et al., 2006a; Pratt-Sitaula et al., 2007; Schiefer et al., 2010; Turowski et al., 2010).

The partitioning between solid and solute loads remains an issue in mountainous areas (West et al., 2002). In the Haut Glacier d’Arolla in the Swiss Alps physical erosion seems more important then chemical denudation by orders of magnitude (Sharp et al., 1995). The exact contrary has been shown for the Green Lakes catchment in the Colorado Front Range by Caine (1992), where chemical denudation rates, although low, are an order of magnitude larger mechanical denudation rates. In the Canadian Rockies, Smith (1992) also found that chemical denudation rates could be much more important than other mechanisms such as solifluction on the slopes. Furthermore, in mountainous settings the importance of chemical weathering depends on the influence of the glacial cover, if present. Glacierized catchments are thought to have significant weathering rates (Prestrud Anderson et al., 1997), yet these catchments are also often the place of a significant mechanical denudation.

Quantifying the overall sediment transport is challenging due to the inherent difficulties in measuring bed load. Therefore, the ratio of bed load to the suspended sediment load transported by mountainous rivers is often unknown. Few assessments in alpine terrain have shown that bed load accounts for a major fraction (X%-Y%) of the total load transported (Galy and France-Lanord, 2001; Lenzi et al., 2003; M´ etivier et al., 2004; Meunier et al.,

Fig. 1.

2006a; Pelpola and Hickin, 2004; Pratt-Sitaula et al., 2007; Schiefer et al., 2010; Wulf et al., 2010). However, bed load is often assumed to be a given fraction of the suspended load. In this study we report a two-year survey on a braided stream in the Chinese Tianshan mountain range: the Urumqi River. We use this survey together with a 25-year record of discharge to perform a mass balance, derive erosion rates in a glacial catchment and discuss the respective contribution of mechanical and chemical weathering to denudation.

We first describe the data acquisition (the complete dataset is available as Supplement), and discuss measurement issues. We then present the daily pattern of sediment transport during two consecutive summers (2005 and 2006). The results are then used to derive a daily mass budget. We show that the concentration of both dissolved and solid loads are highly correlated to discharge. Rating curves are then derived and used together with a 25-year record of daily discharge to estimate yearly fluxes of dissolved and solid material and the corresponding weathering rates. Finally, the results obtained are discussed and compared to existing longer-term measurements of denudation rates. The mountains of Central Asia present an interesting counterpoint to the Himalayan orogeny or Taiwan accretion for the study of erosion and sediment transport. Although the elevation is high, the climate does not produce such intense events as monsoons or yearly typhoons. Precipitation is essentially orogenic and of limited amplitude (Zhao et al., 2008). On average, only 450mmyr−1 of rain falls over the Chinese Tianshan compared to the 2500mmyr−1 of rain that falls over Taiwan. Glacial retreat is well on its way (Aizen et al., 1997; Ye et al., 2005) and the size and depth of the remaining Tianshan glaciers is much smaller than their Himalayan counter part. Yet, this region is the place of significant and active tectonics. Convergence between the Tarim block (Taklamakan Desert) and the Dzunggar block (Dzunggar or Junggar Desert) accounts for a non negligible fraction of the India-Asia convergence (Avouac et al., 1993; Avouac and Tapponnier, 1993; Wang et al., 2001; Yang et al., 2008). The Tianshan mountain range is therefore a place where it is possible to survey sediment transport both, dissolved, suspended and bed load using conventional equipment (Me´ tivier et al., 2004; Meunier et al., 2006a), while tackling questions of geodynamic significance (Avouac et al., 1993; Molnar et al., 1994; Metivier and Gaudemer, 1997; Charreau et al., 2011; Poisson and Avouac, 2004).

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Fig. 2.

2 The Urumqi River

The dataset was acquired on the Urumqi River, a mountain stream located in the northeastern
part of the Tianshan mountain range in China (Fig. 1, a GoogleEarth kml file is enclosed as Supplement). The river flows from south to north and ends in a small reservoir in the Dzunggar Basin. Tianshan is an intracontinental range that was reactivated during the Cenozoic in response to the India-Asia collision (Avouac et al., 1993; Molnar et al., 1994; Metivier and Gaudemer, 1997). It is located both in Khazakhstan and China, 2000 km north of the collision front. The range experiences north-south compressive shortening and accommodates approximately 40% of the convergence (Avouac et al., 1993; Yang et al., 2008). The range extends for more then 2500 km and is bordered to the south and north by two internally drained sedimentary basins: the Tarim and Dzunggar Basins respectively. The Dzungbar Basin covers an area of 130 000km2. The sedimentary infill is of alluvial and lacustrine type. Water comes from the adjacent mountain ranges: Tianshan to the south and Altai to the north. The Dzunggar Basin records approximately 250 million years of sedimentary history. Deposits in front of the Tianshan range have experienced folding in the late Tertiary and Quaternary due to the northward propagation of deformation. Incision and entrenchment of all streams flowing to the basin is one of the main features of late glacial morphology (Molnar et al., 1994; Poisson and Avouac, 2004). The Urumqi, like other rivers, has incised deeply into its alluvial fan and created well defined terraces.

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The headwaters of the Urumqi River originate at 3600ma.s.l. The river originates from a glacier known as Glacier No. 1 that flows from Tangger peak (Fig. 2). The stream flows for 60 km before it leaves the high range and enters its alluvial piedmont. The drainage of the Urumqi at the range front is 925km2. Hydrology is controled by both orographic summer precipitation and glacial melting (Li et al., 2010; Ye et al., 2005).

The survey reported herein took place along a high mountain reach of the river (3200ma.s.l.) in a U shaped glacial valley at a distance of 8km from the headwater glaciers (Figs. 1,2 and 3). This alpine landscape consist of meadows, glacial tills and rock exposures. Rock outcrops consist of diorite, augen gneiss, schists and small outcrops of granite near the headwaters (Yi et al., 2002). There seems to be no limestone outcrop upstream of the survey site. Eventually permafrost is present in the

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Fig. 3.

valley.

One of the advantages of surveying the Urumqi River lies in the existence of a large body of publications and studies on hydrology in this river due to the presence of the Tianshan Glaciological Station of the Chinese Academy of Sciences (e.g. Han et al., 2006; Lee et al., 2002; Li et al., 2006, 2010; Ye et al., 2003, 2005; Yi et al., 2002; Zhang et al., 2005; Zhao et al., 2008).

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The river morphology at the sampling site varies from a wandering to a weakly braided gravel bed stream (Fig. 2). The median grain size is on the order of D50 ! 20mm and D90 ! 160mm (M´ etivier et al., 2004). The bed is organized into patches and there is no developed armour (Figs. 2a–c). The mean annual temperature and precipitation measured at the Daxigou meteorological station near the sampling site are −5.1 #C and 450 mm, respectively (Ye et al., 2005). At this location the river flows for approximately a five month period between mid-May to mid-October, corresponding to the melt period.

Flow is surveyed by the Tianshan Glaciological Station of the Chinese Academy of Sciences from May to September. About 90% to 95% of the annual runnoff occurs during these five months (Li et al., 2010). Based on the glacial runoff measured at the Number 1 glacier by the Chinese Academy of Sciences and on the total surface

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of the glaciers in the catchment, it is possible to estimate that about 40% of the discharge at the sampling site comes from glaciers whereas the remaining 60% comes from precipitation.

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The measurements reported hereafter were performed at two different subsites approximately 130m apart (Figs. 1, 2 and 3) and located approximately 2.5km downstream of the Total Control Station site of the Tianshan Glaciological Station (see Fig. 1 for location). Site 1–1, where measurements were made during the three years of survey, is located downstream of a confluence scour (Fig. 3). Site 1–2 is located under a small iron bridge that was constructed in 2006 on a straight reach of the river just upstream of site 1–1 (Fig. 3). We therefore have a double series of measurements in this area in 2006.

3 Data acquisition

3.1 Water sampling

Water samples were taken with a depth integrating USDH48 sediment sampler. Each sample was taken in the centre of the channel by an operator who manually lowered

Fig. 4.

and raised the sampler at a constant velocity.

Samples were filtered though NalgeneR filtration units using 0.45 µm filters within a couple of hours after being collected. The collection of samples for solute analyses started after 250 ml of river water was passed through the filter. Two vials were collected: one was acifided to pH = 2 for cation analysis and the other one was kept non-acidified for anion and silicic acid measurements. Solute concentrations were measured in Paris by DionexR ion chromatography. For all cations and anions, the precision is better than 5 %. The concentration of bicarbonate ion HCO−3 was deduced from cation and anion concentrations by electrical mass balance.

Filters were dried in a oven at 60 "C and weighted to determine the solid mass of the suspended matter.

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3.2 Bed load

Bed load measurements were made using a hand held pressure difference sampler. The opening of the sampler measured 0.3 by 0.15 m, the expansion ratio was 1.4, and the sampler was equipped with a 0.25mm mesh bag. Given these dimensions, our sampler should have the same properties as a Toutle river sampler (Diplas et al., 2008). These samplers were devised following discussions on the problems associated with using samplers with large pressure differences such as the Helley-Smith sampler (Hubbell, 1987; Thomas and Lewis, 1993; Diplas et al., 2008). Sampling efficiency of the Toutle river sampler ranges between 80–116% (Diplas et al., 2008) so that the measurements obtained are on average likely to be good estimates of the true fluxes. On average, the sampling duration was 120 s per sample. Each individual sample was weighed. We did not follow the cross-section average sampling procedure for the reasons discussed by Liu et al. (2008), yet it is possible to integrate the local transport rates in order to calculate the bed load flux passing through the section. We adopt this procedure here. Bed load catches were then dried and sieved in order to study the fractional transport of sediment (Liu et al., 2011). The average ratio between the dry and wet mass was found to be 0.86 for the Urumqi River.

There has been much debate on bed load sampling techniques especially using portable samplers (Bunte and Abt, 2005; Vericat et al., 2006; Bunte et al., 2008; Diplas et al., 2008). We therefore found it interesting to compare measurements performed at two subsites separated by 200 m. The measurements were not concurrent but were made sufficiently close to one another so that the discharge did not change significantly

Fig. 5.

(see discussion on velocity measurements). Individual local transport rates were integrated over the wetted perimeter to obtain the mass flux passing the section at each 25 subsite. The measurements where then compared (Figure 5) A clear trend is observed and the majority of the measurements are comparable within a factor of two. Almost all bed load rates are comparable within a factor of 5.

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The observed variations can be related to the sampling technique, the inherent stochastic nature of individual grain movement or local degradation or aggradation waves. Nevertheless, it is interesting to note that the majority of our measurements of bed load rates collapse within a factor of 2. This indicates that the sampling technique, within its limitations (Ryan 5 and Porth, 1999; Bunte and Abt, 2005; Vericat et al., 2006; Diplas et al., 2008), seems both robust and reproducible. It also suggests that, on average, bed load transport remains constant along the reach.

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Comment: Part of the results

3.3 Flow velocity and discharge

For each bed load measurement a velocity profile was made at the same location. Ve10 locity was measured with an OTT C20 mechanical velocimeter (Me´ tivier et al., 2004; Meunier et al., 2006b; Liu et al., 2008, 2010). Between one and five individual measurements of the velocity were made depending on flow depth. Each individual measurements gives the velocity averaged over 60 s.

Average flow velocity was calculated by simple discrete integration following:

where vi (zi) is the individual measure of the velocity (in ms−1) of the ith point taken at depth zi where the flow depth is h. Based on continuity assumption we assume that the velocity at the bed, is zero. Discharge is then calculated by transverse integration of the velocity hence

where uj (yj) is the average velocity of the jth point taken at a distance yj from the bank of the stream with width W. Here again continuity implies that the average velocity u

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is zero at the banks. This technique was successfully used by Meunier et al. (2006a) to study the dynamics of flow in a proglacial mountain stream in the French Alps. This technique, although time consuming, has advantages compared to other gauging techniques (see Sanders, 1998). First, it does not necessitate any assumption about the 5 form of the velocity profiles to derive the average flow velocity and discharges. Second, it can be used to derive shear stress distributions on the bed and friction coefficients.

3.4 Relevance of data acquisition

Fig. 6.

To summarize, the survey of the Urumqi River was performed using acquisition and processing procedures that are comparable to classical procedures used by other re10 searchers (Ashworth et al., 1992; Meunier et al., 2006a; Habersack et al., 2008) on several field sites. Our dataset, spans several flood seasons and includes both hydrology and flow velocity measurements, sediment information (bed load and suspended load) and chemical composition. Altogether, 194 gauging and coeval sediment sampling were performed on the river during 2005 and 2006. The dataset is freely available 15 as Supplement.

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Repeated sampling at two geographically close subsites in 2006 allows for a direct estimate of the reproducibility of our measurements. As expected dissolved concentrations are the most reproducible measurement. Concentrations measured at the two subsites are equivalent within 5 %. Discharge and suspended concentrations are found 20 to be consistent within 20 %. The larger uncertainty maybe related to effects such as section topography, sampling time (it takes approximately 30 to 45 min to perform a gaging) and spacing between points (density of the measurements). Sampling time is probably the most important factor. Given the uncertainty related to using mechanical propellers and the fact that discharge varies on a diurnal basis due to glacial melting, 25 Fig. 6 clearly validates the measurements performed.

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Bed load, as discussed above, is the least reproducible quantity measured. Most rates are consistent within a factor of 5 and a little more than half within a factor of 2. Again, this is perhaps due to the sampling procedure, bed composition and the fact

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that bed load is by essence a local phenomenon that is very difficult to sample and integrate over a section (Liu et al., 2008).

In order to simplify the analysis a composite series was made for 2006. For the days on which concurrent measurements were performed at the two subsites, we averaged the resulting values. 5 For the days on which only one section was surveyed, we used the available data. Thus, unless explicitly mentioned in what follows, the 2006 dataset is a composite sample of the measurements performed at the two subsites.

4 Analysis of the results

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Comment: Results

Figure 7 shows the evolution of the total load measured in the Urumqi River together 10 with the repartition of this load into solute, suspended and bed loads. The first striking feature of mass transport in the Urumqi River is the importance of dissolved load.

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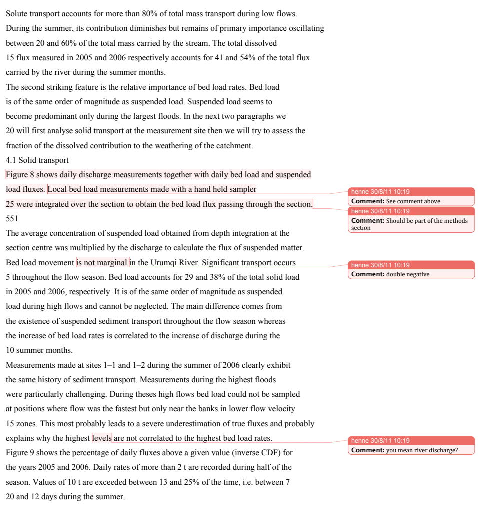
Fig. 7.



Solute transport accounts for more than 80% of total mass transport during low flows. During the summer, its contribution diminishes but remains of primary importance oscillating between 20 and 60% of the total mass carried by the stream. The total dissolved flux measured in 2005 and 2006 respectively accounts for 41 and 54% of the total flux carried by the river during the summer months.

The second striking feature is the relative importance of bed load rates. Bed load is of the same order of magnitude as suspended load. Suspended load seems to become predominant only during the largest floods. In the next two paragraphs we will first analyse solid transport at the measurement site then we will try to assess the fraction of the dissolved contribution to the weathering of the catchment.

4.1 Solid transport

Figure 8 shows daily discharge measurements together with daily bed load and suspended load fluxes. Local bed load measurements made with a hand held sampler were integrated over the section to obtain the bed load flux passing through the section.

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The average concentration of suspended load obtained from depth integration at the section centre was multiplied by the discharge to calculate the flux of suspended matter. Bed load movement is not marginal in the Urumqi River. Significant transport occurs throughout the flow season. Bed load accounts for 29 and 38% of the total solid load in 2005 and 2006, respectively. It is of the same order of magnitude as suspended load during high flows and cannot be neglected. The main difference comes from the existence of suspended sediment transport throughout the flow season whereas the increase of bed load rates is correlated to the increase of discharge during the summer months.

Measurements made at sites 1–1 and 1–2 during the summer of 2006 clearly exhibit the same history of sediment transport. Measurements during the highest floods were particularly challenging. During theses high flows bed load could not be sampled at positions where flow was the fastest but only near the banks in lower flow velocity zones. This most probably leads to a severe underestimation of true fluxes and probably explains why the highest levels are not correlated to the highest bed load rates.

Figure 9 shows the percentage of daily fluxes above a given value (inverse CDF) for the years 2005 and 2006. Daily rates of more than 2 t are recorded during half of the season. Values of 10 t are exceeded between 13 and 25% of the time, i.e. between 7 and 12 days during the summer.

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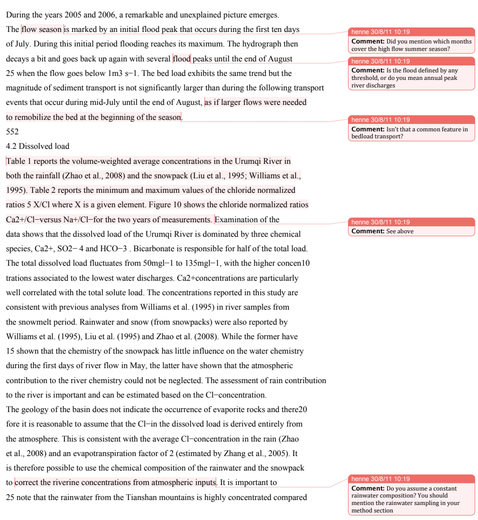
Fig. 8.



During the years 2005 and 2006, a remarkable and unexplained picture emerges. The flow season is marked by an initial flood peak that occurs during the first ten days of July. During this initial period flooding reaches its maximum. The hydrograph then decays a bit and goes back up again with several flood peaks until the end of August when the flow goes below 1m3 s−1. The bed load exhibits the same trend but the magnitude of sediment transport is not significantly larger than during the following transport events that occur during mid-July until the end of August, as if larger flows were needed to remobilize the bed at the beginning of the season.

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4.2 Dissolved load

Table 1 reports the volume-weighted average concentrations in the Urumqi River in both the rainfall (Zhao et al., 2008) and the snowpack (Liu et al., 1995; Williams et al., 1995). Table 2 reports the minimum and maximum values of the chloride normalized ratios 5 X/Cl where X is a given element. Figure 10 shows the chloride normalized ratios Ca2+/Cl−versus Na+/Cl−for the two years of measurements. Examination of the data shows that the dissolved load of the Urumqi River is dominated by three chemical species, Ca2+, SO2− 4 and HCO−3 . Bicarbonate is responsible for half of the total load. The total dissolved load fluctuates from 50mgl−1 to 135mgl−1, with the higher concentrations associated to the lowest water discharges. Ca2+concentrations are particularly well correlated with the total solute load. The concentrations reported in this study are consistent with previous analyses from Williams et al. (1995) in river samples from the snowmelt period. Rainwater and snow (from snowpacks) were also reported by Williams et al. (1995), Liu et al. (1995) and Zhao et al. (2008). While the former have shown that the chemistry of the snowpack has little influence on the water chemistry during the first days of river flow in May, the latter have shown that the atmospheric contribution to the river chemistry could not be neglected. The assessment of rain contribution to the river is important and can be estimated based on the Cl−concentration.

The geology of the basin does not indicate the occurrence of evaporite rocks and therefore it is reasonable to assume that the Cl−in the dissolved load is derived entirely from the atmosphere. This is consistent with the average Cl−concentration in the rain (Zhao et al., 2008) and an evapotranspiration factor of 2 (estimated by Zhang et al., 2005). It is therefore possible to use the chemical composition of the rainwater and the snowpack to correct the riverine concentrations from atmospheric inputs. It is important to note that the rainwater from the Tianshan mountains is highly concentrated compared

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Comment: Isn't that a common feature in bedload transport?

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Fig. 9.

to the world average (Berner and Berner, 1996). This feature is attributed by Zhao et al. (2008) to the leaching of atmospheric dust derived from the Takimakan desert. The origin of chloride is probably desertic evaporite formations. Zhao et al. (2008) have
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shown that, in the glacial valley, winds could carry a large amount of dusts from the Taklimakan Desert, south of the range, and that this desert was probably the main source of NaCl present in the summer orographic precipitation. The dissolved load of the river is thus expected to be a mixing between solutes derived from the rocks between the drainage basin and rainwater. In Table 2, we show the minimum and maximum values of the Cl^- normalized ratios in the rainwater and Urumqi River for all cations and silica. Na^+, Ca^{2+}, Mg^{2+} and K^+ are enriched in the river compared to the rain and most probably derive from silicates (Na^+, Mg^{2+}, K^+) and carbonates (Ca^{2+}). In Fig. 10, Ca^{2+}/Cl^- and Na^+/Cl^- have been plotted for the two years of measurements, the straight line indicates a mixing between two main endmembers, which are likely to be the atmopheric input on one hand and a rock weathering endmember on the other hand. The relative enrichment in Ca with respect to Na for this latter endmember clearly indicates a carbonate weathering source (Negrel et al., 1993). Similar binary mixing relationships can be found using the different elemental ratios. The Urumqi River Basin is essentially a silicate-dominated basin according to the geology, and it would be surprising to find a significant contribution of carbonate weathering. We attribute this significant carbonate contribution either to the contribution of carbonate dust derived from dry atmospheric deposits or to the contribution of disseminated carbonate minerals present in the bedrocks. Outcrops of carbonate rocks are described nearby by Williams et al. (1995), though apparently not upstream of the survey point (Yi et al., 2002), and a number of papers describing river water composition in high physical erosion regimes have noticed that even silicate draining waters can be influenced by carbonate dissolution (e.g. Anderson et al., 2003; Jacobson and Blum, 2000). This peculiarity is attributed by these authors to the contribution of disseminated calcite in the granitic rocks whose weathering is facilitated by glacial abrasion and the rapid production of fresh mineral surfaces by glaciers.

The SO_4^{2-}/Cl^- ratio of the river samples is much higher in the river than in the rainfall.

Fig. 10.

This clearly suggests that a source of sulphate is present in the drainage and that sulphate ions have to be included in the erosion budget. Sulfur oxidation could probably
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be a good candidate for this. This internal (rather than anthropogenic pollution) origin of sulphate is confirmed by the !34S values found by Williams et al. (1995) in the river waters. In particular, it seems that the possibility of the transport of dust particles from the steel mill located in the town of Houxia or from Urumqi is low. Oxidative weathering of pyrite has been described in many places to be a significant source of sulphuric acid and thus of acidity. For example, Anderson et al. (2003) have shown that in glacierized catchments from Alaska, oxidative weathering of pyrite and carbonate weathering are the two over-riding mechanisms explaining the water chemistry. The global importance of carbonate weathering by sulphuric acid is a global feature that has also been recently documented in southern China, Taiwan or the Mackenzie River Basin by Calmels et al. (2007, 2011). The NO_3^-/Cl^- ratio presents an interesting case. This ratio is higher in the river compared to the rainfall, but NH_4^+ is also present in the rainfall. If we calculate the ratio $(NO_3^- + NH_4^+)/Cl^-$ and compare it to the NO_3^-/Cl^- measured in the river, the values become comparable. It is therefore possible that bulk nitrogen has an atmospheric origin and that nitrification occurs in the soil that transforms NH_4^+ into NO_3^-. This reaction provides an additional source of acidity available for chemical weathering. Finally, the rest of acidity is provided by carbonic acid and can be calculated based on the excess of bicarbonate in the river samples. On average, in the upper Urumqi River, the amount of protons derived from sulphuric acid is equivalent to that provided by soil carbonic acid. In a weathering mass budget perspective, bicarbonate, that is of atmospheric origin does not have to be taken into account. In order to calculate the contribution of atmospheric inputs to the river chemistry, the volume-weighted mean annual chemistry of rainfall collection in the glacial valley, 2km upstream from our measurements by Zhao et al. (2008), was used.

where [X]cyclic is the contribution of rainfall for a given element X (Millot et al., 2002; Calmels et al., 2011). Atmospheric contribution was calculated for all the cations plus
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SO_4^{2-} (oxygen is not taken into account in the final balance as it comes from atmospheric CO_2). Half of the corresponding HCO_3^- content comes from the weathering of carbonates and was eventually taken into account (under the form $C0_3^{2-}$)

Fig. 11.

We assume that all Cl^- is of atmospheric origin and we therefore apply the mean annual chemistry of the rainfall correction to the 2005 and 2006 river samples. A significant atmospheric contribution is found for the Cl^-, Na^+ and Mg^{2+} ions whereas Ca^{2+}, Si, K^+ and SO_4^{2-} are essentially derived from chemical weathering. The proportion of HCO_3^- derived from the bedrock was calculated based on the electrical balance: where " denotes atmospheric correction. In the rest of the paper, dissolved concentrations, unless specifically stated, correspond to the fraction that comes from weathering in the catchment.

5 Mass balance and erosion rates

henne 30/8/11 10:19
Comment: Sould be part of your results section

5.1 Rating curves for dissolved and solid concentrations

From our measurements it is possible to look for a relationship between discharge and concentrations both dissolved and solid. Figure 11 shows these results. Figure 11a shows the evolution of the chemical weathering, suspended and bed load concentrations, respectively. Together with the raw data we show the binned averages (larger points). Binning is a simple averaging technique used to reduce noise from raw datasets (Kuhnle, 1992). The bed load concentration is calculated by the ratio of measured bed load fluxes (Q_b), to their measured discharge (Q_w),

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The average value for bed load transport at high flows is low and probably irrelevant because at high flows we were not able to sample the section evenly. The place of the highest flow (hence highest load) could not be sampled leading to a severe underestimation of the fluxes. Apart from this bad value for bedload at high discharges, the picture that emerges is coherent. There is some scatter in the raw data points. Scatter is expected due to the measurement uncertainties discussed above and it is expected to be much larger for bed load than for suspended load and dissolved load. Despite this scatter, the average values exhibit clear trends. The bed load concentration rises from a threshold at around $0.6 m^3 s^{-1}$ to a constant value of around $50 mg l^{-1}$. Hence bed load fluxes become proportional to discharge. This type of evolution has already been noted by Mueller and Pitlick (2005) and Pitlick (2010) for rivers in Colorado. Suspended and chemical loads exhibit opposite power law trends with a chemical concentration

henne 30/8/11 10:19
Comment: You mean cycle?

Fig. 12.

that slowly diminishes with increasing discharge whereas the suspended concentration increases with discharge. As noted earlier, for a significant range of discharges, all three loads are of the same order of magnitude. For small discharges, the chemical load becomes the dominant form of mass transport whereas the suspended load becomes the dominant form of mass movement for large floods. The bed load evolves from a minimal contribution at low discharges to a median contribution at high flows. For a characteristic discharge of about $1 m^3 s^{-1}$, all the concentrations are approximately equal.

Given these correlations and the related measurement uncertainties and in order to simplify the analysis and the mass balance presented herein, we added the bed load and the suspended load together to calculate a total solid load concentration

$$C_{solid} = C_s + C_b, \quad (6)$$

that can be compared to the chemical concentrations (Fig. 11b). As for Fig. 11a, the correlations are evident and can be fitted using simple power laws according to

$$C_{dissolved} = 40\ Q^{-0.2}, \quad R^2 = 0.76 \quad (7)$$

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and

$$C_{solid} = 37\ Q^{0.9} \quad R^2 = 0.96 \quad (8)$$

The prefactors in Eqs. (7) and (8) correspond to the concentration at the characteristic discharge of $1 m^3 s^{-1}$. This discharge therefore corresponds approximately to an inversion in the relative importance of the loads. below $1 m^3 s^{-1}$ chemical weathering makes up the dominant component of mass transport whereas above $1 m^3 s^{-1}$, the solid load becomes the dominant mass transport mechanism.

Finally, it is interesting to note that the correlation obtained for the Urumqi River compares closely to the correlations found by Godsey et al. (2009) for rivers in the United States. The reasons for this nearly chemo-static (the concentration does not depend on discharge) behaviour where the concentration follows a power law dependence on discharge with a small negative ("0.2–0.25) exponent are still debated (Godsey et al., 2009; Devauchelle et al., 2011). However, at least in the case of the Urumqi River, the relatively low value of the exponent shows that the chemical composition is not diluted at high discharge.

5.2 Return period of floods in the Urumqi River

Recently Schiefer et al. (2010) studied the pattern of sediment yield in a montane catchment of British Columbia. They showed that extrapolation of short-term surveys

Fig. 13.

to estimate long-term denudation rates could be biased if the hydrologic regime, especially its variability, was not properly considered. This question was also raised by Wulf et al. (2010) in an analysis of the magnitude frequency distribution of rainfall in the north west Himalays and the correlative importance of rare extreme events on the sedimentary budget of the Baspa River. We address this problem here by studying the magnitude frequency distribution of the discharges measured along the Urumqi River. Upstream of our survey site, the Glaciological station of the Academy of Sciences maintains a hydrologic station where daily discharge is being measured four times a day during five months each year, from May to September (Li et al., 2010). Although

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there may be some small flow after September (more rarely before May), these daily measurements (Fig. 12a) catch most of the discharge of the river. Our record extends from 1983 until 2007; only the year 1996 is characterized by a strong lack of data. On 15 July 2005, the largest flood recorded in the valley occurred with a discharge of 9.56m3 s−1. This flood has a Weibull return period of 25 years, i.e. the length of the record. In order to assess its possibly larger return period, we performed a classical return period assessment using both lognormal and Gumbel distributions (Bennis, 2007). The results are shown in Fig. 12b–c. Both distributions predict all the maximum yearly discharges well except for the largest. The Gumbel distribution predicts that the flood observed in 2005 should occur once every 125 years whereas the lognormal distribution

predicts a return period of 377 years. Even if these return frequencies may be overestimated this analysis shows that the 2005 flood most probably has a large return period, on the order of a century.

We could not sample this flood because the road was dangerous due to the rainfall but we sampled floods of more than 7m3 s−1 which is obviously not orders of magnitude different from 10m3 s−1. Hence, there is no grounded reason why the concentration of material should exhibit a special trend for this special flood. Therefore, we can safely argue that the correlation obtained with our survey is robust in the sense that it holds for the entire range of possible discharges at the centennial time scale.

> henne 30/8/11 10:19
> **Comment:** You could argue in the following way: "Within a range of X to Y m3/s river discharge we find a close correlation (r2 = z) between river discharge and sediment flux. Therefore, we infer that peak river discharges with a magnitude of QX follow the correlation with an estimated sediment flux of SX."

5.3 Influence of daily fluctuations

In order to derive daily denudation rates, we couple the discharge-concentration relationships (7) and (8) together with the daily mean discharge. One can argue that because of glacial melting the Urumqi River experiences a significant variation in terms

Fig. 14.

of the discharge during each 24 h cycle. Because of the exponents of (7) and (8), this influence can be shown to be negligible. For simplicity's sake, let us assume that the hydrograph presents a symmetrical triangular shape with a rising and a falling limb of

> henne 30/8/11 10:19
> **Comment:** Which influence?

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T =12 hours each. The instantaneous discharge is defined according to where Q(t) is the instantaneous discharge as a function of time t, Qmax and Qmin the maximum and minimum daily discharges. The average daily discharge is then #Q$ = 0.5(Qmax+Qmin). Assuming that the minimum discharge (at sunset) is negligible compared to the maximum discharge, Eqs. (9 and 10) become

We then have #Q$ % 0.5 Qmax. Using the relationships (7) and (8) between the concentration

and discharge together with (11), we can then calculate the volumes of mass transported during the rising limb of the hydrograph (the same can be performed for the falling limb using (12)). For the solid load the volume of sediment computed during a period T is Vs,full = Q1.9

maxT/2.9. The same estimate performed using the average discharge leads to Vs,av = (Qmax/2)1.9T . The ratios of these two volumes is independent of both the period T and the maximum discharge Qmax. It is approximately Vs,full/Vs,av %1.3. In the case of dissolved budgets the ratio of these volumes is Vs,full/Vs,av %0.96.

Therefore, in the case of the Urumqi River, we conclude that the use of average daily discharge to calculate the solute and solid transport is relevant.

> henne 30/8/11 10:19
> **Comment:** It is really hard to understand what you mean.

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5.4 Denudation rates

Figure 13 show the "weathering" budget for the 25-year period. The 25-year average values are !17 t×km−2 ×yr−1 for chemical weathering and $29 t×km−2 ×yr−1 for mechanical erosion. This gives a total of 46 tkm−2 yr−1 of erosion on the upper catchment of the Urumqi River. The catchment of the upper reach is mainly composed of diorites, granodiorites, and schists. Assuming an overall density of 2.65 t×m−3, our estimate of the mechanical and chemical weathering corresponds to an average denudation rate of approximately 17–18mMyr−1. As discussed earlier, the chemistry of the cations is dominated by the presence of Ca2+and hence, by the weathering of carbonates. The source inside the basin is still a problem. Available geologic maps such as the one provided

Fig. 15.